Subsurface structural and mineralogical characterization of the Laramide South Prairie fault in the Stillwater Complex, Beartooth Mountains, Montana

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ABSTRACT

Subsurface analysis of the South Prairie fault, a Laramide basement backthrust located in the Stillwater Complex of the Beartooth Mountains, Montana, has allowed the heretofore unparalleled physical-chemical transect study of a deep subsurface Laramide fault. Fracturing exhibits a bimodal network interpreted as Riedel R and R' fractures and, along with alteration, increases toward the heavily altered and cataclasized core zone. The width of the core zone is dependent on the host rock. Mineralogy varies from unaltered norite and gabbronorite in the host rock to characteristic alteration products of clinozoisite and serpentine within the damage zone, with minor tremolite. Veins are composed of Ca-stilbite and minor late-stage carbonate with talc. The core zone contains abundant serpentinite/chlorite. Plagioclase is observed to withstand heavy stable fracturing and minor alteration to clinozoisite at grain boundaries before further alteration to clinozoisite. Orthopyroxene readily undergoes serpentinization at the same conditions. Evidence of pre-, syn-, and postkinematic fluids is abundant and consistent with the estimated South Prairie fault permeability. These observed characteristics suggest synkinematic conditions of temperature ≤300 °C and pressure <400 MPa, consistent with brittle to brittle-plastic deformation, