

STRUCTURALLY-CONTROLLED HYDROTHERMAL DIAGENESIS OF
MISSISSIPPIAN RESERVOIR ROCKS EXPOSED IN THE
BIG SNOWY ARCH, CENTRAL MONTANA

by

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of

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in

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NOMENCLATURE

δ : delta
‰: per mil
Å: angstrom
BSFS: Big Snowy fault system
C: Celsius
CaCO₃: calcite
CaMg(CO₃)₂: dolomite
CMT: Central Montana Trough
CO₂: carbon dioxide
DEM: digital elevation model
DMSNT: Diffraction Management System for NT
Ga: gigaannum
GFTZ: Great Falls Tectonic Zone
GPS: Global Positioning System
HTD: hydrothermal dolomite
ICAL: Imaging and Chemical Analysis Laboratory
ICDD: International Centre for Diffraction Data
km: kilometers
kV: kilovolts
m: meters
Ma: megaannum
mA: milliampere
MBMG: Montana Bureau of Mines and Geology
mm: millimeters
MVT: Mississippi Valley-type
my: million years
NBS: National Bureau of Standards
NRIS: Natural Resource Information System
ppm: parts per million
SEDEX: sedimentary exhalative
SEM: Scanning Electron Microscope
SMOW: Standard Mean Ocean Water
SWC: Swimming Woman Canyon
USGS: United States Geological Survey
UTM: Universal Transverse Mercator
VPDB: Vienna Pee Dee Belemnite
XRD: X-ray diffraction
µm: micrometers

ABSTRACT

The subsurface characterization of three-dimensional structural traps is becoming increasingly important with the advent of new technologies for the sequestration of anthropogenic carbon dioxide, which often takes place within pre-existing, sealed reservoirs to permanently store greenhouse gasses that are detrimental to the global climate. Within the Big Snowy Arch, central Montana, reservoir units that are targets for carbon sequestration have experienced Laramide and younger deformation and widespread Eocene igneous activity, which introduced a heating mechanism for hydrothermal fluid flow and created anisotropy in Mississippian strata. One particular region of interest is the western flank of the Big Snowy Mountains, which contains a northeast-southwest striking, high-angle fault zone which has acted as a conduit for hydrothermal brine solutions into the overlying Phanerozoic rocks. Such fault zones often branch and bifurcate as they propagate up-section through the overburden, until a loss of thermally-driven hydrodynamic pressure terminates the upward movement of carbon dioxide-rich brines, leaving a distinct assemblage of collapse breccia rich in hydrothermal minerals, such as saddle dolomite and sulfide precipitates. To determine the degree of structurally-induced anisotropy within the reservoir units, field techniques (detailed structural measurements and lithologic descriptions) coupled with analytical methods (X-ray diffraction spectrometry, stable carbon and oxygen isotope analyses, secondary electron imagery, and petrography) were utilized. These techniques presented concrete evidence of hydrothermal mineralization and episodic fluid flow within the brecciated region of the fault zone. These areas are major avenues of enhanced porosity and permeability in the subsurface, which has important applications at some sites in Montana where carbon sequestration is under consideration (e.g., Kevin Dome).

INTRODUCTION

Background

Carbon sequestration is a natural geological process that has been occurring throughout geologic history through the deposition of limestone in marine and non-marine settings (Frost and Jakle, 2010). The advent of new technologies has allowed scientists to sequester anthropogenic carbon dioxide (CO₂) within pre-existing, sealed reservoirs to permanently store greenhouse gasses that are detrimental to the global climate. In order for an individual reservoir unit to be considered for this process, it must be thoroughly characterized for porosity, permeability, fractures, faults, and other heterogeneities that may influence how fluids move laterally and vertically through the unit. One component that appears to be important in Paleozoic reservoir rock units is structurally-controlled, low-temperature hydrothermal dolomite (HTD) alteration.

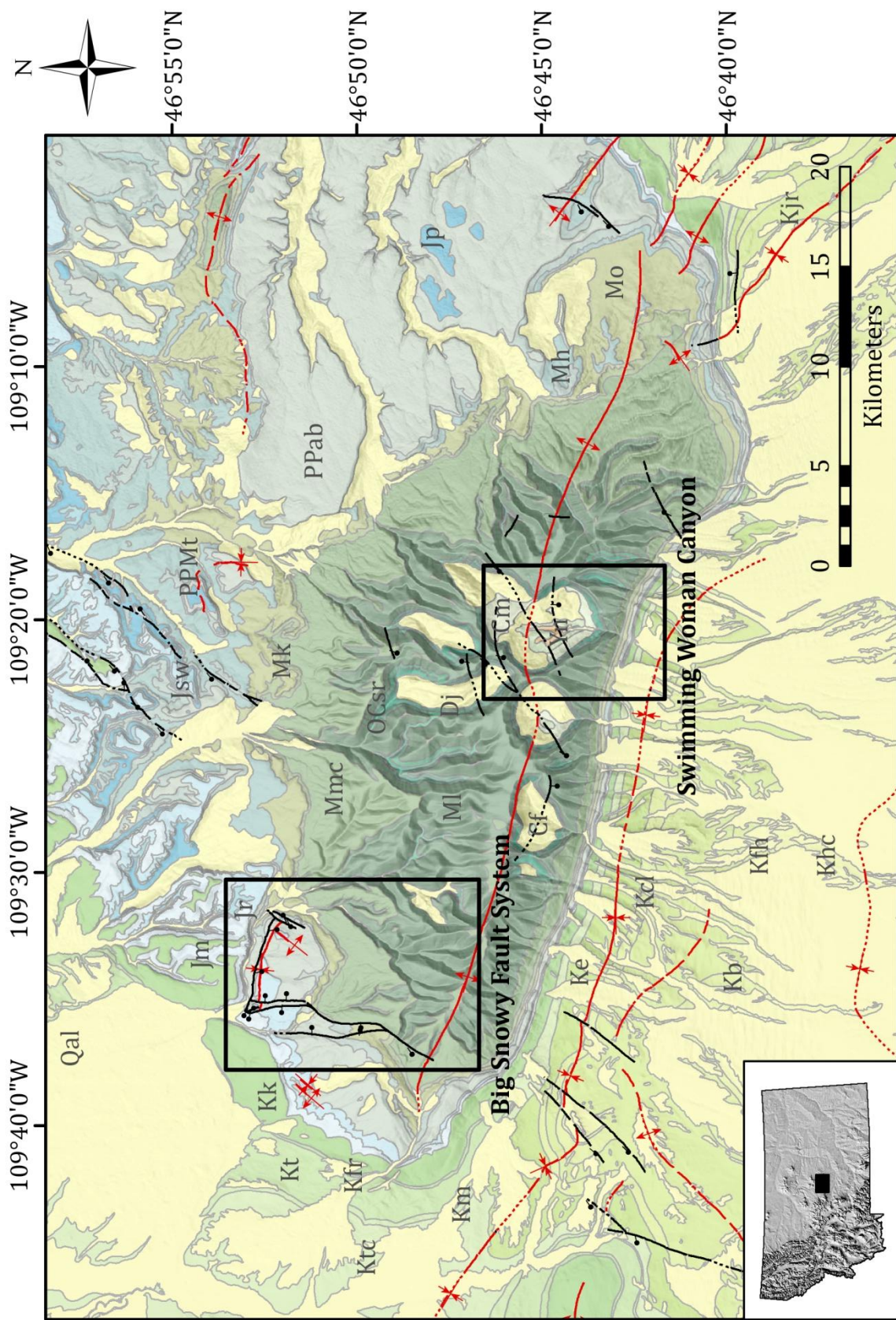
Paleozoic reservoir rocks in central Montana have experienced a long history of tectonic deformation along deep-seated fault systems, many of which have acted as conduits for HTD, sedimentary exhalative (SEDEX), and Mississippi Valley-type (MVT) sulfide mineralization. Faulting within structurally-controlled hydrothermal basins facilitates the movement of deep saline brines, which complicates deep aquifer modeling for carbon sequestration storage. Within the Big Snowy Mountains, reservoir rocks that are targets for carbon sequestration have experienced Laramide and younger deformation and widespread Eocene igneous

activity, which enhanced hydrothermal fluid flow paths and introduced anisotropy to the reservoir.

The study area for this project, located at the western end of the Big Snowy Arch, is focused on a northeast-southwest-striking high-angle fault zone that transects the entire range and is rooted in the Precambrian basement (Figure 1). Basement-rooted faults are well known for their conductivity of warm, hydrothermal brine solutions into the overlying Phanerozoic rocks (Davies and Smith, 2006). These fault zones often branch and bifurcate as they propagate up-section through the overburden above the Precambrian basement, which is very similar to the map view of the fault system under study as viewed obliquely (down-dip) to the north. Ultimately, a loss of thermally-driven hydrodynamic pressure will terminate the upward movement of CO₂-rich brines, leaving an assemblage of hydrothermal collapse breccia which may have enhanced the reservoir properties of Paleozoic reservoir units in central Montana.

Statement of Problem

In order to determine the spatial pattern of lineaments and fractures within the western Big Snowy Mountains, and to understand whether heterogeneities induced by hydrothermal brecciation are either conducive or inhibitive to subsequent fluid flow, the following research questions and hypotheses must be considered:



EXPLANATION			
Qal	Alluvium & landslide deposits	Mk	Kibbey Formation
Khc	Hell Creek Formation	Mmc	Mission Canyon Limestone
Kfh	Fox Hills Formation	MI	Lodgepole Limestone
Kb	Bearpaw Shale	Dj	Jefferson Formation
Kjr	Judith River Formation	Ocsr	Snowy Range Formation
Kcl	Claggett Shale	Cmu	Cambrian rocks, undivided
Ke	Eagle Formation	Cf	Flathead Formation
Ktc	Telegraph Creek Formation	Yn	Newland Formation
Km	Mowry Shale	— —	Approximate fault
Kt	Thermopolis Formation	- - - -	Inferred fault
Kfr	Fall River Formation		Concealed fault
Kk	Kootenai Formation	——	Observed fault
Jm	Morrison Formation	┆	Thrust fault; ball and bar on downthrown blocks
Jsw	Swift Formation	— —	Approximate fold
Jr	Rierdon Formation		Concealed fold
Jp	Piper Formation	——	Observed fold
PPab	Alaska Bench Formation	↕	Anticline
PPMt	Tyler Formation	↕	Syncline
Mh	Heath Formation		
Mo	Otter Formation		

Figure 1. (Continued from previous page). Field area map of the Big Snowy Mountains. The Big Snowy fault system and Swimming Woman Canyon field areas are outlined and displayed over the geologic map for central Montana. Explanation contains geologic units and symbols.

(1) *What structures within the Big Snowy Mountains and related areas serve as an analog to other carbon sequestration sites, and at what scales of observation?* The hypothesis that hydrothermal fluids often follow the paths of least resistance

through open discontinuities suggests that such fluids follow macroscopic fault and fracture systems, the latter of which were a product of shortening associated with the regional Laramide stress field. Field outcrop measurements of fractures at stations adjacent to hydrothermal structures and satellite lineament measurements were coupled with Rockware StereoStat software to resolve the structural and tectonic control over such weaknesses.

(2) *What is the stratigraphic distribution of hydrothermal structures, such as breccia pipes?* It was hypothesized that the size and distribution of hydrothermal breccia pipes would be capacious and abundant proximal to the fault zone compared to those located distally from the fracture system. In order to test this hypothesis, field outcrop measurements and ArcGIS were used to determine the stratigraphic distribution and near-distance proximity of hydrothermal structures that were discovered in the field.

(3) *How does hydrothermal deformation affect reservoir properties for CO₂ sequestration applications? To what extent does HTD diagenesis affect porosity and permeability?* It was hypothesized that hydrothermal fluids often deposit saddle dolomite and other secondary minerals as vein- and matrix-fill material. If HTD was present within the breccia pipes along the Big Snowy fault system (BSFS) and Swimming Woman Canyon (SWC) field areas, one could expect to see excellent secondary porosity and permeability in the carbonate reservoir units, especially in collapse brecciation (sag) features along pre-existing fault and fracture systems. To test this, field studies focused on characterizing the distribution, width, and

lithology of various collapse brecciation features ("breccia pipes") that lie along the trace of the fault under study. In order to test the hypothesis that the brecciating fluids were hydrothermal in origin, X-ray diffraction spectrometry and stable carbon and oxygen isotope analyses were performed on matrix material from brecciated and altered samples, the latter of which were plotted with standard Vienna Pee Dee Belemnite (VPDB) values for comparison. Secondary Electron Imaging was then used with ImageJ software to determine the quantitative changes in porosity values.

(4) *Do hydrothermal breccia pipes serve as a conduit or as a barrier to fluid flow in the subsurface?* The working hypothesis was that multiple crack-sealing events have created rubbly, poorly cemented breccias which aided in transporting fluids throughout the brecciated region. Field outcrop analyses, hand sample descriptions, and thin section petrography were used to create a paragenetic sequence to test this hypothesis.

Applications for Carbon Sequestration

Of all of the naturally occurring greenhouse gases (water vapor, carbon dioxide, methane, nitrous oxide, and ozone), CO₂ is the primary target for mitigation attempts worldwide because it accounts for 64% of emissions contributing to the greenhouse effect (Bachu and Adams, 2003; Şener and Tüfekçi, 2008). Since industrialization, atmospheric CO₂ levels have risen from 280 parts per million (ppm) to 360 ppm. This is a direct result of emissions from the anthropogenic consumption of fossil fuels, which provide 75% of the world's energy in the form of

coal, oil, and gas (Bachu and Adams, 2003; Şener and Tüfekçi, 2008). Fossil fuels remain a major component of energy usage due to their availability, competitive cost, and ease of transport and storage, with coal comprising 50% of electricity generation in the United States alone, and 25% globally (Bachu and Adams, 2003; Frost and Jakle, 2010). Carbon capture and storage technologies are thus becoming an important topic of research for many subdisciplines of geology.

Carbon capture and storage techniques require collecting CO₂ from power plants and other point sources, transporting it in its supercritical fluid-like phase to an injection site, and then pumping it deep underground into geologic storage reservoirs (Frost and Jakle, 2010; Smith et al., 2010). Ideal storage sites include depleted oil and gas reservoirs, deep saline formations, uneconomical coal seams, caverns in salt structures, or basalt formations below 800 meters (m) depth, so that CO₂ remains in a supercritical state with a liquid-like density, allowing it to occupy less pore space than it would in its gaseous phase (Bachu and Adams, 2003; Desideri et al., 2008; Buttinelli et al., 2011).

The first stage in implementing carbon sequestration applications is to characterize the reservoir properties of a potential geologic storage site (Chevalier et al., 2010). This includes identifying the residence time of brines, the capillary seal of the caprocks, and the presence of structures that could act as either a barrier or conduit to subsurface fluid flow. Following injection, the supercritical CO₂ acts as a buoyant plume, which distributes in the pore space of layers away from the injection point and adjacent to caprock seals (Wilkin and Digiulio, 2010). Unsealed

faults and fractures may act as permeable conduits to shallower groundwater reservoirs or to the surface. Although small amounts of CO₂ are not toxic, dissolution into groundwater may lower the pH and dissolve trace metals from the aquifer, increasing the concentration of toxic elements such as lead and arsenic (Keating et al., 2010). Fault leakage also becomes twice as great in unconfined aquifers than in confined units (Burnside et al., 2013). It is therefore imperative to understand the lithologic and structural style of the sequestration site.

Naturally-occurring CO₂ reservoirs may be characterized by four-way structural closure, porous and permeable reservoir units with large volume storage capabilities, a cap rock seal that is not compromised by open through-going faults or fractures, secondary sealed thrust faults which compartmentalize and "stack" the reservoir, and/or abundant reservoir fluids capable of carrying large amounts of CO₂ (Lageson, 2008; Lynds et al., 2010; Smith et al., 2010). In the Mississippian Madison Group reservoir targeted for carbon sequestration at the Moxa Arch-LaBarge Platform in southwest Wyoming, fracturing, tectonic brecciation, and hydrothermal diagenesis have effectively sealed structures during faulting events, compartmentalizing the carbonate unit (Thyne et al., 2010). Creating models that include discontinuities such as these are key to understanding how supercritical CO₂ will behave for geologically stable periods of time (>10,000 years).

If the porosity and permeability of the unit and salinity of the reservoir fluid are uniform throughout the unit, then the thickness of the unit is directly proportional to the amount of CO₂ capable of being stored (Chevalier et al., 2010).

However, models that aim to predict fault properties in the subsurface typically do not account for complex fault geometries, often overlooking possible leakage points at highly fractured, faulted, or altered areas (Dockrill and Shipton, 2010).

Nevertheless, carbon sequestration is still the most viable method of reducing CO₂ emissions. Other solutions, such as enhancing sinks in soils and vegetation or injecting into ocean basins, are often associated with difficulties in land use competition, high cost, technologic development, or a potentially high environmental impact, leading to legal and political issues (Bachu and Adams, 2003). The International Energy Agency aims to reduce CO₂ emissions up to 50% by the year 2050 (Frost and Jakle, 2010; Smith et al., 2010). The least expensive way for this to occur is to rely upon geological carbon capture and storage technologies for at least one fifth of that amount, further necessitating research into the preliminary characterization of reservoirs for carbon sequestration applications.

PREVIOUS INVESTIGATIONS AND NOMENCLATURE

Previous research into hydrothermal diagenesis has focused on building genetic models to identify the extent and degree of alteration in relation to fluid convection cells and/or fault zones. The quality of most carbonate reservoirs worldwide have been affected (whether positively or negatively) by structurally-controlled hydrothermal diagenesis (Smith and Davies, 2006). It has been identified that both the world's largest oil field (Ghawar, Saudi Arabia) and gas field (North Field, Arabian Gulf) contain a structurally-controlled diagenetic component (in these cases, hydrothermal dolomite). Many other fields have been affected by hydrothermal diagenesis, including those in the Devonian and Mississippian of the Western Canadian Sedimentary Basin, the Ordovician Michigan and Appalachian basins, the Ordovician Arbuckle and Ellenburger of the southern United States, the Mesozoic carbonates of the rifted North and South Atlantic margins, and the Cretaceous units of onshore and offshore Spain, among others (Davies and Smith, 2006).

Hydrothermal Fluid Migration

The term "hydrothermal" is oftentimes misapplied in the literature to explain a multitude of different diagenetic phenomena. The expression itself has no genetic implications regarding fluid source; rather, it is merely a descriptive term to describe aqueous solutions that are significantly warmer (geothermal) to hotter (hydrothermal) relative to the surrounding environment (Machel and Lonner, 2006).

2002). A change in ambient temperature is considered "significant" if the fluid exceeds the temperature of the host formation by at least 5° Celsius (C) (Machel and Lonnee, 2002; Smith and Davies, 2006). In most cases, the aqueous solutions, which are typically very saline, will also be at higher pressures than those present in ambient fluids within the host formation. The majority of hydrothermal diagenesis occurs at depths shallower than 1,000 m (in many cases at less than 500 m). To accomplish the significant temperature and pressure differences between the fluid and the host rock, fluids must be rapidly introduced to the system before being able to re-equilibrate to the ambient conditions (Davies and Smith, 2006; Smith and Davies, 2006). This requires both a mechanism for fluid migration through reservoir units and a conduit for the upward migration of heated, overpressured fluids.

Open faults provide the best conduit for fluids to migrate through the sedimentary section (Smith and Davies, 2006). Such regions are episodically dynamic, and are characterized by abrupt changes in applied stress, pore fluid pressure, and rates of fluid flow. Wrench (deep strike-slip) faults, such as the BSFS in the western Big Snowy Mountains, have a vertical to subvertical geometry in the basement and become progressively more oblique towards shallow depths, grading into en echelon shears at the surface (Davies and Smith, 2006). The position of wrench faults with respect to other features, such as sandstone aquifers, basement highs, or shale aquitards, may have a direct impact on fluid flow within the basin (c.f. Vearncombe et al., 1996; Davies and Smith, 2006).

Basement-rooted wrench faults may also result in the development of structural sags in elongate lows similar to negative flower structures (Davies and Smith, 2006; Smith, 2006). Such features may range in size from 300 m to several kilometers (km), extending vertically over tens of meters, and typically develop in long en echelon shear arrays. A structural sag is formed by transtensional faulting as the hanging wall of an extensional fault is down-dropped. This opens fractures which, in addition to the action of the fault, act as a conduit for the upward migration of hydrothermal fluids. This results in (and is often caused by) a loss of volume due to pressure solution and/or the mole-for-mole replacement of limestone by dolomite, as well as the vertical and lateral displacement of rock. The limbs of structural sags are typically areas of intense fracturing, and commonly possess the best porosity (Davies and Smith, 2006; Sagan and Hart, 2006; Smith, 2006).

Hydrothermal Dolomite

Research and discussion into the stoichiometric formation of dolomite has been disputed for many years. "The Dolomite Problem" in geology is that no scientist has yet been able to synthesize dolomite at earth surface temperature and pressure conditions. Interpretations for the environment in which dolomite formed varied throughout the years, with scientists believing in the reflux dolomitization model in the 1960s (and again recently as a model for widespread dolomitization from evaporite sources predominated), mixing zone dolomitization in the 1970s,

seawater dolomitization in the 1980s, and deeper burial and hydrothermal dolomitization from the late 1980s to present (Saller and Dickinson, 2011, and references therein).

The precipitation of dolomite is favored by high temperatures, as the solubility of calcite increases with increasing temperature (Land, 1983). The lower the calcium-magnesium ratio (and usually the higher the temperature), the more favorable the conditions for dolomitization; at higher ratios (and often lower temperatures), metastable calcium-rich dolomitization may occur. Such calcium-rich dolomites are more soluble than ordered dolomite, and thus will often precipitate from more magnesium-rich fluids. This gives way to the dolomitization of more ordered dolomites, since most dolomites form from the replacement of previously-formed carbonates (Land, 1983).

Matrix dolomites form at temperatures at or above the ambient temperature of the host rocks, at depths between 500 and 1,500 meters. These primary dolomite crystals either precipitate as primary sediment or form in megascopic pores as cement, and displace the original pore fluid as they grow (Land, 1983). Such dolomites are inhomogeneous, and consist of multiple generations of dolomite. Saddle dolomites form at higher temperatures (80-100°C), and precipitate as replacive fill either in voids within collapse features or pore space, or as intragranular cement in carbonates as regionally extensive deposits (Leach et al., 1991; Machel and Lonnee, 2002; Conliffe et al., 2012). Saddle dolomite is recognized by a coarsely textured, curved and distorted crystal morphology with undulatory

extinction under magnification (Davies and Smith, 2006). Kinks, bands, steps, and other defects signify that the crystals precipitated at a high rate, with growth occurring at crystal edges (Duggan et al., 2001; Davies and Smith, 2006; Luczaj et al., 2006).

Most (deep) dolomitization models assume the mole-for-mole replacement of calcite with magnesium, which assumes a conservation of naturally-occurring CO₂ and the replacement of approximately half of the calcium content of the limestone with magnesium in solution via concurrent dissolution and precipitation processes (Ehrenberg et al., 2006). Such a phenomenon creates a 13% porosity increase within the newly formed dolostones due to the lower molar volume and greater specific gravity of dolomite compared to limestone (Lovering, 1969; Moore, 2001). Such dolostones also are more resistant to chemical compaction and resulting cementation due to their rigid framework derived from the rhombic crystal habit of dolomite. Understanding the processes and products of dolomitization is thus an integral part of characterizing a reservoir.

Mechanical Properties of Breccia Pipes

When failure (shear) occurs along normal and thrust faults, the abrupt change in pore fluid pressure will allow for the injection of angular breccias toward the locality near the fault tip through which high pressure fluids had been permeating (Phillips, 1972; Davies and Smith, 2006). With each subsequent rupturing event, the thermal buoyancy of the fluids will initiate hydrofracturing at

the tip, which will extend the fault into a progressively more vertical incline. This results in the development of vertical breccia pipes and hydrothermal alteration that is generally confined to the hanging wall side of faults (Figure 2) (Phillips, 1972; Davies and Smith, 2006).

As fluids progressively permeate into the fault tip, they preferentially fill the pore space of rocks peripheral to the fault, oftentimes resulting in a zone of matrix dolomitization or mineralization (Davies and Smith, 2006). The stress acting on the fault, properties of the damage zone, and porosity and permeability of the carbonate rock all determine the size and extent of the zone of mineralization. Once the fault fails, the abrupt drop in pressure and loss of CO₂ by effervescence drives brecciation and the precipitation of coarser saddle dolomite, overprinting the matrix dolomitization. This cycle repeats itself as episodic fault reactivation continues, resulting in a halo of replacive dolomite surrounding the fault (Davies and Smith, 2006; Lopez-Horgue et al., 2010).

The development of these features along active faults is integral to the development and distribution of mineralized haloes and deep dolomite diagenesis. Lateral, unfocused fluid flow, though possible, is not a practical means of forming the laterally extensive zones of dolomite mineralization in the rock record. Fault and fracture networks are necessary to speed the rate of flow and maintain hydrothermal conditions (Smith, 2006). In order to determine the extent of their influence on subsurface reservoirs and reduce the risk in drilling for porous dolomite intervals, three-dimensional seismic imaging and seismic anomaly

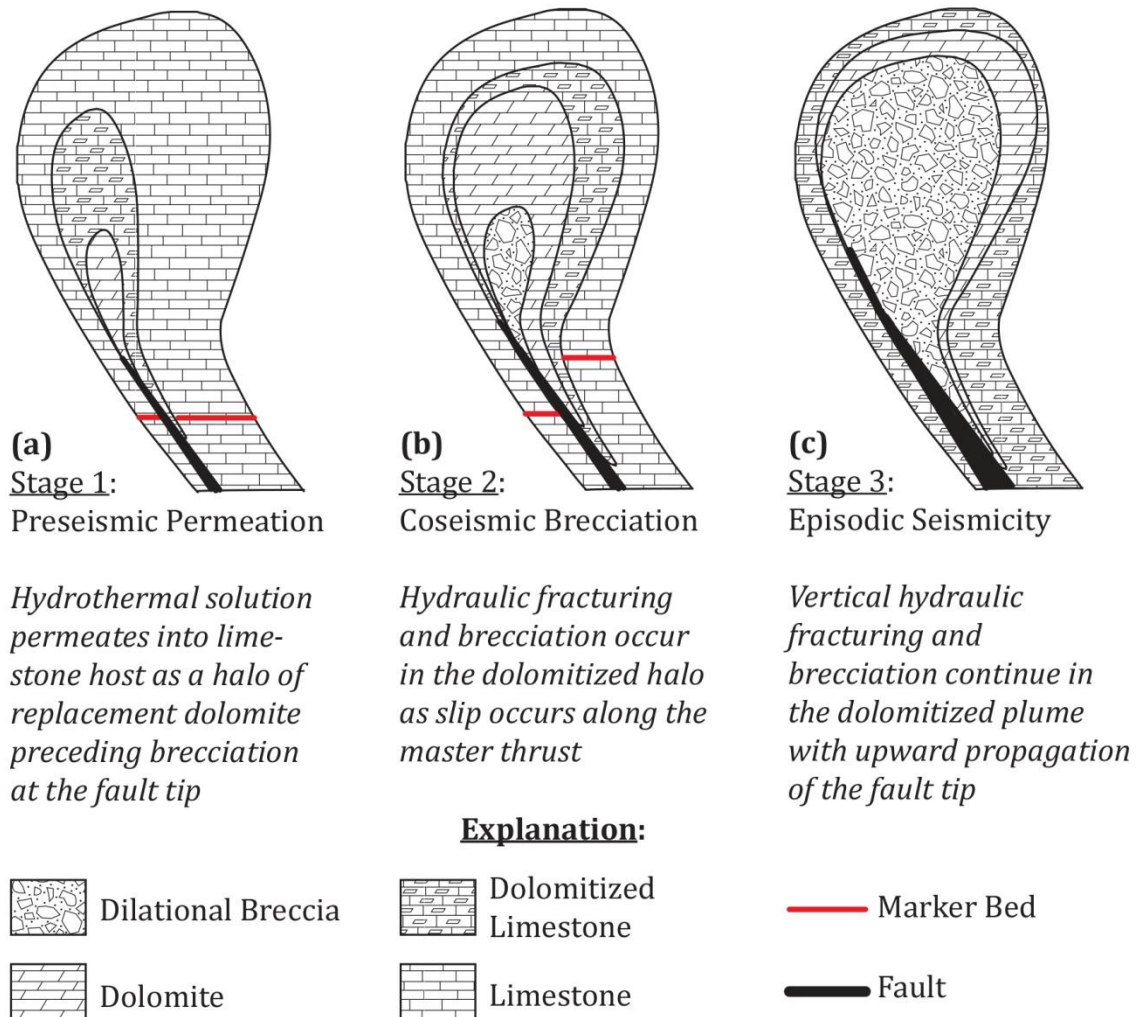


Figure 2. Model for the formation of hydrothermal breccia pipes. Hydrofracturing at the fault tip results in three stages of progressively damaged and mineralized zones. These stages include (a) a zone of permeation at the propagating fault tip, causing extensive hanging wall dolomitization; (b) a region of hydraulic fracturing and brecciation of the previously dolomitized halo, resulting in the precipitation of hydrothermal minerals; and (c) the repetition of seismic events, allowing the brecciated area to become progressively more vertical with continued activity (modified from Phillips, 1972; Davies and Smith, 2006).

mapping must be coupled with horizontal drilling oblique to regional tectonic and structural trends (Davies and Smith, 2006). These techniques are necessary in order to fully comprehend and characterize the reservoir.

Characterizing carbonate reservoirs poses a unique problem due to the complex interplay of petrophysical properties which present complicated vertical and lateral heterogeneities in reservoir facies. Such properties include the original heterogeneities within the facies unit, early diagenetic alteration of the host carbonate, and later diagenetic and structural overprinting affecting the reservoir rock (Westphal et al., 2004). In some localities, the hydrothermal fluids (and thus the brecciation) follow horizontal beds before cutting into stratigraphically younger units. This is a result of the mechanical properties of the unit through which the pipe propagates. In addition to these primary features, the self-healing properties of the breccia pipe strengthen the breccia zone, decreasing permeability in such zones before a new hydrofracturing event takes place (Westphal et al., 2004). As these associated cracks and fractures are further enhanced by hydrofracturing, they can be observed on scales from mm-sized fractures up to km-long faults (Jebrak, 1997).

Fractures and Linear Discontinuities

A fracture is defined as a planar discontinuity in a rock across which there is a loss of cohesion without apparent displacement (Van der Pluijm and Marshak, 2004). Extensional hydrofracturing and hydrothermal brecciation are two important deformation mechanisms which typically increase porosity and permeability in reservoir rocks, whereas pressure solution and fault cataclasis reduce such properties (Marshak and Mitra, 1988; Mitra, 1988; Hooker et al., 2012). In order to characterize such discontinuities on a local scale, the original

depositional and diagenetic properties must be recognized in association with the relative timing of structural and lithotectonic features (Mitra, 1988).

In tectonic systems, fractures are self-similar on a range of scales, meaning that they exhibit fractal behavior and hierarchical organization on all scales of observation (Le Garzic et al., 2011). The growth of fractures is a function of the tensile and shear stresses present within a rock (Gudmundsson et al., 2003). Extension (Mode I) fractures include both hydrofractures and tension fractures, both of which grow perpendicular to and away from the fracture plane, which is indicative of the minimum principal shortening direction. Tension fractures are rare, as they occur when the minimum compressive stress is negative in areas of the shallow crust undergoing active extension. Hydrofractures are much more common, forming at any depth when the pore fluid pressure is equal to or in excess of the tensile strength of the rock. Tensile stresses associated with the formation and growth of hydrofractures open joints up to a considerable distance away from the fracture tip, which have the tendency to link up with continued deformation, forming a fluid conduit. Shear (Mode II and III) fractures form when displacement is parallel with the fracture plane, often resulting in the reactivation of previously formed fractures and faults under different stress regimes. Such shear fractures often link up with normal faults at depth during lengthening and reactivation (Gudmundsson et al., 2003; Laubach, 2003).

In hydrothermal systems, the development of a hydrofracture is induced by the pressure of the solution, which forcibly widens the aperture of the fracture and

extends it, reducing the effective principle stresses in the rock at the fracture tip. As failure occurs, there will be an immediate drop in pressure, allowing the hydrothermal fluids to rush into the newly formed fracture and repeat the process. Each subsequent extension of the fracture will result in a small decrease of the differential stress of the region, allowing fractures to develop at consequently lower stresses during repeated events, and becoming more sensitive to the anisotropies of the rock (Phillips, 1972).

Fractures at multiple scales of observation typically consist of a narrow zone of closely-spaced bed-confined fractures residing within a larger sequence of through-going fractures (Gross and Eyal, 2007). The growth of fractures through stratigraphic layers is controlled by the mechanical properties of the unit. Competent units, such as carbonates, commonly have higher fracture densities than mechanically weak units, such as shales and sandstones (Mitra, 1988). A majority of fractures and veins will arrest at the contacts with different mechanical properties, creating a barrier that controls the length and distribution of fractures (Gross and Eyal, 2007). For those fractures that manage to propagate through layers with different mechanical properties, aperture will vary as a function of the Young's modulus. Aperture will increase in softer units (low Young's modulus) and decrease in stronger units (high Young's modulus) (Caine and Forster, 1999; Gudmundsson et al., 2003).

Fracture intensity increases with decreasing bed thickness and grain size (Mitra, 1988). In thin- to medium-bedded rocks with closely-spaced fractures,

through-going fractures form from the linkage of planar faults in a narrow zone across the unit (Graham Wall et al., 2006; Gross and Eyal, 2007; Sheldon and Micklethwaite, 2007). As brittle deformation continues, pre-existing fracture planes will preferentially become reactivated, developing into zones of similarly-aligned fractures with significant aperture across mechanical boundaries determined by the amount of strain present within the unit. This results in increased hydraulic communication between units due to the multi-scale linkage of fracture clusters, which forms a network of hydraulically-connected discontinuities that cut across stratigraphic boundaries (Gross and Eyal, 2007). These fracture corridors (“meshes”) result in zones of more intensely fractured rocks that are concentrated near fault systems and are dependent upon the properties of the shorter, disconnected joints and fractures attributed to reactivation and dilation (Le Garzic et al., 2011; Mondal and Mamtani, 2013).

The structural position exhibits a strong control on the amount of fracturing within a unit (Mitra, 1988). Structural positions that are more prone to fracturing include brittle, thin-bedded, fine-grained units located within angular fold hinges, steep forelimbs of folds, or fault zones. Flexural slip and interbed shearing reduce porosity and permeability in a vertical direction and compartmentalize the units laterally. As folding continues, deformation becomes more localized. Strain concentrates in the fold hinge, resulting in high fracture intensities. The steepening of forelimbs results both in bedding normal fractures and pressure solution and cataclasis, causing the fractures to fill with pressure solved minerals during

subsequent deformation (Mitra, 1988). In order for fractures to remain open, the development of fracture porosity must exceed that of synkinematic cementation. It is therefore important to recognize the causes of fracture growth and linkage, as well as primary and diagenetic cements that heterogeneously affect the rock mass.

Fault Zone Architecture and Fluid Flow

Faulting, like fracturing, behaves on a self-similar scale, where macroscopic failure is a result of the linkage of microscopic discontinuities in the rock (Sheldon and Micklethwaite, 2007). Distributed fracturing will eventually link up across mechanical boundaries and develop faults or shear zones, which in turn fracture the surrounding rock, resulting in analogous behavior on the decimeter to kilometer scale (Graham Wall et al., 2006; Sheldon and Micklethwaite, 2007). Faulting is caused by the shear stress acting on a plane under load (Sibson, 1990).

Whether a fault acts as a conduit, barrier, or combined conduit-barrier system is dependent upon the fracture permeability and entrained sediment grain size, which varies laterally across a fault zone as a function of the hydromechanical properties of the fault (Figure 3) (Caine et al., 1996; Gudmundsson et al., 2003). A fault zone is a region of branching, anastomosing, and linking fault cores and damage zones within a relatively undeformed protolith (Le Garzic et al., 2011). The strength of the fault is governed by the fluid pressure in the fault core and damage zone; as the fluid pressure increases, the effective normal stress decreases, and thus the strength is decreased (Jeanne et al., 2013).

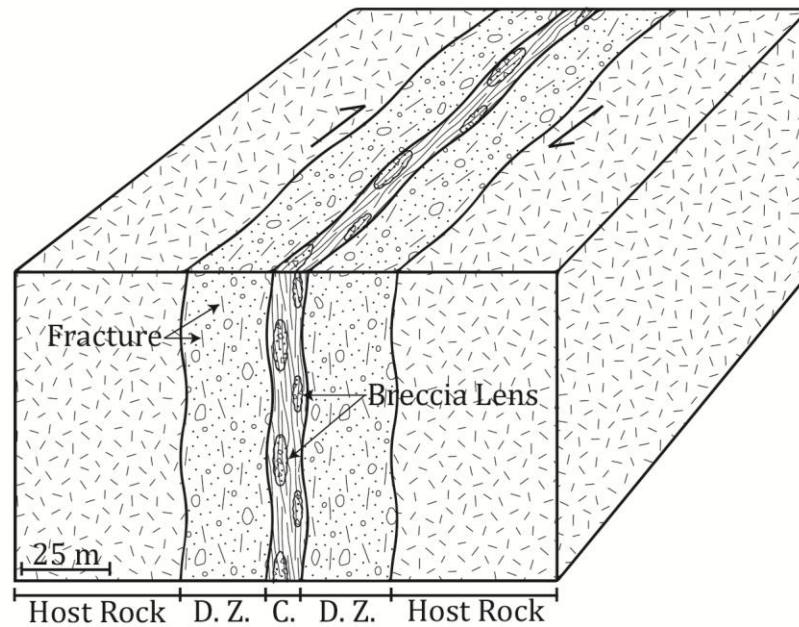


Figure 3. Generalized hydromechanical units of a strike-slip fault zone. A typical fault consists of a centralized fault core (C.) composed of clay, gouge, and tectonic breccias, which is surrounded by a highly fractured damage zone (D. Z.). The fault zone generally branches and anastomoses through the undeformed host rock (modified from Gudmundsson et al., 2003).

The fault core accommodates most of the displacement within the fault zone, and consists of slip surfaces, clay smears, cataclastic and brecciated rocks, unconsolidated gouge, and deformation bands. Cement precipitation, coupled with cataclasis, form permeability barriers in the subsurface, restricting fluid flow in a direction perpendicular to the fault plane (Caine et al., 1996; Evans et al., 1997; Antonellini and Aydin, 1999; Heynekamp et al., 1999; Nelson et al., 1999; Gudmundsson et al., 2003; Le Garzic et al., 2011). Pore size may be reduced by cataclasis, grain boundary sliding, grain rotation or reorganization, or diagenesis (Sigda et al., 1999). With a decrease in pore size, diagenesis may compartmentalize the reservoir by the formation of capillary barriers.

The boundaries between the fault core and damage zone are generally sharp, and are characterized by a reduction in permeability and strength across the contact as the gouge content accumulates and confining pressure increases (Chester and Logan, 1986). A fault damage zone consists of heterogeneously distributed subsidiary fractures, faults, cleavage, and veins of various sizes due to the initiation, propagation, and accommodation of slip (Heynekamp et al., 1999; Nelson et al., 1999; Gudmundsson et al., 2003; Le Garzic et al., 2011). Fractures found within the damage zone are three to five times greater than the density of fractures in the fault core, and are typically proportional to the thickness of the damage zone, which often results in a damage zone that is as much as 10^4 times more permeable than the core or protolith due to a slower response to changes in confining pressure (Evans et al., 1997).

The boundary between the fault damage zone and undeformed protolith is generally gradational. The protolith is characterized by intermediate permeabilities, which are inversely proportional to the confining pressure, and respond much more drastically to such changes in comparison to the fault core or damage zone (Evans et al., 1997). It contains short, disconnected fractures that are commonly cemented and are the site of more concentrated weathering processes.

The model for the formation and evolution of fault zones over time can be attributed to the fault acting as a valve or pump during seismic events. During an earthquake cycle, tectonic loading results in the variations of deviatoric and mean stresses (Wong and Zhu, 1999). In the fault valve model, overpressured fluids

episodically breach impermeable seals capping compartments, causing the upward discharge of fluids to a higher compartment before reaching hydrostatic equilibrium, resulting in hydrothermal self-sealing and the re-building of fluid pressure at depth (Sibson, 1990; Nelson et al., 1999). The timing of the failure is dependent upon the tectonic shear stress and fluid pressure during the interseismic period, which rebuilds toward the critical value needed to trigger the next episode of slip. The ability of a fault to act as a valve is dependent upon the faults forming a permeable pathway during the post-failure period, and to act as seals during the interseismic period (Sibson, 1990; Byerlee, 1993; Caine and Forster, 1999).

The flow properties of a fault may evolve over time (Caine et al., 1996). A core may act as a conduit during rupturing events, but rapidly seal and become a barrier to flow during the interseismic period as open voids are filled with mineral precipitates (Caine et al., 1996; Sheldon and Micklethwaite, 2007). A fault that acted initially as a high-permeability conduit may later heal and become a barrier to fluid flow due to cementation or pore collapse (Heynekamp et al., 1999; Sigda et al., 1999). During the seismic cycle, a fault may periodically open and seal as a consequence of deformation processes, alternating between high and low permeability regimes. This model may be used as an analog to describe the formation, mineralization, and migration of hydrothermal breccia pipes in the subsurface.

GEOLOGIC SETTING

The Big Snowy Mountains of central Montana are a basement-cored Laramide uplift that delineates the northernmost topographic extent of Laramide-style deformation in the northern Rocky Mountains. The Big Snowy Mountains are an asymmetric anticline with a sinuous strike of 109° , with a westward plunge. The arch is approximately 65 km long by 30 km wide, and rises 900 to 1,200 meters above the surrounding plains (Reeves, 1931). Resistant limestone of the Madison Group comprises most of the peaks in the Big Snowy Mountains. The southern limb of the anticline is characterized by steep, inclined beds that dip at 45° - 60° and 60° - 90° south for Paleozoic and Cretaceous strata, respectively. The northern limb of the anticline consists of rocks that gently dip 8° - 10° north (Reeves, 1931).

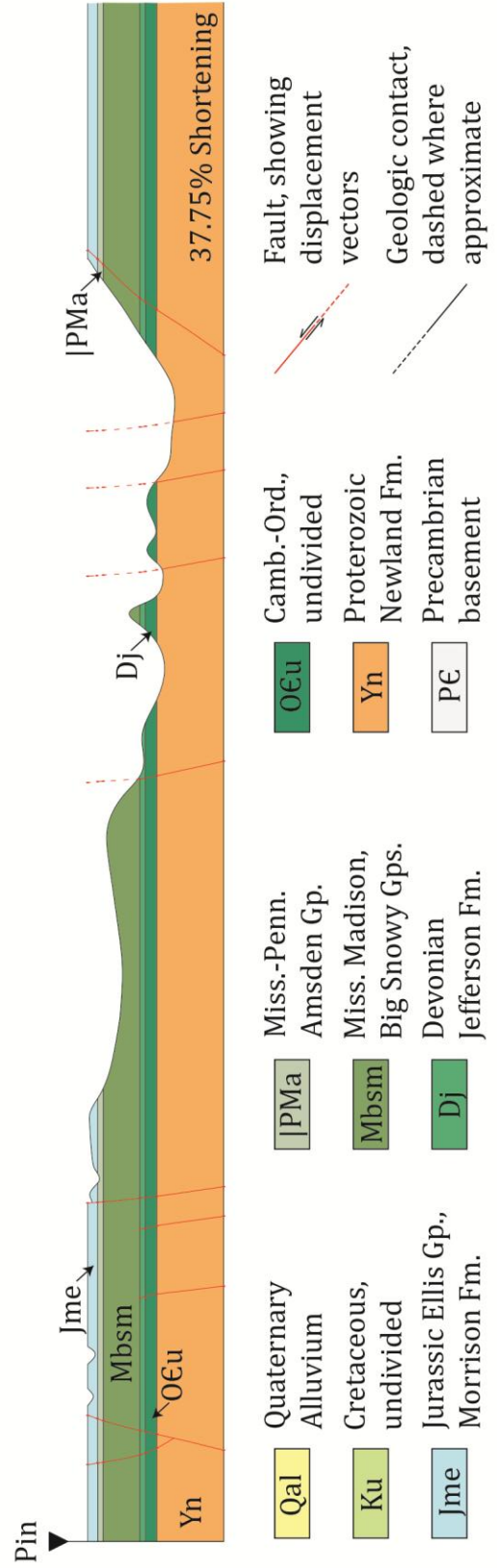
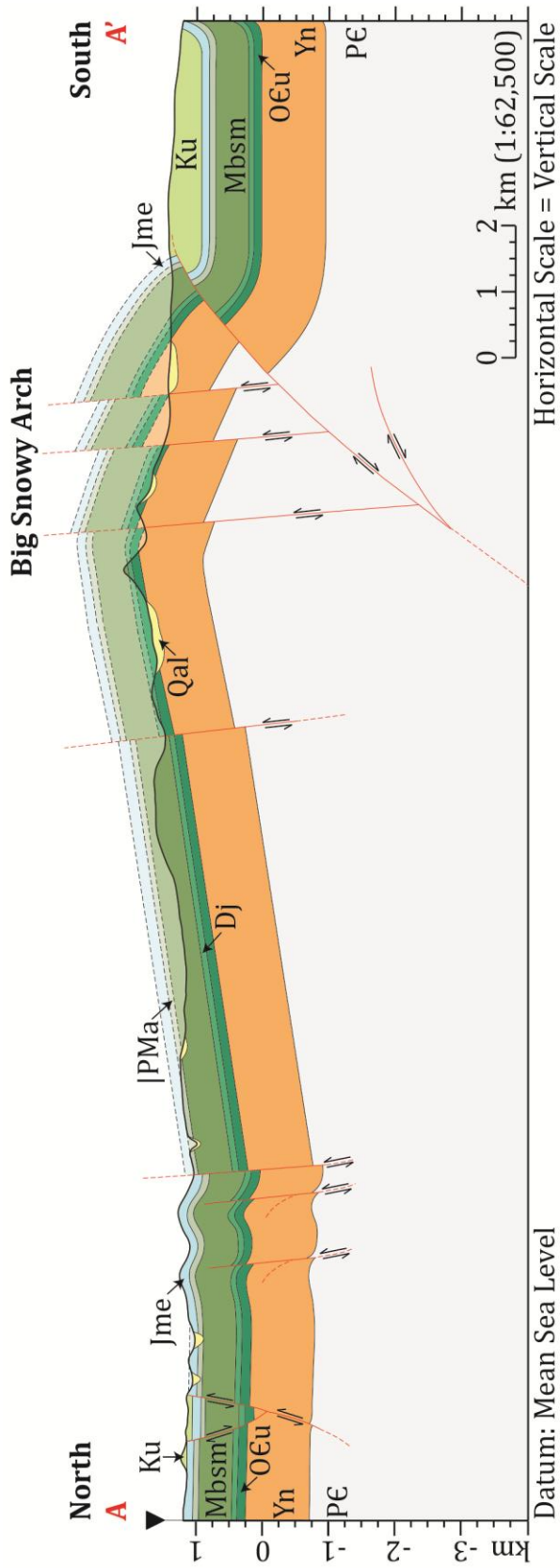
The BSFS, located along the western flank of the Big Snowy Mountains, has the geometry of a transtensional left-lateral wrench fault in map-view, which is often associated with normal faults that diverge at the surface and form grabens that represent negative flower structures or transtensional pull-aparts at depth. The latter of these structures has been interpreted in the literature to be due to the relaxation of Laramide compressive stresses following folding (Nelson, 1993). This left-lateral wrenching is indicative of en echelon faulting due to the northwest-southeast extensional component of Laramide deformation, which has been demonstrated by Nelson (1993) to shallow and merge into bedding planes of Jurassic units due to a lessening amount of extensional strain. The Big Snowy Arch on a larger scale was formed due to the reactivation of a high angle reverse fault at

depth, which splits upward through the overburden and passes into a fault-propagation fold (Figure 4) (Nelson, 1993).

Collectively, the Big Snowy Mountains, Little Belt Mountains, Judith Mountains, and Cat Creek-Devil's Basin Uplift form a regional, rectangular plateau in central Montana (Figure 5) (Reeves, 1931). The Judith Mountains are late Cretaceous (Eocene) to Tertiary laccolithic domes that formed concurrently with the Moccasin Mountains to the west. Between the Judith Mountains and the Big Snowy Mountains are low, circular laccolithic domes. The Cat Creek-Devil's Basin Uplift consists of numerous domes as well, each of which trend N70°W, with en echelon shears trending N35°W to N55°W, and transverse faults trending N50°E to N60°E. The broad, shallow Bull Mountains syncline lies south of the south of the Cat Creek-Devil's Basin Uplift. Further south, past the Bull Mountains syncline, is the Lake Basin fault zone, which parallels the faults to the north located in the Cat Creek-Devil's Basin. The Little Belt Mountains are a plunging anticline that lies to the west of the Big Snowy Mountains, which exposes igneous rocks and Precambrian through Cretaceous strata. This region was not glaciated, but has been eroded by active stream processes and down-cutting (Weed and Pirsson, 1900).

Regional Tectonic Framework

The Big Snowy Mountains lie within the Central Montana Trough (CMT), which is interpreted to represent a Mesoproterozoic intracratonic rift basin that formed circa 1.4 gigaannum (Ga) (Shepard, 1993; Marshak et al., 2000). Throughout



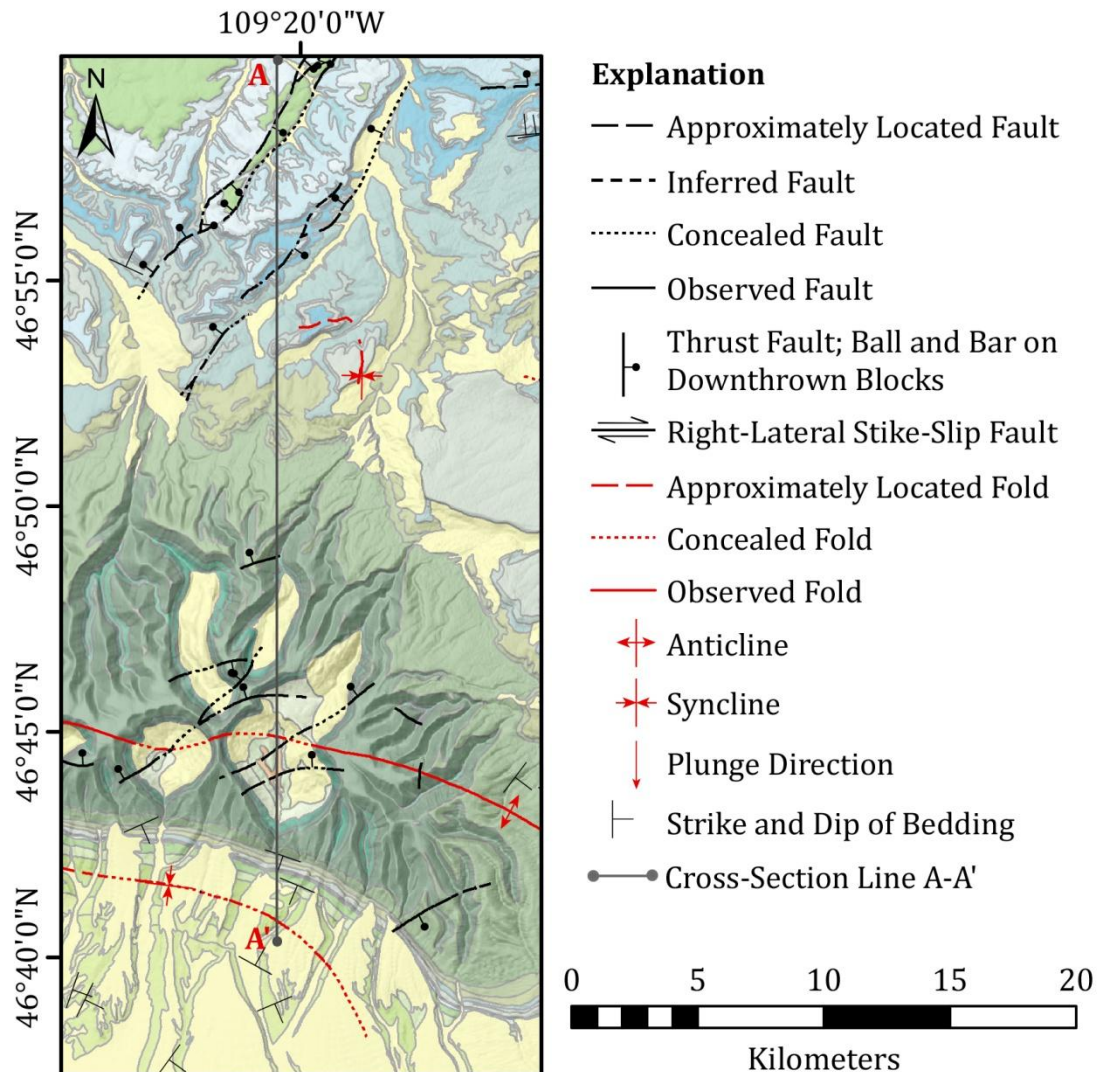
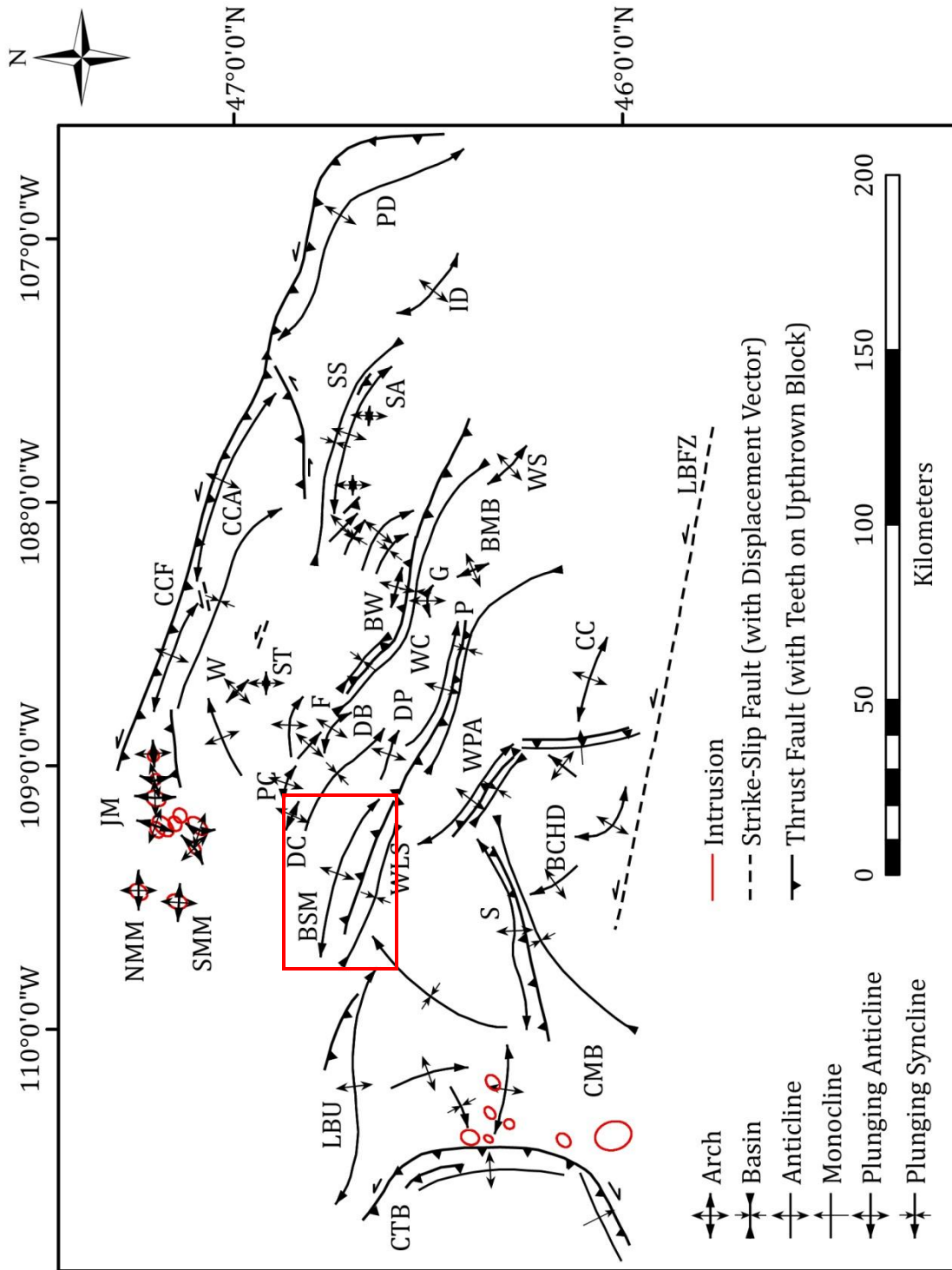


Figure 4. (Continued from previous page). Structural cross-section of the Big Snowy Arch. The cross-section (previous page) exhibits a high-angle basement fault that branches upward into a fault-propagation fold, causing the northern flank of the Big Snowy Mountains to be characterized by shallowly-dipping strata and the southern edge to be more steeply dipping. The subsurface geometry is the controlling factor for the formation of many of the hydrothermal features seen in outcrop. Below the cross-section is a palinspastic restoration of the cross-section, exhibiting the geometry of subsurface faults prior to deformation. A field area map (above) shows the location of cross-section line A-A' through Swimming Woman Canyon and the SWC field area, as well as the geologic formations and features used to construct the cross-section. Abbreviations on the previous page include "Gp(s)." for "group(s)," "Fm." for "formation," "Miss." for Mississippian, and "Penn." for Pennsylvanian.



EXPLANATION:

BCHD	Big Coulee-Hailstone Dome	LBFZ	Lake Basin Fault Zone
BMB	Bull Mountains Basin	LBU	Little Belt Uplift
BSM	Big Snowy Mountains	NMM	North Moccasin Mountains
BW	Big Wall	P	Pole Creek
CC	Crooked Creek Anticline	PC	Potter Creek
CCA	Cat Creek Anticline	PD	Porcupine Dome
CCF	Cat Creek Fault	S	Shawmut Anticline
CMB	Crazy Mountains Basin	SA	Sumatra Anticline
CTB	Cordilleran Thrust Belt	SMM	South Moccasin Mountains
DB	Devil's Basin	SS	Sumatra Syncline
DC	Durfee Creek	ST	Spindletop
DP	Devil's Pocket	W	Winnett Syncline
F	Flatwillow	WC	Willow Creek
G	Gage	WLS	Wheatland Syncline
ID	Ingomar Dome	WPA	Woman's Pocket Anticline
JM	Judith Mountains	WS	Wolf Spring

Figure 5. (Continued from previous page). Tectonic map of central Montana (modified from Woodward, 1997), with the Big Snowy Mountains field area outlined (red box).

geologic history, fault zones associated with the rift have been reactivated multiple times caused by adjustment along basement fault blocks under changing stress conditions. The Laramide orogeny structurally inverted the CMT as a complex anticlinorium to form the landscape seen today. The Laramide orogeny was associated with a northeast-southwest shortening direction that reactivated deep-seated faults formed during Mesoproterozoic rifting (Brown, 1993). This region was made even more dynamically complex during the Eocene, when multiple intrusive complexes in the area introduced a higher geothermal gradient and forced deep subsurface brine solutions upward along steep basement faults, creating

hydrothermal structures such as breccia pipes in the overburden along the fault and fracture systems (Davies and Smith, 2006). In order to determine how these breccia pipes affect deep aquifer modeling for CO₂ sequestration, it is first necessary to understand the tectonic driving mechanisms that caused such structural overprinting in central Montana.

Archean to Proterozoic

The basement rocks that underlie the central Montana region are composed of a late Archean high-grade metamorphic and plutonic suite of rocks belonging to the Wyoming Province, which are typically composed of fine-grained schist and gneiss that exhibit a strong foliation (Figure 6) (Nelson, 1993; Woodward et al., 1997). The associated foliations strike west-northwest and dip steeply, which caused the basement to inherit a structural grain which later influenced middle to late Proterozoic fracture orientations and created mechanical anisotropy within the crystalline rocks (Woodward et al., 1997). During the Paleoproterozoic, the Laurentian craton assembled by plate collisions with Archean terranes, resulting in the collisional belt of the Trans-Hudson orogen (Whitmeyer and Karlstrom, 2007). The Big Snowy Mountains are situated atop the Great Falls Tectonic Zone (GFTZ), a northeast-trending suture zone of structural and tectonic basement anomalies separating the Wyoming and Medicine Hat provinces, which has been recurrently active throughout geologic time and reflects the reactivated movement of inherited basement structures (O'Neill and Lopez, 1985; Vogl et al., 2004).

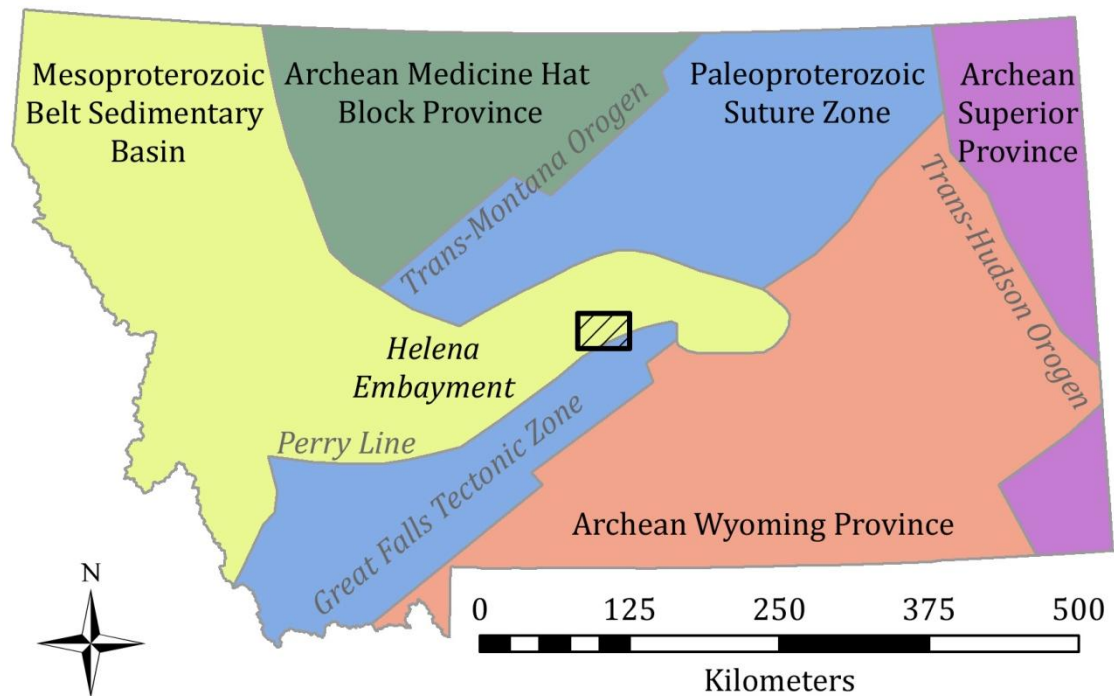


Figure 6. Archean provinces of Montana. The location of the Big Snowy Mountains (outlined in the hachured box) is superimposed on top of Archean-Proterozoic orogenic and tectonic features (modified from Sims et al., 2004).

During the middle to late Proterozoic, central Montana rifted and formed the CMT, which has been interpreted by some authors to be an aulacogen related to the breakup of Rodinia (e.g., Winston, 1986; Shepard, 1993). The intracratonic rift that developed reflects extensional faulting, and may be attributed to the amalgamation and separation of supercontinents during the Proterozoic (Marshak et al., 2000). The extensional (normal) faults that bound the CMT enclosed a transtensional depocenter approximately 480 to 640 km long and 80 km wide, which formed a narrow estuary that connected the CMT to the Belt Basin proper (Sims et al., 2004). The southern margin of this trough was bounded by an east-west striking growth fault, termed the Willow Creek/Perry Line, which allowed rapid subsidence and

deposition in the trough (Harris, 1957; Sims et al., 2004). The northern margin of the central Montana rift is roughly parallel to the southern margin and partly coincides with the trace of the Cat Creek fault, indicating that high-angle planar to listric normal faults that developed in association with the rifting event were later influential to the roughly east/northeast-west/northwest-trending reactivated lineaments displayed in map view today (Marshak et al., 2000; Sims et al., 2004).

Paleozoic

The CMT, which had remained negative during Archean to Proterozoic time, was uplifted during the late Cambrian due to reverse faulting concurrent with sedimentation (Nelson, 1993). The inversion of this trough took place along southwest dipping faults located along the crustal block southwest of the Cat Creek fault (Nelson, 1995). This episode of reverse faulting was followed by normal faulting in the pre-middle Ordovician, which was unrelated to regional tectonic events, but resulted in an uneven pulsating phase of sedimentation across the craton. Reverse faulting once again took place along the Cat Creek fault during latest Devonian to earliest Mississippian, which has been interpreted to be in response to stresses triggered by accretion of the Antler arc west of Montana, and records 50-90 meters of throw (Nelson, 1995). This faulting resulted in the uplift of the east-west trending "Central Montana High" as a horst block, and the Big Snowy and Crazy Mountain troughs, both of which were products of brittle failure of the weak basement rocks bordering the Central Montana High (Adams, 1999).

Faults remained inactive during the Mississippian period, allowing gradual subsidence of the previously uplifted blocks along bounding faults and formation of a negative depositional basin along the trace of the CMT (Nelson, 1995). This formed a large, shallow sea approximately 640 to 800 km east-west, 100-120 km north-south, and 90 m deep, which connected the Panthalassic Ocean to the restricted Williston Basin (Shepard, 1993). Tectonic subsidence continued to the middle Pennsylvanian, when widespread normal faulting with displacements up to 430 m and throw down to the south coupled with tilting initiated, which ended by the early Mesozoic (Nelson, 1995).

Mesozoic

The central Montana area remained stable to late Jurassic/Cretaceous time (Nelson, 1995). Pre-Jurassic folding shifted the axis of the CMT from the Sumatra trend to the Cat Creek trend (Norwood, 1965), while minor flexure periodically uplifted the Belt Island (Maughan, 1993). These fault trends heavily controlled the deposition of Jurassic sediments (cf. Figure 5).

Cenozoic

During the late Cretaceous to early Tertiary, the Laramide orogeny upwarped features in the CMT and again structurally inverted pre-existing synclines into present-day anticlinoria along reverse and left-lateral oblique strike-slip faults (Norwood, 1965; Nelson, 1995). The onset of the Laramide orogeny during the Maastrichtian stage was approximately synchronous across the foreland, as crustal

blocks in the Laramide province were shifted eastward and northward along pre-existing structural fabrics against northernmost Montana, which remained stable (Nelson, 1993). This was initiated by the change from steep to shallow slab subduction along the western North American craton, which may have been driven by a number of factors, including (1) increased velocity of convergence; (2) increased motion of the overriding plate in a trenchward direction; (3) decreased age and increased buoyancy of the subducting oceanic plate; or (4) other irregularities in the buoyancy of the oceanic plate due to the presence of a plateau or aseismic ridge (Dickinson et al., 1988).

The Laramide orogeny initiated shortening parallel to the vector of low-angle oblique plate convergence and subduction along the western margin of the continent (Erslev, 1993). The N40°E to N50°E directed convergence prompted northeast-directed thrust faulting along a décollement rooted in the lower crust of the Laramide foreland, resulting in an anastomosing oblique array of arch-like culminations that are connected by northeast- and southwest-directed master faults. Several of these north- and west-trending basement cored uplifts contain a significant component of strike-slip displacement, and have experienced between 10-15% strain and up to 50 km shortening in a direction perpendicular to slip along the major thrust fault (Brown, 1993; Erslev, 1993; Erslev and Koenig, 2009). Deformation became compartmentalized along different faults as individual faults accommodated the lateral offset across the foreland (Brown, 1993). Their size is often reflective of heterogeneity in the amount of crustal strain, which is driven by

shear between the continental lithosphere and subduction of the underlying oceanic lithosphere (Dickinson et al., 1988).

Laramide arches are defined by marginal thrust and reverse faults, which dip both under and away from the range (Erslev, 1993). Such master thrusts may be either emergent thrusts or blind thrusts that tie into upper imbricate back thrusts, the latter of which form the structure of the Big Snowy Arch. Compressive stresses oriented in a northeast-southwest direction favorably reactivated pre-existing basement-rooted structures, allowing those oriented east-northeast, east, or east-southeast to be reactivated as left-lateral oblique-slip faults, and those oriented southeast, south-southeast, or north-south to be reactivated as right-lateral low angle dip-slip reverse faults (Brown, 1993; Nelson, 1993). This reactivation had a significant control over the pattern of structural development in the foreland (Figure 7) (Brown, 1993).

Laramide deformation ended earlier in the north (50-55 megannum (Ma)) than in the south (35-40 Ma) (Dickinson et al., 1988). This is similar to the pattern of diachronous, north-to-south sweep of Eocene-Oligocene volcanism across the foreland, the majority of which succeeded Laramide tectonism.

Local Stratigraphy and Paleoenvironmental Setting

The stratigraphy of the Big Snowy Mountains is best expressed in terms of the major sequence boundaries in the stratigraphic record. A sequence is a package of rocks that was deposited in a single epeiric flooding event and is bounded by

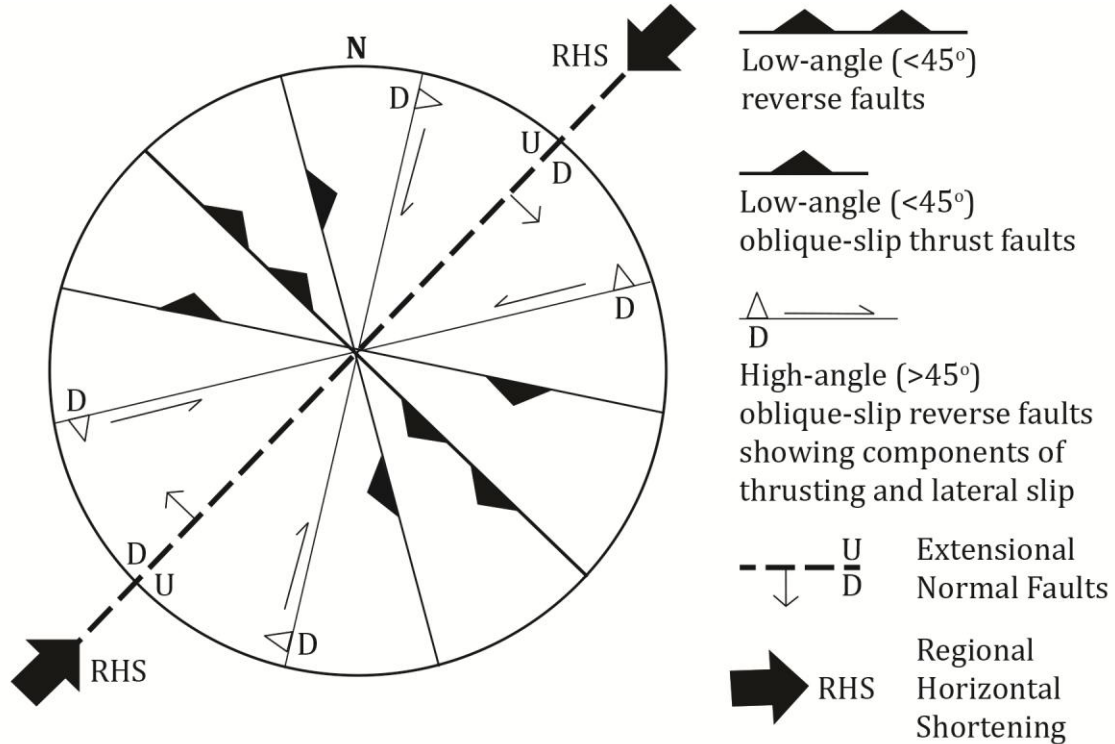


Figure 7. Laramide regional stress-strain field. The NE-SW oriented regional horizontal shortening (RHS) direction represents the maximum amount of shortening associated with Laramide deformation. The varying orientations of Laramide-related structures are superimposed (modified from Brown, 1993).

cratonic erosional disconformities (Nelson, 1993). Each depositional cycle follows the same four stages: (1) transgressive onlap of sediments concurrent with stable tectonism; (2) increased tectonism and its associated influence on deposition; (3) the culmination of tectonism defining topographically positive and negative elements; and (4) general uplift and erosion of the positive features, causing a cessation in sedimentation (Sloss, 1950). The stratigraphic record in central Montana is indicative of multiple higher-order frequency sequences, which contain a significant eustatic control in response to tectonism, and result in long periods of alternating erosion and non-deposition (Figure 8).

ROCK UNITS

	Sandstone		Calcareous Shale		Argillaceous Limestone
	Argillaceous Sandstone		Shale		Dolomite
	Siltstone		Gypsum		Dolomitic Limestone
	Silty Shale		Sandy Limestone		Limestone
	Carbonaceous Shale		Argillaceous Dolomite		Undifferentiated Igneous rocks

ABBREVIATIONS

Chart Heading: "SEQ." - Sequence; "FM." - Formation

System Column: "O" - Ordovician; "Dev." - Devonian; "P" - Pennsylvanian

Series Column: "Prot." - Proterozoic; "M" - Middle; "U" - Upper;
 "L" - Lower; "Kinder." - Kinderhookian;
 "Meramec." - Meramecian

Figure 8. (Continued from previous page). Stratigraphic column of central Montana. Geologic groups and formations are displayed to scale, and are shown alongside their respective Sloss Sequence (modified from Nelson, 1993; Porter et al., 1996). Abbreviations in the stratigraphic column are used for clarity, and are indicated on the legend above.

Paleozoic

F. Reeves discovered middle to late Proterozoic through recent strata in his initial reconnaissance of the Big Snowy Mountains in 1931. The oldest exposed rocks are Belt Supergroup metasedimentary rocks, which are found only at the head of Swimming Woman Canyon (Reeves, 1931). Belt sediments were deposited in an epicontinental basin (the CMT/Helena Embayment), the latter of which is an east-

trending rift of the Belt Basin. Rapid downwarping and subsidence of the CMT allowed more than 4,500 m of shallow water sediments to accumulate on the irregularly eroded crystalline basement (Shepard, 1993; Nelson, 1995). Coarse syntectonic sediments adjacent to the Perry Line grade north into the fine-grained sediments which are exposed at Swimming Woman Canyon (Nelson, 1995). Rapid, long-lived deposition was possible due to high angle growth faults along the southern boundary of the Helena Embayment.

Prior to regression of the Belt seaway, thick packages of limy shale and conglomeratic limestone were deposited (Norwood, 1965; Shepard, 1993). At the end of the Precambrian, uplift, deformation, and erosion leveled the landscape and allowed inundation of the middle Cambrian sea to occur. The first Sloss depositional sequence, the Sauk Sequence, consists of middle Cambrian through lower Ordovician formations (Sloss, 1950; Norwood, 1965). Cambrian and Ordovician strata record the deposition of a transgressive onlapping sequence onto the shelf from the west.

The second sequence, the Tippecanoe, contains middle Ordovician through Silurian strata. Ordovician sediments lapped onto the shelf from the south, and deposited into a gradually deepening sea before being mostly removed by erosion (Norwood, 1965; Maughan, 1989; Shepard, 1993). This erosion completely removed all but the lowermost Silurian sediments from the area. The Kaskaskia Sequence initiated in the middle to upper Devonian coincident with transgression onto the Central Montana High from the northwest, resulting in the deposition of

intertonguing terrigenous clastic material with thick packages of carbonates and shales (Sloss, 1950; Maughan, 1989; Maughan, 1993). These sediments were later eroded and removed from a large part of central Montana during pre-Mississippian uplift (Norwood, 1965).

Mississippian deposition began with the Madison Group limestones, which were deposited on a 400 km ramp that extended from the present day Canadian Arctic to New Mexico. Its deposition in Montana and Wyoming was bounded by the CMT and Williston Basin to the north/northeast, the Transcontinental Arch to the east, and the Antler Highlands to the west (Katz et al., 2007). The CMT was the area of most pronounced subsidence, owing possibly due to differential back bulge subsidence rates and flexure controlled by the Antler Orogeny to the west (Sonnenfeld, 1996).

The Madison Group represents a 2nd order supersequence of approximately 12 million years (my) in duration (357-345 Ma), and is capped by a regional karsted unconformity that represents 5-34 my of missing time (Sonnenfeld, 1996; Katz et al., 2007). The Madison 2nd order supersequence is composed of two composite sequences (the Lodgepole and Mission Canyon formations), six 3rd order sequences, and numerous higher frequency cycles, the latter of which represent fluctuations in sea level and variations in sediment supply rate and accommodation space. The 3rd order sequences represent culminations of progradational and aggradational cycles, and are sites of pronounced evaporite and argillaceous material, karstification, and early dolomitization (Figure 9) (Sonnenfeld, 1996; Katz et al., 2007).

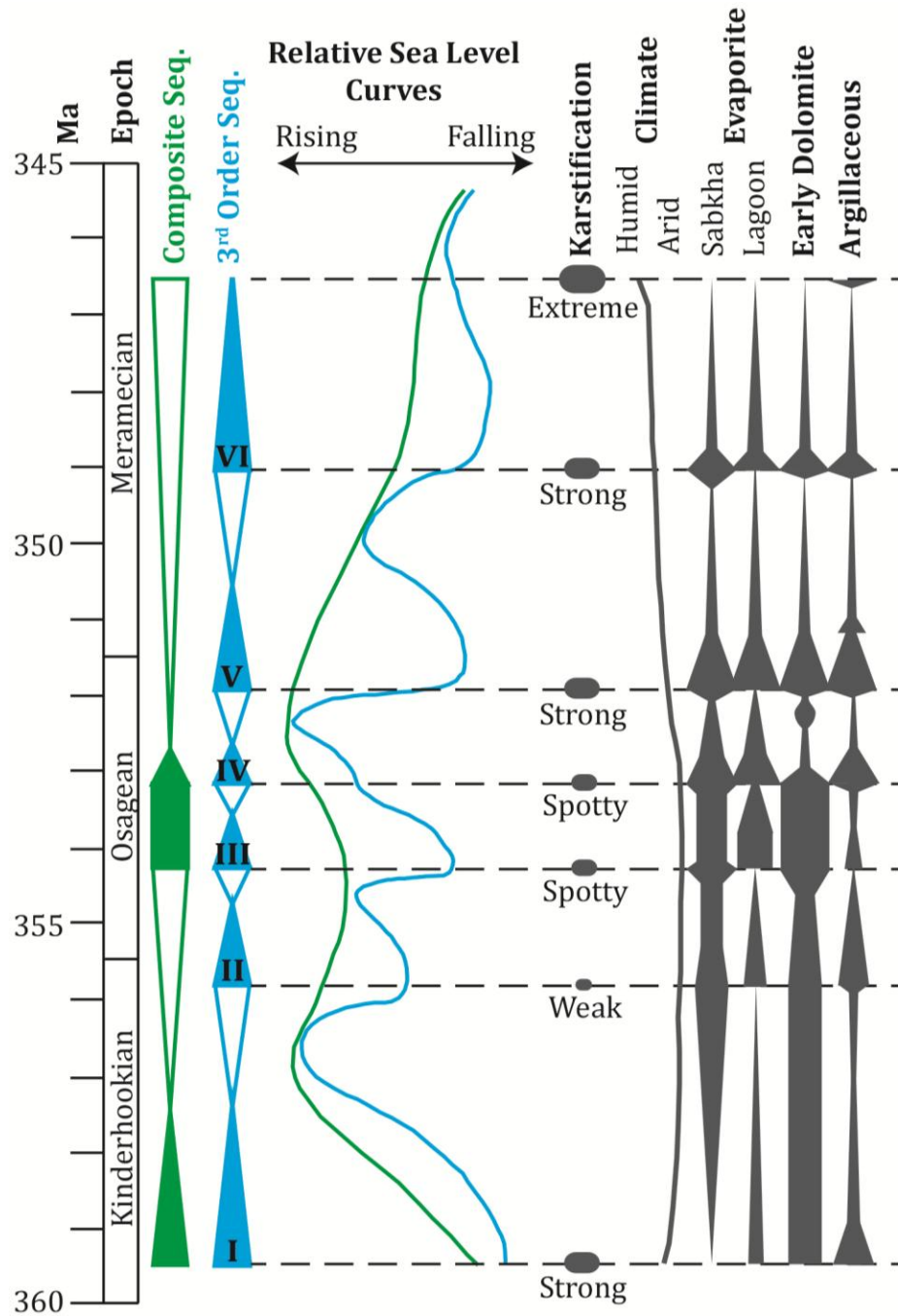


Figure 9. Variations in stratigraphic attributes related to sequences of the Madison Group carbonates. The vertical axis represents time rather than thickness, the latter of which varies as a function of location (modified from Sonnenfeld, 1996). Note that sequence boundaries are typified by the presence of evaporites and argillaceous material, karstification, and the precipitation of early dolomites. The green curve represents the relative sea level curve in relation to composite sequences; the blue curve is in relation to third order sequences. "Sequence" is abbreviated by "Seq."

The first composite sequence, the Lodgepole Formation, was deposited during the Kinderhookian to lower Osagean time as a progradational package of shallow water marine carbonates (Sonnenfeld, 1996). Sequence I contains the late Kinderhookian lower member of the Lodgepole Formation, which began with epeirogenic uplift and contains ten intermediate scale cycles of retrogradational to progradational stacking. Sequence II begins in the lower Osagean, and contains a similar pattern of ten intermediate scale cycles, but thins more rapidly in a landward direction than Sequence I. The Lodgepole Formation thus marks an overall relative fall in sea level, resulting in a seaward stepping package of rock and a basinward shift in accommodation (Sonnenfeld, 1996). One important characteristic of the Lodgepole Formation is the presence of Waulsortian mounds, which developed in deep (70-100 m), calm waters (Shepard and Precht, 1989). Microbial Waulsortian mounds formed along the margin of the Central Montana High due to a break in slope caused by steep basement faults (Smith, 1982; Smith and Custer, 1987). The growth of such mud mounds would have been terminated by a rise in eustatic sea level or increase in subsidence, causing the Waulsortian build-ups to be partially buried in lime mudstone (Smith and Custer, 1987). The Waulsortian mounds at Swimming Woman Canyon in the Big Snowy Mountains are interpreted to have nucleated from and were enhanced by hydrothermal brine solutions. These fluids would have migrated through reactivated Proterozoic faults from the basement, and may have been the site for hydrothermal fluid flow through the overburden, resulting in the development of hydrothermal breccia pipes.

The second composite sequence, the Mission Canyon Formation, was deposited in the distal part of the ramp, and represents a change from restricted lagoonal facies to regionally extensive grainstone deposits from lower Osagean to Meramecian time (Katz et al., 2007). This facies change was driven by a long-term eustatic rise in sea level, which may reflect changes in the back-bulge subsidence rates in the Antler foreland basin. Sequence III marks the base of the Mission Canyon Limestone. Its aggradational grainstone facies formed circulation barriers to the north and west, which facilitated the deposition of thick lagoonal deposits in restricted marine conditions, and was attributed to a relative rise in sea level (Sonnenfeld, 1996). The high rates of accommodation culminated with a thick package of shallow water facies, resulting from a relative fall in sea level and localized karsting. Once peak aggradation was reached, there was a relative rise in sea level, and a landward shift in sedimentation.

Upper Osagean through lower Meramecian Sequences IV through VI represent thinning-upward packages of rock, each with karsted sequence boundaries representing a long-term decrease in accommodation and increasingly humid conditions (Sonnenfeld, 1996). Sequence IV of the Mission Canyon Formation began at the peak transgressive phase, with a continued landward shift in accommodation. It resulted in the resistant, cliff-forming limestones which form the bluffs present in the Big Snowy Mountains. Both karstification and hydrothermal brecciation later destroyed bedding relationships in Sequence IV. Sequence V resulted from a relative fall in sea level, with an upper evaporite solution zone, a

basinward shift in sabkha evaporites (toward the CMT), and enhanced erosion by karst dissolution. Sequence VI continues to thin toward the upper Madison unconformity, and reflects the overall long-term decrease in accommodation space (Sonnenfeld, 1996).

The Big Snowy Group represents a middle Meramecian marine regression and late Meramecian/Chesterian transgression associated with glacioeustasy, where the rate of subsidence overall exceeded the rate of deposition (Maughan, 1993; Shepard, 1993). The onset of the Absaroka Sequence was coeval with deposition of the Amsden Group in a shallow, nearshore environment during the late Mississippian/early Pennsylvanian. Marine waters then regressed from the central Montana area completely, with rivers and streams cutting deep channels into the underlying strata (Shepard, 1993).

Mesozoic

The Zuni Sequence began coevally with the deposition of the Jurassic Ellis Group in the Sundance Sea, which was initiated by local subsidence and uplift events following the Triassic-aged closure of the CMT (Maughan, 1993). This sequence continued throughout the Cretaceous, when the Western Interior Seaway occupied most of Montana, which allowed high eustatic sea levels to load thick sedimentary deposits into basins. Final regression of the late Cretaceous seaway from central Montana was associated with the onset of Laramide tectonism (Dickinson et al., 1988).

Cenozoic

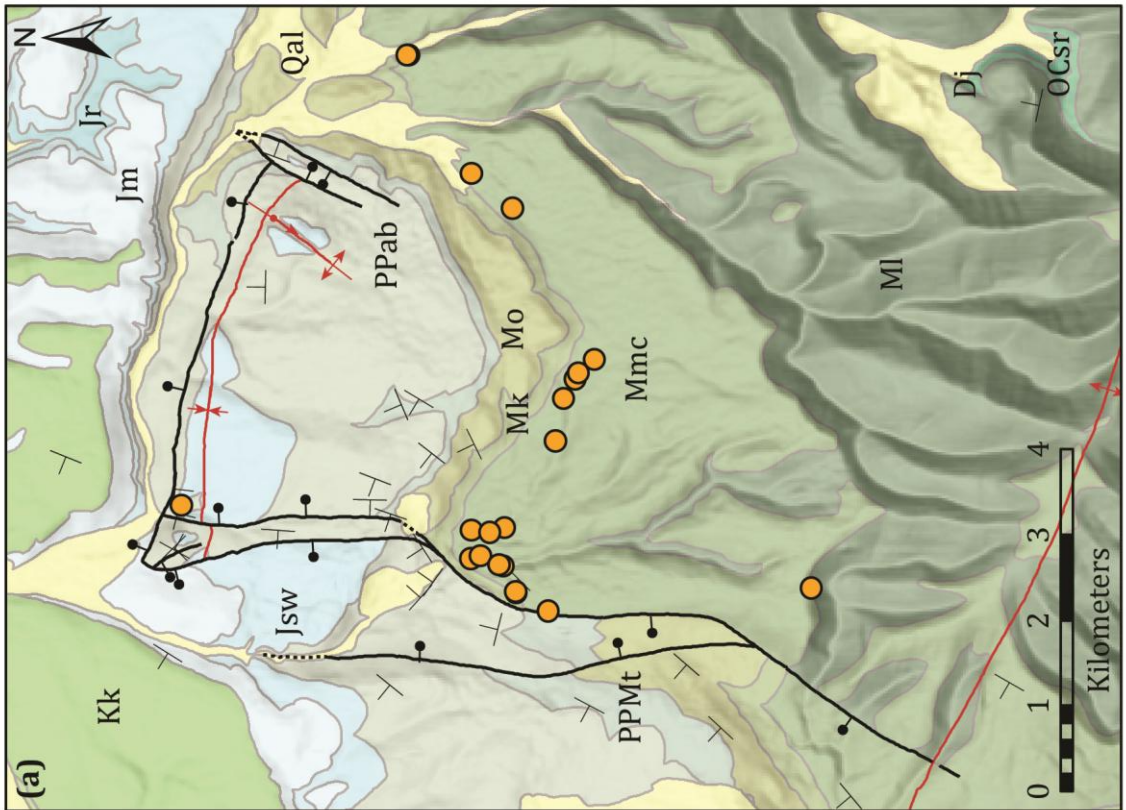
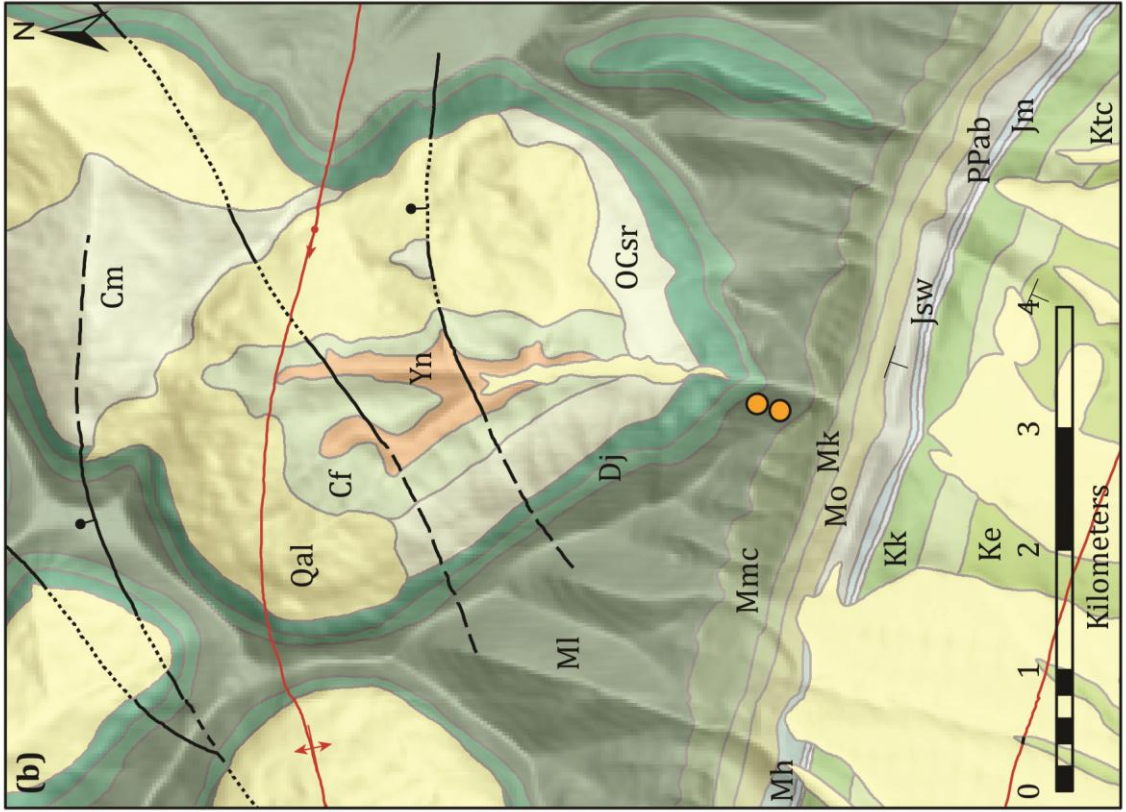
Eocene igneous activity acted as a catalyst for the hydrothermal activity associated with tectonic brecciation. Almost all of the intrusions in the Big Snowy and Little Belt Mountains were emplaced during the Eocene epoch, between 47 to 69 Ma (Nelson, 1993). Stocks, dikes, laccoliths, and sills in central Montana are strongly alkaline to subalkaline, and together comprise the Central Montana Alkaline Province (Chadwick, 1972). These rocks are intrusive and volcanic units that form isolated uplifts along the Rocky Mountain Front, and may have provided the heating mechanism to circulate geothermal and hydrothermal fluids through the subsurface.

METHODOLOGY

Field Outcrop Methods

Field work in the Big Snowy Mountains was concentrated along outcrops exposed in canyons following the traces of the BSFS and SWC (Figure 10). These two field areas were chosen because they are regions where the most outcrop was exposed, and because they follow important structural trends which may have acted as conduits for hydrothermal fluids from the basement. Field work began with gaining permission to access each private parcel of land containing outcrop of interest that had been previously identified using Google Earth imagery. Each outcrop was investigated for evidence of hydrothermal brecciation and alteration. If a breccia pipe was present, the coordinate position and orientation of the breccia pipe was recorded via use of a handheld Garmin Oregon 450 Global Positioning System (GPS) and Brunton compass, the former of which is accurate to approximately five meters (Appendix A).

A measuring tape was used to collect dimension measurements (width and height) of each breccia pipe. The measuring tape was used to collect in-depth descriptions of the breccia pipes, along with any heterogeneity within, marking differences in hydrothermal alteration, porosity, and/or permeability, as well as the interval at which it occurred (Figure 11). The same scale was then used to photograph the breccia pipe morphology and composition, from a distance and at selected intervals. Each of the different zones of the breccia pipe was then sampled,



EXPLANATION:

Qal	Alluvium & landslide deposits	Mo	Otter Formation
Ke	Eagle Formation	Mk	Kibbey Formation
Ktc	Telegraph Creek Formation	Mmc	Mission Canyon Limestone
Kk	Kootenai Formation	MI	Lodgepole Limestone
Jm	Morrison Formation	Dj	Jefferson Formation
Jsw	Swift Formation	OCsr	Snowy Range Formation
Jr	Rierdon Formation	Cmu	Cambrian rocks, undivided
PPab	Alaska Bench Formation	Cf	Flathead Formation
PPMt	Tyler Formation	Yn	Newland Formation
Mh	Heath Formation		Hydrothermal breccia pipe
	Approximately located fault		Observed fold
	Inferred fault		Anticline
	Concealed fault		Syncline
	Observed fault		Plunge direction
	Thrust fault; ball and bar on downthrown blocks		

Figure 10. (Continued from previous page). Field area maps of the BSFS and SWC. The BSFS field area (a) displays the location of 22 breccia pipes along the trace of the fault under study; the SWC field area (b) displays the location of two breccia pipes at the canyon entrance. The extent of each of the field areas is indicated on Figure 1. The ball and bar symbol is on the downthrown side of each fault, which is represented by a thick black line, and is dashed where approximate. Red lines indicate the axis of the fold hinge (see Figure 4 for full fold and fault symbol explanation). Appendix A lists the GPS coordinate locations for each breccia pipe.

with notes as to the location at which the sample was taken and a thorough rock description. Samples were then returned to Montana State University for geochemical and laboratory analyses.

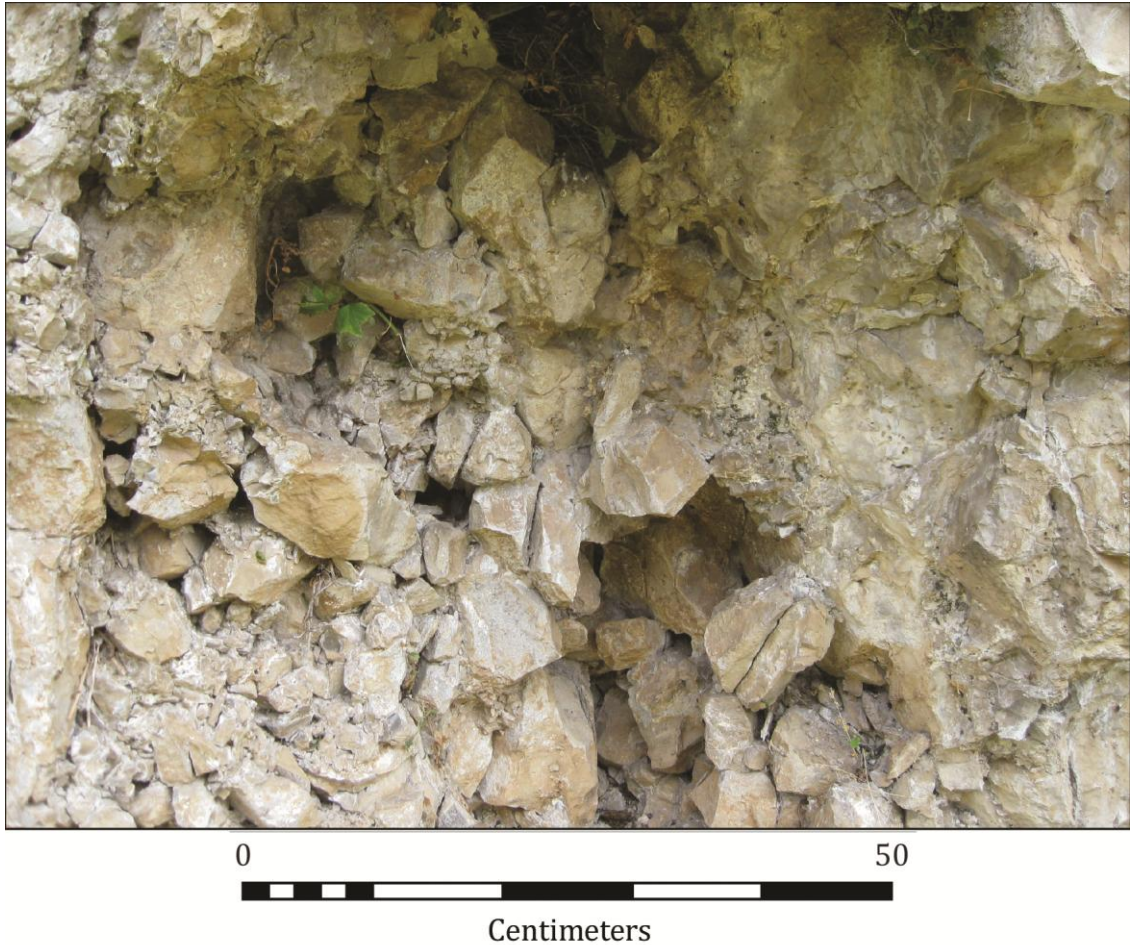


Figure 11. Sampling technique for the interior heterogeneity of a breccia pipe. The above breccia pipe (BSM-007) along the BSFS exhibits a complex internal structure. In this example, the interior of the breccia pipe (center) is composed of large, rotated clasts and open void space. Clast size and rotation decreases toward the contacts on either side of the conduit, and the concentration of clasts increases. One field sampling technique involved the use of a measuring tape to describe the breccia pipe heterogeneity present within its interior.

The description and classification of breccias was determined by the amount of fragment separation and rotation within the rock (Laznicka, 1988). Numerous researchers have sought to apply a genetic classification to breccias based on the mechanism of their formation (e.g., Sibson, 1986; Jebrak, 1997), resulting in overcomplicated classification schemes (Mort and Woodcock, 2008). Perhaps the

most inclusive classification is that of Laznicka (1988), which categorizes three gradational members of breccias: (1) crackle/rupture/shatter; (2) mosaic/net-veined/subsidence; and (3) rubble/chaotic (Figure 12). Crackle breccias are characterized by over 75% clasts and under 10° average rotation. Such breccias generally consist of a high-density network of anastomosing fractures, which often causes between 1-5% expansion. Mosaic breccias contain 60-75% clasts, with 10-20° rotation. These breccias typically form from the further expansion of crackle breccias by 5-20%. They are characterized by fitted clasts which are separated by empty or filled voids, and are commonly termed “jigsaw breccias” if there is little rotation. Rubble breccias have less than 60% clasts and over 20° average rotation. This is the most expanded breccia, displaying up to 50% dilation. If such breccias have unrotated clasts, they are simply classified as fractured breccias (Westphal et al., 2004; Mort and Woodcock, 2008).

Thirteen select breccia pipe outcrops along the BSFS were revisited following their initial description to perform a fracture analysis on either side of each of the pipes. The circle inventory method was used to measure mesoscopic (outcrop-scale) fractures, in which all systematic (parallel to sub-parallel, evenly-spaced) fractures within a circle of one meter diameter were recorded, defining a fracture station (Marshak and Mitra, 1988). This method defined fracture stations one meter in diameter located on either side of the breccia pipe based on fracture sets that best represented the scale and frequency of such discontinuities at the desired location (Figure 13). At each fracture station, dip, the average dip direction for the

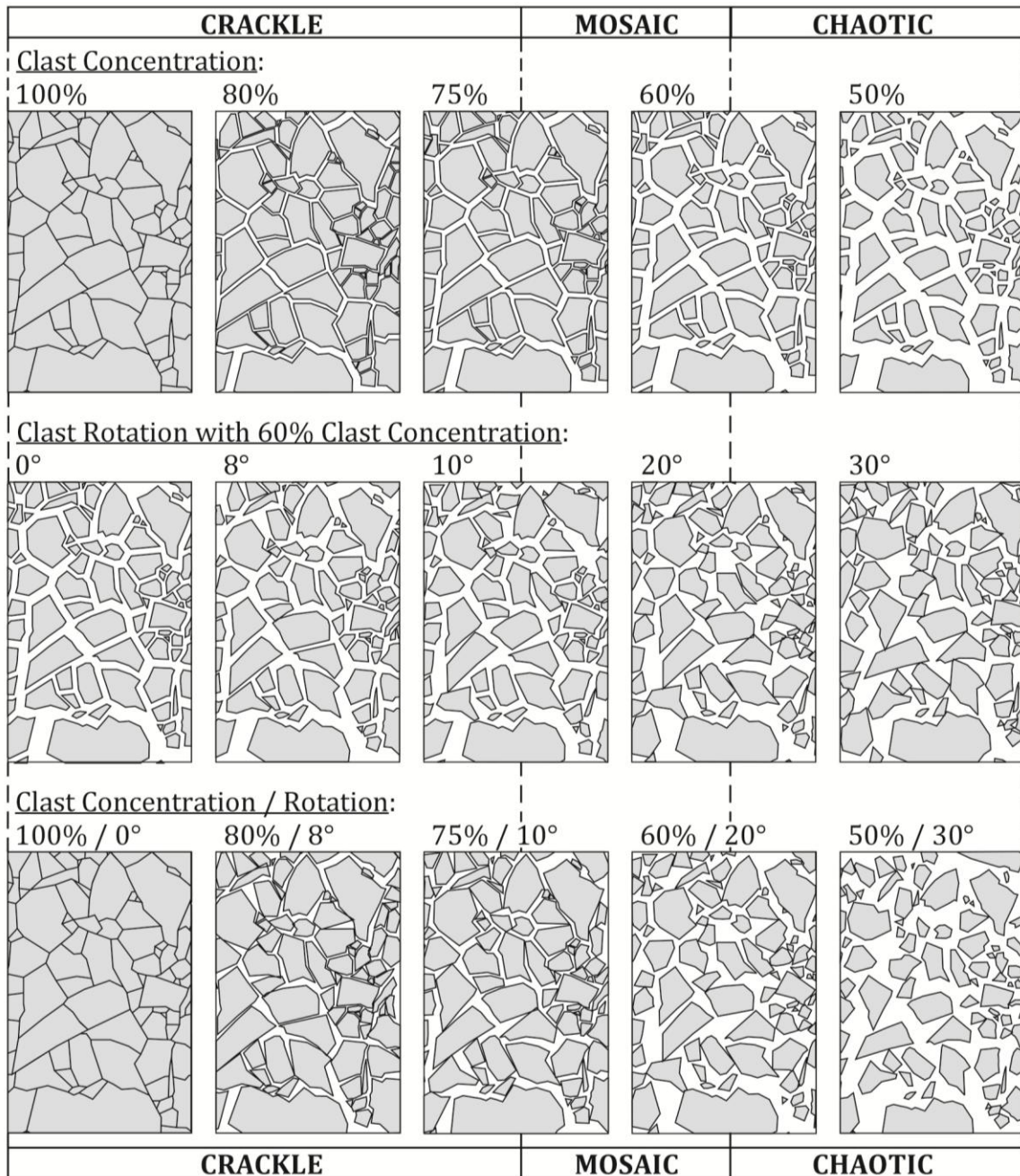


Figure 12. Breccia end-member classification. Model for the progressive deformation of a brecciated fabric from crackle to chaotic, accomplished either from decreasing the clast concentration, increasing the average clast rotation, or combining the effects of both decreased clast concentration and increased clast rotation (modified from Mort and Woodcock, 2008).

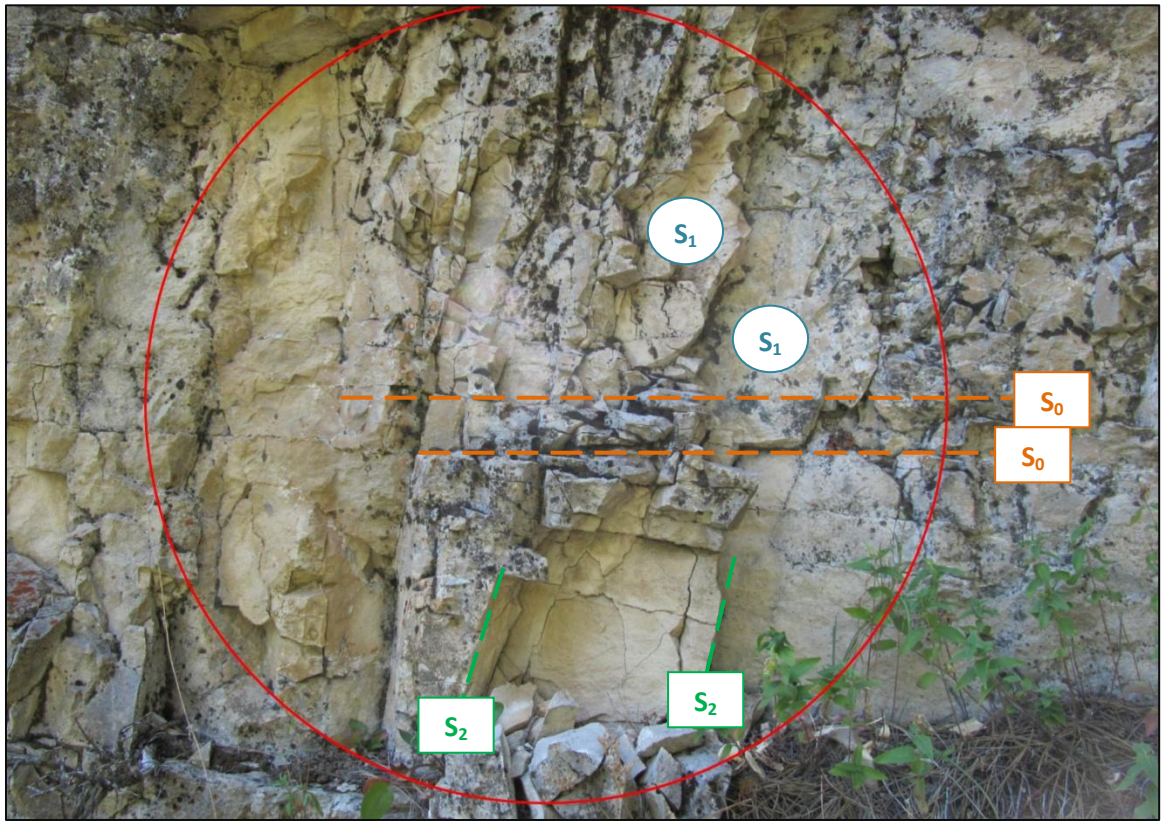


Figure 13. Fracture station along the BSFS. Station BSM-020 E (the wall rock on the east side of breccia pipe BSM-020) exhibits two dominant systematic fracture sets in the Mission Canyon Limestone. The red circle is approximately one meter in diameter. Within this circle, dip, average dip direction, and fracture length for each of the sets was measured. " S_0 " (orange) is the bedding plane; " S_1 " (blue) is the primary shear fracture face; and " S_2 " (green) is the secondary shear fracture plane.

systematic set, and fracture length were measured and recorded. A total of 737 fractures were measured using this method (Appendix B).

In order to visually express the fracture orientations at each station, Rockware StereoStat version 1.6.1 was used to display the azimuth and dip data from outcrop measurements. Fracture measurements were summarized per fracture station into those that were defined as strike, dip, oblique set one, oblique set two, and other lineaments as suggested by Lageson et al. (2012). For fracture

stations containing multiple sets of systematic fractures, the average of each set was used (Table 1). "Strike" (b-c) lineaments were defined as being within $\pm 15^\circ$ of the fold hinge (109°), or having a strike direction between 94° and 124° . "Dip" (a-c) lineaments were within $\pm 15^\circ$ orthogonal to the fold hinge (199°), or between 184° and 214° . Two sets of oblique fractures were also defined with azimuths at approximately $\pm 45^\circ$ to the fold hinge line. "Oblique Set 1" trends northeast-southwest with azimuths between 49° and 79° , whereas "oblique set 2" trends northwest-southeast with azimuths between 139° and 169° . All other lineament measurements were labeled under the category of "other". Rockware StereoStat was then used to plot the average strike planes and dip poles for each systematic fracture set measured along the BSFS.

Laboratory Analyses

X-Ray Diffraction Spectrometry

X-ray diffraction (XRD) spectrometry was performed at the Imaging and Chemical Analysis Laboratory (ICAL) at Montana State University. XRD is a useful technique that aids in identifying bulk mineral phase compositions from well-mixed, homogenized rock particles approximately 5-10 micrometers (μm) in size. XRD spectrometry was performed on 29 samples from the BSFS along the western flank of the Big Snowy Mountains and 14 samples from SWC along the southern edge of the range. Every best attempt was taken to obtain samples from the matrix of a brecciated rock; however, in some cases it was only possible to use whole rock

samples. Sample locations were chosen for each sample and then drilled out of the rock using a power drill with interchangeable Dremel router bits (Figure 14).

Powdered and whole samples were then ground to the desired size using a diamonite mortar and pestle, which was cleaned using clean quartz powder between each use.

Matrix material from 31 breccia samples, clast material from two breccia samples, precipitates in vugs from one breccia sample, whole rock material from six samples, vein fill from one sample, replacement material from one sample, and the rind from one sample were powdered for use in this study. Two loading techniques were used for each of the powdered samples. For samples with ample (greater than one teaspoon) powder, metal cup mounts were used. Each mount was affixed with a glass plate and filled using a metal scoop. Care was taken not to tap or knock the mount to ensure random orientations of grains within the sample holder before removing the glass plate. For samples with very small amounts of powder, the sample was sprinkled carefully and evenly on a petrographic slide lightly coated in petroleum jelly. Using either method, the mount or slide could then be centered onto the XRD sample holder so that the maximum width of the powdered sample would be hit by the X-rays. To ensure that all directions of the randomly-oriented crystals are sampled, the machine's goniometer rotates the arm of the machine containing the cathode tube at an angle of 2θ , thus producing numerous peak diffraction patterns (Bish et al., 1989).

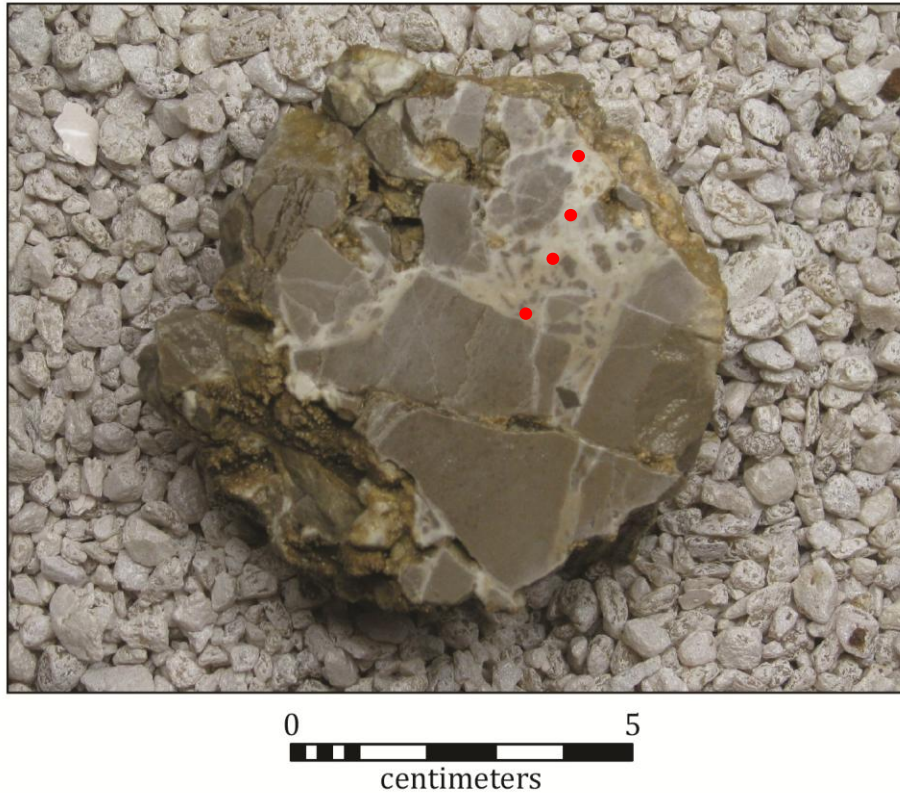


Figure 14. Hand sample of a breccia displaying XRD sample drill locations. The above is a well-cemented breccia from breccia pipe BSM-007b, with red dots that indicate the locations of powdered samples extracted for XRD analyses.

XRD was performed using a SCINTAG X1 Diffraction Spectrometer and computer-aided mineral identification system. This model of diffractometer operates by heating a filament within the cathode tube to produce electrons, which are then accelerated toward the sample holder by applying a voltage of 1.00 kilovolts (kV) at a sample distance of 250 millimeters (mm). Once the emitted electrons dislodge the inner shell electrons of the powdered sample, an X-ray spectrum ($\text{CuK}\alpha 1$) is produced with a wavelength of 1.540562 angstroms ($\text{\AA}$). The intensity of the reflected X-ray is then recorded, and a relative peak height in intensity occurs, which is recorded in counts. The detector setup is a liquid nitrogen

cooled solid state detector with a Bragg-Brentano theta:theta configuration, and the diffractometer is accurate to within 0.2 degrees.

At the beginning of each XRD session at ICAL, the goniometer was initialized using SCINTAG Diffraction Management System for NT (DMSNT) software and automatically aligned using a brass plate using both a coarse (0.3 second preset time, 0.05 degree step size, 1 degree start/stop offset) and fine (0.3 second preset time, 0.01 degree step size, 0.2 degree start/stop offset) alignments. The purpose of these alignments was to maximize the peak intensity and minimize the offsets added to the experimental diffraction pattern. Peak intensities were generally between ~10,000-12,000 and offsets <0.05, so as not to be too high to compare to standards in the computer database. Each of the 43 samples was then run using the same parameters. The slit sizes were kept fixed for each run, with the tube having 2 mm (divergence) and 4 mm (scatter) slit widths, and the detector having 0.5 mm (scatter) and 0.2 mm (receiving) slit widths. The scan event operated with a 0.02° step size with a start angle of 20° and a stop angle of 80°. Each scan ran continuously at 0.6 seconds per step at a rate of 2.00 degrees per minute.

Once each scan was complete, a raw curve was saved to the computer. Using DMSNT software, the background was subtracted and peaks found by converting peaks to lines, with a more in-depth visual confirmation that all peaks were identified by the computer software. The International Centre for Diffraction Data (ICDD) was used in conjunction with LookPDF software using search match techniques to match diffraction patterns from each scan with standard patterns in

the diffraction database. Each card was then superimposed on the experimental pattern to identify the individual crystal structures within the sample (Appendix C).

Once X-ray diffraction was performed on the samples from the BSFS and SWC, the relative compositions of minerals within the sample could be quantified. Chave (1952) was the first to determine a partial solid-state solution between calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) using XRD. This method is particularly useful because it relates the differences in ionic sizes between substituting and host cations, which are expressed by the interplanar d-spacing for the major cleavage (104) of calcite. This experiment, chemically determined, resulted in an empirical curve relating calcite and dolomite, and has been utilized and refined in later experiments by Goldsmith et al. (1955, 1961), Goldsmith and Graf (1958), Milliman et al. (1971), Bischoff et al. (1983), and most recently, Zhang et al. (2010). The results from this project's X-ray diffraction analyses were compared with the experimental curve from the Zhang et al. (2010) paper, which characterized the ordered and disordered magnesium content of samples based on numerous researchers' findings (Figure 15).

Stable Isotopes

Stable isotope analysis is a useful tool for studying the influences of meteoric and/or marine waters on a carbonate system, and aims to identify the different sources of dissolved carbonate as well as the rock-water interactions that commonly drive carbonate diagenesis (Arthur et al., 1983). In this study, stable carbon and oxygen isotope values were measured at the University of Michigan Stable Isotope

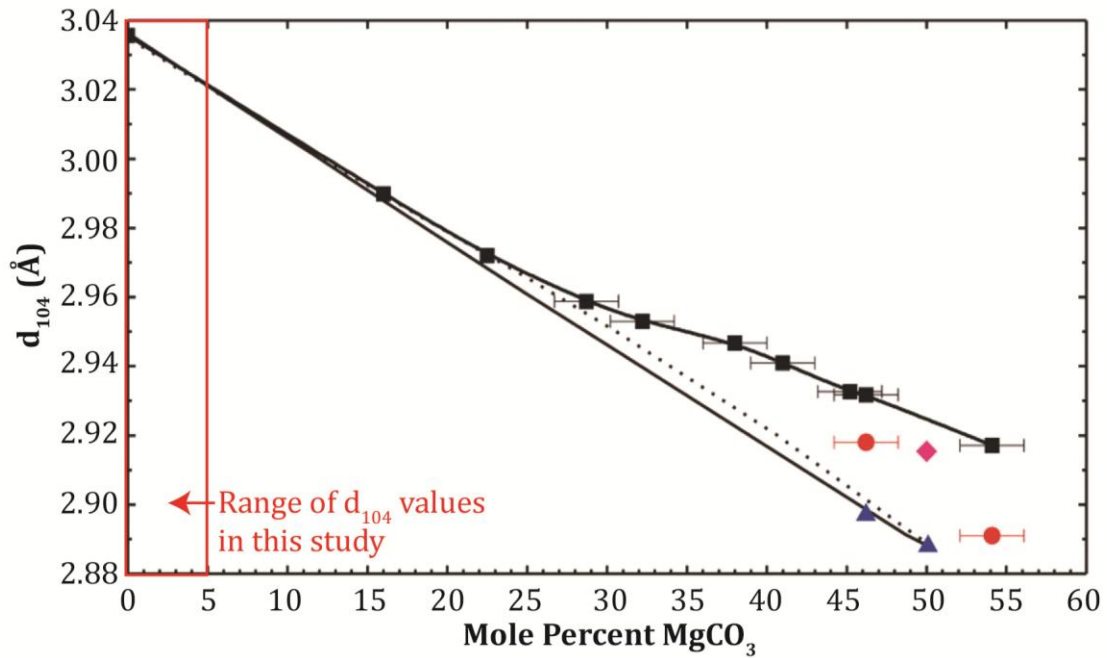


Figure 15. Empirical curve between d_{104} values and mole percent dolomite. Black squares are disordered dolomite data points from the Zhang et al. (2010) study; blue triangles are from ordered dolomite samples; the pink diamond is from an almost-ordered dolomite sample; and red circles are from weakly ordered dolomite. The straight solid and dashed black lines are the idealized curves from Goldsmith and Graf (1958) and Goldsmith et al. (1961) (modified from Zhang et al., 2010).

Laboratory to determine the source of the water as given by the isotopic signature within matrix material of the brecciated samples. The same powdered samples were used as in the XRD analysis; therefore, no additional preparations were necessary.

An isotopic analysis was performed by reacting a minimum of ten micrograms of the powdered sample in stainless steel boats with four drops of anhydrous phosphoric acid for eight minutes (twelve for predominately dolomitic samples) in a borosilicate reaction vessel at $77 \pm 1^\circ\text{C}$. These reaction vessels were then placed in a Finnigan MAT Kiel IV preparation device coupled with a Finnigan MAT 253 triple collector isotope mass spectrometer. ^{17}O data was corrected for acid

fractionation by correcting to a best-fit regression line determined by the standard NBS 19. This method is accurate within 0.1‰ (Wingate, 2013). Results were categorized in a spreadsheet based on breccia pipe location and sample material, and then graphed as a scatter plot with laboratory standards.

Stable isotope results are given in comparison to the standard VPDB, which is calibrated through the analysis of an international reference laboratory standard from the U.S. National Bureau of Standards (NBS) (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 oxygen and hydrogen ratios are similar to that of the average ocean water, which can be compared to VPDB values 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 VPDB or SMOW, and units are per mil (‰) (Faure, 1998).

Secondary Electron Imaging and ImageJ Statistical Calculations

A Scanning Electron Microscope (SEM) was used in ICAL at Montana State University to obtain high resolution images of samples from the Big Snowy Mountains. The SEM at ICAL uses a highly-focused beam of electrons from a LaB_6

source to scan a sample. The interaction between the electrons and the surface of the sample creates a two-dimensional image, which displays the variations in textures and topography. This results in magnifications up to 100,000 times and resolutions up to 40 Å in some samples (Montana State University Department of Physics, 2011). The SEM at ICAL is a JEOL JSM-6100, which was used to take topographical images of ten samples from the BSFS and six samples from SWC. Rock samples were whole chips approximately 3-5 mm in length. Samples were mounted on a coater tray and secured using carbon tape, then sputter coated with iridium at 20 milliamperes (mA) for 20 seconds. Digital images were taken using MImage version 1.0.

Greyscale SEM images were then imported into BoneJ, a plug-in of the freeware ImageJ version 1.47 in order to determine the two-dimensional cross-sectional porosity present within the brecciated samples. This was accomplished by correcting each photo with a color threshold, which then aided in calculating percent area porosity.

Petrography

Hand samples collected from each of the breccia pipes were cut and sent to Spectrum Petrographics, Inc. for the preparation of thin-section slides. Thirty thin sections from the BSFS and thirteen thin sections from SWC were analyzed to determine their mineralogical composition, diagenetic history, deformation structures, and brecciated fabric associated with each of the hydrothermal breccia pipes. Each slide was standard size, 30 micrometers thick, and vacuum embedded

with Epotek 301. Half of each slide was stained with alizarin red-S to determine which carbonate minerals were present. Photomicrographs were taken of areas of each thin section slide to illustrate typical properties of each brecciated sample using a Leica DM2500P microscope coupled with camera and Leica Application Suite version 4.1 software.

Geo-Visualization

Stratigraphic and Near-Distance Computations using ArcMap

To determine if the distribution of breccia pipes was related to their proximity to a prominent, favorably-oriented structural feature, ArcMap 10.1 was used to map the distribution of hydrothermal breccia pipes in relation to the BSFS. The geologic map, downloaded from Montana's Natural Resource Information System (NRIS), was first imported into ArcGIS version 10.1 software as an .e00 file, which contained four separate layers. To view these in ArcGIS, the .e00 files were converted to four coverage files: (1) contacts_cov (geologic formations); (2) faults_cov (fault lines); (3) folds_cov (fold axes); and (4) s_d_cov (strike and dip measurements). Most important to the scope of this project were the geologic formations and fault lines, so contacts_cov and faults_cov were converted again to shapefiles, resulting in two new layers: contacts_shp.shp and faults_shp.shp. These conversions were necessary in order to project and edit the items. The two shapefiles were projected to the correct coordinate system, and the attribute table for the contacts shapefile was edited to add fields for geologic period and name of

the geologic formation (Appendices C and D). The Montana Bureau of Mines and Geology (MBMG) codes in this table were also edited to remove special characters which are not compatible with ArcGIS (e.g., "€" was changed to "C", "|P" to "PP"), and the geologic formations were renamed (e.g., the many categories of Quaternary sediments became "Alluvium and Landslide Deposits") and dissolved to simplify the geologic map. The attributes in the dissolved contacts shapefile were joined with those from the original shapefile, so that fewer entries were present within the attribute table, yet all contained both the original and edited information present (such as MBMG code, geologic age, and geologic formation). The dissolved contacts shapefile was labeled using the MBMG code, and displayed along with the faults shapefile with colors loosely based off of the United States Geological Survey (USGS) color scheme.

The original land ownership map used, downloaded from NRIS, was a .pdf file which displayed parcel numbers for each property. This .pdf image was converted to a .tif image, and then georeferenced to match the existing data frame in GIS. Fergus County Cadastral data, downloaded from the same source, was then imported on top of this for editing. The attribute table for cadastral data was edited by adding a field for parcel number based off of the original .tif image. This step was important because it assigned an identification number to each landowner; therefore, it displayed much more clearly the fact that the cadastral data contained many more segments of land (many segments of a parcel owned by the same rancher) than the original .tif did. This parcel number was used to dissolve cadastral data, so that the

final map presented only one parcel of land per owner. The attributes from the original cadastral shapefile were joined with that of the dissolved cadastral file, and edited with supplemental information that was gathered during the field season (Appendices D and E).

GPS coordinates could then be superimposed onto the map marking the locations of hydrothermal breccia pipes. To do this, a worksheet was first created in Microsoft Excel with breccia pipe number, GPS coordinates (degrees/ minutes/ seconds), decimal degrees latitude/ longitude, and width. This information was then geocoded as XY coordinates into ArcGIS software, and displayed on the map with symbology proportional to breccia pipe width. A statistical analysis (termed "near" in ArcGIS) could then be performed which found the proximity of each breccia pipe to the closest segment of the fault line. These results were given in decimal degrees, converted to meters, and displayed alongside the breccia pipe width measurements.

Satellite Lineament Measurements using Google Earth Pro

Google Earth Pro was used in conjunction with ArcMap 10.1 to perform a fracture analysis of the Big Snowy Mountains. Since the Big Snowy Mountains are mostly covered in dense forestry, all major drainages were believed to follow fracture systems due to their shared orientation, with the assumption that channels follow joints which were later widened by geomorphologic processes. The inventory method of fracture analysis was used to collect fracture measurements at a variety of scales of observation. At its fullest extent, and in order to view the entire

structure and drainage pattern of the Big Snowy Mountains, a scale of 1:150,000 was used to manually map the azimuth and length of dominant lineaments using the ruler tool in Google Earth Pro. The image was then repeatedly zoomed in to closer views to comprehensively map all lineaments within the Big Snowy Mountains at scales to 1:3,000, which is the finest resolution for the Big Snowy Mountains available in Google Earth Pro release 7.1.2.2041. Using this method, 1,545 lineaments were measured and recorded into an Excel spreadsheet (Appendix F).

These measurements were imported as a table into ArcMap 10.1, converted into a shapefile, projected into Universal Transverse Mercator (UTM) coordinates, and categorized based on their angle with respect to the fold hinge ($\pm 15^\circ$). The field calculator was then used to find both the azimuth and length (in meters) for each lineament measurement. Lineaments were then grouped and colored based on orientation with respect to the fold hinge by the same scheme that was used for the outcrop fracture analysis and as defined by Lageson et al. (2012). Strike and dip (assumed vertical) data was then imported into Rockware StereoStat and plotted on a rose diagram, with each petal normalized to the length of the fractures at that orientation. The Laramide stress field, fault axis, and fold orientation were then superimposed on the diagram.

RESULTS AND DISCUSSION

Field Outcrop Products

Breccia Pipe Heterogeneities

Physical brecciation occurs through a cyclic process due to overpressurization and depressurization in the subsurface, causing failure in the material (Phillips, 1972; Laznicka, 1988; Jebrak, 1997; Cas et al., 2011). Outcrops of hydrothermal breccia pipes are characterized by chemical bleaching. This bleaching has often been attributed to the migration of hydrocarbon-bearing solutions (e.g., Jurassic sandstones on the Colorado Plateau) or carbon dioxide degassing reactions (Parry et al., 2004). The presence of hydrothermal alteration in outcrop along the BSFS and SWC is obvious due to the addition and redistribution of iron and formation of crusts and veins of limonite and manganese oxide, all of which are delineated by sharp linear contacts separating the brecciated area from a relatively undeformed host rock on either side (Figure 16).

The host rock on either side of a hydrothermal breccia pipe displays minimal fracturing, and its bedding remains undisturbed by the injection of breccias (Figure 17). Breccias show no extreme evidence of crushing or shearing due to tectonic processes, but rather are characterized by the reduction and rotation of clasts within a finer matrix. Most breccia pipes display a zonation of alteration and mechanical differences within the confines of the breccia pipe, which are represented by the overprinting of chaotic, poorly-cemented, matrix-rich breccias

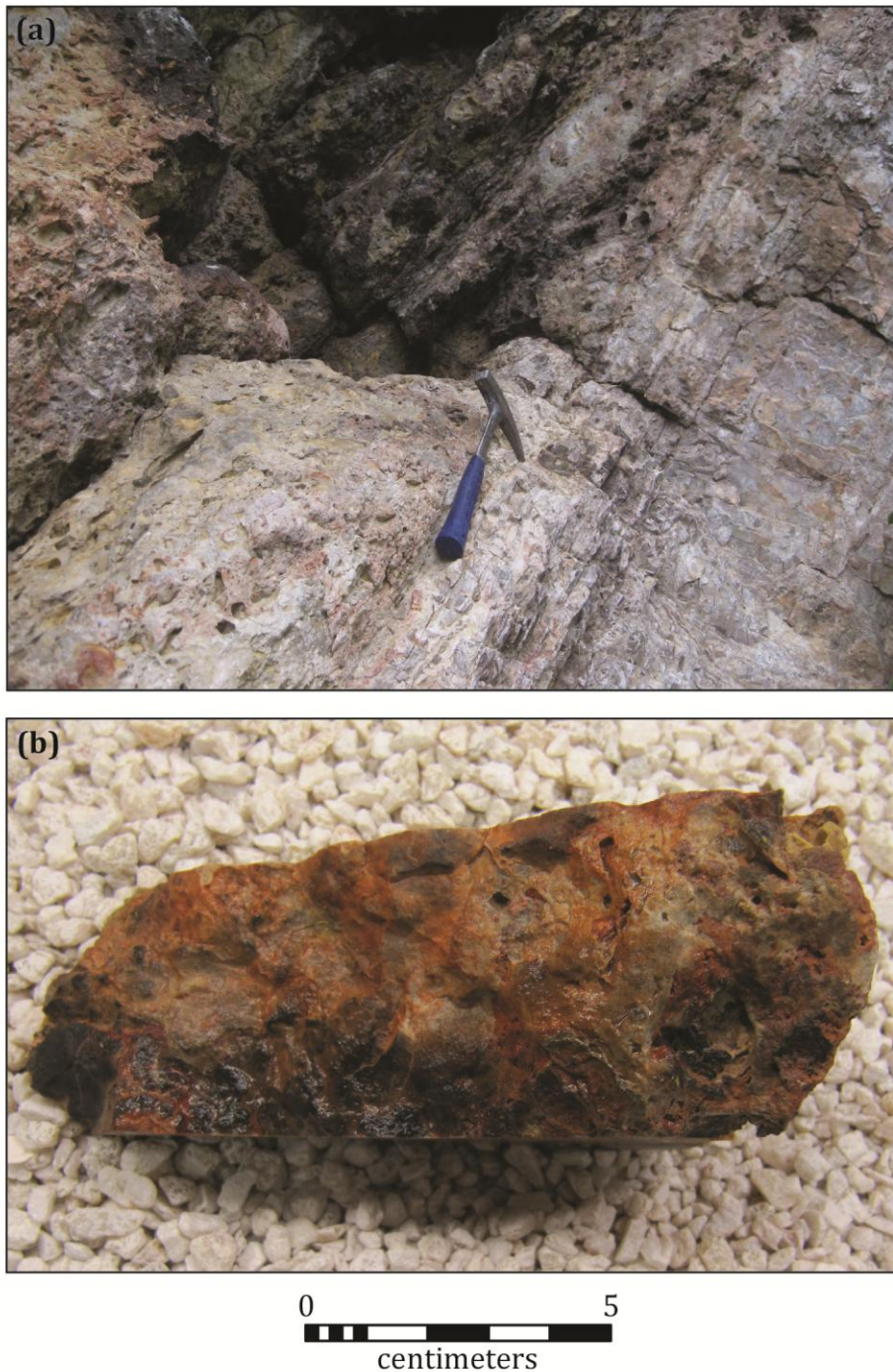


Figure 16. Outcrop and hand sample photographs displaying surficial staining along a breccia pipe. The photo of outcrop SWC-03 (a) is a level view of an angular bedding plane cutting towards the top right of the picture; hand sample SWC-03a (b) is a whole hand sample from same outcrop. These photographs are from a breccia pipe at the mouth of SWC, where limonite and manganese oxide stains are prevalent across the entirety of the breccia pipe.

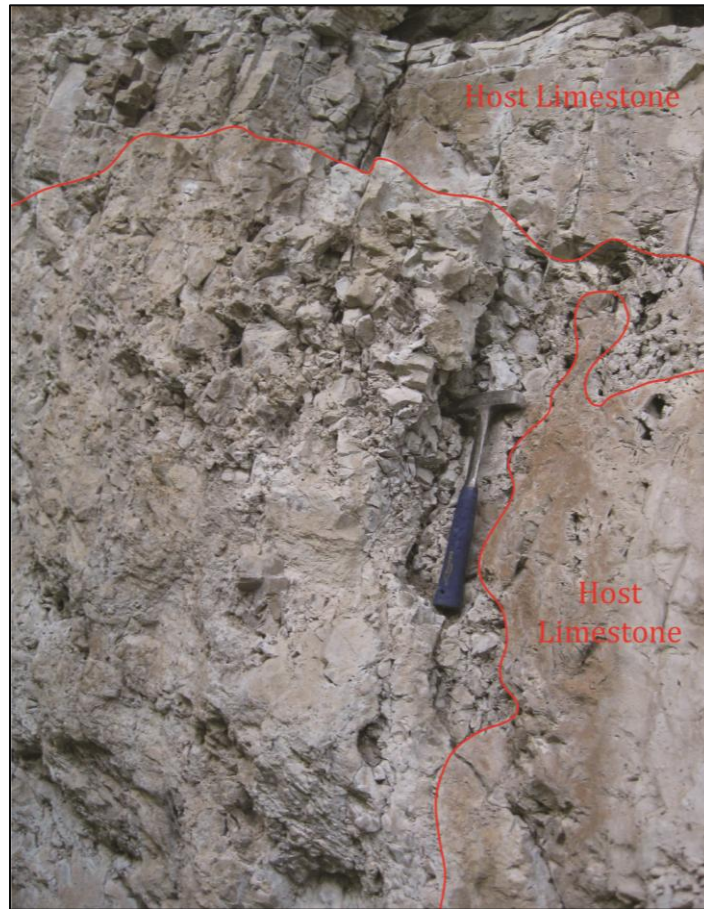


Figure 17. Outcrop photograph of the sharp contacts of a vertical breccia pipe. The contact, located at the red line located above and to the right of the rock hammer, separates brecciated limestone (left) from massive, slightly fractured protolith (above; right) at breccia pipe BSM-004 along the BSFS.

over mosaic or crackle breccias that are generally cemented into a more coherent texture (Figure 18). Such zones are interpreted to represent pathways which were more conducive to episodic rupture and fluid flow, and served as fluid "raceways" in the subsurface during crack-seal processes. The near-vertical boundaries of the breccia body indicate that they were formed subsequent to major folding events in the anticlinorium, and typically cross-cut joints and fractures in outcrop.



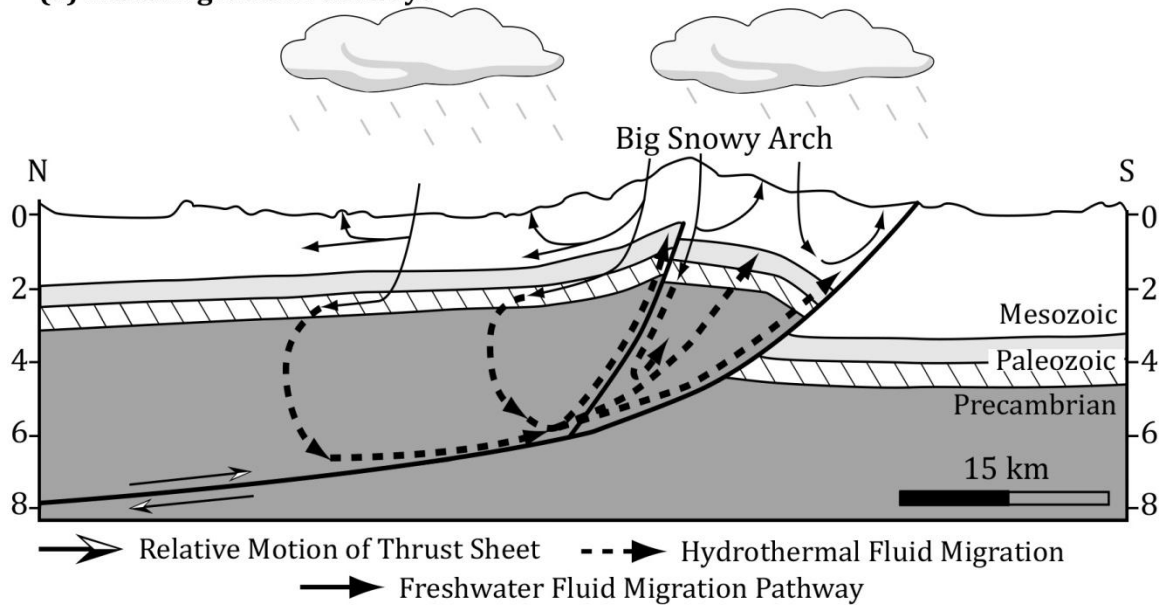
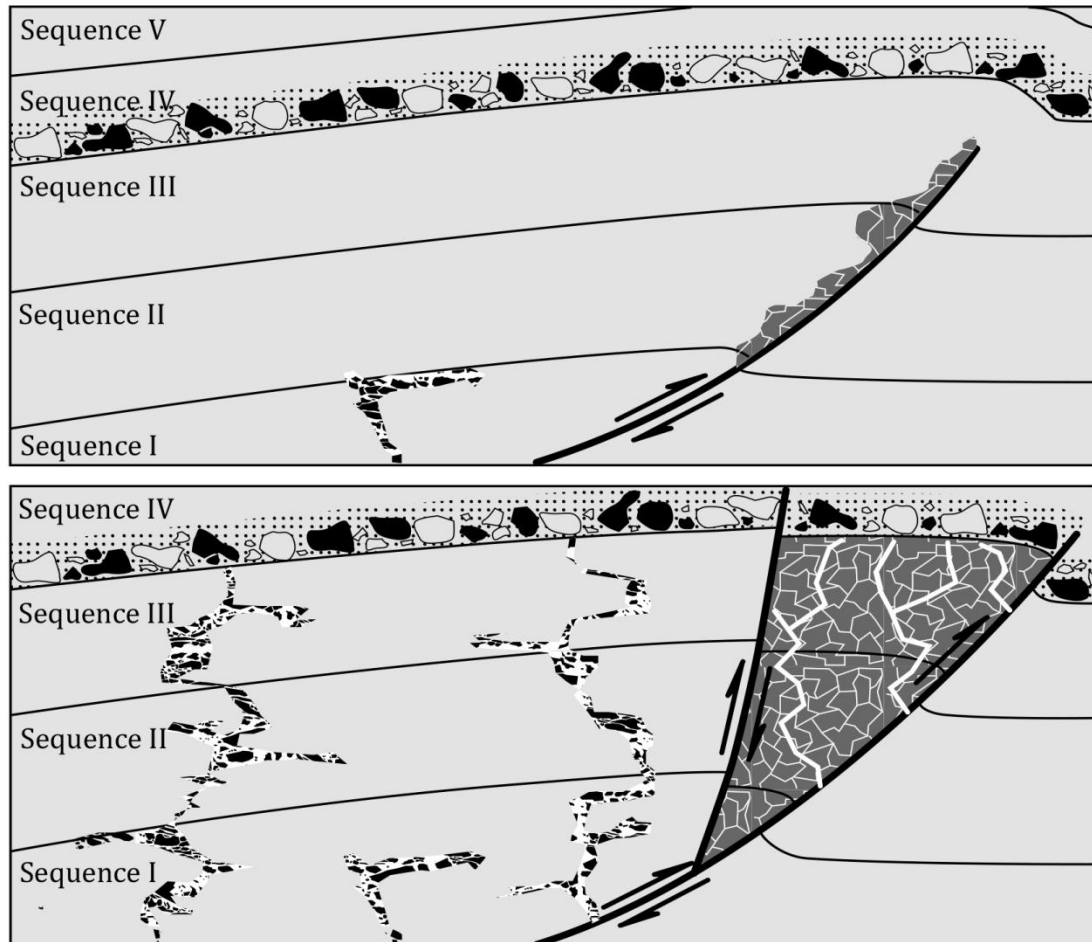
Figure 18. Outcrop photograph exhibiting the internal heterogeneities within a breccia pipe. The field outcrop photographs (a and b) of breccia pipe BSM-020 along the BSFS show zones of more intense brecciation and alteration, as indicated by the red arrows. These areas are interpreted to have been more permeable conduits for fluid flow during previous reactivation events.

There were two main expressions of hydrothermal brecciation and alteration within the carbonate protolith in the Big Snowy Mountains. The first style, and the most common, was dependent upon the mechanical strength of the rock. Finely crystalline limestones, which are mechanically stiff units, were generally the localities of laterally extensive brecciation. The model for the formation of this type of brecciation is similar to that which Gundmundsson et al. (2003) described in his description of fracture arrest (c.f. "Previous Investigations and Nomenclature"). Through more coherent lithologies, fracturing and brecciation will progress vertically from the upward propagation and hydrofracturing of overpressured fluids. Once the breccia pipe reaches an argillaceous layer, the brecciation will arrest at the seal and spread out laterally along the contact (Figure 19). Along the BSFS and SWC, this phenomenon was observed at irregular intervals along many of the hydrothermal breccia pipes. Brecciation often breached the confining unit and continued in an anastomosing pattern as a dikelet approximately 0.25 meters wide, and extending up to approximately one to five meters vertically before terminating upward in a more argillaceous unit. This demonstrates that although breccia pipes are confined to the mechanically stiff units of the Mission Canyon Limestone, they may branch and bifurcate upward through units that usually act as a seal. Such a relationship has been proposed by Katz et al. (2006) in relationship to the major sequence boundaries of the Madison Group carbonates (Figure 20).

The second style of brecciation in the Big Snowy Mountains is less extensive in scope, and is limited to the location of solution collapse karsting in the upper part



Figure 19. Outcrop photographs revealing the nature of breccia contacts with argillaceous seals. Breccia pipe BSM-015 (a) along the BSFS shows the termination pattern against a top impermeable argillaceous seal, which arrested the propagation of the breccia pipe; BSM-019 (b) exhibits the complex internal shearing in an argillaceous bed from the movement of hydrothermal fluids.

(a) Fluid Migration Pathways**(b) Formation of Breccia Bodies**

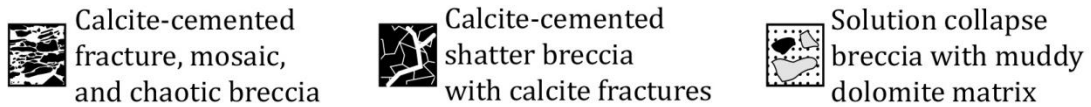
EXPLANATION:

Figure 20. (Continued from previous page). Model for the formation and fluid source of a hydrothermal breccia pipe. In this model, hydrothermal fluids are sourced by a combination of meteoric and basement fluids that flow along pre-existing structures in the subsurface. (a) Hydrothermal fluids rise along pre-existing structures, preferentially hydrofracturing the hanging wall side of features; (b) brecciation continues along the thrust sheet, forming shatter breccias in an increasingly vertical pattern. In both cases, hot fluids rise through strata in an unpredictable pattern, creating off-shoots near sequence boundaries due to major changes in mechanical properties (modified from Katz et al., 2007).

of the Mississippian Mission Canyon limestone. Sequences III, IV, and locally V in the Madison Group carbonates are capped by solution collapse breccias that correlate to regional unconformities (Sonnenfeld, 1996). These breccias were probably the site of reactivation following Laramide deformation, and preferentially focused fluid flow, hydrofracturing the rock above karst features (Figure 21). The hydrothermal breccias associated with karst features are restricted both in location and size to the properties of the karst collapse feature. In Figure 21, a small cave approximately two meters wide is the site for a sill of hydrothermal brecciation. It is interpreted that this cavity lies along a 3rd order sequence boundary in the Mississippian Mission Canyon Limestone, which was marked by karstification and collapse, and was the site for later hydrothermal alteration due to a pre-existing weakness along the unconformable bedding contact.



Figure 21. Outcrop photograph of a breccia pipe focused by karsting and solution collapse. Breccia pipe BSM-011 along the BSFS formed in relation to karstification along a regional unconformity of the Mission Canyon Limestone. Hydrothermal fluids were probably focused into these voids, preferentially hydrofracturing the surrounding wall rock in more recent brecciation events.

Hand Sample Descriptions

Crackle, mosaic, and chaotic breccias are all present within breccia pipes found in the BSFS and SWC, although chaotic are by far the most common. The presence of highly altered chaotic breccias indicate that multiple episodes of fluid flow affected the breccia pipe, and allowed the host rock to evolve from a coherent limestone to a crackle breccia, which then proceeded to fracture and brecciate into a mosaic or chaotic breccia. Hand samples vary in the degree of cementation from an incoherent, matrix-supported rock to a coherent cemented breccia, where the cement is characterized by crystalline precipitates in void space or replacement

textures and matrix is defined as an aggregate of fine-grained clasts and alteration minerals as particulate matter (Figures 22, 23). These textures are more easily recognized and interpreted by means of a petrographic analysis.

Fracture Station Measurements

The fracture analysis on field outcrops indicates that most fractures on either side of breccia pipes are in-line or at a high-angle to the normal of the fold hinge line, and are in-line with the Laramide shortening direction (Table 1). Five sets of fractures were measured in the field. Their groupings were based off of the average orientation of the fold hinge (which strikes 109°) of the Big Snowy Mountains, which was found by measuring lineament data publicly available from NRIS and imported into ArcMap. Hinge-parallel (b-c) fractures are extensional joints that are within 15° of the strike of the fold hinge, indicating that they formed in relation to outer arc extension (Lageson et al., 2012; Lynn, 2012). Hinge-perpendicular (a-c) joints are extensional joints that formed within the specified range of the normal to the fold hinge, indicating that they were most likely a product of Laramide-shortening.

Both b-c and a-c joints are interpreted to be mode I extensional joints, where b-c joints represent outer-arc extension of a bed during flexural slip at the location of maximum curvature in the fold hinge, and a-c joints represent plunge-parallel extension across the fold hinge area and limbs. Both sets of oblique fractures are associated with a range of values approximately 30° to the Laramide shortening direction, representing a shear array of oblique lineaments (Lageson et al., 2012;

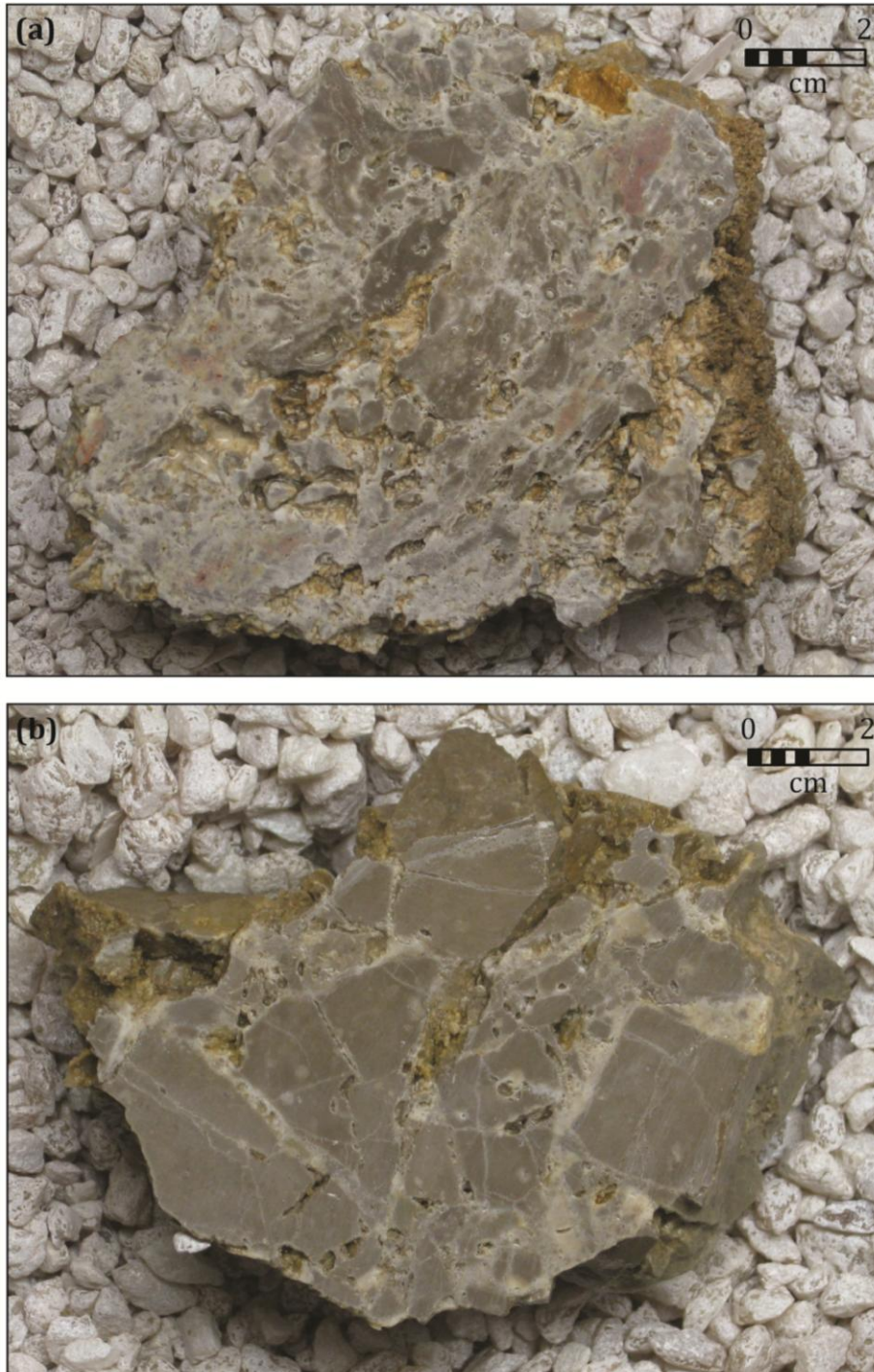


Figure 22. Brecciated hand samples displaying heterogeneous alteration, rotation, and fragmentation. Sample BSM-17b (a) is a poorly cemented, matrix-supported rubble breccia consisted of highly fragmented, rotated clasts; sample BSM-018c (b) is a well-cemented, clast-supported crackle breccia, showing little rotation. The cut face of this sample is pocketed by small, deep holes that are a result of drilling for powdered matrix material for laboratory analyses.

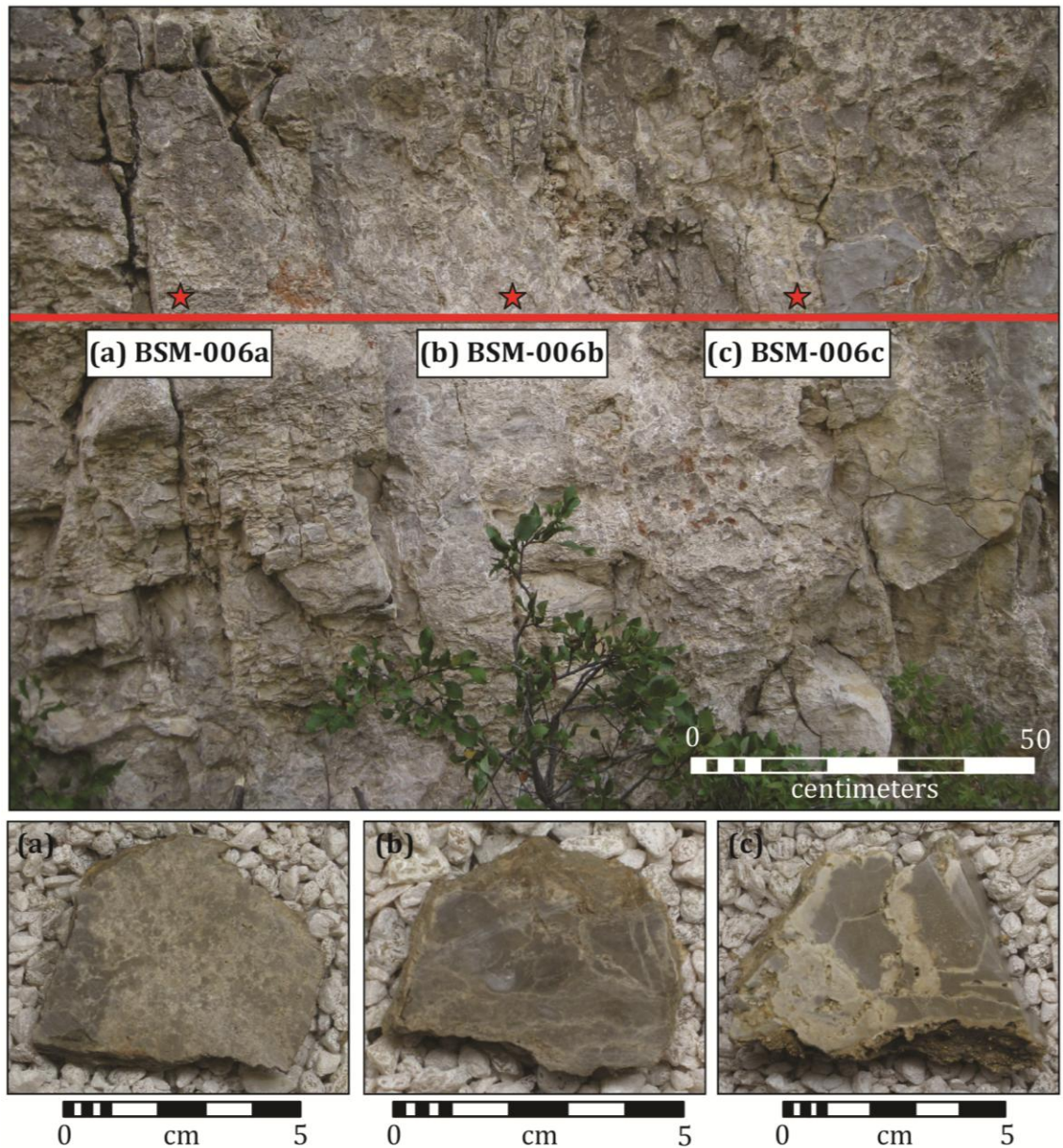


Figure 23. Brecciated samples displaying the internal zonation of a breccia pipe. Breccia pipe BSM-006 (top) shows the progression from outer (left) to inner (right) regions of the pipe. Sample BSM-006a (a) was taken from a matrix-poor, clast-supported crackle breccia near the contact with the undeformed wall rock. Sample BSM-006b (b) was taken in a patch of more deformed material, resulting in a more fractured mosaic breccia exhibiting a slight rotation of clasts and a higher matrix content. Sample BSM-006c (c) was taken from the internal conduit of the breccia pipe, where the matrix concentration was highest and there was a maximum separation of clasts, resulting in a chaotic breccia. All three samples were taken within one meter of each other, exemplifying their extremely heterogeneous nature.

Lynn, 2012). Such oblique fractures were initially interpreted to represent a conjugate array of fractures due to their orientation and geometry; however, because there was no evidence to suggest that they formed simultaneously, they were purely classified as an oblique joint set. Other fractures are those that lie within the range of directions associated with b-c, a-c, and oblique joints (Figure 24).

The Rockware StereoStat analysis reveals that the majority of fracture stations consist of dip-parallel (a-c) joints that formed due to plunge-parallel extension (Figure 25). Fifteen of the fracture stations contained a set of a-c joints, two stations contained b-c joints, six contained a set of fractures in line with oblique set 1, and eleven contained a dominant set of fractures at other unclassified orientations. Those outcrops with the highest fracture densities (BSM-016 E, BSM-020 E, BSM-020 W, and BSM-019 E) were characterized by an array of fractures at varying orientations (dip, strike, dip, and oblique set 1; respectively), suggesting that fracture density was not strongly controlled by a single dominant set of fractures. However, the absence of other fractures in highly fractured areas suggests that the regional tectonic framework strongly affected the emplacement of hydrothermal breccia pipes.

Fractures attributes, including dip, dip direction, and length, were measured in order to predict how fractures formed in relation to the regional stress field. Spacing, aperture, and vein fill were not quantitatively measured, but were described in relation to the mechanical stratigraphy of the unit in which the

Table 1. Table of average fracture station measurements used for StereoStat analysis. Each fracture station is color-coordinated according to the scheme in Figure 24.

Breccia Pipe ID and Direction	Average Dip (°)	Average Dip Direction (°)	Average Fracture Length (millimeters)	Fractures Measured
BSM-004 N	84	300	174	28
BSM-004 S	80	112	105	15
BSM-007 N	68	139	90	25
BSM-007 S	81	97	521	6
BSM-009 N	72	134	125	21
BSM-009 S	86	307	309	4
	76	227	118	28
BSM-010 N	66	129	51	11
	76	217	75	14
BSM-010 S	75	119	36	5
	62	218	129	22
BSM-011 N	82	123	199	4
	82	166	219	17
BSM-011 S	86	334	182	15
BSM-012 N	75	139	152	16
BSM-012 S	74	137	88	17
BSM-015 N	60	179	199	11
	72	165	206	9
BSM-015 S	86	119	124	23
BSM-016 E	78	120	50	65
BSM-016W	86	122	145	35
BSM-017 N	55	112	124	38
	27	309	316	12
BSM-017 S	75	305	174	30
BSM-018 E	85	208	250	7
	48	118	148	12
	54	297	100	8
BSM-018 W	68	125	201	33
BSM-019 E	86	145	159	38
BSM-019 W	64	95	256	26
BSM-020 E	80	200	147	51
BSM-020 W	80	106	213	47
BSM-021 E	73	113	198	19
BSM-021 W	85	112	418	24

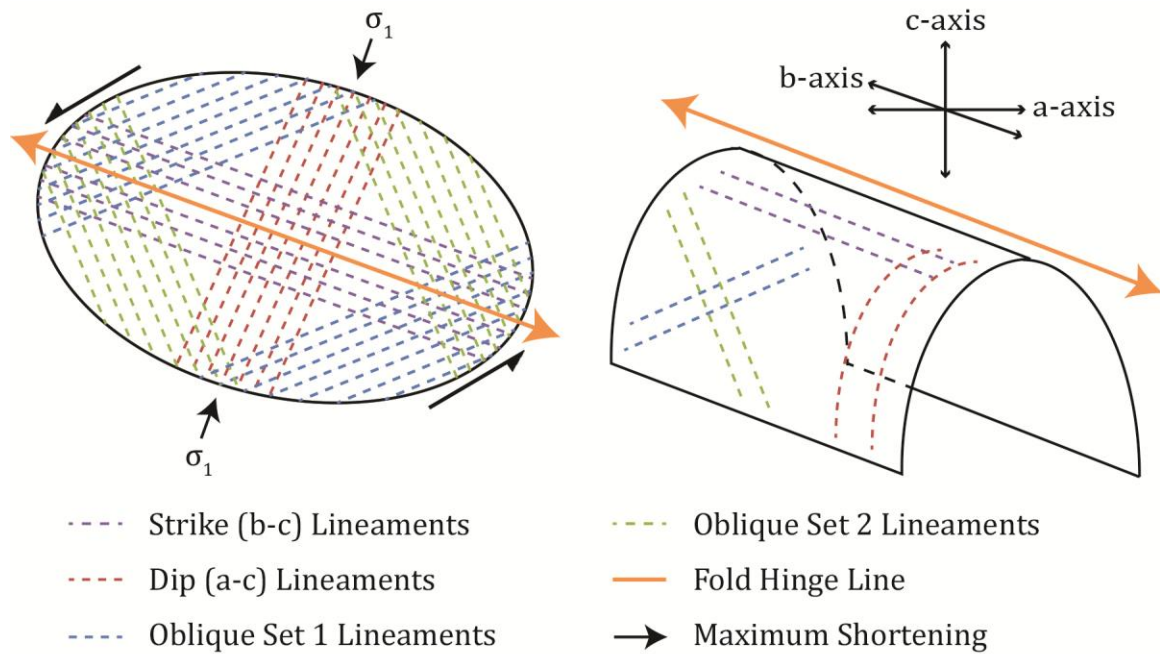


Figure 24. Terminology for strike, dip, and oblique lineaments in relation to the geometry of an anticline. (Left) Strike (b-c joints; purple), dip (a-c joints; red), and oblique (set 1 is blue; set 2 is green) lineaments in relation to the interpreted shortening direction σ_1 displayed on a strain ellipse with the fold hinge line of the Big Snowy Mountains (orange) superimposed; (Right) lineaments in relation to the geometry of an upright anticline (modified from Lageson et al., 2012).

fractures formed. The spacing of fractures was much closer in more thinly-bedded units than the massive crystalline limestones that most breccia pipes propagated through (Figure 26). This agrees with the observation of Mitra (1988) that fracture intensity increases with decreasing bed thickness. Because fracture stations were restricted to within approximately 15 meters of the breccia pipe walls, the lithology of the unit (the Mission Canyon Limestone) did not vary to the degree in which large differences in aperture would be seen, as described by Gudmundsson et al. (2003). All fracture stations exhibited negligible aperture with no vein fill, indicating that they were probably not the sites for the migration of large volumes of fluid flow.

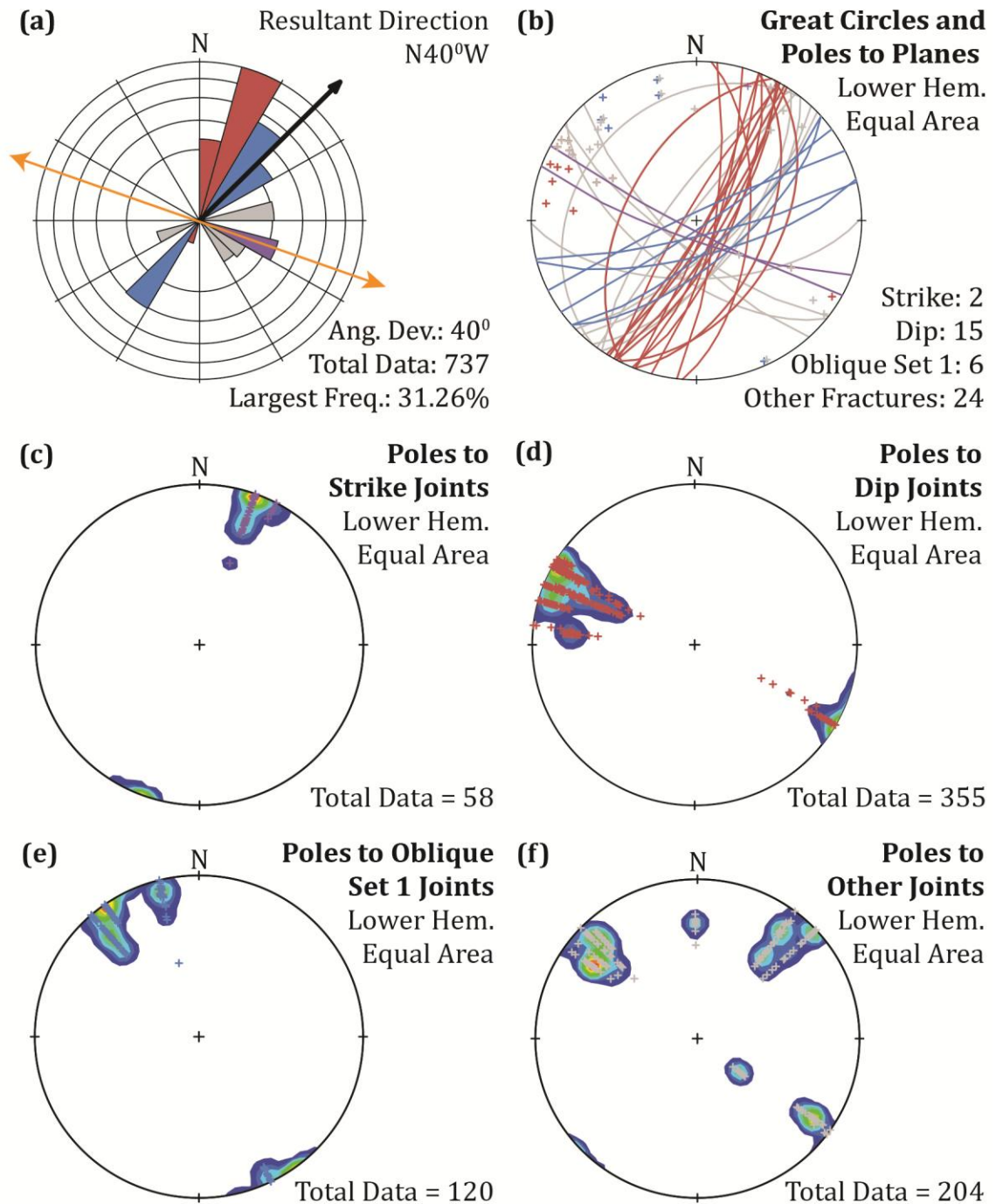


Figure 25. Rockware StereoStat analyses of planes and poles for strike and dip attributes from field fracture stations. Strike (purple), dip (red), oblique set 1 (blue), and other (grey) fractures are represented. The rose diagram (a) contains data from all 737 fractures measured, and is normalized to the sum length of all fractures in each petal. The stereonet (b) displays strike (planes) and dip (poles) for the average measurements at each fracture station. Contoured poles to planes (c through f) for each joint set utilize all fracture measurements from each of the fracture stations.



Figure 26. Outcrop photograph of fracture density and aperture in an argillaceous unit. This close-up of fracture station BSM-019 E along the BSFS is of fractures that are located in a more argillaceous unit, exhibiting a higher fracture density and larger aperture than was present in the more massive crystalline limestone that composes most of the Mission Canyon Formation.

Laboratory Results

X-Ray Diffraction Peak Results

The amount of saddle and matrix dolomite, calcite, and quartz in breccia samples from the BSFS and SWC indicate that calcite is the predominant mineral in whole, matrix, vein, vug, rind, replacement, and clast fill (Table 2). In all the samples (excluding the sample from the Devonian Jefferson dolomite, which was used as a control representing a composition of 100% dolomite), dolomite reaches a maximum value of 5%, as determined by experimental curves. The distribution of

Table 2. Relative percentages of dolomite, calcite, and quartz determined from XRD peaks and experimental curves. Unless otherwise indicated next to the breccia pipe identification (ID), samples are of matrix material.

Sample ID and Location	d₁₀₄ (Å)	Relative % Dolomite	Relative % Calcite	Relative % Quartz
BSM-001c	3.029	4	96	0
BSM-002b	3.029	4	96	0
BSM-003a	3.052	0	100	0
BSM-004d whole	3.035	2	98	0
BSM-005b	3.031	3	97	0
BSM-006c	3.052	0	100	0
BSM-007b	3.029	4	96	0
BSM-007b clast	3.050	0	100	0
BSM-007c whole	3.036	1	89	10
BSM-008b	3.028	4	96	0
BSM-009e	3.029	4	96	0
BSM-010c	3.052	0	100	0
BSM-011a vein	3.049	0	100	0
BSM-012a	3.051	0	95	5
BSM-013a	3.051	0	100	0
BSM-014a	3.025	5	30	65
BSM-015b whole	3.042	0	100	0
BSM-016a	3.029	4	96	0
BSM-017c	3.030	3	87	10
BSM-018b	3.029	4	96	0
BSM-019a whole	3.029	4	91	5
BSM-019b vug	3.030	3	97	0
BSM-019c whole	3.030	3	97	0
BSM-020a whole	3.029	4	91	5
BSM-020c clast	3.030	3	97	0
BSM-021b	3.029	4	96	0
BSM-022a	3.031	3	97	0
BSM-F2c	3.029	4	66	30
BSM-F3b	3.030	3	72	25
SWC-01a whole	3.029	4	86	10
SWC-01b	3.034	2	22	75
SWC-01c	3.032	3	62	35
SWC-01d	3.031	3	82	15
SWC-01e	3.034	2	93	5

Table 2. Continued from previous page.

SWC-01f	3.031	3	57	40
SWC-02 whole (control)	2.886	100	0	0
SWC-03a replaced	3.032	3	82	15
SWC-03b whole	3.032	3	87	10
SWC-03C	3.032	3	92	5
SWC-03C rind	3.030	3	92	5
SWC-03D	3.034	2	93	5
SWC-03E	3.032	3	87	10
SWC-03F whole	3.032	3	92	5

dolomite throughout the samples does not seem to be related to the type of sample or region in which the sample was collected, suggesting that dolomitization permeated all regions of the breccia pipe and host rock during fluid migration. The one vein sample (BSM-011a vein), which cross-cuts other features within the sample, indicates that it may have formed at a later stage than dolomitization.

The distribution of siliceous material does suggest some local control over the composition of the samples. Along the BSFS, small amounts of quartz are mostly confined to those samples which are ground whole rock, which does not give any evidence to the provenance of the material. However, in SWC, each of the samples (exempting the control sample, SWC-02 whole) was siliceous, though still not related to any specific type or locality of sample. This suggests that the two breccia pipes found at SWC were sourced by more siliceous fluids than those along the BSFS, and indicates that multiple thermal convection cells were present in the Big Snowy Mountains, resulting in different styles of brecciation and varying mineralization in hydrothermal structures.

Carbon and Oxygen Isotopic Compositions

Isotope fractionation is an important process because it drives isotopes to partition between two phases with different isotopic ratios depending on the ambient conditions at the time of formation. The isotopic signature of marine water is governed by the $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and ambient temperature of the fluid, and can be used in identifying the source of the percolating solutions that formed the hydrothermal breccia pipes studied in the Big Snowy Mountains (Arthur et al., 1983).

Carbon Isotopes. Along the BSFS, $\delta^{13}\text{C}$ values range from -6.38‰ to 3.27‰. This encompasses 21 matrix samples from hydrothermal breccias (-2.63‰ to 2.14‰), two clasts (2.73‰ to 2.97‰), one vein (3.27‰), two whole rocks (0.59‰ to 0.82‰), one sample with calcitic vugs (0.58‰), and two matrix samples from a fault breccia (-6.38‰ to -4.23‰). At SWC, $\delta^{13}\text{C}$ values range from -2.04‰ to 4.01‰. These values include eight matrix samples (0.25‰ to 1.72‰), four whole rocks (0.58‰ to 4.01‰), replacement material from one sample (-2.04‰), and the rind from one sample (0.97‰) (Table 3; Figure 27).

The resultant carbon isotope values may be compared to known values to interpret their origin. Throughout Phanerozoic time, the $\delta^{13}\text{C}$ composition was $0.56 \pm 1.55\text{‰}$ (for marine fluids) and $-4.93 \pm 2.75\text{‰}$ (for non-marine fluids) (Figure 28) (Faure, 1998; Ripperdan, 2001). Fluctuations in marine water occur because carbonate material precipitates in equilibrium with the CO_2 of the atmosphere; therefore, the marine carbonate will be enriched in ^{13}C relative to CO_2 , which has

Table 3. Stable carbon and oxygen isotope results. Values are color-coded according to the scheme in Figure 27.

Breccia Pipe ID	$\delta^{13}\text{C}$ (‰ VPDB)	$\delta^{18}\text{O}$ (‰ VPDB)
BSM-001c	1.06	-15.72
BSM-002b	1.54	-15.35
BSM-003a	-0.47	-17.05
BSM-004d	1.57	-11.56
BSM-005b	1.43	-12.71
BSM-006c	0.32	-16.47
BSM-007b	0.65	-17.99
BSM-007b clast	2.73	-8.98
BSM-007c	1.26	-14.98
BSM-008b	-0.10	-16.79
BSM-009e	0.73	-16.34
BSM-010c	2.14	-10.91
BSM-011a vein	3.27	-12.25
BSM-012a	-2.63	-18.70
BSM-013a	0.91	-14.10
BSM-014a	-0.64	-15.45
BSM-015b	1.53	-12.21
BSM-016a	0.70	-12.60
BSM-017c	0.08	-15.81
BSM-018b	1.14	-16.29
BSM-019a whole	0.82	-19.62
BSM-019b vugs	0.58	-17.85
BSM-019c whole	0.59	-19.15
BSM-020a	1.52	-14.06
BSM-020c clast	2.97	-5.56
BSM-021b	0.92	-15.16
BSM-022a	1.60	-10.91
BSM-F2c	-6.38	-7.09
BSM-F3b	-4.23	-16.59
SWC-01a whole	0.58	-14.12
SWC-01b	0.61	-9.97
SWC-01c	0.60	-11.59
SWC-01d	0.25	-12.31
SWC-01e	0.84	-11.18
SWC-01f	0.50	-11.79
SWC-02a whole	4.01	-3.28
SWC-03a replacement	-2.04	-12.13
SWC-03b whole	0.74	-12.20

Table 3. Continued from previous page.

SWC-03c	0.96	-12.37
SWC-03c rind	0.97	-11.40
SWC-03d	0.34	-13.05
SWC-03e	1.72	-9.02
SWC-03f whole	1.60	-9.60
Standard	1.94	-2.20
Standard	1.90	-2.22
Standard	1.89	-2.28
Standard	1.97	-2.20
Standard	2.01	-2.14
Standard	1.86	-2.20
Standard	1.94	-2.10
Standard	2.03	-2.24
Standard	1.97	-2.18
Standard	1.97	-2.11
Standard	1.97	-2.13
Standard	1.97	-2.10
Standard	2.03	-2.15

typical $\delta^{13}\text{C}$ values of approximately 0‰. The depletion in ^{13}C in non-marine carbonates may be attributed to the oxidation of plant material to bicarbonate, which in turn produces biogenic carbon.

The majority of carbon isotope values fall between the 0.00‰ and 2.00‰ range, which is at the lower limit of $\delta^{13}\text{C}$ values during the Mississippian period (Figure 28) (Ripperdan, 2001). There are no values above the upper limit of this period ($\sim 5.00\%$), which suggests that there was little biogenic influence; therefore, it may be assumed that these values represent a marine (rather than meteoric) origin given by the signature of the Mississippian host rocks (Faure, 1998).

Clasts and vein fill material fit the isotopic signature of the Mississippian period ($\sim 2.00\%$ to 5.00%) well, with average isotopic compositions near the

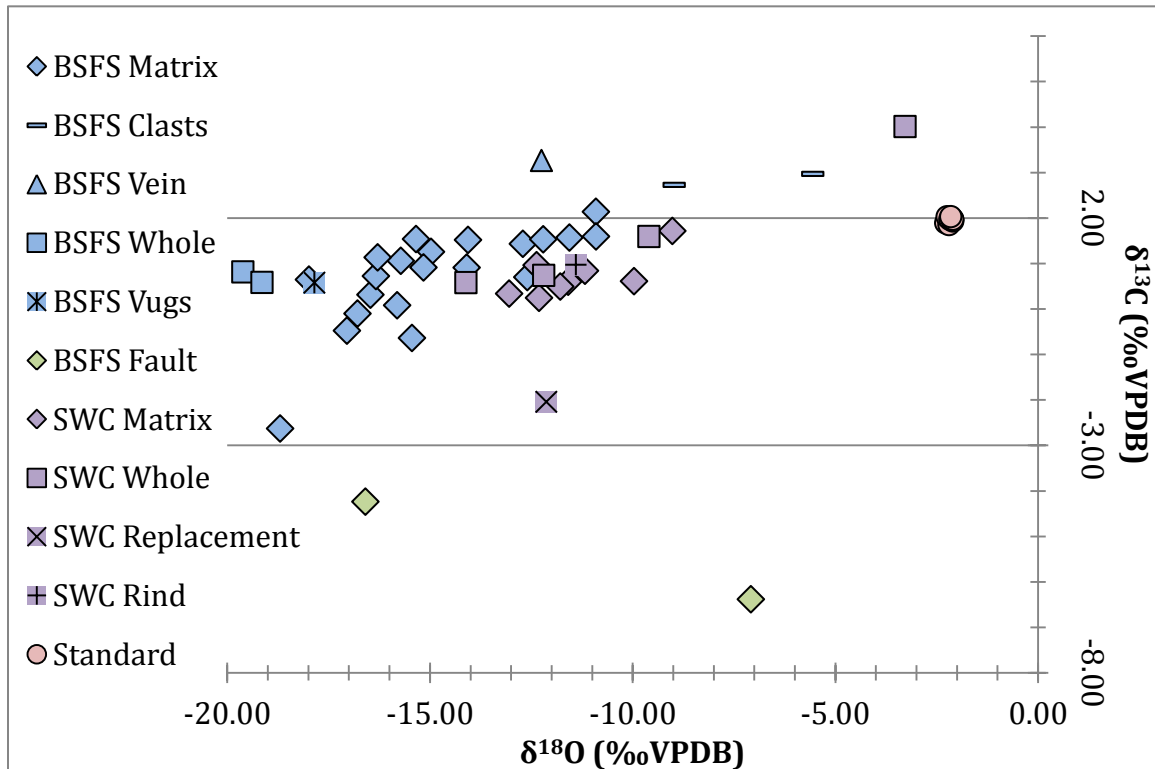


Figure 27. Stable carbon and oxygen isotope results. Stable isotope analysis contrasts samples from various parts of a breccia pipe in comparison to standard laboratory samples (pink circles). There is a slight downward linear trend (down to the left on the graph) indicating mixing between marine and meteoric waters. Marine waters, which may originally be trapped within the pore spaces or layers of a sedimentary rock, are often isotopically altered by isotope exchange reactions with the host rocks and downward-percolating meteoric fluids (Faure, 1998). This results in connate waters whose isotopic signature is a mixture of formational and meteoric fluids.

2.00‰ expected for lower to middle Mississippian units. Clasts, of course, are simply part of the wall rock, and thus would have the same signature as the Mississippian Mission Canyon Formation. The isotopic signatures of vein fill material here suggest that they must have been formed from early marine diagenetic waters prior to meteoric infiltration. The wide ranges in the rest of the values, when displayed on a graph, exhibit a slight downward linear trend, which

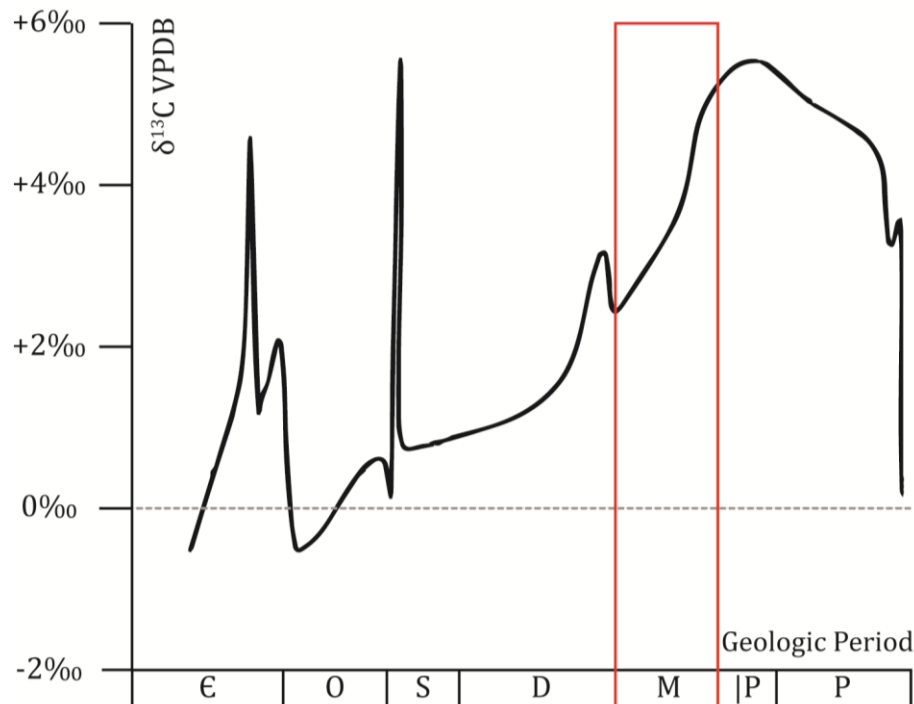


Figure 28. Typical Paleozoic carbon isotope values (modified from Ripperdan, 2001). During the Mississippian period (red box), values ranged between two and five ‰.

may be due to marine and meteoric waters mixing. This feature is likewise evidenced by the strong depletion of ^{18}O values for both field areas.

Oxygen Isotopes. $\delta^{18}\text{O}$ values encompassed a much greater distribution of values than $\delta^{13}\text{C}$ compositions had. Along the BSFS, oxygen isotope values ranged from -5.56‰ to -19.62‰, which was inclusive of matrix samples (-10.91‰ to -18.70‰), clasts (-5.56‰ to -8.98‰), a vein (-12.25‰), whole rocks (-19.15‰ to -19.62‰), vugs (-17.85‰), and fault breccias (-7.09‰ to -16.59‰). At SWC, $\delta^{18}\text{O}$ values were between -3.28‰ and -14.12‰, including matrix samples (-9.02‰ to 13.05‰), whole rock (-3.28‰ to -14.12‰), replacement material (-12.13‰), and a weathering rind (-11.40‰) (Table 3; Figure 27).

The strongly depleted ^{18}O content of these samples indicates that increased temperatures were present during fluid circulation events, giving strong evidence towards the hypothesis for the presence of hydrothermal fluids. This indicates that the oxygen isotopic signature is influenced by the presence of non-marine fluids (in this case, most likely a mixture of hot, isotopically depleted basement fluids and meteoric waters). The wide range in oxygen isotope values may indicate that there were multiple episodes of hydrothermal fluid migration through the host rocks with varying temperatures; thus, more depleted values are interpreted to represent episodes with higher temperature fluids (and vice versa). Additionally, later stage cementation events become progressively lighter in both carbon and oxygen signatures; therefore, successive generations of cementation will display increasingly more depleted isotopic signatures (Hoefs, 2009). However, it is important to note that magnesian calcites are enriched in $\delta^{18}\text{O}$ compared to pure calcites at 25°C by 0.06‰ per mole percent MgCO_3 (Arthur et al., 1983). Similarly, dolomites may concentrate $\delta^{18}\text{O}$ by as much as 6‰ relative to calcite. Although XRD results indicate an overall minimal ($<4\%$) concentration of dolomite within most samples, this does explain the relatively higher ^{18}O content of sample SWC-02a, which was 100% dolomite.

Interpretation. Stable isotope results indicate a slightly positive carbon signature and a highly depleted oxygen composition. The distinct groupings of isotopic compositions within field localities and sample type illustrate that these geographic and petrographic distinctions reflect different genetic processes at play

within the system (Budai et al., 1984). Two outliers were present that affect the overall range of isotope values for each field area. At the BSFS, the lowest carbon and oxygen for hydrothermal matrix fill material belonged to BSFS-012a, which had a $\delta^{13}\text{C}$ low of -2.63‰ and a $\delta^{18}\text{O}$ low of -18.70‰ . Excluding these values, the BSFS would have a new range of isotopic values starting at -0.64‰ (for carbon) and -17.05‰ (for oxygen). In SWC, whole rock sample SWC-02a (a dolomite), was characterized by an isotopic high of 4.01‰ (for carbon) and -3.28‰ (for oxygen). Excluding these values, SWC would have a new range of isotopic compositions beginning at 1.60‰ (the highest $\delta^{13}\text{C}$) and -9.02‰ (the highest $\delta^{18}\text{O}$).

These results are significant in the interpretation of how hydrothermal systems formed within the carbonate units in central Montana. The stable carbon and oxygen isotopic composition within the matrix material is a direct indication of the isotopic composition within the fluid, temperature of formation, and type of dissolved carbon in the hydrothermal fluid (Hoefs, 2009). Because the solubility of carbonate material decreases with increasing temperature, new carbonate material may not be precipitated simply by the cooling of a hydrothermal fluid in a closed system; rather, an open system must be present in which outside factors such as CO_2 degassing, fluid-rock fractionation processes, or fluid mixing may be responsible for the precipitation of carbonate material.

The temporal variation in the amount of $\delta^{13}\text{C}$ during the Mississippian is related to the hierarchy of sequence stratigraphic cycles discussed earlier (Katz et al., 2007). Because the isotopic fractionation of inorganic carbon is determined by

productivity in shallow ocean waters, there is a general trend toward more positive values during marine transgressions, indicating that there was removal of light carbon from the inorganic carbon pool through enhanced productivity or the accumulation of organic matter in ocean basins. Consequently, during marine regressions, a relative fall in sea level would result in the recycling of isotopically light carbon back into the water column. Therefore, during a typical sequence, carbon isotope values will be at their highest at the time of the formation of the maximum flooding surface, and become progressively more negative towards each regional unconformity surface (Katz et al., 2007). Breccia samples collected along the BSFS and SWC exhibit lighter than expected ^{13}C isotopic values, indicating that their location along such third order sequence boundaries may exhibit a controlling factor over their isotopic signature.

Secondary Electron Imaging and ImageJ Pore-Space Analyses

SEM images were used to determine the secondary porosity associated with matrix dolomitization, which was too fine to see through petrographic analysis. The Mission Canyon Limestone was finely crystalline to peloidal in places. It was characterized by low intrinsic porosity and permeability; however, matrix material in brecciated regions of the Mission Canyon Formation added a strong secondary fabric to the rock, creating open vuggy space and intercrystalline porosity. Such textures were best analyzed using SEM imaging (Figure 29). The images from this type of analysis revealed a matrix that was composed of rounded calcite crystals

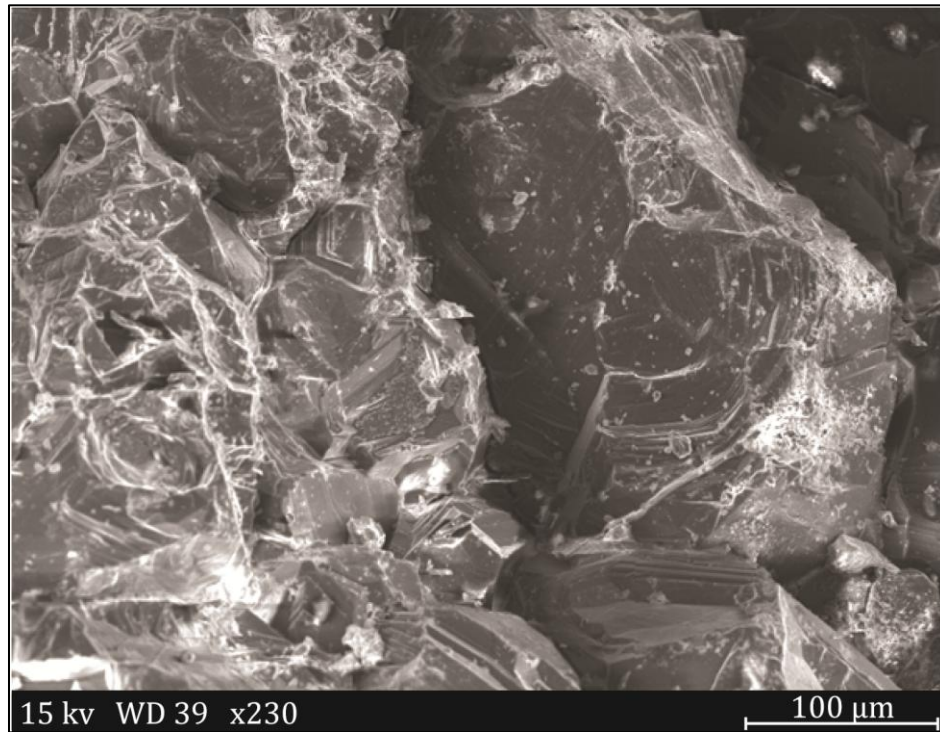


Figure 29. SEM image of a breccia sample from the BSFS. This sample (BSM-007c) was taken from the fine-grained matrix material within clasts in the interior of a hydrothermal breccia pipe. SEM is a useful technique because it clearly displays the highly brecciated nature and vuggy textures present within the breccia matrix. Calcitic cements (above) in most samples are anhedral to subhedral, indicating rounding by fluid flow and abrasion processes.

with varying degrees of dissolution and replacement textures. When these greyscale images were imported into the BoneJ extension of ImageJ, two-dimensional cross-sectional percent porosity calculations indicated a 5-25% porosity increase, highlighting the importance of the secondary development of porosity on much smaller scales than can be measured or quantified through petrographic means (Figure 30).

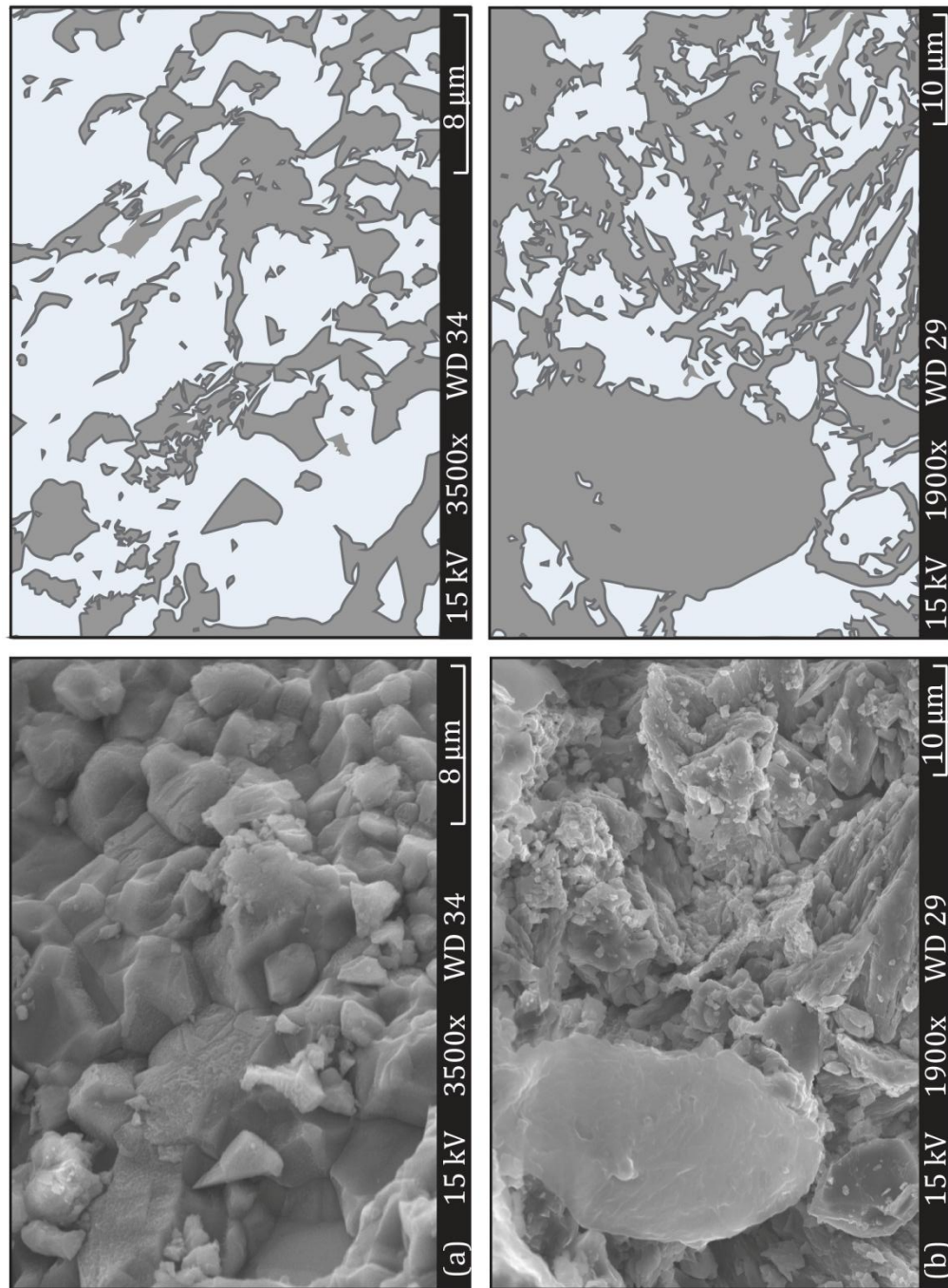


Figure 30. SEM and BoneJ analyses of matrix material from breccias highlighting the amount of porosity present. SEM (left) and the BoneJ plug-in of ImageJ (right) analyses were of matrix material from breccias BSM-007a (a) and BSM-013a (b). Color thresholds (dark grey enhancement in the images on the right) were applied, which emphasize the increase in two-dimensional area porosity. Calculations revealed a 5 to 25% increase in area porosity.

Petrography

Thin section petrography revealed brecciated fabrics with multiple generations of cementation in void space created by hydrofracturing. Cement types ranged from fine to coarse crystalline bladed to blocky isopachous cement, to blocky to coarse mosaic cements lining cavities, veins, and clast fragments. Cement compositions included euhedral to anhedral calcite, anhedral dolomite, and euhedral to anhedral quartz. Calcitic cements were common within all stages of diagenesis, and represented multiple stages of growth and cementation in the paragenetic sequence (Figure 31a). Dolomite cements were typically present both as fine anhedral bladed isopachous cements lining clast fragments and as in-situ replacement within the crystalline limestone host (Figures 31b, 31c). Only one sample contained euhedral dolomite rhombs overprinting earlier brecciation phases, indicating that dolomitization was not synchronous with the hydrothermal event, and in the majority of cases preceded brecciation.

Many thin sections displayed the growth of carbonate cements bridging pore throats, decreasing the secondary permeability that brecciation and fracturing had produced. Samples from SWC commonly contained doubly-terminated Herkimer quartz crystals, which were severely dissolved and replaced with carbonate cements (Figure 32a). Late stage sulfides and iron oxides stained the surfaces of each of the thin section slides, and were often present both as void fill and in veins that cross-cut the entire sample (Figure 32b). It was younger than dolomitic rims and cements, and formed in syntaxial veins and voids on top of older cements.

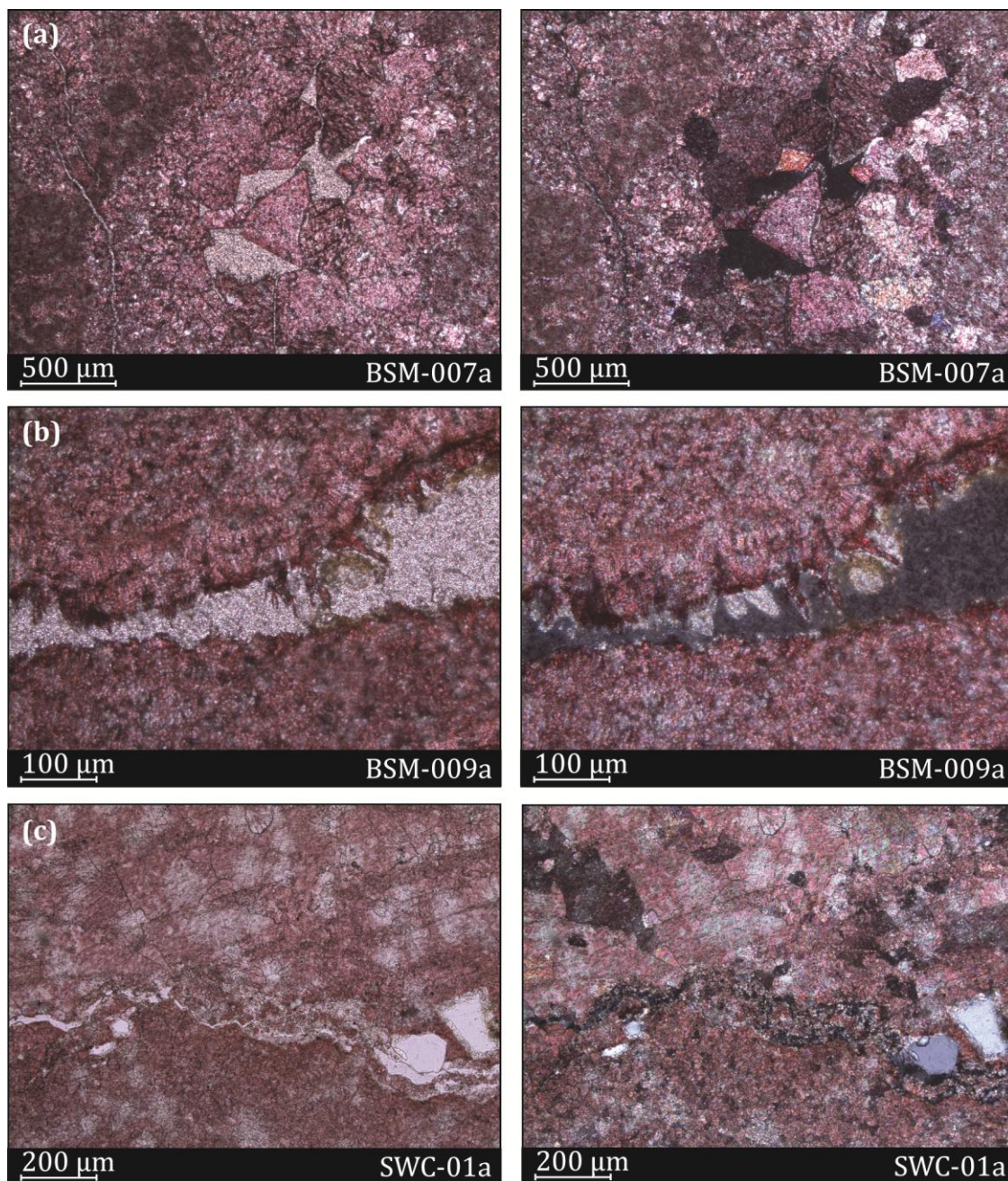


Figure 31. Petrographic images of hydrothermal breccias showing the different stages (zones) of cementation and replacement. The left column displays samples in plane-polarized light; the right in cross-polarized light. BSM-007a (a) is an example of a sample with multiple stages of calcite cementation, beginning with a fine isopachous cement and progressing inward with the formation of a coarser mosaic cement. Fine anhedral dolomite cement lines clasts and voids. BSM-009a (b) displays a coarser anhedral bladed dolomite cement and minor iron-oxide staining as a syntaxial rim. SWC-01a (c) shows the in-situ replacement of dolomite within large clasts of calcite. A through-fracture contains entrained subhedral quartz.

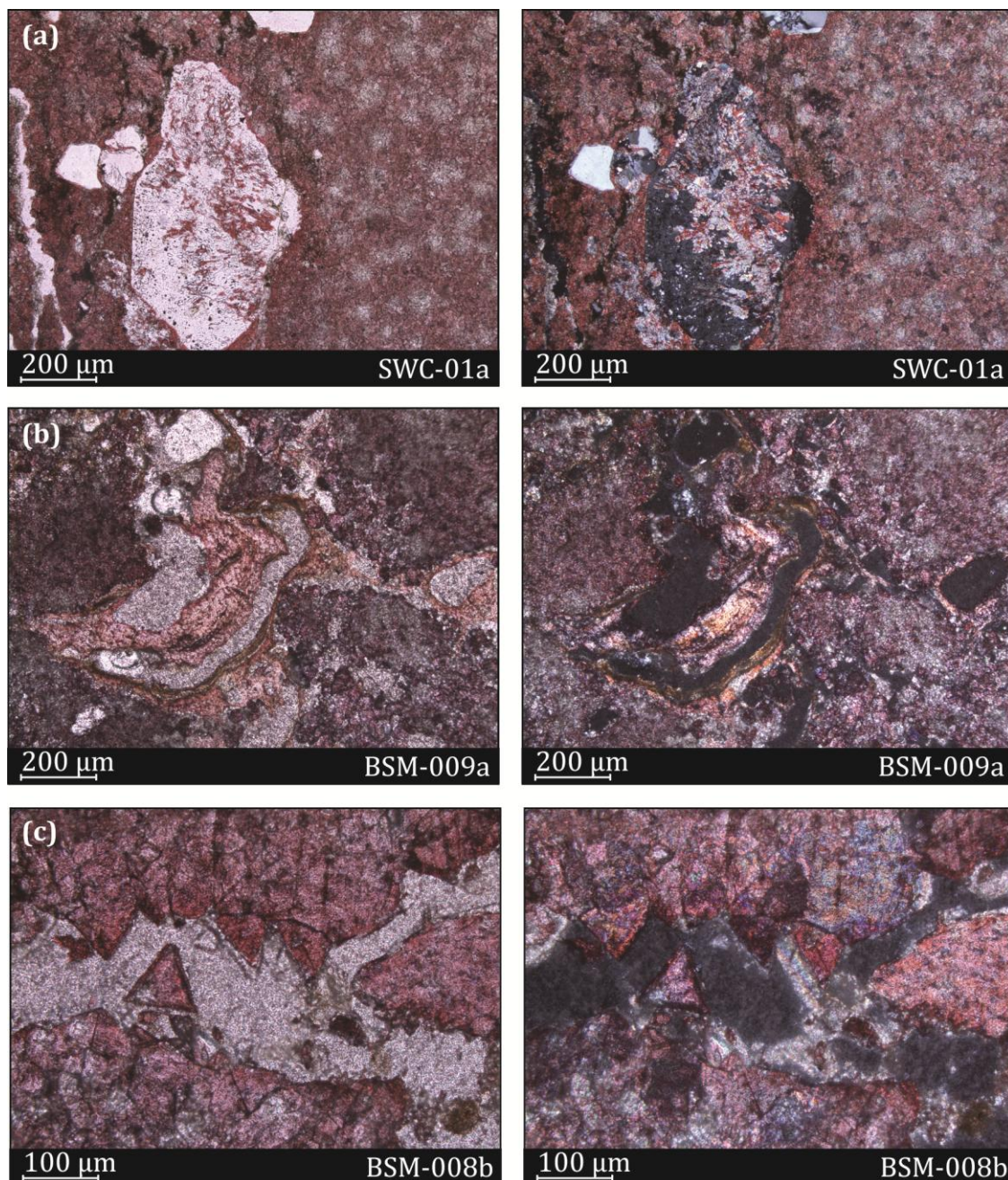
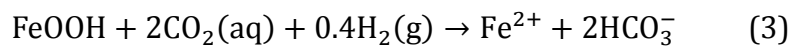


Figure 32. Petrographic images of hydrothermal breccias exhibiting the variations in secondary mineral precipitation and porosity development. The left column displays samples in plane-polarized light; the right in cross-polarized light. SWC-01a (a) shows a highly replaced Herkimer quartz crystal surrounded by calcite rhombs and matrix dolomitization. BSM-009a (b) displays a vug lined with early calcite and dolomite cements and late-stage iron. BSM-008b (c) is of a void that had been created by fracturing, and is lined by coarse calcitic cements. This void has been bridged by a late-stage dolomite cement event, which is interpreted to reduce the permeability that had been created by tectonic events.

Faceted crystals that point inward indicate that growth was into open pore space, and commonly crowd out as growth toward the center occurs, resulting in fewer crystals in the middle of the void (e.g., Figures 31a, 31b). Anhedral crystals may indicate that growth was into open space, but was later overprinted by succeeding fracture sealing events (e.g., Figure 31a) (Laubach, 2003). Precipitation often occurs at faster rates on broken surfaces, such as on broken bridges, than that on euhedral surfaces in-between bridges (Hooker et al., 2012). This results in the growth of bridges connecting clasts (Figure 32c). The presence of iron-oxides, as seen in Figure 32b, was probably promoted by the dissolution of carbon dioxide, which encourages the dissolution of iron hydroxides in redox reactions, such as



(Wilkin and Digiulio, 2010).

Paragenetic Sequence. The paragenetic sequence for the formation of hydrothermal breccias may have progressed as follows. Prior to dolomitization, early diagenesis may have resulted in the compaction, cementation, and suturing of grains. These primary features would have resulted in decreased porosity and permeability of the protolith. Secondary in-situ dissolution and matrix dolomitization, along with extensive solution collapse brecciation along sequence boundaries, would have created a higher permeability of the brecciated region, and late-stage inter-crystalline porosity due to dolomitization. The facilitation of faulting, fracturing, and brecciation would have created voids for the further precipitation of matrix dolomite, quartz, and calcite. Such features tend to create

bridges, meniscus cements, and coarse syntaxial vein fill, destroying permeability (Figure 32c). Late-stage tectonic stylolitization would have followed mineralization.

The presence of micrite envelopes lining peloidal grains in the limestone wall rock and fibrous cements within primary fractures is indicative of submarine diagenesis, and are the oldest features seen in thin section. Shallow burial diagenesis is supported by the neomorphism of micrite to microspar to sparry calcite, suggesting that the original micritic cements have been diagenetically overprinted with the secondary sparry cements seen in Figures 31-33. Subsurface diagenesis enhanced this overprinting with the formation of blocky, sparry calcitic cement, stylolites, dolomitization, and sulfide mineralization, all of which are present internally within the most chaotic and fractured breccia samples (e.g., Figures 31b, 32b, 32c). The alternation of calcite and dolomite precipitates may be a result of late stage calcite saturation as magnesium was exhausted or calcium was liberated during dolomitization, or due to a drop in temperature moving a fluid from dolomite to calcite supersaturation. Because coarse dolomite crystals overgrow equant calcite cements, they most likely formed following meteoric diagenesis (Qing and Mountjoy, 1994; Lopez-Horgue et al., 2010).

The latest event in the paragenetic sequence was the cementation of previously open fractures, which reduced the overall open length and connectivity, and thus the associated permeability across a brecciated sample (e.g., Figure 32c) (Hooker et al., 2012). Crack-seal textures formed as cement was precipitated during progressive widening and fracturing events, forming localized permeability barriers

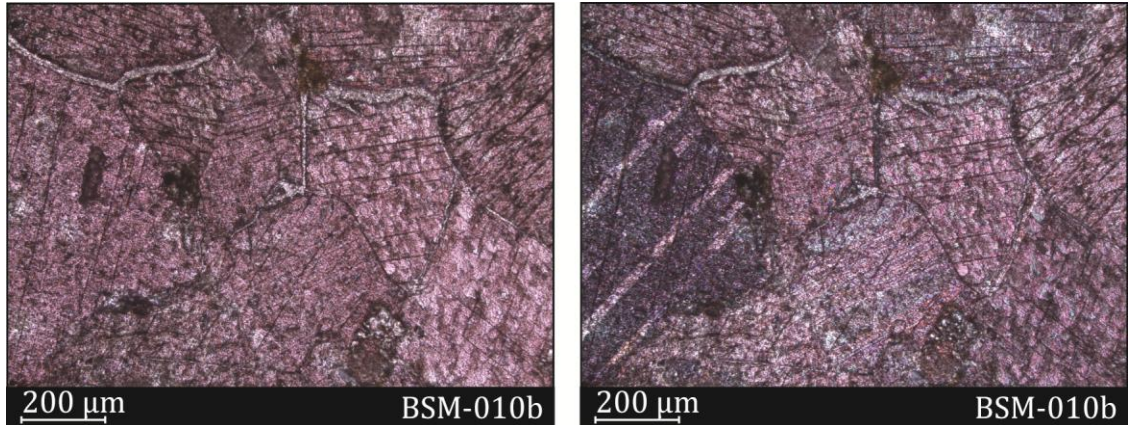


Figure 33. Petrographic images of a hydrothermal jigsaw breccia with coarse mosaic twinned calcitic clasts. The left column displays the sample in plane-polarized light; the right in cross-polarized light. Sample BSM-010b is composed of coarse mosaic calcite clasts in a jigsaw breccia. The calcite is twinned, which indicates that their formation was associated with tectonic faulting.

as cement bridges (Laubach, 2003; Hooker et al., 2012). Such events may be associated with faulting events, which are represented in thin section by the formation of tectonic stylolites, cross-cutting fractures, twinned calcites, undulose extinction, and sulfide mineralization (Wierzbicki et al., 2006). Twinned calcites are the best represented of these features in thin section, especially in late-stage coarse mosaic calcitic cements (Figure 33).

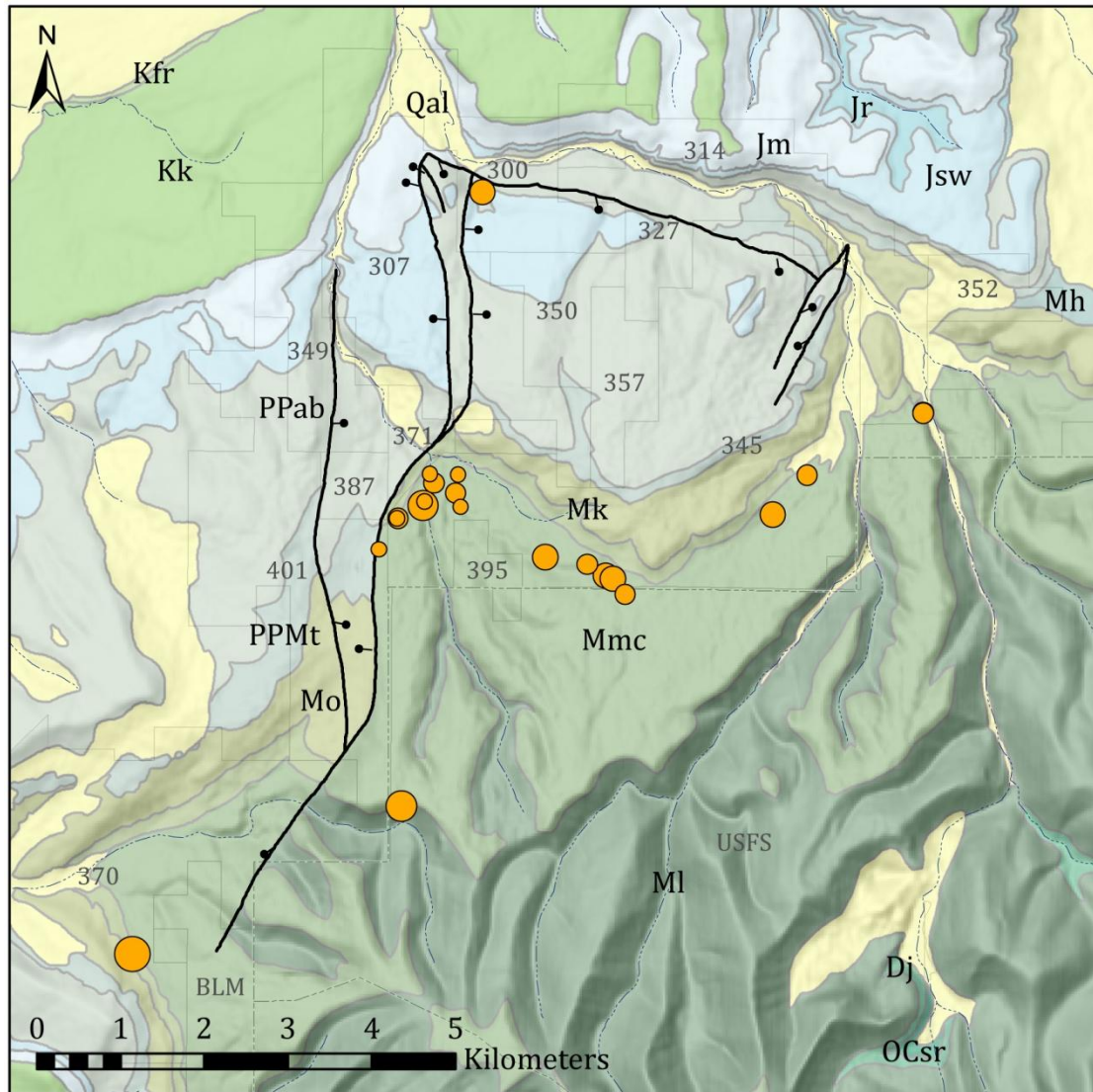
Geo-Visualization Outcomes

Near-Distance Proximity Calculations

The ArcMap analysis of breccia pipe distribution in the BSFS superimposed geology, land ownership, and breccia pipe locations together over a digital elevation model (DEM) image with drainages. Since outcrop was extremely limited in the

western Big Snowy Mountains, the location of breccia pipes was mostly confined to canyons located in drainages along the fault zone. The significance of the DEM and drainages is that it visually displays the location of these canyons, without adding complication (as topographic lines would) (Figure 34). The attribute information, which had been joined and edited, provided some of the most important (non-visual) data to the project, as it offered a database with information regarding geologic contact and fault locations, ownership information and parcel boundaries, and breccia pipe location and width.

The statistical analyses, reported in Table 4, suggest that the distribution of breccia pipes was not dependent on a pipe's proximity to a major through-going fault system. Although there is a loose correlation between distance from the fault and breccia pipe width (especially with the removal of any outliers), the location of geologic contacts on the map seems to control the distribution of breccia pipes more than their proximity to the fault zone. On the map in Figure 34, all breccia pipes (orange symbols) follow the contact between the Mississippian Mission Canyon Limestone and the overlying Mississippian, Pennsylvanian, or Jurassic units. This phenomenon agreed with field observations, where breccia pipes were located along the upper portion of the Mission Canyon Formation (Sequence IV and/or V boundaries), and fluids dispersed laterally along the karsted unconformities. This suggests that mechanical stratigraphy and sequence boundaries exhibit more control over hydrothermal brecciation than proximity to major fluid conduits does.



Qal	Alluvium & landslide deposits	Mh	Heath Formation
Kfr	Fall River Formation	Mo	Otter Formation
Kk	Kootenai Formation	Mk	Kibbey Formation
Jm	Morrison Formation	Mmc	Mission Canyon Limestone
Jsw	Swift Formation	Ml	Lodgepole Limestone
Jr	Rierdon Formation	Dj	Jefferson Formation
PPab	Alaska Bench Formation	OCsr	Snowy Range Formation
PPMt	Tyler Formation	●	Hydrothermal breccia pipe

Figure 34. Map of the BSFS (bold black line) showing geologic formations, drainages, parcel boundaries, and breccia pipes. Parcels are outlined lightly in grey and labeled according to the owner (Appendix E). Breccia pipes are represented by orange symbols, which are proportional to their width (Table 4).

Table 4. Breccia pipe width and calculated "near-distance" proximity to the BSFS.

Breccia Pipe ID	Width (feet)	Width (meters)	Near Distance (degrees)	Near Distance (meters)
BSM-001	21.5	6.5532	0.018794	2086.134
BSM-002	26.9	8.19912	0.018701	2075.811
BSM-003	57.8	17.61744	0.010444	1159.284
BSM-004	182.9	55.74792	0.013118	1456.098
BSM-005	1.8	0.54864	0.002116	234.876
BSM-006	14.8	4.51104	0.002202	244.422
BSM-007	9.1	2.77368	0.002466	273.726
BSM-008	17.2	5.24256	0.003569	396.159
BSM-009	52.8	16.09344	0.004407	489.177
BSM-010	7.2	2.19456	0.004223	468.753
BSM-011	10.1	3.07848	0.004835	536.685
BSM-012	6.5	1.9812	0.008032	891.552
BSM-013	19.8	6.03504	0.006301	699.411
BSM-014	1.9	0.57912	0.000517	57.387
BSM-015	32.4	9.87552	0.001418	157.398
BSM-016	38.5	11.7348	0.028611	3175.821
BSM-017	31	9.4488	0.029611	3286.821
BSM-018	19.5	5.9436	0.03112	3454.32
BSM-019	25.5	7.7724	0.025617	2843.487
BSM-020	38.7	11.79576	0.020334	2257.074
BSM-021	17.5	5.334	0.009188	1019.868
BSM-022	42.7	13.01496	0.01194	1325.34

Satellite Lineament Analysis

Lineaments were mapped in Google Earth Pro based off the assumptions that geomorphologic and physiographic features were tectonically controlled, and that dark two-dimensional bands on outcrop photographs represented a structural discontinuity related to joints or fractures. This resulted in the mapping of high-angle structural features rather than low-angle lineaments, as such attributes were

difficult to distinguish from stratigraphic boundaries or vegetation on satellite image (Figure 35). Lineaments were classified using the same orientation and color scheme as in the field outcrop fracture analysis (c.f. Figure 24), but plotted as a rose diagram rather than a series of stereonet projections (Figure 36). Measurements from Google Earth Pro were normalized to the length of the lineament measured on satellite imagery, indicating a maximum shortening direction of approximately N18°E. This shortening direction is not quite in line with the N40°E to N50°E by Brown (1993) or Erslev (1993). These results suggest that there is an additional structural control on the planes of weakness. The discrepancy between the maximum shortening direction in the literature and the calculated shortening direction using Rockware StereoStat may be due to (1) an array of Belt-age faults along the trace of the former CMT; (2) a more complex stress field in the northern Rocky Mountain region; and/or (3) a dissimilar geographic position relative to the subducting plate along the western margin of the craton. The structural overprinting of these different lineament and tectonic features (such as reactivated Proterozoic faults) has been well-documented in the literature and attributed to progressive overprinting of transpressive and rotational zones of shear (e.g., Lageson et al., 2012, and references therein), which resulted in an en echelon array of mountain ranges in Montana and Wyoming (c.f. Figure 5).

It is important to note that the pre-existing structural grain often causes a localized structural diversity due to inherited weaknesses within the crust, resulting in multidirectional deformation and oblique flexural slip along foliation surfaces

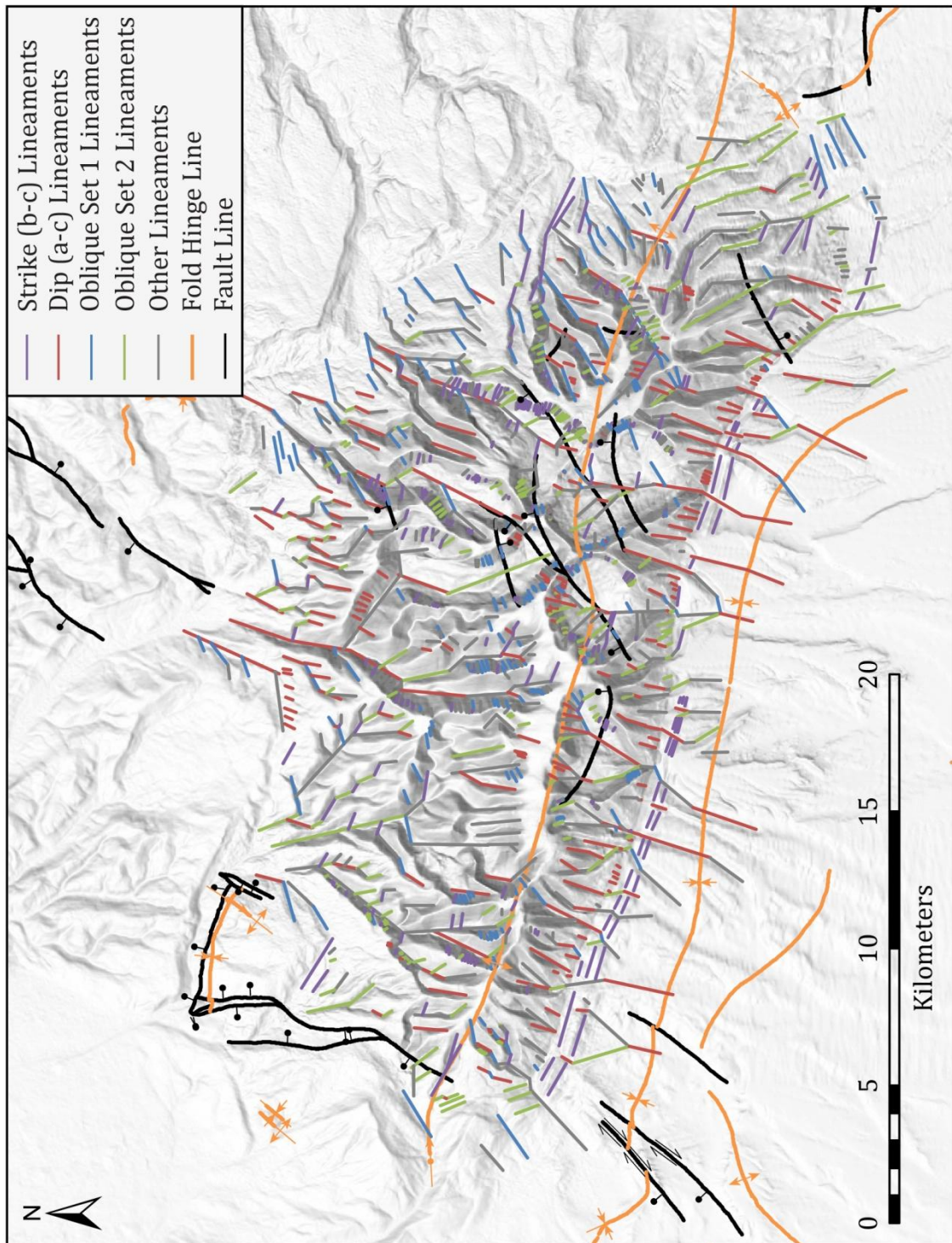


Figure 35. Map of lineaments traced in the Big Snowy Mountains using Google Earth Pro. Lineaments are color coded based on the scheme in Figure 24, and are displayed over a high-resolution DEM image.

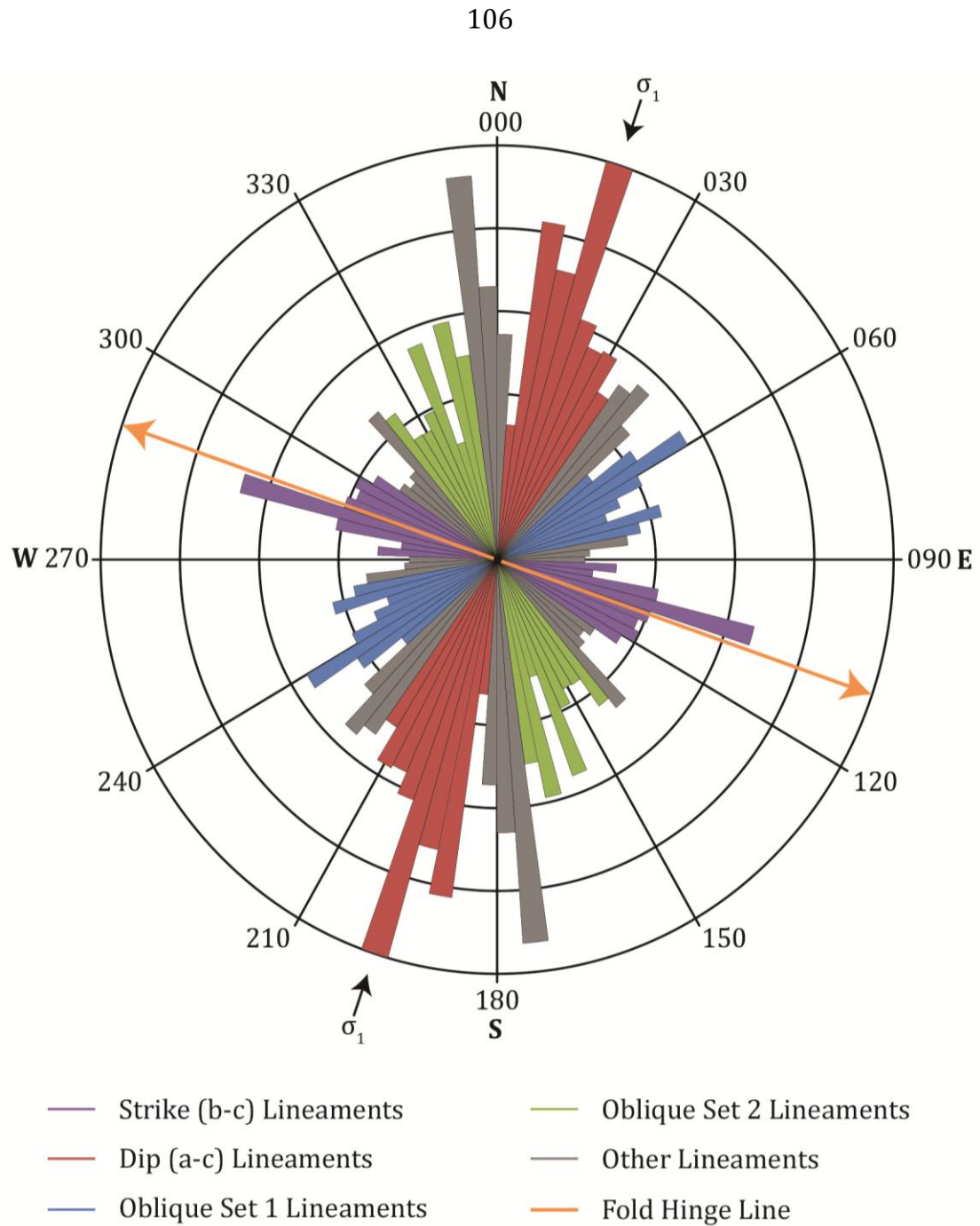


Figure 36. Rose diagram plot representing the total length and distribution of lineaments measured in Google Earth Pro. Strike (purple), dip (red), two sets of oblique (blue and green), and other (grey) lineaments are displayed, along with the fold hinge line of the Big Snowy Mountains (orange) and the regional maximum shortening direction (σ_1).

(Brown, 1993; Erslev and Koenig, 2009). Tectonic lineaments of the central Montana region generally display characteristic left-lateral shearing, which is particularly obvious along the Cat Creek, Lake Basin, and Nye-Bowler fault zones. These oblique en echelon zones form due to the mirroring effect of dextral motion to the southeast of the orogen and associated sinistral motion to the north (Erslev and Koenig, 2009). Such anisotropies within the basement may be due to the lithology, structural fabric, inclination and orientation of basement-rooted faults, and/or geometry of the basement-sediment contact (Brown, 1993). This often produces regions of intense deformation which are linked by zones of wrench deformation (Dickinson et al., 1988).

The reactivation of pre-existing tectonic features is associated with the formation and reactivation of a variety of fractures at different orientations and structural-lithic positions. This results in the formation of a fracture mesh, which is a regional thoroughfare for the passage of overpressured fluids through time (Iriarte et al., 2012). As fluids circulated due to heated convection in the subsurface, such fracture arrays resulted, which concentrated the precipitation of fluids and their solutes in more deformed regions. The development of this structural corridor served as the pathway for multiple episodes of fluid flow and may have resulted in the growth, coalescence, and overprinting of structurally-controlled mineralization and extension of fluid flow pathways to neighboring areas. The northeast-southwest Laramide shortening direction would have favored the formation of opening-mode joints, resulting in an array of oblique shear fractures (Hennings et al., 2000). Layer-

parallel shortening associated with Laramide deformation produced northeast-southwest bed-perpendicular Mode I opening joints and veins in the hinge and backlimb of the arch (Beaudoin et al., 2011).

IMPLICATIONS FOR CARBON SEQUESTRATION APPLICATIONS

The formation of hydrothermal structural features, such as breccia pipes, creates reservoir scale anisotropy in reservoir units, the former of which are not easily detected by current methods of subsurface imaging or modeling. In selecting sites for carbon capture and storage technologies, it is crucial to evaluate and avoid structures that pose a risk of leakage. Structures that are pervaded by numerous faults and breccia zones can create permeability networks that can cause anisotropy in fluid flow through the structure. If these permeability networks were to breach the seal on a potential CO₂ trap, there would be a high risk of leakage.

The Big Snowy Mountains of central Montana were used as an analog to other sequestration sites due to the similar structural and geologic situations of the field sites. The Big Snowy Mountains serve as a unique field area due to the exposure of Proterozoic through recent strata within canyons that are accessible across the range. Such canyons expose reservoir units which are being targeted for live injection at the Kevin Dome sequestration site in northern Montana. Like the Big Snowy Mountains, Kevin Dome is an arch containing Paleozoic reservoir units capped by regionally extensive evaporative horizons, the latter of which act as self-healing seals. To the east of Kevin Dome lie the Sweetgrass Hills, a series of Eocene-aged intrusions which may have enhanced the local geothermal gradient and allowed hydrothermal fluids to migrate in convection cells similar to that in central Montana. This raises the likelihood that hydrothermal structures propagated through fault and fracture systems within the intended reservoir units.

Evidence of hydrothermal fluid migration within the Big Snowy Mountains was present within the highly bleached and altered Mission Canyon Limestone near the locality of hydrothermal breccia pipes. The flashing/effervescence of CO₂ is caused by rapid phase separation, and is well documented in the literature (e.g., Leach et al., 1991; Davies and Smith, 2006; Katz et al., 2006). The mechanism of hydrocarbon bleaching is only sustainable within the upper one to two kilometers of the crust, and is only effective at precipitating hydrothermal minerals at depths shallower than 500 meters. With a rapid drop in confining pressure, saddle dolomite, platy calcite, and sulfide minerals will precipitate (Leach et al., 1991; Simmons and Christenson, 1994; Davies and Smith, 2006). Because hydrothermal waters are typically at a higher temperature, salinity, and acidity than meteoric waters, there will be selective dissolution of the wall rock, hydrothermal cementation, and bleaching of the host formation, particularly during rupturing events (Katz et al., 2006). This observation suggests that the breccias formed by hydrothermal processes, and that these processes were associated with the enhancement of porosity and permeability within the altered host rock.

The movement and direction of the overpressured hydrothermal brecciating fluids are attributed to the inherent lithologic heterogeneities in addition to fracturing and faulting, as suggested by Westphal et al. (2004). Field reconnaissance revealed that brecciation preferentially parallels bedding planes along major lithologic contacts, indicating that (1) bedding planes along major sequence boundaries are weaknesses along which fluids may favorably migrate; and (2) the

Mission Canyon Limestone acts as a more structurally competent unit within the region, through which fractures more readily initiate and propagate. It has been well established in the literature that Mode I extensional joints and fractures exert a strong control over subsurface production (e.g., Garland et al., 2012). Small fractures or fracture clusters may be difficult to detect, but often determine the reservoir-scale flow parameters. Such fractures may continue to propagate and grow into larger fracture meshes even in the absence of large-scale structures. This allows hydrothermal mineralization and brecciation to propagate much further from the trace of the fault zone than previously expected, enhancing reservoir properties in units (such as the Mission Canyon Limestone) which may have had poor intrinsic porosity and/or permeability.

The orientation of the stress field surrounding a fault or hydrofracture controls the development of porosity and permeability throughout the reservoir (Sibson, 1994). Factors that affect anisotropy in this manner include dilatancy along a fault zone, rupture irregularities due to fault slip, or fluid overpressurization. Overpressurization results in fluid migration, which reduces the frictional strength of the fault. These same processes may be used to model hydrothermal breccia pipes and their reactivation (Phillips, 1972; Sibson, 1994). The model for the formation of hydrothermal breccia pipes was best described by Smith (2006). In this model, fluids under high pressures and temperatures migrate along basement-rooted, high-angle faults. Such heated, overpressured fluids leach limestones, producing vugs into which the saturated fluids precipitate calcite, dolomite, or other hydrothermal

minerals. Hydrofracturing and brecciation continue until a mechanically weak unit is reached. In such an instance, the flow of fluids will spread out laterally across the contact, producing a larger extent of matrix mineralization. This model results in the compartmentalization of reservoir units.

Within the Madison Group, carbonate reservoir units are separated into compartments governed by the formation of horizontal flow barriers along sequence boundaries. Because sequence boundaries are characterized by enhanced porosity-occluding dolomitization and evaporitic and argillaceous beds, flow will be obstructed in a direction normal to stratigraphic layering. The result of these relationships is an overall increase in porosity; both vertically through open joints, fractures, and faults within the reservoir unit; as well as juxtaposed laterally against an upper argillaceous or evaporitic seal. However, the internal heterogeneity of a breccia pipe may have channelized local late-stage fluid flow events, allowing for further cementation of the brecciated region, and a small-scale reduction of the overall permeability within some of the secondary conduits.

RESEARCH CONCLUSIONS

The following explanations to research questions may serve as a useful tool for characterizing the heterogeneities created by hydrothermal diagenesis:

(1) *What structures within the Big Snowy Mountains and related areas serve as an analog to other carbon sequestration sites, and at what scales of observation?* In order to test the hypothesis that hydrothermal fluids follow the path of least resistance along fault and fracture conduits in the subsurface, regional lineament measurements were taken at a variety of scales. Field outcrop measurements of fractures at stations adjacent to hydrothermal structures indicate that dip and a dominant set of oblique joints mainly controlled the local emplacement of vertical breccia pipes. On a larger scale, satellite and DEM imagery reveal that dip joints are the most prevalent in the Big Snowy Mountains, though an array of strike and oblique joints formed in association with tectonic uplift. Because these fractures, joints, and lineaments are in line with the approximate northeast-southwest Laramide shortening direction, tectonics did in fact exert a strong structural control over outcrop-scale heterogeneities. However, the regional overprinting of successive tectonic events along the trace of the former CMT introduced a multitude of other orientations caused by a pre-existing structural grain dating back to the Proterozoic, which may not necessarily be present at other sequestration sites.

(2) *What is the stratigraphic distribution of hydrothermal structures, such as breccia pipes?* Unlike the original prediction, the proximity to major fault zones did not influence the size and distribution of hydrothermal breccia pipes. Mapping the

distribution of breccia pipes in ArcGIS did however reveal that all breccia pipes measured along the BSFS and SWC lie along stratigraphic contacts. This suggests that the emplacement of hydrothermal breccia pipes was strongly influenced by the lithologic variations along third order sequence boundaries within the Madison Group carbonates.

(3) *How does brittle hydrothermal deformation affect reservoir properties for CO₂ sequestration applications? To what extent does HTD diagenesis affect porosity and permeability?* To determine how faults and fractures controlled hydrothermal diagenesis, field and laboratory analyses focused on describing the alteration processes both qualitatively and quantitatively. At first glance in both outcrop and hand sample, it was noticeable that hydrothermal breccias were bleached in color compared to the protolith, indicating chemical dissolution and alteration which is typical of a hydrothermal source.

To further demonstrate that the rocks were hydrothermal in origin, XRD and stable isotope analyses focused on comparing the attributes of brecciated samples with literature-reviewed data on global Mississippian carbonates. Stable isotope analyses results indicated strongly negative $\delta^{18}\text{O}$ values compared to the standard (VPDB). This isotopic depletion often indicates higher temperatures during vein- and matrix-filling stages due to a decrease in oxygen fractionation between water and calcite (Budai and Wiltschko, 1987). Stable carbon isotopes indicate a marine (rather than biogenic source), as they fall within the expected range of isotope concentrations for marine carbonates (Hoefs, 2009). This suggests that

hydrothermal fluids were derived from a mixing zone of meteoric and basement fluids, and were most likely introduced to the host rocks during multiple episodes of fluid flow, as indicated by their highly variable nature. Such fluids likely permeated along fracture networks, dissolving the host rock and increasing reservoir quality. This idea is supported by Secondary Electron Imaging analysis coupled with ImageJ software, which quantified a 5-25% increase in two-dimensional area porosity within brecciated samples.

(4) *Do hydrothermal breccia pipes serve as a conduit or as a barrier to fluid flow in the subsurface?* The combination of field outcrop and laboratory analyses suggest that hydrothermal breccia pipes form a combined conduit-barrier system similar to that of a fault. Hydrothermal fluids migrating along permeable conduits caused early dissolution and precipitation of cements, which likely increased porosity and permeability in the subsurface. With increased brecciation events and multiple episodes of fluid migration, late-stage precipitates such as calcite, quartz, and iron may have occluded porosity in some areas. Therefore, structurally-controlled hydrothermal diagenesis acts as a conduit-barrier system, both as a concentrated pipe localized along structural features as well as a diffuse sheet along stratigraphic and mechanical boundaries.

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APPENDICES

APPENDIX A

BSFS AND SWC SAMPLE COORDINATES

Breccia Pipe ID	Latitude (°N)	Longitude (°W)
BSM-001	46.85685	109.51332
BSM-002	46.85693	109.51337
BSM-003	46.81456	109.59503
BSM-004	46.79856	109.63717
BSM-005	46.84547	109.59578
BSM-006	46.84553	109.59564
BSM-007	46.85025	109.59061
BSM-008	46.84928	109.59008
BSM-009	46.84686	109.59172
BSM-010	46.84733	109.59150
BSM-011	46.85022	109.58625
BSM-012	46.84669	109.58581
BSM-013	46.84822	109.58664
BSM-014	46.84213	109.59867
BSM-015	46.88058	109.58243
BSM-016	46.83932	109.56305
BSM-017	46.83900	109.56202
BSM-018	46.83730	109.55997
BSM-019	46.84052	109.56597
BSM-020	46.84137	109.57253
BSM-021	46.85020	109.53152
BSM-022	46.84592	109.53688
BSM-F2	46.79403	109.63939
BSM-F3	46.84683	109.53933
SWC-01	46.71715	109.34352
SWC-02	46.72068	109.34182
SWC-03	46.71625	109.34450

APPENDIX B

FIELD OUTCROP FRACTURE STATION MEASUREMENTS

Breccia Pipe ID and Direction	Dip (°)	Average Dip Direction	Length (mm)
BSM-004 N	90	299.5	142
BSM-004 N	86	299.5	97
BSM-004 N	87	299.5	125
BSM-004 N	86	299.5	125
BSM-004 N	85	299.5	119
BSM-004 N	86	299.5	119
BSM-004 N	83	299.5	182
BSM-004 N	90	299.5	102
BSM-004 N	78	299.5	165
BSM-004 N	76	299.5	131
BSM-004 N	70	299.5	227
BSM-004 N	72	299.5	153
BSM-004 N	79	299.5	159
BSM-004 N	89	299.5	415
BSM-004 N	84	299.5	352
BSM-004 N	84	299.5	364
BSM-004 N	86	299.5	358
BSM-004 N	89	299.5	205
BSM-004 N	90	299.5	136
BSM-004 N	90	299.5	153
BSM-004 N	87	299.5	239
BSM-004 N	90	299.5	261
BSM-004 N	85	299.5	80
BSM-004 N	84	299.5	91
BSM-004 N	83	299.5	85
BSM-004 N	79	299.5	97
BSM-004 N	80	299.5	114
BSM-004 N	82	299.5	80
BSM-004 S	89	111.5	19
BSM-004 S	90	111.5	19
BSM-004 S	80	111.5	116
BSM-004 S	78	111.5	145
BSM-004 S	77	111.5	48
BSM-004 S	78	111.5	523
BSM-004 S	88	111.5	63
BSM-004 S	85	111.5	68

BSM-004 S	82	111.5	48
BSM-004 S	86	111.5	106
BSM-004 S	81	111.5	63
BSM-004 S	70	111.5	87
BSM-004 S	70	111.5	92
BSM-004 S	69	111.5	97
BSM-004 S	70	111.5	87
BSM-007 N	72	139.0	129
BSM-007 N	69	139.0	96
BSM-007 N	62	139.0	54
BSM-007 N	68	139.0	96
BSM-007 N	69	139.0	43
BSM-007 N	72	139.0	16
BSM-007 N	73	139.0	91
BSM-007 N	65	139.0	32
BSM-007 N	64	139.0	171
BSM-007 N	85	139.0	54
BSM-007 N	58	139.0	123
BSM-007 N	58	139.0	48
BSM-007 N	70	139.0	80
BSM-007 N	57	139.0	43
BSM-007 N	59	139.0	38
BSM-007 N	75	139.0	48
BSM-007 N	72	139.0	70
BSM-007 N	86	139.0	102
BSM-007 N	69	139.0	107
BSM-007 N	70	139.0	107
BSM-007 N	62	139.0	241
BSM-007 N	77	139.0	75
BSM-007 N	59	139.0	102
BSM-007 N	58	139.0	225
BSM-007 N	80	139.0	54
BSM-007 S	72	97.0	467
BSM-007 S	78	97.0	750
BSM-007 S	66	97.0	200
BSM-007 S	90	97.0	492
BSM-007 S	90	97.0	758
BSM-007 S	88	97.0	458

BSM-009 N	90	134.0	175
BSM-009 N	64	134.0	194
BSM-009 N	81	134.0	119
BSM-009 N	75	134.0	94
BSM-009 N	74	134.0	113
BSM-009 N	45	134.0	113
BSM-009 N	85	134.0	119
BSM-009 N	78	134.0	100
BSM-009 N	84	134.0	88
BSM-009 N	84	134.0	69
BSM-009 N	82	134.0	81
BSM-009 N	83	134.0	88
BSM-009 N	80	134.0	88
BSM-009 N	85	134.0	125
BSM-009 N	69	134.0	194
BSM-009 N	56	134.0	163
BSM-009 N	55	134.0	131
BSM-009 N	74	134.0	81
BSM-009 N	54	134.0	225
BSM-009 N	58	134.0	138
BSM-009 N	68	134.0	75
BSM-009 N	63	134.0	175
BSM-009 S	79	307.0	300
BSM-009 S	88	307.0	120
BSM-009 S	88	307.0	480
BSM-009 S	90	307.0	338
BSM-009 S	62	227.3	143
BSM-009 S	85	227.3	98
BSM-009 S	87	227.3	113
BSM-009 S	53	227.3	150
BSM-009 S	70	227.3	98
BSM-009 S	86	227.3	53
BSM-009 S	88	227.3	30
BSM-009 S	87	227.3	38
BSM-009 S	89	227.3	68
BSM-009 S	90	227.3	60
BSM-009 S	46	227.3	173
BSM-009 S	49	227.3	68

BSM-009 S	56	227.3	75
BSM-009 S	67	227.3	45
BSM-009 S	84	227.3	120
BSM-009 S	63	227.3	68
BSM-009 S	63	227.3	218
BSM-009 S	88	227.3	90
BSM-009 S	77	227.3	113
BSM-009 S	80	227.3	315
BSM-009 S	84	227.3	60
BSM-009 S	83	227.3	263
BSM-009 S	88	227.3	308
BSM-009 S	76	227.3	120
BSM-009 S	90	227.3	158
BSM-009 S	70	227.3	45
BSM-009 S	87	227.3	120
BSM-009 S	70	227.3	90
BSM-010 N	84	128.5	69
BSM-010 N	64	128.5	49
BSM-010 N	61	128.5	54
BSM-010 N	65	128.5	54
BSM-010 N	65	128.5	59
BSM-010 N	71	128.5	34
BSM-010 N	75	128.5	74
BSM-010 N	53	128.5	44
BSM-010 N	53	128.5	49
BSM-010 N	62	128.5	34
BSM-010 N	68	128.5	34
BSM-010 N	53	216.5	69
BSM-010 N	74	216.5	118
BSM-010 N	73	216.5	79
BSM-010 N	74	216.5	69
BSM-010 N	73	216.5	113
BSM-010 N	74	216.5	59
BSM-010 N	79	216.5	217
BSM-010 N	80	216.5	44
BSM-010 N	79	216.5	49
BSM-010 N	90	216.5	54
BSM-010 N	90	216.5	44

BSM-010 N	78	216.5	49
BSM-010 N	71	216.5	49
BSM-010 N	74	216.5	39
BSM-010 S	78	119.2	30
BSM-010 S	77	119.2	25
BSM-010 S	73	119.2	49
BSM-010 S	70	119.2	39
BSM-010 S	75	119.2	39
BSM-010 S	70	217.8	153
BSM-010 S	75	217.8	84
BSM-010 S	66	217.8	108
BSM-010 S	70	217.8	74
BSM-010 S	83	217.8	54
BSM-010 S	81	217.8	54
BSM-010 S	66	217.8	54
BSM-010 S	73	217.8	69
BSM-010 S	63	217.8	89
BSM-010 S	65	217.8	64
BSM-010 S	60	217.8	89
BSM-010 S	57	217.8	54
BSM-010 S	55	217.8	64
BSM-010 S	52	217.8	241
BSM-010 S	55	217.8	256
BSM-010 S	59	217.8	296
BSM-010 S	53	217.8	241
BSM-010 S	55	217.8	241
BSM-010 S	58	217.8	103
BSM-010 S	55	217.8	207
BSM-010 S	48	217.8	153
BSM-010 S	50	217.8	89
BSM-011 N	80	123.0	199
BSM-011 N	83	123.0	199
BSM-011 N	79	123.0	199
BSM-011 N	85	123.0	199
BSM-011 N	80	166.0	216
BSM-011 N	85	166.0	261
BSM-011 N	88	166.0	229
BSM-011 N	84	166.0	137

BSM-011 N	84	166.0	59
BSM-011 N	86	166.0	706
BSM-011 N	78	166.0	105
BSM-011 N	90	166.0	72
BSM-011 N	78	166.0	333
BSM-011 N	79	166.0	98
BSM-011 N	84	166.0	98
BSM-011 N	83	166.0	281
BSM-011 N	86	166.0	131
BSM-011 N	80	166.0	144
BSM-011 N	72	166.0	216
BSM-011 N	73	166.0	216
BSM-011 N	78	166.0	418
BSM-011 S	88	334.2	75
BSM-011 S	86	334.2	458
BSM-011 S	79	334.2	173
BSM-011 S	81	334.2	75
BSM-011 S	90	334.2	180
BSM-011 S	90	334.2	105
BSM-011 S	90	334.2	413
BSM-011 S	88	334.2	263
BSM-011 S	80	334.2	68
BSM-011 S	88	334.2	105
BSM-011 S	89	334.2	210
BSM-011 S	84	334.2	188
BSM-011 S	85	334.2	203
BSM-011 S	86	334.2	98
BSM-011 S	80	334.2	120
BSM-012 N	90	138.8	148
BSM-012 N	68	138.8	156
BSM-012 N	66	138.8	477
BSM-012 N	84	138.8	86
BSM-012 N	76	138.8	359
BSM-012 N	89	138.8	55
BSM-012 N	66	138.8	273
BSM-012 N	84	138.8	94
BSM-012 N	88	138.8	109
BSM-012 N	58	138.8	63

BSM-012 N	71	138.8	117
BSM-012 N	74	138.8	164
BSM-012 N	60	138.8	94
BSM-012 N	78	138.8	78
BSM-012 N	75	138.8	78
BSM-012 N	80	138.8	78
BSM-012 S	75	137.0	96
BSM-012 S	73	137.0	177
BSM-012 S	80	137.0	86
BSM-012 S	81	137.0	80
BSM-012 S	78	137.0	113
BSM-012 S	75	137.0	64
BSM-012 S	66	137.0	96
BSM-012 S	76	137.0	80
BSM-012 S	67	137.0	70
BSM-012 S	73	137.0	43
BSM-012 S	80	137.0	96
BSM-012 S	78	137.0	107
BSM-012 S	70	137.0	86
BSM-012 S	73	137.0	48
BSM-012 S	69	137.0	91
BSM-012 S	70	137.0	80
BSM-012 S	72	137.0	86
BSM-015 N	57	179.0	135
BSM-015 N	62	179.0	60
BSM-015 N	63	179.0	705
BSM-015 N	62	179.0	98
BSM-015 N	67	179.0	120
BSM-015 N	57	179.0	240
BSM-015 N	49	179.0	240
BSM-015 N	60	179.0	165
BSM-015 N	61	179.0	128
BSM-015 N	63	179.0	90
BSM-015 N	64	179.0	210
BSM-015 N	64	165.0	270
BSM-015 N	66	165.0	248
BSM-015 N	84	165.0	180
BSM-015 N	80	165.0	248

BSM-015 N	74	165.0	135
BSM-015 N	81	165.0	195
BSM-015 N	84	165.0	173
BSM-015 N	39	165.0	240
BSM-015 N	79	165.0	165
BSM-015 S	85	118.5	200
BSM-015 S	82	118.5	71
BSM-015 S	87	118.5	150
BSM-015 S	90	118.5	236
BSM-015 S	90	118.5	93
BSM-015 S	90	118.5	107
BSM-015 S	84	118.5	86
BSM-015 S	83	118.5	86
BSM-015 S	79	118.5	286
BSM-015 S	85	118.5	107
BSM-015 S	90	118.5	100
BSM-015 S	85	118.5	107
BSM-015 S	84	118.5	79
BSM-015 S	84	118.5	79
BSM-015 S	84	118.5	64
BSM-015 S	90	118.5	207
BSM-015 S	80	118.5	136
BSM-015 S	90	118.5	114
BSM-015 S	86	118.5	221
BSM-015 S	89	118.5	107
BSM-015 S	84	118.5	93
BSM-015 S	87	118.5	71
BSM-015 S	89	118.5	50
BSM-016 E	70	119.7	56
BSM-016 E	59	119.7	56
BSM-016 E	88	119.7	33
BSM-016 E	71	119.7	33
BSM-016 E	69	119.7	100
BSM-016 E	68	119.7	44
BSM-016 E	85	119.7	28
BSM-016 E	90	119.7	28
BSM-016 E	88	119.7	33
BSM-016 E	81	119.7	22

BSM-016 E	82	119.7	33
BSM-016 E	86	119.7	28
BSM-016 E	90	119.7	33
BSM-016 E	84	119.7	28
BSM-016 E	87	119.7	33
BSM-016 E	80	119.7	106
BSM-016 E	83	119.7	111
BSM-016 E	85	119.7	67
BSM-016 E	69	119.7	100
BSM-016 E	68	119.7	94
BSM-016 E	68	119.7	100
BSM-016 E	75	119.7	61
BSM-016 E	69	119.7	39
BSM-016 E	84	119.7	39
BSM-016 E	89	119.7	28
BSM-016 E	89	119.7	28
BSM-016 E	72	119.7	33
BSM-016 E	70	119.7	39
BSM-016 E	80	119.7	39
BSM-016 E	51	119.7	28
BSM-016 E	86	119.7	33
BSM-016 E	67	119.7	67
BSM-016 E	77	119.7	22
BSM-016 E	75	119.7	22
BSM-016 E	90	119.7	22
BSM-016 E	84	119.7	28
BSM-016 E	70	119.7	50
BSM-016 E	85	119.7	44
BSM-016 E	88	119.7	44
BSM-016 E	65	119.7	56
BSM-016 E	78	119.7	122
BSM-016 E	73	119.7	33
BSM-016 E	81	119.7	61
BSM-016 E	80	119.7	72
BSM-016 E	65	119.7	33
BSM-016 E	67	119.7	28
BSM-016 E	86	119.7	28
BSM-016 E	77	119.7	72

BSM-016 E	78	119.7	50
BSM-016 E	59	119.7	72
BSM-016 E	90	119.7	50
BSM-016 E	70	119.7	61
BSM-016 E	75	119.7	28
BSM-016 E	85	119.7	67
BSM-016 E	80	119.7	78
BSM-016 E	76	119.7	89
BSM-016 E	68	119.7	56
BSM-016 E	85	119.7	33
BSM-016 E	82	119.7	28
BSM-016 E	80	119.7	28
BSM-016 E	70	119.7	56
BSM-016 E	86	119.7	39
BSM-016 E	77	119.7	83
BSM-016 E	80	119.7	44
BSM-016 E	75	119.7	22
BSM-016 W	90	121.8	106
BSM-016 W	87	121.8	124
BSM-016 W	87	121.8	177
BSM-016 W	87	121.8	115
BSM-016 W	90	121.8	142
BSM-016 W	89	121.8	150
BSM-016 W	82	121.8	168
BSM-016 W	88	121.8	124
BSM-016 W	86	121.8	212
BSM-016 W	90	121.8	195
BSM-016 W	87	121.8	106
BSM-016 W	84	121.8	186
BSM-016 W	86	121.8	150
BSM-016 W	88	121.8	133
BSM-016 W	84	121.8	204
BSM-016 W	85	121.8	80
BSM-016 W	85	121.8	97
BSM-016 W	82	121.8	106
BSM-016 W	87	121.8	115
BSM-016 W	88	121.8	142
BSM-016 W	82	121.8	133

BSM-016 W	90	121.8	115
BSM-016 W	88	121.8	389
BSM-016 W	81	121.8	97
BSM-016 W	83	121.8	106
BSM-016 W	89	121.8	159
BSM-016 W	85	121.8	133
BSM-016 W	86	121.8	115
BSM-016 W	88	121.8	142
BSM-016 W	85	121.8	133
BSM-016 W	86	121.8	106
BSM-016 W	82	121.8	265
BSM-016 W	83	121.8	88
BSM-016 W	87	121.8	71
BSM-016 W	87	121.8	195
BSM-017 N	64	112.0	93
BSM-017 N	65	112.0	160
BSM-017 N	42	112.0	133
BSM-017 N	61	112.0	100
BSM-017 N	72	112.0	100
BSM-017 N	66	112.0	127
BSM-017 N	64	112.0	160
BSM-017 N	67	112.0	113
BSM-017 N	64	112.0	100
BSM-017 N	50	112.0	187
BSM-017 N	58	112.0	147
BSM-017 N	60	112.0	140
BSM-017 N	62	112.0	87
BSM-017 N	61	112.0	107
BSM-017 N	63	112.0	73
BSM-017 N	60	112.0	87
BSM-017 N	62	112.0	153
BSM-017 N	55	112.0	87
BSM-017 N	41	112.0	113
BSM-017 N	56	112.0	87
BSM-017 N	54	112.0	33
BSM-017 N	49	112.0	187
BSM-017 N	53	112.0	180
BSM-017 N	50	112.0	140

BSM-017 N	52	112.0	60
BSM-017 N	49	112.0	113
BSM-017 N	60	112.0	133
BSM-017 N	62	112.0	113
BSM-017 N	48	112.0	40
BSM-017 N	58	112.0	133
BSM-017 N	51	112.0	160
BSM-017 N	52	112.0	67
BSM-017 N	47	112.0	147
BSM-017 N	45	112.0	160
BSM-017 N	40	112.0	173
BSM-017 N	43	112.0	213
BSM-017 N	40	112.0	173
BSM-017 N	54	112.0	113
BSM-017 N	27	309.2	233
BSM-017 N	26	309.2	120
BSM-017 N	26	309.2	400
BSM-017 N	26	309.2	347
BSM-017 N	28	309.2	887
BSM-017 N	30	309.2	807
BSM-017 N	31	309.2	87
BSM-017 N	29	309.2	127
BSM-017 N	30	309.2	147
BSM-017 N	27	309.2	160
BSM-017 N	23	309.2	247
BSM-017 N	23	309.2	233
BSM-017 S	65	305.0	90
BSM-017 S	75	305.0	90
BSM-017 S	90	305.0	72
BSM-017 S	83	305.0	138
BSM-017 S	79	305.0	108
BSM-017 S	76	305.0	108
BSM-017 S	75	305.0	144
BSM-017 S	77	305.0	90
BSM-017 S	77	305.0	90
BSM-017 S	77	305.0	108
BSM-017 S	76	305.0	228
BSM-017 S	79	305.0	156

BSM-017 S	84	305.0	84
BSM-017 S	78	305.0	306
BSM-017 S	80	305.0	126
BSM-017 S	74	305.0	216
BSM-017 S	73	305.0	462
BSM-017 S	73	305.0	288
BSM-017 S	73	305.0	288
BSM-017 S	67	305.0	102
BSM-017 S	67	305.0	60
BSM-017 S	68	305.0	240
BSM-017 S	78	305.0	156
BSM-017 S	80	305.0	114
BSM-017 S	73	305.0	270
BSM-017 S	75	305.0	102
BSM-017 S	75	305.0	288
BSM-017 S	70	305.0	264
BSM-017 S	64	305.0	288
BSM-017 S	68	305.0	150
BSM-018 E	82	207.7	455
BSM-018 E	90	207.7	136
BSM-018 E	78	207.7	530
BSM-018 E	84	207.7	91
BSM-018 E	90	207.7	98
BSM-018 E	86	207.7	129
BSM-018 E	86	207.7	311
BSM-018 E	70	118.0	98
BSM-018 E	43	118.0	68
BSM-018 E	31	118.0	83
BSM-018 E	31	118.0	76
BSM-018 E	56	118.0	265
BSM-018 E	38	118.0	265
BSM-018 E	46	118.0	106
BSM-018 E	45	118.0	182
BSM-018 E	50	118.0	121
BSM-018 E	44	118.0	83
BSM-018 E	61	118.0	212
BSM-018 E	60	118.0	220
BSM-018 E	45	297.0	114

BSM-018 E	38	297.0	152
BSM-018 E	56	297.0	30
BSM-018 E	65	297.0	76
BSM-018 E	73	297.0	76
BSM-018 E	45	297.0	76
BSM-018 E	55	297.0	121
BSM-018 E	55	297.0	159
BSM-018 W	68	125.3	150
BSM-018 W	69	125.3	82
BSM-018 W	68	125.3	41
BSM-018 W	66	125.3	61
BSM-018 W	62	125.3	143
BSM-018 W	70	125.3	82
BSM-018 W	55	125.3	184
BSM-018 W	62	125.3	361
BSM-018 W	66	125.3	320
BSM-018 W	65	125.3	272
BSM-018 W	65	125.3	395
BSM-018 W	62	125.3	218
BSM-018 W	65	125.3	286
BSM-018 W	70	125.3	578
BSM-018 W	70	125.3	143
BSM-018 W	74	125.3	238
BSM-018 W	65	125.3	286
BSM-018 W	74	125.3	190
BSM-018 W	74	125.3	184
BSM-018 W	74	125.3	143
BSM-018 W	81	125.3	224
BSM-018 W	66	125.3	122
BSM-018 W	73	125.3	102
BSM-018 W	72	125.3	299
BSM-018 W	69	125.3	218
BSM-018 W	66	125.3	88
BSM-018 W	67	125.3	286
BSM-018 W	68	125.3	177
BSM-018 W	55	125.3	204
BSM-018 W	71	125.3	177
BSM-018 W	70	125.3	143

BSM-018 W	68	125.3	136
BSM-018 W	84	125.3	116
BSM-019 E	84	145.3	159
BSM-019 E	82	145.3	198
BSM-019 E	90	145.3	167
BSM-019 E	90	145.3	317
BSM-019 E	89	145.3	206
BSM-019 E	75	145.3	151
BSM-019 E	87	145.3	79
BSM-019 E	87	145.3	103
BSM-019 E	90	145.3	111
BSM-019 E	87	145.3	143
BSM-019 E	90	145.3	175
BSM-019 E	80	145.3	79
BSM-019 E	90	145.3	103
BSM-019 E	90	145.3	103
BSM-019 E	90	145.3	127
BSM-019 E	88	145.3	175
BSM-019 E	85	145.3	389
BSM-019 E	89	145.3	127
BSM-019 E	88	145.3	270
BSM-019 E	83	145.3	214
BSM-019 E	83	145.3	246
BSM-019 E	85	145.3	230
BSM-019 E	77	145.3	167
BSM-019 E	85	145.3	206
BSM-019 E	86	145.3	246
BSM-019 E	90	145.3	127
BSM-019 E	90	145.3	222
BSM-019 E	87	145.3	87
BSM-019 E	90	145.3	95
BSM-019 E	90	145.3	151
BSM-019 E	90	145.3	87
BSM-019 E	79	145.3	143
BSM-019 E	78	145.3	79
BSM-019 E	83	145.3	79
BSM-019 E	85	145.3	87
BSM-019 E	90	145.3	127

BSM-019 E	90	145.3	119
BSM-019 E	84	145.3	127
BSM-019 W	50	95.2	94
BSM-019 W	63	95.2	94
BSM-019 W	63	95.2	381
BSM-019 W	64	95.2	319
BSM-019 W	61	95.2	531
BSM-019 W	62	95.2	331
BSM-019 W	61	95.2	375
BSM-019 W	66	95.2	681
BSM-019 W	67	95.2	188
BSM-019 W	69	95.2	338
BSM-019 W	65	95.2	456
BSM-019 W	65	95.2	306
BSM-019 W	70	95.2	163
BSM-019 W	68	95.2	175
BSM-019 W	60	95.2	194
BSM-019 W	61	95.2	138
BSM-019 W	68	95.2	163
BSM-019 W	69	95.2	219
BSM-019 W	65	95.2	288
BSM-019 W	65	95.2	206
BSM-019 W	66	95.2	69
BSM-019 W	69	95.2	269
BSM-019 W	55	95.2	163
BSM-019 W	70	95.2	188
BSM-019 W	65	95.2	156
BSM-019 W	66	95.2	175
BSM-020 E	89	200.0	59
BSM-020 E	89	200.0	276
BSM-020 E	90	200.0	192
BSM-020 E	87	200.0	197
BSM-020 E	90	200.0	84
BSM-020 E	72	200.0	187
BSM-020 E	70	200.0	153
BSM-020 E	90	200.0	39
BSM-020 E	70	200.0	118
BSM-020 E	83	200.0	222

BSM-020 E	87	200.0	246
BSM-020 E	90	200.0	266
BSM-020 E	89	200.0	158
BSM-020 E	86	200.0	128
BSM-020 E	89	200.0	113
BSM-020 E	90	200.0	232
BSM-020 E	77	200.0	138
BSM-020 E	84	200.0	192
BSM-020 E	82	200.0	281
BSM-020 E	82	200.0	172
BSM-020 E	84	200.0	222
BSM-020 E	86	200.0	251
BSM-020 E	78	200.0	394
BSM-020 E	68	200.0	177
BSM-020 E	73	200.0	153
BSM-020 E	75	200.0	325
BSM-020 E	69	200.0	84
BSM-020 E	45	200.0	69
BSM-020 E	88	200.0	177
BSM-020 E	86	200.0	64
BSM-020 E	89	200.0	158
BSM-020 E	90	200.0	69
BSM-020 E	80	200.0	369
BSM-020 E	90	200.0	99
BSM-020 E	88	200.0	69
BSM-020 E	72	200.0	64
BSM-020 E	86	200.0	84
BSM-020 E	90	200.0	84
BSM-020 E	64	200.0	74
BSM-020 E	63	200.0	54
BSM-020 E	86	200.0	54
BSM-020 E	84	200.0	133
BSM-020 E	77	200.0	54
BSM-020 E	65	200.0	25
BSM-020 E	66	200.0	39
BSM-020 E	63	200.0	69
BSM-020 E	71	200.0	163
BSM-020 E	64	200.0	74

BSM-020 E	84	200.0	74
BSM-020 E	90	200.0	123
BSM-020 E	89	200.0	207
BSM-020 W	85	106.3	120
BSM-020 W	86	106.3	144
BSM-020 W	84	106.3	128
BSM-020 W	85	106.3	144
BSM-020 W	90	106.3	144
BSM-020 W	89	106.3	160
BSM-020 W	88	106.3	304
BSM-020 W	90	106.3	224
BSM-020 W	77	106.3	256
BSM-020 W	86	106.3	240
BSM-020 W	84	106.3	200
BSM-020 W	78	106.3	200
BSM-020 W	79	106.3	200
BSM-020 W	69	106.3	144
BSM-020 W	74	106.3	264
BSM-020 W	72	106.3	192
BSM-020 W	73	106.3	176
BSM-020 W	70	106.3	224
BSM-020 W	77	106.3	248
BSM-020 W	74	106.3	432
BSM-020 W	81	106.3	520
BSM-020 W	83	106.3	744
BSM-020 W	85	106.3	176
BSM-020 W	75	106.3	168
BSM-020 W	80	106.3	192
BSM-020 W	80	106.3	88
BSM-020 W	80	106.3	224
BSM-020 W	75	106.3	168
BSM-020 W	80	106.3	224
BSM-020 W	83	106.3	160
BSM-020 W	81	106.3	104
BSM-020 W	83	106.3	104
BSM-020 W	81	106.3	160
BSM-020 W	77	106.3	264
BSM-020 W	75	106.3	232

BSM-020 W	82	106.3	560
BSM-020 W	80	106.3	160
BSM-020 W	78	106.3	152
BSM-020 W	80	106.3	192
BSM-020 W	73	106.3	280
BSM-020 W	90	106.3	120
BSM-020 W	79	106.3	120
BSM-020 W	84	106.3	96
BSM-020 W	85	106.3	160
BSM-020 W	85	106.3	200
BSM-020 W	79	106.3	152
BSM-020 W	70	106.3	160
BSM-021 E	80	112.5	157
BSM-021 E	80	112.5	110
BSM-021 E	82	112.5	205
BSM-021 E	70	112.5	276
BSM-021 E	78	112.5	220
BSM-021 E	78	112.5	220
BSM-021 E	69	112.5	417
BSM-021 E	78	112.5	134
BSM-021 E	65	112.5	118
BSM-021 E	64	112.5	205
BSM-021 E	65	112.5	307
BSM-021 E	63	112.5	94
BSM-021 E	66	112.5	354
BSM-021 E	77	112.5	197
BSM-021 E	72	112.5	213
BSM-021 E	79	112.5	228
BSM-021 E	73	112.5	39
BSM-021 E	77	112.5	134
BSM-021 E	76	112.5	134
BSM-021 W	90	111.5	136
BSM-021 W	89	111.5	218
BSM-021 W	89	111.5	245
BSM-021 W	84	111.5	190
BSM-021 W	90	111.5	340
BSM-021 W	78	111.5	231
BSM-021 W	81	111.5	177

BSM-021 W	86	111.5	367
BSM-021 W	85	111.5	476
BSM-021 W	86	111.5	639
BSM-021 W	90	111.5	422
BSM-021 W	85	111.5	313
BSM-021 W	87	111.5	299
BSM-021 W	80	111.5	1143
BSM-021 W	81	111.5	871
BSM-021 W	86	111.5	245
BSM-021 W	76	111.5	340
BSM-021 W	76	111.5	667
BSM-021 W	90	111.5	218
BSM-021 W	82	111.5	490
BSM-021 W	85	111.5	490
BSM-021 W	85	111.5	408
BSM-021 W	86	111.5	653
BSM-021 W	90	111.5	449

APPENDIX C

XRD PEAK DIFFRACTION DATA

ID: BSM-001c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.458	3.0296	1847.8	100	0.1	184.8
39.455	2.282	898.43	48.62	0.1	53.9
48.579	1.8726	504.28	27.29	0.02	40.3
43.238	2.0907	322.98	17.48	0.1	25.8
36.029	2.4908	245.32	13.28	0.06	24.5
47.604	1.9086	186.85	10.11	0.08	22.4
23.123	3.8433	160.8	8.7	0.02	16.1
47.2	1.924	136.67	7.4	0.06	8.2
64.733	1.4389	108.48	5.87	0.12	8.7
57.49	1.6017	94.33	5.11	0.08	9.4
31.54	2.8342	81.67	4.42	0.1	1.6
60.759	1.5231	49.1	2.66	0.1	4.9
43.5	2.0787	46.67	2.53	0.08	0.9

ID: BSM-002b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.46	3.0294	5155	100	0.1	206.2
39.475	2.2809	389.58	7.56	0.04	46.8
43.226	2.0913	296.58	5.75	0.06	29.7
29.62	3.0134	278.33	5.4	0.06	16.7
57.464	1.6024	259.67	5.04	0.08	20.8
47.576	1.9097	246.45	4.78	0.12	29.6
48.575	1.8727	214.53	4.16	0.12	25.7
36.037	2.4902	173.9	3.37	0.1	20.9
23.099	3.8473	144.83	2.81	0.04	14.5
64.74	1.4387	115	2.23	0.12	2.3
60.758	1.5231	84.78	1.64	0.12	10.2
31.518	2.8362	70.27	1.36	0.08	5.6
47.18	1.9248	68.33	1.33	0.12	2.7
29.814	2.9943	66.08	1.28	0.02	4
61.06	1.5163	48.33	0.94	0.08	1
65.62	1.4216	48.33	0.94	0.02	3.9

ID: BSM-003a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.236	3.0521	1307	100	0.12	130.7
48.38	1.8798	253.33	19.38	0.06	10.1

39.265	2.2926	240.9	18.43	0.1	19.3
42.994	2.102	216.57	16.57	0.02	21.7
47.36	1.9179	140.27	10.73	0.08	14
35.843	2.5032	129.67	9.92	0.08	10.4
57.251	1.6078	97.85	7.49	0.1	5.9
22.814	3.8947	93.27	7.14	0.04	11.2
64.54	1.4427	70	5.36	0.1	1.4
46.98	1.9325	65	4.97	0.04	2.6
26.43	3.3695	64.57	4.94	0.06	3.9
29.58	3.0174	63.33	4.85	0.02	1.3
60.5	1.529	43.33	3.32	0.02	0.9

ID: BSM-004d					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.396	3.0359	5864.1	100	0.1	586.4
39.423	2.2838	1266.3	21.59	0.02	126.6
48.514	1.8749	975.18	16.63	0.1	136.5
43.161	2.0942	936.43	15.97	0.06	93.6
47.504	1.9124	833.63	14.22	0.1	116.7
35.963	2.4952	750.58	12.8	0.12	90.1
57.404	1.6039	440.82	7.52	0.1	52.9
23.041	3.8569	422.33	7.2	0.04	42.2
47.124	1.9269	318.42	5.43	0.1	31.8
64.683	1.4399	289.03	4.93	0.1	40.5
60.677	1.525	250.77	4.28	0.14	30.1
65.629	1.4214	140.27	2.39	0.06	19.6
56.561	1.6258	137.85	2.35	0.14	13.8
29.72	3.0035	121.67	2.07	0.1	7.3
61.389	1.509	110.93	1.89	0.12	13.3
31.42	2.8448	107.85	1.84	0.12	10.8
72.9	1.2965	102.08	1.74	0.14	14.3
39.7	2.2685	101.67	1.73	0.12	4.1
61.034	1.5169	100.67	1.72	0.1	14.1
63.062	1.4729	93.5	1.59	0.14	9.4
47.82	1.9005	86.83	1.48	0.14	5.2
70.27	1.3384	82.28	1.4	0.12	9.9
77.153	1.2353	79.57	1.36	0.14	11.1
76.32	1.2467	63.33	1.08	0.06	3.8
23.8	3.7355	61.67	1.05	0.14	1.2

ID: BSM-005b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.445	3.031	1040.6	100	0.02	124.9
35.991	2.4933	174.4	16.76	0.06	17.4
39.471	2.2811	174.18	16.74	0	24.4
47.566	1.9101	158.88	15.27	0.12	19.1
43.218	2.0916	142.83	13.73	0.1	14.3
48.584	1.8724	125.43	12.05	0.14	15.1
23.1	3.8471	113.33	10.89	0.1	6.8
57.48	1.602	85	8.17	0.06	1.7
24.68	3.6043	68.33	6.57	0.12	0
22.66	3.9208	56.67	5.45	0.12	1.1
47.18	1.9248	48.08	4.62	0.02	2.9

ID: BSM-006c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.239	3.0519	1799.9	100	0.14	216
46.949	1.9337	550.43	30.58	0	33
43.022	2.1007	443.87	24.66	0.12	35.5
39.268	2.2925	235.3	13.07	0.04	28.2
48.371	1.8802	224.83	12.49	0.06	27
35.813	2.5053	216.72	12.04	0.08	17.3
47.353	1.9182	180.13	10.01	0.06	21.6
22.893	3.8814	141.15	7.84	0.12	19.8
29.58	3.0174	105	5.83	0.08	4.2
57.244	1.608	101.4	5.63	0.06	8.1
28.8	3.0974	78.33	4.35	0.12	0
29.716	3.004	47.15	2.62	0.12	2.8
60.52	1.5286	46.67	2.59	0.08	3.7
64.54	1.4427	45	2.5	0.08	2.7
36.02	2.4913	45	2.5	0.06	2.7

ID: BSM-007b clast					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.256	3.0501	2886.7	100	0.1	288.7
39.274	2.2921	467.43	16.19	0.1	56.1
48.388	1.8795	435.2	15.08	0.04	60.9
47.376	1.9173	412.67	14.3	0.08	57.8
43.036	2.1001	403.13	13.97	0.12	48.4

35.829	2.5042	359.72	12.46	0.12	28.8
22.909	3.8787	257.47	8.92	0.08	25.7
57.275	1.6072	166.65	5.77	0.14	16.7
47.02	1.931	136.67	4.73	0.14	10.9
31.28	2.8572	128.33	4.45	0.06	5.1
64.526	1.443	109.62	3.8	0.1	13.2
60.531	1.5283	88.48	3.07	0.12	10.6
65.496	1.424	63.48	2.2	0.02	3.8
56.422	1.6295	62.77	2.17	0.12	3.8
61.24	1.5123	61.67	2.14	0.06	1.2
72.8	1.298	45	1.56	0.04	1.8

ID: BSM-007b matrix					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.463	3.0292	1231.5	100	0.16	123.2
39.484	2.2804	274.52	22.29	0.06	27.5
43.234	2.0909	234.48	19.04	0.1	18.8
36.036	2.4903	179	14.53	0.08	14.3
47.564	1.9101	163.53	13.28	0.1	19.6
26.678	3.3388	141.18	11.46	0.08	8.5
48.583	1.8725	116.37	9.45	0	14
23.128	3.8426	106.17	8.62	0.12	17
47.22	1.9233	83.33	6.77	0.12	0
57.467	1.6023	70.72	5.74	0.12	8.5
64.74	1.4387	53.33	4.33	0.1	1.1
60.72	1.524	46.67	3.79	0.02	4.7
56.619	1.6243	43.15	3.5	0.041	1.8
61.12	1.515	38.33	3.11	0.02	0.8

ID: BSM-007c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.395	3.036	4981.7	100	0.12	498.2
35.893	2.4999	1036.2	20.8	0.06	124.3
48.486	1.8759	912.6	18.32	0.1	109.5
39.388	2.2857	639.28	12.83	0.1	102.3
43.136	2.0954	576.32	11.57	0.06	69.2
47.463	1.914	525.53	10.55	0.06	84.1
23.089	3.8489	332.48	6.67	0.12	19.9
26.573	3.3517	308.68	6.2	0.16	30.9

64.628	1.441	299.83	6.02	0.12	36
57.362	1.605	263.22	5.28	0.12	42.1
22.961	3.8702	236.35	4.74	0.16	28.4
47.081	1.9286	202.22	4.06	0.12	24.3
29.606	3.0148	180.87	3.63	0.12	10.9
60.644	1.5257	168.87	3.39	0.16	23.6
30.801	2.9005	159.27	3.2	0.14	9.6
61.32	1.5105	148.33	2.98	0.12	17.8
70.221	1.3393	121.1	2.43	0.12	14.5
56.453	1.6287	111.87	2.25	0.14	13.4
65.623	1.4215	102.02	2.05	0.12	10.2
60.968	1.5184	98.33	1.97	0.1	11.8
72.833	1.2975	96.75	1.94	0.04	13.5
63.043	1.4733	88.3	1.77	0.12	12.4
77.133	1.2356	82.65	1.66	0.14	11.6
69.16	1.3572	80	1.61	0.14	3.2

ID: BSM-008b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.476	3.0279	2347.5	100	0.1	281.7
48.579	1.8726	443.73	18.9	0.12	35.5
39.493	2.2799	316	13.46	0.1	37.9
43.241	2.0906	274.78	11.71	0.12	33
57.5	1.6015	236.67	10.08	0.12	4.7
36.044	2.4897	213.93	9.11	0.08	21.4
47.588	1.9092	203.82	8.68	0.14	28.5
23.121	3.8436	156.3	6.66	0.08	15.6
47.212	1.9236	80.28	3.42	0.02	6.4
64.733	1.4389	56.67	2.41	0.1	6.8
60.779	1.5227	50.9	2.17	0.12	5.1

ID: BSM-009e					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.459	3.0295	1749.8	100	0.1	210
57.549	1.6002	373.85	21.37	0.12	22.4
39.499	2.2796	237.82	13.59	0.06	28.5
36.038	2.4902	176.87	10.11	0.02	21.2
47.568	1.91	173.82	9.93	0.12	20.9
43.234	2.0909	166.73	9.53	0.12	26.7

48.575	1.8727	163.6	9.35	0.16	16.4
23.111	3.8454	154.38	8.82	0.02	15.4
64.72	1.4391	71.67	4.1	0.08	1.4
47.193	1.9243	63.88	3.65	0.12	5.1
43.52	2.0778	51.67	2.95	0.1	1
30.42	2.936	43.33	2.48	0.06	0.9
30	2.9761	43.33	2.48	0.02	2.6

ID: BSM-010c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.238	3.0519	2231	100	0.12	267.7
35.819	2.5049	354.57	15.89	0.04	42.5
39.264	2.2926	287.78	12.9	0.12	34.5
48.359	1.8806	272.78	12.23	0.12	32.7
43.018	2.1009	197.95	8.87	0.04	23.8
47.368	1.9176	194	8.7	0.12	27.2
22.896	3.8809	142.17	6.37	0.12	17.1
57.255	1.6077	123.27	5.53	0.1	9.9
47	1.9317	75	3.36	0.14	7.5
26.46	3.3657	65	2.91	0.12	2.6
36.04	2.49	60	2.69	0.04	2.4
64.521	1.4431	57.33	2.57	0.08	5.7
56.4	1.63	56.67	2.54	0.1	2.3
60.547	1.5279	53.55	2.4	0.1	5.4

ID: BSM-011a vein					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.27	3.0487	1407.4	100	0.12	197
47.399	1.9164	223.53	15.88	0.04	31.3
23.38	3.8017	193.33	13.74	0.14	7.7
22.904	3.8796	192.52	13.68	0.02	23.1
35.838	2.5036	185.05	13.15	0.06	18.5
43.055	2.0992	164.52	11.69	0.1	26.3
39.288	2.2913	159.43	11.33	0.04	22.3
48.38	1.8798	131.67	9.36	0.14	13.2
36.02	2.4913	81.67	5.8	0.16	3.3
29.78	2.9976	78.33	5.57	0.14	1.6
60.58	1.5272	75	5.33	0.14	6
48.2	1.8864	73.33	5.21	0.12	2.9

48.033	1.8926	68.7	4.88	0.04	8.2
31.26	2.859	53.33	3.79	0.1	3.2
47.005	1.9315	53.05	3.77	0.1	7.4
57.34	1.6055	41.67	2.96	0.08	4.2

ID: BSM-012a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.256	3.0501	5713.7	100	0.08	342.8
43.028	2.1004	1296.6	22.69	0.06	77.8
39.275	2.292	1009.9	17.68	0.08	80.8
48.371	1.8801	821.47	14.38	0.06	82.1
47.375	1.9173	667	11.67	0.08	53.4
35.831	2.5041	615.63	10.77	0.06	36.9
22.908	3.879	390.78	6.84	0.08	31.3
26.47	3.3645	350.42	6.13	0.06	21
57.263	1.6075	327.7	5.74	0.02	26.2
46.979	1.9326	233.15	4.08	0.08	18.7
65.474	1.4244	216.35	3.79	0.08	17.3
60.535	1.5282	210.22	3.68	0.1	16.8
64.553	1.4425	208.87	3.66	0.04	25.1
56.44	1.629	180	3.15	0.08	7.2
60.88	1.5204	118.33	2.07	0.08	4.7
72.761	1.2986	108.48	1.9	0.04	13
62.92	1.4759	106.92	1.87	0.1	6.4
31.309	2.8547	80.77	1.41	0.06	6.5
61.263	1.5118	59.57	1.04	0.12	6
26.94	3.3068	57.18	1	0.08	4.6
77.04	1.2368	56.67	0.99	0.12	5.7
43.26	2.0897	51.67	0.9	0.1	1

ID: BSM-013a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.243	3.0514	8850.2	100	0.08	708
48.351	1.8809	409.55	4.63	0.08	41
22.882	3.8833	227.7	2.57	0.04	18.2
43.011	2.1012	221.87	2.51	0.06	22.2
39.259	2.2929	206.92	2.34	0.12	20.7
35.805	2.5058	170.93	1.93	0.1	20.5
47.361	1.9179	146.22	1.65	0.1	20.5

57.19	1.6094	126.73	1.43	0.06	10.1
29.6	3.0154	108.33	1.22	0.14	4.3
61.24	1.5123	76.67	0.87	0.1	0
46.98	1.9325	75	0.85	0.08	4.5
60.68	1.5249	46.67	0.53	0.06	1.9
60.56	1.5276	45	0.51	0.04	2.7
29.758	2.9998	43.83	0.5	0	2.6

ID: BSM-014a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
26.681	3.3384	4756.4	100	0.1	380.5
29.493	3.0262	2060.9	43.33	0.08	206.1
20.884	4.25	1104.8	23.23	0.0983	108.6
39.512	2.2788	517.97	10.89	0.1	51.8
50.17	1.8169	263.28	5.54	0.06	26.3
48.637	1.8705	246.87	5.19	0.1	24.7
47.643	1.9072	238.12	5.01	0.08	33.3
23.091	3.8486	224.97	4.73	0.1	22.5
36.569	2.4552	198.45	4.17	0.1	19.8
59.993	1.5407	177.75	3.74	0.04	17.8
36.059	2.4887	175.53	3.69	0.1	14
43.248	2.0902	161.35	3.39	0.12	19.4
54.936	1.67	129.67	2.73	0.06	10.4
64.818	1.4372	98.3	2.07	0.1	9.8
65.711	1.4198	83.93	1.76	0.14	10.1
67.784	1.3813	82.47	1.73	0.1	6.6
47.236	1.9227	80.2	1.69	0.1	8
73.46	1.288	80	1.68	0.08	3.2
40.34	2.2339	76.67	1.61	0.1	3.1
68.175	1.3744	70.98	1.49	0.04	7.1
42.503	2.1252	68.03	1.43	0.1	6.8
57.55	1.6002	67.08	1.41	0.1	6.7
31.533	2.8348	63.1	1.33	0.1	6.3
30.82	2.8988	61.67	1.3	0.12	3.7
68.34	1.3715	56.67	1.19	0.08	2.3
45.82	1.9787	55	1.16	0.1	3.3
60.883	1.5203	53.47	1.12	0.04	5.3
58.26	1.5824	50	1.05	0.04	2

ID: BSM-015b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.341	3.0414	3178.8	100	0.16	445
48.49	1.8758	978.33	30.78	0.14	117.4
47.475	1.9135	822.27	25.87	0.1	115.1
39.373	2.2866	807.53	25.4	0.14	113.1
35.82	2.5048	716.67	22.55	0.14	71.7
43.114	2.0964	696.73	21.92	0.02	97.5
57.376	1.6046	577.87	18.18	0.14	69.3
22.973	3.8681	259.9	8.18	0.14	41.6
64.645	1.4406	259.77	8.17	0.12	31.2
60.644	1.5257	255.93	8.05	0.14	35.8
47.083	1.9285	241.85	7.61	0.12	33.9
61.343	1.51	229.28	7.21	0.14	13.8
65.576	1.4224	136.8	4.3	0.08	13.7
60.989	1.5179	135.02	4.25	0.06	10.8
56.549	1.6261	133.18	4.19	0.12	18.6
72.92	1.2962	91.67	2.88	0.12	7.3
63.017	1.4739	87.12	2.74	0.1	10.5
70.251	1.3388	81.05	2.55	0.1	8.1
43.36	2.0851	65	2.04	0.08	1.3
77.2	1.2347	65	2.04	0.08	5.2

ID: BSM-016a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.461	3.0293	3071.4	100	0.06	245.7
47.583	1.9094	369.15	12.02	0.08	36.9
39.483	2.2804	335.28	10.92	0.06	46.9
43.224	2.0913	328.73	10.7	0.08	26.3
36.033	2.4905	315.08	10.26	0.08	25.2
48.581	1.8725	290.7	9.46	0.14	34.9
23.108	3.8459	249.53	8.12	0.08	15
57.44	1.603	120	3.91	0.08	9.6
47.16	1.9256	111.67	3.64	0.1	8.9
60.74	1.5236	81.67	2.66	0.12	4.9
64.8	1.4376	80	2.6	0.06	1.6
31.5	2.8378	73.33	2.39	0.08	5.9
56.582	1.6252	52.33	1.7	0.06	3.1
29.9	2.9859	51.67	1.68	0.08	3.1

61.159	1.5141	49.67	1.62	0.02	4
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ID: BSM-017c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.456	3.0299	1882.7	100	0.1	225.9
43.226	2.0912	305.25	16.21	0.06	36.6
39.475	2.2809	286.98	15.24	0.12	34.4
48.582	1.8725	266.5	14.16	0.1	32
36.033	2.4905	205.6	10.92	0.12	20.6
47.562	1.9102	204.58	10.87	0.12	24.5
23.119	3.844	155.97	8.28	0.08	15.6
57.471	1.6022	93.27	4.95	0.02	13.1
26.64	3.3434	85	4.51	0.12	5.1
47.32	1.9194	81.67	4.34	0.08	1.6
47.22	1.9233	76.67	4.07	0.04	6.1
60.78	1.5226	76.67	4.07	0.12	3.1
48.44	1.8776	68.33	3.63	0.02	5.5
56.62	1.6242	61.67	3.28	0.14	1.2
64.74	1.4387	52.38	2.78	0.04	6.3
48.88	1.8618	48.33	2.57	0.12	1.9
72.96	1.2956	41.67	2.21	0.02	0.8

ID: BSM-018b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.459	3.0296	1320	100	0.08	132
47.597	1.9089	931.37	70.56	0.1	74.5
47.16	1.9256	356.67	27.02	0.06	7.1
36.039	2.49	279.8	21.2	0.06	22.4
39.489	2.2801	215.73	16.34	0.08	30.2
43.234	2.0909	193.37	14.65	0.14	19.3
48.583	1.8724	175.9	13.33	0.1	10.6
23.106	3.8462	137.63	10.43	0.02	11
64.741	1.4387	134.35	10.18	0.08	10.7
57.448	1.6028	103.52	7.84	0.06	6.2
31.509	2.837	80.87	6.13	0.06	4.9
29.84	2.9917	63.33	4.8	0.04	3.8
60.74	1.5236	61.67	4.67	0.08	2.5

ID: BSM-019a whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.46	3.0294	5022.3	100	0.06	401.8
43.234	2.0909	878.62	17.49	0.08	70.3
39.488	2.2802	727.95	14.49	0.08	72.8
48.581	1.8725	655.9	13.06	0.06	65.6
36.046	2.4896	593.45	11.82	0.08	47.5
47.576	1.9097	436.65	8.69	0.08	52.4
23.114	3.8448	311.05	6.19	0.1	18.7
57.481	1.6019	211.03	4.2	0.08	21.1
26.683	3.3381	165.58	3.3	0.12	13.2
64.733	1.4389	159.12	3.17	0.12	12.7
60.755	1.5232	149.85	2.98	0.1	15
47.181	1.9247	132.4	2.64	0.12	15.9
69.277	1.3552	115.48	2.3	0.1	9.2
31.512	2.8367	110.87	2.21	0.1	8.9
65.72	1.4196	88	1.75	0	7
63.131	1.4715	83.6	1.66	0.08	5
61.08	1.5159	73.33	1.46	0.06	0
56.633	1.6239	65.88	1.31	0.08	7.9
61.444	1.5078	65.67	1.31	0.08	5.3
29.809	2.9948	59.8	1.19	0.08	3.6
73.02	1.2947	51.67	1.03	0.06	3.1

ID: BSM-019b vug					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.458	3.0297	1444.7	100	0.02	173.4
60.763	1.523	366.43	25.36	0.1	44
39.485	2.2803	290.35	20.1	0.12	29
43.244	2.0904	240.63	16.66	0.02	33.7
47.589	1.9092	213.97	14.81	0.04	21.4
36.032	2.4905	205.58	14.23	0.1	20.6
48.6	1.8718	190	13.15	0.1	15.2
23.12	3.8438	171.28	11.86	0.04	17.1
29.88	2.9878	100	6.92	0.14	2
47.178	1.9249	86.53	5.99	0.08	6.9
31.5	2.8378	65	4.5	0.1	2.6
39.72	2.2674	58.33	4.04	0.08	2.3
57.447	1.6028	55.18	3.82	0.02	3.3

22.84	3.8903	48.33	3.35	0.06	1
61.54	1.5057	45	3.11	0.12	0.9
56.62	1.6242	43.33	3	0.02	0.9

ID: BSM-019c whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.444	3.0311	4020.3	100	0.1	321.6
39.469	2.2812	855.6	21.28	0.06	85.6
47.571	1.9099	720.85	17.93	0.08	72.1
43.215	2.0918	715.77	17.8	0.08	57.3
36.022	2.4912	615.43	15.31	0.08	49.2
48.571	1.8729	600.3	14.93	0.1	60
23.091	3.8487	438.72	10.91	0.08	43.9
57.461	1.6024	294.3	7.32	0.12	23.5
47.175	1.925	201.65	5.02	0.1	24.2
64.708	1.4394	187.42	4.66	0.1	18.7
26.651	3.342	152.62	3.8	0.08	9.2
56.622	1.6242	134.23	3.34	0.08	10.7
72.961	1.2956	133.45	3.32	0.1	10.7
60.721	1.524	124.55	3.1	0.08	12.5
31.509	2.8369	116.87	2.91	0.1	9.3
65.681	1.4204	75.23	1.87	0.04	9
70.28	1.3383	65	1.62	0.1	5.2
61.46	1.5074	62.47	1.55	0.12	6.2
61.06	1.5163	60	1.49	0.08	4.8
63.14	1.4713	51.67	1.29	0.08	2.1

ID: BSM-020a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.471	3.0283	4063	100	0.06	406.3
39.488	2.2802	738.32	18.17	0.1	73.8
43.236	2.0908	630.83	15.53	0.06	50.5
23.111	3.8454	545.48	13.43	0.1	32.7
48.589	1.8722	510.48	12.56	0.1	51
47.587	1.9093	455.33	11.21	0.06	63.7
36.05	2.4893	424.32	10.44	0.08	42.4
57.489	1.6017	333.13	8.2	0	33.3
47.188	1.9245	235.85	5.8	0.1	23.6
60.774	1.5228	139.53	3.43	0.14	16.7

31.511	2.8368	132.83	3.27	0.1	8
64.744	1.4387	129.15	3.18	0.06	15.5
56.655	1.6233	98.33	2.42	0.1	5.9
65.752	1.419	92.78	2.28	0.12	9.3
43.4	2.0833	80	1.97	0.04	0
61.46	1.5074	71.67	1.76	0.02	1.4
72.96	1.2956	68.33	1.68	0.12	2.7
61.04	1.5168	63.33	1.56	0.1	2.5
39.74	2.2663	50	1.23	0.04	3

ID: BSM-020c clast					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.458	3.0296	2575.4	100	0.1	309.1
39.494	2.2798	378.2	14.68	0.12	45.4
43.228	2.0912	362.83	14.09	0.12	36.3
48.579	1.8726	347.98	13.51	0.1	48.7
36.025	2.491	325.75	12.65	0.12	32.6
47.586	1.9093	290.63	11.28	0.1	34.9
23.1	3.8471	275.67	10.7	0.1	27.6
57.491	1.6017	110.33	4.28	0.12	13.2
48.82	1.8639	86.67	3.37	0.14	3.5
47.213	1.9235	82.08	3.19	0.04	8.2
64.738	1.4388	73.67	2.86	0.04	8.8
56.68	1.6227	70	2.72	0.12	2.8
70.36	1.337	68.33	2.65	0.16	1.4
60.77	1.5229	56.33	2.19	0.12	9
31.512	2.8367	51.83	2.01	0.02	6.2

ID: BSM-021b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.459	3.0295	4740.9	100	0.1	568.9
47.584	1.9094	611.12	12.89	0.02	61.1
43.239	2.0907	582.65	12.29	0.12	46.6
39.485	2.2803	575.05	12.13	0.08	57.5
48.59	1.8722	516.77	10.9	0.08	51.7
36.029	2.4908	514.93	10.86	0.1	41.2
23.106	3.8461	406.93	8.58	0.02	40.7
65.708	1.4199	372.47	7.86	0.08	22.3
57.476	1.6021	325.57	6.87	0.1	32.6

60.738	1.5236	191.92	4.05	0.1	15.4
47.191	1.9244	170.2	3.59	0.1	17
64.745	1.4386	100.52	2.12	0.08	14.1
31.493	2.8384	94.98	2	0.1	7.6
77.22	1.2344	83.33	1.76	0.08	3.3
72.98	1.2953	81.67	1.72	0.06	6.5
63.14	1.4713	70	1.48	0.14	4.2
56.654	1.6233	69.43	1.46	0.06	5.6
70.327	1.3375	62.53	1.32	0.14	8.8
26.66	3.3409	46.67	0.98	0.08	0.9
39.74	2.2663	45	0.95	0.04	0.9

ID: BSM-022a					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.443	3.0311	1284.6	100	0.08	102.8
48.539	1.874	207.35	16.14	0.08	20.7
39.465	2.2814	204.7	15.94	0.06	20.5
36.02	2.4913	145	11.29	0.04	8.7
23.093	3.8482	122.07	9.5	0.06	9.8
43.186	2.0931	121.98	9.5	0.1	12.2
47.564	1.9102	111.95	8.72	0.1	11.2
29.8	2.9957	96.67	7.53	0.06	5.8
47.159	1.9256	57.27	4.46	0.1	3.4
57.54	1.6004	55	4.28	0.1	1.1
57.441	1.603	53.38	4.16	0.1	5.3
29.98	2.9781	50	3.89	0.02	2

ID: BSM-F2c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.459	3.0295	1020.5	100	0.06	122.5
26.659	3.3411	435.35	42.66	0.08	34.8
39.476	2.2808	211.48	20.72	0.12	12.7
23.096	3.8477	123.15	12.07	0.08	7.4
43.24	2.0906	120	11.76	0.08	2.4
36.06	2.4887	115	11.27	0.04	9.2
48.593	1.8721	90.47	8.87	0.08	12.7
47.56	1.9103	80	7.84	0.02	4.8
36.9	2.4339	63.33	6.21	0.06	1.3
36.86	2.4365	55	5.39	0.02	4.4

36.74	2.4442	55	5.39	0.06	2.2
33.339	2.6853	53.33	5.23	0.14	4.3
57.491	1.6017	46.77	4.58	0.06	2.8

ID: BSM-F3b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.446	3.0308	1142.3	100	0.12	114.2
36.014	2.4918	239.47	20.96	0.1	19.2
26.671	3.3396	227.05	19.88	0.1	22.7
39.48	2.2806	118.2	10.35	0.08	16.5
48.568	1.873	115.22	10.09	0.08	11.5
43.209	2.092	107.42	9.4	0.14	8.6
47.533	1.9113	105.7	9.25	0.08	8.5
29.819	2.9938	100.1	8.76	0.02	8
23.096	3.8478	97.55	8.54	0.08	11.7
47.18	1.9248	78.33	6.86	0.1	1.6

ID: SWC-01a whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.463	3.0292	2654.2	100	0.06	212.3
39.485	2.2803	622.08	23.44	0.08	62.2
48.565	1.8731	596.3	22.47	0.08	59.6
26.678	3.3387	595.12	22.42	0.04	47.6
43.231	2.091	565.5	21.31	0.08	33.9
47.578	1.9096	548.57	20.67	0.1	65.8
36.031	2.4906	358.2	13.5	0.1	35.8
23.101	3.847	258.28	9.73	0.04	15.5
57.461	1.6025	175.9	6.63	0.06	17.6
42.52	2.1243	151.67	5.71	0.1	6.1
64.726	1.439	147.78	5.57	0.12	8.9
47.187	1.9245	144.1	5.43	0.1	14.4
60.715	1.5241	99.97	3.77	0.04	6
61.451	1.5076	76.27	2.87	0.02	9.2
56.62	1.6242	71.67	2.7	0.1	1.4
50.16	1.8172	58.33	2.2	0.06	2.3
29.8	2.9957	55	2.07	0.04	2.2
61.1	1.5154	51.67	1.95	0.12	2.1
65.709	1.4198	51.2	1.93	0.06	6.1
31.52	2.836	46.67	1.76	0.12	3.7

ID: SWC-01b					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
26.652	3.3419	1678.8	100	0.1	167.9
48.54	1.874	770	45.87	0.04	30.8
29.411	3.0344	708.4	42.2	0.1	42.5
20.857	4.2555	247.01	14.71	0.1253	30.9
26.84	3.3189	155	9.23	0.04	6.2
50.1	1.8192	138.33	8.24	0.02	11.1
39.463	2.2815	123.18	7.34	0.1	14.8
47.534	1.9113	120.37	7.17	0.04	9.6
36.543	2.4569	111.77	6.66	0.06	8.9
36.002	2.4926	99.63	5.93	0.02	8
43.18	2.0934	85	5.06	0.08	3.4
27.499	3.2409	70.18	4.18	0.08	7
23.54	3.7762	68.33	4.07	0.06	2.7
27.12	3.2853	68.33	4.07	0.12	1.4
23.073	3.8516	62.65	3.73	0.04	6.3
27.64	3.2247	60	3.57	0.02	2.4
47.2	1.924	55	3.28	0.08	1.1
57.44	1.603	51.67	3.08	0.04	1
42.48	2.1262	50	2.98	0.08	3
29.94	2.982	45	2.68	0.02	0.9
59.923	1.5424	44.3	2.64	0.1	4.4

ID: SWC-01c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.435	3.032	1204.7	100	0.06	120.5
26.651	3.3421	712.65	59.16	0.06	42.8
39.448	2.2824	311.63	25.87	0.04	31.2
36.02	2.4913	206.67	17.16	0.1	8.3
47.546	1.9108	177.17	14.71	0.04	17.7
43.213	2.0919	168.3	13.97	0.1	20.2
23.088	3.8492	145.27	12.06	0.12	8.7
57.431	1.6032	130.32	10.82	0.08	13
48.546	1.8738	129.73	10.77	0.1	15.6
26.82	3.3214	100	8.3	0.12	4
64.66	1.4403	56.67	4.7	0.1	4.5
47.21	1.9236	44.15	3.66	0.1	3.5
63.101	1.4721	41.72	3.46	0.08	4.2

ID: SWC-01d					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.443	3.0311	1406.8	100	0.1	112.5
26.673	3.3394	452.38	32.16	0.06	27.1
39.459	2.2818	242.15	17.21	0.02	29.1
48.546	1.8738	178.45	12.68	0.08	17.8
47.553	1.9106	174.83	12.43	0.06	17.5
43.206	2.0922	164.87	11.72	0.14	13.2
23.086	3.8495	144.27	10.26	0.12	14.4
36.011	2.492	119.05	8.46	0.08	16.7
47.18	1.9248	106.67	7.58	0.02	2.1
57.441	1.603	104.42	7.42	0.1	6.3
26.84	3.3189	70	4.98	0.1	1.4
29.792	2.9965	56.45	4.01	0.06	3.4
60.74	1.5236	45	3.2	0.04	1.8

ID: SWC-01e					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.42	3.0335	1535.6	100	0.04	184.3
26.656	3.3415	240.92	15.69	0.1	24.1
39.439	2.2829	195.15	12.71	0.06	23.4
42.44	2.1281	168.33	10.96	0.08	6.7
48.56	1.8733	166.67	10.85	0.12	16.7
47.537	1.9112	143.38	9.34	0.1	20.1
43.203	2.0923	134.72	8.77	0.02	16.2
35.996	2.4929	125.62	8.18	0.12	12.6
23.08	3.8504	110	7.16	0.04	4.4
57.42	1.6035	76.67	4.99	0.12	3.1
47.153	1.9258	54.57	3.55	0.1	5.5
36.24	2.4767	53.33	3.47	0.14	1.1
29.023	3.074	47.22	3.07	0.1	3.8
26.856	3.317	40.98	2.67	0.04	2.5

ID: SWC-01f					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.448	3.0307	745.35	100	0	44.7
26.666	3.3402	560.78	75.24	0.06	33.6
20.9	4.2468	157.58	21.14	0.0673	10.6
36.02	2.4913	145	19.45	0.06	5.8

48.52	1.8747	121.67	16.32	0	9.7
39.514	2.2787	106.6	14.3	0.04	10.7
43.223	2.0914	87.73	11.77	0.1	7
29.68	3.0075	85	11.4	0.08	0
23.1	3.8471	78.33	10.51	0.06	0
50.14	1.8179	65	8.72	0.08	1.3
47.54	1.9111	55	7.38	0.02	3.3

ID: SWC-02a whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
30.972	2.8849	3468.4	100	0.06	346.8
41.164	2.1911	679.72	19.6	0.06	68
50.566	1.8036	368.63	10.63	0.08	51.6
44.956	2.0147	342.82	9.88	0.02	27.4
51.097	1.7861	295.48	8.52	0.06	47.3
37.386	2.4034	192.75	5.56	0.1	23.1
24.103	3.6893	135.93	3.92	0.12	8.2
35.322	2.539	115.42	3.33	0.12	13.8
58.92	1.5662	106.67	3.08	0.12	8.5
63.458	1.4647	104.02	3	0.06	8.3
59.847	1.5441	101.98	2.94	0.1	14.3
33.544	2.6694	92.35	2.66	0.06	11.1
22.059	4.0262	87.42	2.52	0.08	5.2
43.828	2.0639	71.2	2.05	0.06	4.3
26.251	3.3921	68.53	1.98	0.12	5.5
67.4	1.3883	66.67	1.92	0.14	5.3
45.906	1.9752	65.57	1.89	0.16	3.9
30.56	2.9229	61.67	1.78	0.08	3.7
49.32	1.8462	58.33	1.68	0.14	7
65.1	1.4317	53.33	1.54	0.08	1.1
37.927	2.3704	50.67	1.46	0.02	3
65.172	1.4302	47	1.36	0.12	5.6
29.48	3.0274	45	1.3	0.08	0.9

ID: SWC-03a replaced					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.427	3.0328	777.53	100	0.04	108.9
48.569	1.8729	483.65	62.2	0.06	29
26.639	3.3435	208.85	26.86	0.14	12.5

23.08	3.8504	130	16.72	0.02	5.2
39.456	2.282	87.12	11.2	0.16	13.9
60.7	1.5245	75	9.65	0.16	3
43.214	2.0918	73.28	9.43	0.02	7.3
36.04	2.49	62.48	8.04	0.1	10
47.537	1.9112	52.98	6.81	0.14	7.4
43.08	2.098	45	5.79	0.06	0.9
31.42	2.8448	35	4.5	0.04	0.7

ID: SWC-03b whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.44	3.0315	2820	100	0.1	225.6
47.561	1.9103	591.08	20.96	0.08	47.3
48.563	1.8732	588.67	20.87	0.08	47.1
39.464	2.2815	511.42	18.14	0.06	40.9
43.21	2.092	451.13	16	0.08	27.1
26.664	3.3404	416.13	14.76	0.08	33.3
36.016	2.4916	320.93	11.38	0.08	25.7
23.089	3.849	228.32	8.1	0.02	22.8
57.462	1.6024	186.38	6.61	0.06	14.9
64.7	1.4395	115	4.08	0.1	6.9
31.489	2.8387	100.67	3.57	0.08	6
60.729	1.5238	100.52	3.56	0.08	10.1
47.169	1.9252	98.58	3.5	0.06	9.9
56.611	1.6245	93.88	3.33	0.08	5.6
63.12	1.4717	60	2.13	0.1	1.2
65.66	1.4208	55	1.95	0.02	2.2
72.94	1.2959	50	1.77	0.06	2
39.74	2.2663	48.33	1.71	0.04	1
70.28	1.3383	46.67	1.65	0.04	1.9
36.54	2.4571	40	1.42	0.04	3.2

ID: SWC-03c					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.439	3.0316	1152.5	100	0.06	115.3
36	2.4927	266.67	23.14	0.06	10.7
43.238	2.0907	220.73	19.15	0.06	17.7
39.46	2.2817	215.72	18.72	0.1	17.3
48.558	1.8734	114.22	9.91	0.04	13.7

26.66	3.3409	111.67	9.69	0.08	6.7
47.5	1.9126	91.67	7.95	0.08	7.3
23.055	3.8545	91.03	7.9	0.04	5.5
29.08	3.0682	90	7.81	0.08	5.4
57.4	1.604	58.33	5.06	0.12	4.7
47.18	1.9248	50	4.34	0.08	2

ID: SWC-03c rind					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.443	3.0311	3006.6	100	0.1	240.5
39.471	2.2811	583.7	19.41	0.1	58.4
47.564	1.9101	434.27	14.44	0.08	43.4
48.569	1.873	417.52	13.89	0.1	41.8
43.212	2.0919	407.82	13.56	0.04	40.8
36.014	2.4917	318.17	10.58	0.1	31.8
23.089	3.8489	256.17	8.52	0.1	25.6
30.963	2.8857	173.58	5.77	0.1	17.4
26.675	3.3391	156.18	5.19	0.12	15.6
57.456	1.6026	147.08	4.89	0.1	14.7
60.734	1.5237	127	4.22	0.1	7.6
47.182	1.9247	101.3	3.37	0.02	12.2
64.725	1.439	99.4	3.31	0.1	8
56.62	1.6242	85	2.83	0.06	1.7
31.5	2.8378	71.67	2.38	0.04	2.9
61.14	1.5145	43.33	1.44	0.08	1.7

ID: SWC-03d					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.416	3.0339	1071.2	100	0.06	128.5
48.542	1.8739	163.45	15.26	0.04	16.3
36.024	2.4911	140.55	13.12	0.12	8.4
26.62	3.3459	136.67	12.76	0.02	5.5
23.054	3.8546	126.25	11.79	0.06	7.6
39.437	2.283	113.77	10.62	0.16	18.2
47.536	1.9112	98.17	9.16	0.16	11.8
43.191	2.0929	95.53	8.92	0.02	15.3
31	2.8824	48.33	4.51	0.12	1
47.2	1.924	40	3.73	0.1	0.8

ID: SWC-03e					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.441	3.0314	1230.2	100	0.06	147.6
30.974	2.8848	461.07	37.48	0.06	64.5
36.042	2.4899	238.03	19.35	0.12	23.8
26.675	3.3391	173.48	14.1	0.02	10.4
39.49	2.2801	147.72	12.01	0.14	14.8
43.2	2.0924	143.33	11.65	0.1	8.6
23.109	3.8457	109.22	8.88	0.1	6.6
41.175	2.1906	94.3	7.67	0.12	11.3
47.563	1.9102	80.58	6.55	0.06	4.8
48.594	1.872	80.37	6.53	0.1	12.9
51.08	1.7866	66.67	5.42	0.06	4
29.9	2.9859	66.67	5.42	0.16	1.3
44.941	2.0153	43.33	3.52	0.06	4.3

ID: SWC-03f whole					
Degree	Position	Rel. Int.	FWHM (L)	ESD	Area
29.436	3.0318	2611.9	100	0.12	209
39.468	2.2813	434.12	16.62	0.08	43.4
36.013	2.4918	427.68	16.37	0.08	34.2
48.559	1.8733	389.9	14.93	0.02	39
47.553	1.9106	371.7	14.23	0.06	37.2
43.213	2.0919	357.1	13.67	0.08	28.6
23.084	3.8497	218.97	8.38	0.1	26.3
57.459	1.6025	192	7.35	0.08	19.2
26.648	3.3425	145.53	5.57	0.1	11.6
47.174	1.925	112.35	4.3	0.1	11.2
60.724	1.5239	94.07	3.6	0.1	7.5
56.624	1.6241	66.27	2.54	0.08	5.3
64.716	1.4392	65.77	2.52	0.1	7.9
31.46	2.8413	56.67	2.17	0.08	3.4
61.06	1.5163	51.67	1.98	0.02	1
29.8	2.9957	50	1.91	0.12	1
65.67	1.4206	47.65	1.82	0.1	4.8
72.928	1.2961	45.48	1.74	0.1	4.5

APPENDIX D

GIS DATA DICTIONARY

Dataset:	Montana Towns
Source:	Montana's National Resource Information System Montana State Library
Date:	11/01/2003
Data Type:	Shapefile Feature Class; Vector Digital Data
Scale:	1:24,000
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator
Attribute Field:	Four fields of interest:
<u>Value Field</u>	<u>Description</u>
NAME	Name of the town
LON	Longitude position of the town
LAT	Latitude position of the town

Dataset:	National Elevation Dataset for Montana (2002)
Source:	Montana's National Resource Information System Montana State Library U.S. Geological Survey
Date:	04/01/2002
Data Type:	Graphics Interchange Format (gif)
Scale/Cell Size:	1:60,000; Cell Size 30x30
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator

Dataset:	Drainages
Source:	Montana's National Resource Information System Montana State Library U.S. Geological Society U.S. Environmental Protection Agency
Date:	2000
Data Type:	Shapefile Feature Class; Vector Digital Data
Scale:	1:100,000
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator
Attribute Field:	One field of interest:
<u>Value Field</u>	<u>Description</u>
FTYPE	Type of NHD network element

Dataset:	Geology
Source:	Montana Bureau of Mines and Geology (MBMG)
Date:	1996

Data Type:	ArcInfo Coverage Export file (.e00)
Scale:	1:100,000
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator
Attribute Field:	Four coverage fields of interest:
<u>Value Field</u>	<u>Description</u>
Contacts	Boundaries of geologic formations
<u>MBMG CODE</u>	<u>Abbreviation of formation</u>
	Qal Alluvium/Landslide Deposits
	Ke Eagle Formation
	Ktc Telegraph Creek Formation
	Kt Thermopolis Shale
	Kfr Fall River Sandstone
	Kk Kootenai Formation
	Jm Morrison Formation
	Jsw Swift Sandstone
	Jr Rierdon Formation
	PPab Alaska Bench Formation
	PPMt Tyler Formation
	Mh Heath Formation
	Mo Otter Formation
	Mk Kibbey Formation
	Mmc Mission Canyon Formation
	Ml Lodgepole Formation
	Dj Jefferson Formation
	OCsr Snowy Range Formation
	Cm Cambrian rocks (middle), undivided
	Cf Flathead Formation
	Yn Newland Formation

Dataset:	Fergus and Wheatland Counties Cadastral Data
Source:	Montana's National Resource Information System Montana State Library Montana Department of Administration/Information Technology Services Division Montana Department of Revenue Fergus and Wheatland Counties
Date:	04/01/2009
Data Type:	Geographic Coordinate Data Base (GCDB); Vector Digital Data
Scale:	Not Available from Metadata
Projection:	NAD 1983 UTM Zone 12N (meters);

Attribute Field:	Transverse Mercator
<u>Value Field</u>	<u>Description</u>
PARCELID	Feature Parcel identifier number (geocode)
OWNERCLASS	Generalized ownership categories
COUNTYCD	Numeric code for Montana Counties
OWNCODE	Numeric code for ownership categories
Dataset:	Montana 2001-2002 Highway Map Data
Source:	Montana's National Resource Information System Montana State Library
Date:	03/2001
Data Type:	Shapefile Feature Class; Vector Digital Data
Scale:	1:1,500,000
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator
Attribute Field:	Six categories of interest:
<u>Value Field</u>	<u>Description</u>
Town	Point locations of Montana towns
Name	Name of town
County	Name of the county that the town is in
Highway	Interstate, U.S., and state highways in Montana
Surface	Road surface or type
Route	Highway Route Number
Class	Interstate or Primary
Routetype	Interstate, U.S., Montana, or Business
Dataset:	National Forests and Ranger Districts in Montana
Source:	Montana's National Resource Information System Montana State Library
Date:	10/14/2002
Data Type:	Shapefile Feature Class; Vector Digital Data
Scale:	1:100,000
Projection:	NAD 1983 UTM Zone 12N (meters); Transverse Mercator
Attribute Field:	1 field of interest:
<u>Value Field</u>	<u>Description</u>
FOREST	Name of forest

Dataset:	Breccia Pipe Locations
Source:	Garmin Oregon 450 GPS
Date:	2012
Data Type:	GPS Coordinates (DDMMSS)
Accuracy:	Within 10 feet
Projection:	GCS Coordinates

APPENDIX E

GIS METADATA

Metadata for Breccia Pipes, Big Snowy Mountains, MT

- [Identification Information](#)
- [Data Quality Information](#)
- [Spatial Data Organization Information](#)
- [Spatial Reference Information](#)
- [Entity and Attribute Information](#)
- [Distribution Information](#)
- [Metadata Reference Information](#)

Identification Information:

Citation:

Originator: Sarah R. Jeffrey
 Publication date: 12/10/2012
 Title: Breccia Pipes, Big Snowy Mountains, MT
 Publication place: Bozeman, Montana
 Publisher: Montana State University

Abstract:

Location and width of twenty-two breccia pipes located in the Big Snowy Mountains of central Montana, with associated geologic formation and parcel of property, in proximity to the main northeast-southwest trending fault zone under study.

Purpose: Display and analysis of location of hydrothermal breccia pipes.

Supplemental information:

Locations of the breccia pipes displayed were derived from a handheld Garmin Oregon 450t unit, with accuracy within a few meters. Field measurements were taken in degrees-minutes-seconds format and converted to decimal degrees latitude-longitude.

Width of hydrothermal breccia pipes was measured in feet where accessible, and estimated where not. Steep slopes, talus slopes, or dense vegetation were some of the factors which may have introduced ambiguity to the data. These measurements were later converted to meters.

Geologic formation and fault location were sourced from the Montana Bureau of Mines and Geology (MBMG) Geologic Mapping Program for the Big Snowy Mountains Quadrangle (<http://www.mbm.gmtech.edu/gmr/gmr-statemap.asp>). Contacts data was simplified and dissolved based on the geology present in the field.

Many of these breccia pipes are located upon private parcels of land, as referenced in the attribute table. These parcels are numbered in reference to

land ownership maps of the Big Snowy Mountains Land Management Map located at Montana's Natural Resource Information System (NRIS) website (<http://nris.mt.gov/gis/ownmaps.asp>).

Time period of content:

Calendar date: 12/10/2012

Currentness reference: publication date

Status:

Progress: Ongoing

Maintenance and update frequency: Annually

Point of contact:

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Data Quality Information:

Attribute accuracy report:

The use of geologic maps from the Montana Bureau of Mines and Geology (MBMG) introduces ambiguity in the results of this layer. Prior to statistical analysis, the breccia pipes were classified on lithology based on their location plotted on the MBMG map. This process is dependent not only upon the scale and accuracy of the MBMG map and handheld GPS unit used, but also upon the interpretation of the geologists who mapped the field area.

Since, in many cases, geology is mapped via satellite imagery or prior descriptions, ambiguity may exist as to the geologic formation present and location of the fault. To correct this, each outcrop was examined to be sure that the breccia pipe sample was indeed in the correlative formation on the map. However, limited outcrop in the area was prohibitive of comprehensive geologic mapping during the field season.

The scale of the MBMG map is 1:100,000, which indicates that the horizontal accuracy is (on the map) 0.5 millimeters and (on the ground) 50.8 meters.

Additionally, the accuracy of the handheld GPS unit is one to two meters. Although exact location is not vital to the scope of this layer, it is important to note that many of the breccia pipes were located very close to one another, and thus may appear to overlap, depending on the scale of the map. The map scale falls within range of the U.S. National Map Accuracy Standard.

Logical consistency report: None

Completeness report:

The breccia pipes were mapped based on those landowners who were contacted and gave permission for access to outcrop. Therefore, the breccia pipe locations shown are only those found within the parcels listed in the attribute table.

Horizontal Positional Accuracy Report:

The coordinate for each breccia pipe is located within the area considered to define the parcel.

Lineage:

Source information:

Originator: Montana Bureau of Mines and Geology

Publication date: 1996

Title: Big Snowy Mountains 100k

Publication place: Montana Bureau of Mines and Geology

Publisher: Montana Bureau of Mines and Geology

Online linkage:

http://www.mbm.g.mtech.edu/mbmgcat/public/ListCitation.asp?selectby=series&series_type=MBMG&series_number=341&series_sub=&

Source scale denominator: 100,000

Type of source media: online

Source contribution:

This is a source of the Montana Bureau of Mines and Geology STATEMAP and EDMAP Programs, administered by the U.S. Geological Survey as a part of the National Mapping Act of 1992.

Calendar date: 1992

Source information:

Originator: Montana's Natural Resource Information System (NRIS)

Publication date: 04/01/2009

Title: Fergus County Cadastral Owner Parcel

Publication place: Helena, MT

Publisher: Montana State Library

Online linkage: <http://giscoordination.mt.gov/cadastral/msdi.asp>

Source scale denominator:

Type of source media: online

Source contribution:

Montana Cadastral Framework is built primarily upon the measurement based cadastral reference of the Geographic Coordinate Database (GCDB) maintained by the Bureau of Land Management (BLM), with tax parcels as defined by the Department of Revenue.

Calendar date: 04/01/2009

Process step:

The MBMG contacts and fault coverage files were converted to shapefiles for editing. Fields were added for period of geologic formation and name of geologic formation.

Process date: 12/06/2012

Process step:

Select geologic formations from the MBMG contacts basemap were dissolved and joined with the original file for simplification. Special characters were removed from the MBMG code field.

Process date: 12/06/2012

Process step:

A field was added in the Cadastral attribute table for parcel number. This field was used to dissolve parcel data and join with the original shapefile. Supplemental data, such as owner address and phone number, were added.

Process date: 12/06/2012

Process step:

GPS X-Y coordinates were geocoded. Near distance proximity analysis was performed, relating breccia pipe location to the fault zone.

Process date: 12/06/2012

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Spatial Data Organization Information:

Point and vector object information:

SDTS object type: Entity point

SDTS object count: 22

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Spatial Reference Information:

Horizontal coordinate system definition:

Grid coordinate system name: State Plane Coordinate System
 SPCS zone identifier: 2500
 Lambert conformal conic:
 Standard parallel: 45.000000
 Standard parallel: 49.000000
 Longitude of central meridian: -109.500000
 Latitude of projection origin: 44.250000
 False easting: 600000.000000
 False northing: 0.000000
 Planar distance units: meters
 Geodetic model:
 Horizontal datum name: North American Datum of 1983
 Ellipsoid name: Geodetic Reference System 80
 Semi-major axis: 6378137.000000
 Denominator of flattening ratio: 298.257222

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Entity and Attribute Information:

Entity type label: XYBreccias.dbf

Entity type definition: Feature attribute table

Attribute label: FID

Attribute definition: Internal feature number.

Attribute label: Shape

Attribute definition: Feature geometry.

Attribute label: BP_ID

Attribute definition: Unique Identification number for breccia pipe.

Attribute label: LatDD

Attribute definition: Latitude position of the breccia pipe.

Range domain minimum: 46.798556

Range domain maximum: 46.880583

Attribute units of measure: decimal degrees

Attribute label: LongDD

Attribute definition: Longitude position of the breccia pipe.

Range domain minimum: -109.513317

Range domain maximum: -109.637167

Attribute units of measure: decimal degrees

Attribute label: Width

Attribute definition: Width of the breccia pipe.

Range domain minimum: 0.5

Range domain maximum: 55.7

Attribute units of measure: meters

Attribute label: NearDist

Attribute definition: Near distance of breccia pipe to fault zone.

Range domain minimum: 0.000517

Range domain maximum: 0.03112

Attribute units of measure: decimal degrees

Attribute label: Parcel

Attribute definition: Parcel number from land ownership.

Attribute Value	Definition of Attribute Value
300	Simpson Ranch, c/o Hickey Ranch
307	Nelson Ranch
314	T J Butcher Ranch
327	T J Butcher Ranch
345	T J Butcher Ranch
349	McCarthy Ranch, c/o Hannah Ranch
350	Hickey Ranch
352	Wilcox Ranch
357	Nelson Ranch
370	Three Bar Ranch
371	Tucek Ranch, c/o Hertel Ranch
387	Hertel Ranch
395	Best Ranch
401	Hannah Ranch

BLM	Bureau of Land Management Area
USFS	U.S. Forest Service Area

Attribute label: GEOL

Attribute definition: Geologic Formation.

Attribute Value	Definition of Attribute Value
Mmc	Mission Canyon Formation

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Distribution Information:

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Distribution liability:

Users must assume responsibility to determine the usability of this data for their purposes.

Standard order process:

Digital form:
 Format name: ESRI Shapefile

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Metadata Reference Information:

Metadata date: 12/10/2012

Metadata contact:

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APPENDIX F

SATELLITE IMAGERY FRACTURE MEASUREMENTS

Shape Length	Length (m)	Azimuth (°)	Dip (°)
0.020405	2235	8	90
0.046129	4987	346	90
0.021999	2154	29	90
0.016482	1789	347	90
0.004837	369	86	90
0.021706	2402	4	90
0.013203	1464	355	90
0.008198	746	317	90
0.011712	1300	356	90
0.039576	3367	306	90
0.018942	1983	19	90
0.038334	3988	158	90
0.023319	2254	31	90
0.007588	748	329	90
0.02046	2273	357	90
0.013192	1345	335	90
0.013678	1500	8	90
0.016419	1800	188	90
0.004914	542	352	90
0.00431	478	355	90
0.009214	947	336	90
0.004194	465	182	90
0.005307	567	195	90
0.005017	543	192	90
0.01852	1955	17	90
0.00911	1012	1	90
0.009117	1006	352	90
0.007476	827	353	90
0.018285	1894	20	90
0.005517	587	15	90
0.012023	1131	322	90
0.007402	777	18	90
0.01578	1753	357	90
0.01098	1095	331	90
0.008957	920	336	90
0.009208	1010	350	90
0.00633	513	296	90
0.006067	651	344	90

0.013252	1271	33	90
0.03855	3790	329	90
0.018628	1989	195	90
0.005713	635	357	90
0.008086	691	307	90
0.017722	1966	355	90
0.015761	1223	282	90
0.01648	1362	300	90
0.011426	1027	315	90
0.013122	1422	346	90
0.009127	726	291	90
0.007884	695	312	90
0.014201	1088	263	90
0.01079	836	282	90
0.006075	666	8	90
0.007372	693	322	90
0.015605	1222	286	90
0.010626	975	318	90
0.012315	1368	357	90
0.006942	710	335	90
0.015199	1672	351	90
0.020427	2080	23	90
0.010971	1209	6	90
0.007448	799	14	90
0.007463	829	0	90
0.008756	950	11	90
0.013554	1429	17	90
0.005052	543	193	90
0.011761	952	62	90
0.014284	1507	17	90
0.01375	1493	11	90
0.010178	1128	355	90
0.011946	1126	35	90
0.015295	1698	2	90
0.007522	816	11	90
0.014261	1328	321	90
0.015132	1595	17	90
0.009733	897	39	90
0.007161	789	6	90
0.018439	1852	26	90

0.012593	1399	1	90
0.004927	417	53	90
0.016882	1649	30	90
0.015191	1383	40	90
0.01167	1256	13	90
0.005299	574	347	90
0.014047	1309	37	90
0.016217	1262	105	90
0.009869	920	37	90
0.010017	947	35	90
0.025737	2106	119	90
0.012529	1172	142	90
0.010766	1192	184	90
0.012111	1344	182	90
0.012168	1333	188	90
0.010388	1145	172	90
0.008656	891	202	90
0.009108	850	141	90
0.007887	764	147	90
0.013492	1223	137	90
0.021965	2215	205	90
0.030563	3388	175	90
0.04173	3867	218	90
0.013497	1233	220	90
0.01374	1198	47	90
0.008601	827	212	90
0.007008	546	73	90
0.009654	1073	177	90
0.013844	1535	175	90
0.015706	1737	174	90
0.014531	1612	176	90
0.008432	921	189	90
0.011219	1230	188	90
0.022325	2459	172	90
0.017141	1866	168	90
0.009302	841	221	90
0.007428	654	132	90
0.012142	1337	171	90
0.004311	391	137	90
0.009962	829	122	90

0.036712	3679	206	90
0.01148	1124	148	90
0.011793	1189	205	90
0.012495	1110	44	90
0.010094	1115	173	90
0.013895	1114	64	90
0.016749	1758	198	90
0.014241	1516	195	90
0.010416	927	224	90
0.026279	2736	199	90
0.020445	1880	39	90
0.009802	926	215	90
0.017479	1940	181	90
0.011894	954	293	90
0.015211	1247	298	90
0.010294	876	306	90
0.007482	578	280	90
0.01331	1407	197	90
0.01127	864	263	90
0.012474	953	269	90
0.02573	2125	237	90
0.011698	993	232	90
0.007019	537	86	90
0.029318	2432	236	90
0.015754	1518	32	90
0.022377	1997	314	90
0.016314	1360	122	90
0.010373	820	68	90
0.013071	1206	218	90
0.012628	1371	191	90
0.01177	946	243	90
0.006659	704	197	90
0.025653	2178	232	90
0.024311	1864	276	90
0.017636	1463	236	90
0.011479	1115	210	90
0.01354	1066	249	90
0.013315	1052	248	90
0.008484	814	212	90
0.008737	668	273	90

0.005575	426	84	90
0.033686	2963	46	90
0.02244	1884	54	90
0.013868	1208	48	90
0.004853	472	30	90
0.004064	449	5	90
0.002628	239	41	90
0.013068	1436	351	90
0.009763	858	46	90
0.005094	549	345	90
0.004231	329	254	90
0.004251	424	27	90
0.00569	631	2	90
0.004008	364	41	90
0.011073	1229	356	90
0.006559	715	348	90
0.021641	1959	41	90
0.009342	746	245	90
0.004367	443	24	90
0.006334	687	11	90
0.00248	205	237	90
0.006548	529	242	90
0.005816	570	209	90
0.010601	819	257	90
0.003924	332	53	90
0.00341	343	25	90
0.004759	409	230	90
0.00349	304	47	90
0.004904	375	274	90
0.006101	480	70	90
0.00372	411	354	90
0.004384	340	283	90
0.003459	318	39	90
0.002355	199	53	90
0.00829	886	15	90
0.005518	549	27	90
0.001549	159	22	90
0.005649	622	7	90
0.005603	507	41	90
0.00276	283	22	90

0.005081	565	358	90
0.008158	693	52	90
0.001645	156	35	90
0.00078	76	30	90
0.002252	233	21	90
0.001634	159	30	90
0.002085	212	23	90
0.0016	155	32	90
0.007247	699	32	90
0.00544	552	24	90
0.007345	805	8	90
0.002185	231	341	90
0.001109	121	10	90
0.003204	328	335	90
0.00834	860	337	90
0.005121	569	1	90
0.000826	91	187	90
0.00116	104	222	90
0.002558	277	191	90
0.009824	1065	167	90
0.007783	865	358	90
0.00334	310	320	90
0.003313	328	28	90
0.013519	1209	43	90
0.006319	649	22	90
0.006398	667	338	90
0.010082	1117	355	90
0.009224	1004	10	90
0.007465	829	1	90
0.005924	641	12	90
0.005218	525	25	90
0.004992	442	45	90
0.005948	479	115	90
0.006009	511	52	90
0.004159	330	67	90
0.004559	448	329	90
0.002289	230	152	90
0.002268	215	144	90
0.002255	217	145	90
0.001923	153	112	90

0.00342	271	110	90
0.004056	320	109	90
0.001695	139	118	90
0.003456	364	17	90
0.003467	331	33	90
0.007189	762	16	90
0.003563	377	197	90
0.003532	374	342	90
0.002576	286	360	90
0.001696	187	352	90
0.002808	296	340	90
0.004026	426	16	90
0.00365	333	318	90
0.004202	467	358	90
0.002454	251	335	90
0.004114	353	308	90
0.00986	768	284	90
0.002789	269	326	90
0.002568	275	14	90
0.006488	631	327	90
0.002996	328	8	90
0.003169	337	342	90
0.001806	168	321	90
0.003655	394	345	90
0.007244	557	260	90
0.00226	176	285	90
0.004834	370	272	90
0.005959	456	266	90
0.007504	589	287	90
0.008104	712	312	90
0.005823	446	275	90
0.003591	306	232	90
0.004277	338	290	90
0.00344	264	261	90
0.002759	213	258	90
0.008662	663	275	90
0.004545	395	310	90
0.003915	299	266	90
0.003796	290	267	90
0.001937	186	325	90

0.002902	222	269	90
0.003001	237	289	90
0.002469	192	253	90
0.001441	119	300	90
0.000757	58	274	90
0.000493	38	271	90
0.000525	40	268	90
0.000505	39	262	90
0.000456	39	230	90
0.000472	39	235	90
0.000443	36	240	90
0.000521	40	258	90
0.001021	107	340	90
0.000781	84	346	90
0.001149	123	344	90
0.001269	140	5	90
0.000838	93	5	90
0.000715	79	3	90
0.0007	78	360	90
0.000802	89	1	90
0.000757	84	2	90
0.002226	230	337	90
0.004099	333	297	90
0.009397	868	319	90
0.004666	368	289	90
0.006272	564	315	90
0.01789	1610	316	90
0.002672	205	276	90
0.004421	338	271	90
0.00161	124	259	90
0.001762	135	272	90
0.002297	177	280	90
0.001522	119	285	90
0.001125	89	291	90
0.001317	146	3	90
0.001245	136	349	90
0.00089	92	338	90
0.000891	99	358	90
0.000843	94	359	90
0.000945	103	11	90

0.000867	94	346	90
0.002558	219	307	90
0.001955	207	17	90
0.003859	358	320	90
0.002234	209	321	90
0.002182	239	8	90
0.006989	747	343	90
0.001457	158	346	90
0.003923	376	325	90
0.009945	1071	13	90
0.001002	110	350	90
0.002574	276	14	90
0.000846	93	8	90
0.001247	138	357	90
0.001702	189	357	90
0.001127	120	15	90
0.001275	137	13	90
0.002021	224	355	90
0.00197	217	6	90
0.000687	74	344	90
0.002102	199	34	90
0.004106	372	41	90
0.002026	166	59	90
0.004908	407	56	90
0.002186	231	17	90
0.007832	699	223	90
0.00352	385	349	90
0.00131	128	29	90
0.001482	145	30	90
0.001133	116	22	90
0.001047	105	25	90
0.000697	64	39	90
0.000736	75	22	90
0.00076	81	15	90
0.002099	226	12	90
0.002978	319	14	90
0.0009	82	41	90
0.001358	114	54	90
0.001341	127	34	90
0.00154	128	57	90

0.00201	166	58	90
0.002712	224	300	90
0.001568	132	54	90
0.001246	100	63	90
0.001295	117	42	90
0.000843	69	59	90
0.001066	88	58	90
0.002703	214	68	90
0.000508	42	57	90
0.000547	42	78	90
0.000978	75	87	90
0.00191	147	78	90
0.000545	43	72	90
0.001424	110	99	90
0.000945	73	103	90
0.00104	79	90	90
0.00132	122	140	90
0.003049	251	120	90
0.003656	300	119	90
0.003012	254	125	90
0.002374	193	117	90
0.001508	122	116	90
0.003498	283	116	90
0.002037	183	135	90
0.00297	280	142	90
0.001436	148	156	90
0.004368	357	59	90
0.00419	320	89	90
0.004086	376	39	90
0.001117	108	32	90
0.001975	211	343	90
0.002532	204	63	90
0.005865	593	24	90
0.002993	242	62	90
0.001425	146	22	90
0.001145	114	27	90
0.002122	208	29	90
0.003694	410	1	90
0.003585	374	19	90
0.005383	501	321	90

0.001214	135	358	90
0.005907	646	9	90
0.005108	534	19	90
0.003087	342	3	90
0.002653	203	267	90
0.003265	259	290	90
0.003662	293	244	90
0.003658	280	267	90
0.001457	114	252	90
0.000861	66	266	90
0.000555	44	248	90
0.000515	43	235	90
0.000649	50	278	90
0.001353	103	91	90
0.001952	153	252	90
0.001127	87	258	90
0.001065	86	241	90
0.001428	113	247	90
0.000533	51	213	90
0.000983	79	243	90
0.001199	96	244	90
0.001396	110	249	90
0.001628	130	246	90
0.001427	116	241	90
0.001781	138	255	90
0.00276	211	264	90
0.006233	476	268	90
0.000602	47	253	90
0.001241	95	266	90
0.000959	73	264	90
0.001004	77	271	90
0.001251	96	261	90
0.00142	111	251	90
0.001099	86	252	90
0.001305	104	245	90
0.0014	110	251	90
0.000731	61	304	90
0.000734	69	322	90
0.000436	46	341	90
0.000296	32	344	90

0.000361	40	356	90
0.000844	92	10	90
0.000599	65	12	90
0.000454	50	353	90
0.000521	58	353	90
0.008318	663	292	90
0.009906	996	332	90
0.012439	1112	314	90
0.003578	388	11	90
0.010192	930	318	90
0.002718	245	316	90
0.002826	268	323	90
0.00384	376	29	90
0.005026	558	2	90
0.004759	405	306	90
0.009413	1043	355	90
0.000523	53	23	90
0.000619	52	54	90
0.003752	392	19	90
0.001796	150	56	90
0.006543	562	50	90
0.006004	464	76	90
0.003526	329	37	90
0.003259	254	104	90
0.005341	416	104	90
0.001643	129	107	90
0.002459	190	101	90
0.001393	132	35	90
0.000887	84	35	90
0.000564	53	35	90
0.002135	199	36	90
0.000696	65	36	90
0.001246	123	28	90
0.000837	80	33	90
0.000659	65	28	90
0.001043	93	44	90
0.001295	120	38	90
0.002633	247	36	90
0.001877	167	44	90
0.001383	114	120	90

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0.001846	154	56	90
0.00179	149	55	90
0.001725	146	53	90
0.001581	133	54	90
0.001981	167	54	90
0.00143	119	56	90
0.001272	103	62	90
0.00161	132	59	90
0.00174	143	58	90
0.001757	142	62	90
0.003626	291	64	90
0.001375	110	65	90
0.002084	162	74	90
0.003572	287	64	90
0.004005	306	89	90
0.000712	57	115	90
0.001625	129	110	90
0.002261	183	115	90
0.002689	215	113	90
0.002634	237	136	90
0.003119	276	133	90
0.002727	243	134	90
0.001833	158	128	90
0.001872	161	128	90
0.002004	188	142	90
0.001615	137	126	90
0.001527	124	116	90
0.009773	768	70	90
0.006885	531	280	90
0.01204	997	57	90
0.002249	232	21	90
0.002645	256	31	90
0.002257	221	29	90
0.001998	207	20	90
0.00489	457	36	90
0.002995	274	40	90
0.004319	464	13	90
0.007127	770	12	90
0.005043	522	20	90

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0.001821	194	15	90
0.001594	165	20	90
0.001535	169	7	90
0.001514	168	3	90
0.002231	184	58	90
0.003711	367	28	90
0.005742	448	285	90
0.006238	651	19	90
0.006271	606	31	90
0.006614	543	59	90
0.00955	743	74	90
0.005625	438	104	90
0.005969	466	105	90
0.005364	593	353	90
0.010971	1212	5	90
0.003317	315	34	90
0.002143	194	41	90
0.003831	341	44	90
0.002257	205	41	90
0.003754	343	40	90
0.006261	603	32	90
0.002938	302	22	90
0.005377	449	55	90
0.001755	195	1	90
0.00212	236	360	90
0.002116	231	348	90
0.003242	359	354	90
0.003159	351	358	90
0.002187	243	357	90
0.003616	348	325	90
0.00633	703	1	90
0.003036	325	194	90
0.003013	323	194	90
0.001936	206	196	90
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0.011669	1294	355	90
0.007011	724	337	90
0.002265	245	346	90
0.005619	499	224	90
0.012052	1304	166	90
0.004845	519	194	90
0.010452	1143	169	90
0.010911	1143	159	90
0.014839	1508	154	90
0.015314	1526	151	90
0.016445	1822	3	90
0.009818	1041	341	90
0.010458	901	308	90
0.003826	293	265	90
0.00679	521	262	90
0.005765	446	256	90
0.002242	172	260	90
0.003363	297	225	90
0.005164	447	228	90
0.005325	427	244	90
0.005499	495	222	90
0.002864	219	270	90
0.005308	421	247	90
0.004498	369	239	90
0.011045	850	259	90
0.005059	393	254	90
0.004346	368	233	90
0.00338	319	215	90
0.006931	545	250	90
0.006683	619	218	90
0.004742	394	236	90
0.005811	463	245	90
0.003622	278	276	90

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0.004632	426	219	90
0.002839	277	148	90
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0.003436	378	171	90
0.002189	181	121	90
0.005791	642	183	90
0.002054	173	124	90
0.00192	168	130	90
0.001785	157	132	90
0.004721	520	172	90
0.004059	439	166	90
0.002723	259	144	90
0.002795	303	166	90
0.002885	309	343	90
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0.00238	258	346	90
0.003118	304	148	90
0.003724	396	162	90
0.001679	186	184	90
0.00325	316	210	90
0.003058	263	230	90
0.003524	272	257	90
0.004297	356	236	90
0.004081	333	240	90
0.004138	329	246	90
0.004199	330	250	90
0.003564	274	80	90
0.001354	113	235	90
0.001441	130	42	90
0.001888	209	356	90
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0.002399	260	11	90
0.004174	450	12	90
0.005109	438	308	90
0.006627	519	286	90
0.00453	439	327	90
0.001857	199	343	90
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0.002596	263	334	90
0.004201	334	291	90
0.005216	401	278	90
0.004984	418	303	90
0.003226	275	306	90
0.001515	140	319	90
0.002075	226	190	90
0.006499	563	228	90
0.002819	312	183	90
0.003919	429	188	90
0.004305	398	218	90
0.001993	171	230	90
0.001429	113	248	90
0.001154	93	243	90
0.001617	125	257	90
0.001103	88	245	90
0.0016	125	252	90
0.00259	211	298	90
0.002184	220	333	90
0.003201	247	281	90
0.001661	147	313	90
0.005819	445	271	90
0.004913	376	272	90
0.002947	267	136	90
0.005827	449	258	90
0.002154	231	194	90
0.001421	140	208	90
0.00173	184	196	90
0.001077	111	202	90
0.001204	120	207	90
0.002097	214	202	90
0.003706	292	249	90
0.004062	345	232	90
0.001696	133	287	90
0.003128	250	292	90
0.003312	278	303	90
0.003125	271	310	90
0.002567	235	318	90
0.002936	316	344	90

0.001858	189	334	90
0.003861	386	331	90
0.001857	162	47	90
0.002812	289	336	90
0.00286	278	327	90
0.002729	278	335	90
0.002442	256	339	90
0.008237	674	239	90
0.001892	173	318	90
0.00424	325	275	90
0.003477	284	240	90
0.009156	729	292	90
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0.015673	1302	302	90
0.011434	875	274	90
0.016539	1285	283	90
0.007759	634	240	90
0.005195	455	226	90
0.01138	890	286	90
0.001719	186	165	90
0.009403	730	254	90
0.008205	639	253	90
0.007572	601	247	90
0.003206	253	290	90
0.002865	219	262	90
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0.019198	1467	86	90
0.006733	578	230	90
0.012222	994	240	90
0.010615	1043	209	90
0.007316	625	230	90
0.012842	1102	230	90
0.006796	747	171	90
0.007869	719	220	90
0.00945	768	240	90
0.002883	320	176	90
0.005484	492	222	90
0.005647	503	224	90
0.004278	329	258	90
0.003422	295	229	90

0.00259	220	232	90
0.003042	265	227	90
0.004068	316	253	90
0.002426	217	223	90
0.003908	299	85	90
0.007429	678	220	90
0.013921	1542	174	90
0.00677	667	149	90
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0.009642	812	233	90
0.010911	1108	204	90
0.003656	326	134	90
0.006457	503	253	90
0.003141	340	166	90
0.008328	738	224	90
0.010317	1118	166	90
0.006717	589	226	90
0.010313	845	239	90
0.003747	325	130	90
0.004326	357	120	90
0.00446	358	114	90
0.003356	266	111	90
0.003969	304	96	90
0.004549	348	92	90
0.005752	439	91	90
0.005184	404	105	90
0.005724	443	101	90
0.004388	355	116	90
0.002457	230	142	90
0.006214	487	107	90
0.002281	192	124	90
0.005135	413	114	90
0.006211	557	135	90
0.002874	220	92	90
0.002	156	106	90
0.002115	230	347	90
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0.004151	427	156	90
0.003059	234	91	90
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0.004557	353	102	90
0.004488	355	110	90
0.003721	305	119	90
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0.003494	275	109	90
0.002863	224	106	90
0.002964	231	104	90
0.004642	355	93	90
0.003907	299	95	90
0.005563	433	104	90
0.00509	395	103	90
0.003483	275	109	90
0.003113	266	127	90
0.003056	283	140	90
0.002892	261	136	90
0.002976	276	140	90
0.00386	375	147	90
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0.003073	268	130	90
0.002397	187	106	90
0.002261	177	106	90
0.004131	331	113	90
0.001745	156	134	90
0.001506	141	141	90
0.001534	170	176	90
0.002186	241	351	90
0.001793	182	154	90
0.001347	119	132	90
0.001313	106	114	90
0.001973	187	144	90
0.005717	488	127	90
0.001659	157	143	90
0.003292	311	143	90
0.001514	153	153	90
0.001367	146	162	90
0.001543	163	161	90
0.004331	448	157	90
0.000305	28	139	90
0.000302	28	139	90

0.000312	28	133	90
0.000311	29	139	90
0.000605	58	144	90
0.000611	56	139	90
0.000373	35	140	90
0.000648	54	123	90
0.001097	99	135	90
0.002557	232	137	90
0.006211	675	190	90
0.001259	139	173	90
0.006675	658	208	90
0.003785	289	269	90
0.013425	1029	262	90
0.009561	742	283	90
0.003365	259	258	90
0.004041	313	256	90
0.002443	191	285	90
0.00266	287	346	90
0.003486	358	336	90
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0.00275	283	336	90
0.00521	476	318	90
0.004281	408	324	90
0.001733	167	325	90
0.007514	830	353	90
0.006581	667	154	90
0.002484	276	181	90
0.005682	442	284	90
0.002338	207	313	90
0.002773	229	300	90
0.003846	336	311	90
0.002395	188	287	90
0.011185	906	241	90
0.004462	341	273	90
0.007036	613	310	90
0.00487	392	294	90
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0.002192	190	310	90
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0.004767	370	283	90
0.005056	410	241	90
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0.008611	835	211	90
0.008006	698	47	90
0.00727	598	238	90
0.005462	582	195	90
0.020173	1558	256	90
0.005663	517	40	90
0.003752	382	154	90
0.005922	655	173	90
0.005105	515	25	90
0.011977	1269	196	90
0.008317	769	218	90
0.00958	809	233	90
0.002742	299	168	90
0.013952	1437	201	90
0.004767	431	136	90
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0.005891	626	162	90
0.005596	483	229	90
0.007187	616	230	90
0.005057	464	219	90
0.008232	851	201	90
0.003172	244	78	90
0.00811	646	245	90
0.006391	591	218	90
0.004504	399	224	90
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0.006538	724	183	90
0.015912	1475	217	90
0.007032	600	231	90
0.004012	322	243	90
0.002105	165	107	90
0.001895	188	150	90
0.001973	191	147	90
0.003077	254	57	90
0.003259	249	92	90
0.004364	338	103	90
0.003165	242	91	90

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0.002107	173	119	90
0.001465	117	112	90
0.001672	133	112	90
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0.001406	115	119	90
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0.000298	31	156	90
0.000207	19	139	90
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0.000739	57	103	90
0.003087	317	202	90
0.004092	312	269	90
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0.002405	184	266	90
0.001707	130	271	90
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0.001532	121	290	90
0.001261	97	278	90
0.002187	179	299	90
0.002699	241	315	90
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0.00275	233	306	90
0.002975	274	319	90
0.003056	284	320	90
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0.004423	411	320	90
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0.0046	403	311	90
0.003818	302	290	90
0.001479	124	303	90
0.004146	318	278	90
0.003629	277	268	90

0.001665	127	268	90
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0.004395	355	296	90
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0.006401	671	198	90
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0.002825	269	324	90
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0.016905	1299	259	90
0.010062	768	266	90
0.012615	1096	228	90
0.006464	506	251	90
0.004877	506	200	90
0.003653	406	177	90
0.008074	831	201	90
0.012274	1153	142	90
0.007323	608	122	90
0.002721	256	142	90
0.013809	1415	202	90
0.004904	374	88	90
0.003918	434	355	90
0.002155	185	128	90
0.002802	266	144	90
0.001842	178	147	90
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0.00839	932	179	90
0.005208	539	201	90
0.002696	299	174	90
0.004611	383	236	90
0.003102	309	151	90

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0.008134	771	214	90
0.003148	326	157	90
0.003768	405	193	90
0.002131	236	184	90
0.002687	270	152	90
0.002799	301	13	90
0.001816	186	155	90
0.009259	903	210	90
0.00199	152	263	90
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0.006598	730	174	90
0.002146	207	31	90
0.00719	655	137	90
0.004061	316	105	90
0.001592	126	67	90
0.005625	625	177	90
0.002606	238	220	90
0.01189	1248	198	90
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0.001962	217	184	90
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0.003783	371	29	90
0.003913	433	183	90
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0.014816	1467	208	90
0.005738	622	167	90
0.004725	446	215	90
0.002186	219	152	90
0.007835	845	12	90
0.007361	572	105	90
0.004825	505	339	90

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0.006058	600	208	90
0.011091	849	263	90
0.002916	287	29	90
0.002822	304	13	90
0.0033	332	25	90
0.003176	323	23	90
0.003463	346	26	90
0.004021	380	34	90
0.003486	384	351	90
0.00498	547	350	90
0.004556	365	113	90
0.004011	306	92	90
0.005525	423	96	90
0.005137	394	96	90
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0.003048	259	126	90
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0.003324	263	110	90
0.003448	376	168	90
0.004288	339	68	90
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0.00307	235	93	90
0.003117	241	75	90
0.003947	309	71	90
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0.001535	155	25	90
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0.00374	332	133	90
0.000721	56	79	90
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0.001028	79	260	90
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0.003611	330	220	90

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0.003201	345	192	90
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0.00332	298	222	90
0.000518	50	212	90
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0.002812	225	244	90
0.002313	187	242	90
0.001646	130	247	90
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0.002475	189	267	90
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0.002319	177	272	90
0.001939	148	271	90
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0.001833	140	273	90
0.001088	84	281	90
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0.00149	133	314	90
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0.000997	77	278	90
0.000693	55	289	90
0.000454	36	294	90
0.001013	87	309	90
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0.005155	426	237	90
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0.004067	374	39	90
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0.002969	230	103	90
0.002588	249	32	90
0.004309	361	55	90
0.00306	255	122	90
0.004484	345	98	90
0.006957	764	170	90
0.002007	160	246	90
0.008437	765	137	90
0.001876	208	182	90
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0.001616	145	223	90
0.00609	666	189	90
0.000886	80	222	90
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0.000584	46	289	90
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0.003153	260	238	90
0.002587	217	234	90
0.00453	346	266	90
0.004881	379	254	90
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0.005448	433	246	90
0.004475	343	262	90
0.003412	269	248	90
0.003247	251	256	90
0.002632	202	277	90
0.00154	118	263	90
0.003259	251	100	90
0.005751	463	114	90
0.009183	729	111	90
0.00245	219	43	90
0.002392	211	225	90
0.002024	178	226	90
0.00181	150	237	90
0.002228	188	233	90
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0.000949	75	248	90
0.004184	439	198	90
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0.0047	522	176	90
0.002901	222	262	90
0.00373	290	253	90
0.003233	248	261	90
0.003235	251	254	90
0.002702	210	253	90
0.005124	391	272	90
0.002521	197	286	90
0.003086	239	255	90
0.004522	346	264	90
0.001759	134	268	90
0.004568	351	260	90
0.004273	327	262	90
0.003603	276	275	90
0.001131	86	264	90
0.001546	118	262	90
0.001476	113	264	90
0.001385	108	251	90
0.001704	132	283	90
0.002527	195	281	90
0.002591	200	282	90
0.003352	268	293	90
0.003452	342	330	90
0.003488	308	313	90
0.003097	268	309	90
0.003911	342	311	90
0.003926	337	308	90
0.004222	342	296	90
0.002283	176	279	90
0.009873	828	234	90
0.0046	434	215	90
0.003392	261	259	90
0.022103	2315	198	90
0.007635	800	198	90
0.014075	1145	60	90

0.007992	822	202	90
0.037316	3801	203	90
0.012189	1038	231	90
0.006562	502	82	90
0.007126	568	245	90
0.009518	749	249	90
0.028312	2168	261	90
0.00267	293	187	90
0.002874	314	189	90
0.00287	303	197	90
0.002645	274	200	90
0.004242	441	200	90
0.002823	290	202	90
0.00399	400	206	90
0.015673	1620	157	90
0.017745	1375	75	90
0.036447	3189	131	90
0.008362	652	72	90
0.005091	391	80	90
0.01583	1755	175	90
0.007088	699	149	90
0.00538	447	122	90
0.008973	950	16	90
0.007768	616	111	90
0.006244	494	67	90
0.008177	665	60	90
0.006356	489	78	90
0.002329	178	272	90
0.003362	364	191	90
0.002963	320	192	90
0.002338	245	198	90
0.004344	354	240	90
0.004818	393	240	90
0.003201	255	246	90
0.009128	895	209	90
0.00397	356	223	90
0.003818	322	233	90
0.003361	308	220	90
0.004071	331	241	90
0.004812	368	273	90

0.006076	464	272	90
0.005191	411	290	90
0.012379	1362	187	90
0.001704	138	241	90
0.003131	253	242	90
0.003134	249	246	90
0.003736	296	247	90
0.003768	294	252	90
0.003569	283	291	90
0.013913	1073	258	90
0.025138	2794	179	90
0.009658	871	136	90
0.006197	488	289	90
0.010183	829	118	90
0.012274	1007	119	90
0.004056	399	149	90
0.006095	635	338	90
0.004997	410	120	90
0.006229	639	156	90
0.005927	475	114	90
0.005305	586	173	90
0.013338	1026	99	90
0.001979	156	69	90
0.001695	134	67	90
0.002486	201	61	90
0.001525	141	140	90
0.001514	148	149	90
0.001433	131	138	90
0.00352	384	168	90
0.007157	757	197	90
0.001801	137	269	90
0.003834	426	177	90
0.004215	330	251	90
0.005249	428	240	90
0.003088	236	263	90
0.004276	475	181	90
0.002701	296	188	90
0.002747	210	268	90
0.002724	209	262	90
0.002776	225	242	90

0.001438	118	238	90
0.002504	191	272	90
0.003412	262	278	90
0.002512	218	48	90
0.005509	423	260	90
0.005318	578	190	90
0.006138	675	187	90
0.00308	297	146	90
0.008546	948	182	90
0.006079	466	81	90
0.005733	508	45	90
0.004701	392	55	90
0.001352	147	11	90
0.002141	177	301	90
0.003599	275	89	90
0.003773	324	128	90
0.005031	404	114	90
0.005664	607	14	90
0.003307	343	157	90
0.006606	618	142	90
0.0044	461	199	90
0.011615	1279	172	90
0.009237	996	193	90
0.003763	404	164	90
0.006397	528	121	90
0.0046	399	130	90
0.004597	398	130	90
0.004539	460	154	90
0.005256	466	44	90
0.004504	484	164	90
0.006974	762	169	90
0.004948	520	160	90
0.004753	367	101	90
0.003612	400	355	90
0.003839	384	152	90
0.0096	1067	179	90
0.006336	486	97	90
0.007197	553	98	90
0.004952	470	144	90
0.002658	203	90	90

0.004387	356	116	90
0.00154	126	239	90
0.002616	204	252	90
0.00247	208	234	90
0.003643	283	255	90
0.003565	296	236	90
0.003212	246	265	90
0.002832	220	255	90
0.003515	289	120	90
0.00374	286	93	90
0.00424	342	242	90
0.003772	305	242	90
0.0034	260	272	90
0.00305	241	290	90
0.003167	256	296	90
0.003712	286	279	90
0.003411	265	284	90
0.00335	261	285	90
0.001773	163	319	90
0.003488	268	261	90
0.002802	217	281	90
0.002986	231	283	90
0.00278	252	317	90
0.004216	326	282	90
0.003751	402	164	90
0.006116	587	146	90
0.002511	192	272	90
0.002268	183	295	90
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0.001762	149	305	90
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0.000383	43	358	90
0.000526	58	3	90
0.000656	73	360	90
0.000863	94	9	90
0.000494	53	344	90
0.000399	44	353	90

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0.001251	129	22	90
0.001272	123	327	90
0.000917	90	328	90
0.000911	95	339	90
0.001027	107	338	90
0.000876	91	338	90
0.000761	62	298	90
0.000683	55	294	90
0.000579	55	323	90
0.00085	76	314	90
0.004024	314	252	90
0.002999	237	290	90
0.000466	50	346	90
0.000636	68	344	90
0.000363	39	347	90
0.00081	87	345	90
0.000954	97	334	90
0.000695	74	343	90
0.000752	61	296	90
0.000719	60	301	90
0.00084	75	313	90
0.000895	80	315	90
0.000706	63	314	90
0.000996	91	318	90
0.001554	139	315	90
0.001599	144	316	90
0.001543	118	278	90
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0.000542	54	330	90
0.000567	44	278	90
0.000523	52	332	90
0.000893	91	334	90
0.000961	77	293	90
0.00087	67	279	90
0.009599	1034	193	90
0.01885	1467	73	90

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0.011622	955	58	90
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0.010234	865	125	90
0.013174	1209	139	90
0.014869	1614	167	90
0.00538	562	159	90
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0.003899	378	147	90
0.005615	443	109	90
0.007316	673	139	90
0.006553	634	147	90
0.014307	1092	88	90
0.023585	1944	58	90
0.008666	892	156	90
0.004335	446	156	90
0.009002	922	156	90
0.001779	177	27	90
0.003199	323	153	90
0.000593	61	335	90
0.000528	53	332	90
0.000584	59	334	90
0.000551	55	331	90
0.000588	58	331	90
0.000566	56	330	90
0.000715	73	336	90
0.000439	46	338	90
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0.000444	47	342	90
0.000546	55	331	90
0.000391	42	346	90
0.000428	46	12	90
0.000437	46	16	90
0.000381	41	15	90
0.000304	30	332	90
0.000314	31	332	90
0.000296	32	350	90

0.001648	147	314	90
0.002809	217	281	90
0.001401	154	6	90
0.004182	450	13	90
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0.001948	151	102	90
0.001437	112	104	90
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0.00231	254	351	90
0.002182	234	344	90
0.001214	119	329	90
0.001309	130	331	90
0.000717	56	75	90
0.000724	56	76	90
0.000535	42	69	90
0.000419	33	66	90
0.000427	34	69	90
0.000524	41	72	90
0.000487	39	67	90
0.000469	37	69	90
0.00042	33	70	90
0.001039	83	65	90
0.000909	71	73	90
0.00083	64	81	90
0.000544	42	88	90
0.000457	35	94	90
0.000403	31	105	90
0.000353	28	108	90
0.000278	22	106	90
0.000515	40	75	90
0.000519	40	84	90
0.000586	49	122	90
0.000945	80	126	90
0.000582	48	121	90
0.0009	77	127	90
0.001032	87	124	90
0.000917	80	130	90
0.001079	83	79	90
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0.003198	289	42	90

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0.002967	232	252	90
0.002191	173	249	90
0.002447	191	253	90
0.002069	161	254	90
0.001912	148	255	90
0.001955	153	251	90
0.00304	316	20	90
0.003177	310	30	90
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0.009346	989	341	90
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0.011395	901	68	90
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0.003044	338	357	90
0.00378	420	357	90
0.005204	415	246	90
0.002641	211	246	90
0.021926	2395	349	90
0.012023	1304	346	90
0.007838	630	294	90
0.006471	506	285	90
0.002876	318	353	90
0.023363	2558	8	90
0.007474	723	326	90
0.01107	1073	327	90
0.004937	549	359	90
0.022176	2095	323	90
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0.007778	851	9	90
0.017369	1486	51	90
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0.026866	2712	25	90
0.003617	299	301	90
0.004298	354	299	90
0.005684	609	14	90
0.012486	1301	19	90
0.013047	1241	34	90
0.018444	1564	52	90
0.017113	1675	29	90

0.016621	1820	8	90
0.019494	2099	13	90
0.01333	1380	21	90
0.007345	758	21	90
0.013357	1191	44	90
0.007748	599	257	90
0.013988	1552	355	90
0.013935	1443	337	90
0.011466	1230	14	90
0.007436	750	333	90
0.009826	1092	0	90
0.00493	530	13	90
0.004867	511	340	90
0.009861	1096	359	90
0.009805	956	30	90
0.010645	1032	327	90
0.003186	354	356	90
0.008442	938	357	90
0.007539	604	65	90
0.015932	1466	39	90
0.023238	2442	18	90
0.004849	513	17	90
0.025276	2671	17	90
0.01544	1456	35	90
0.005337	556	19	90
0.02324	2524	11	90
0.021224	1933	40	90
0.020148	2141	342	90
0.010762	1166	12	90
0.019997	1633	240	90
0.004283	343	293	90
0.003959	321	296	90
0.003922	315	114	90
0.017338	1344	102	90
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0.00397	319	294	90
0.003075	250	117	90
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0.006636	519	286	90
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0.007192	565	288	90
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0.005061	396	286	90
0.003888	302	283	90
0.002926	228	284	90
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0.007821	623	292	90
0.008289	664	113	90
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0.005827	458	107	90
0.008149	647	111	90
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0.008263	653	290	90
0.007013	554	109	90

0.006112	492	114	90
0.007333	588	114	90
0.006759	548	117	90
0.008452	689	118	90
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0.006324	494	106	90
0.025955	2022	105	90
0.019114	1496	106	90
0.01585	1299	299	90
0.010943	893	298	90
0.007572	799	341	90
0.007741	812	340	90
0.008563	892	338	90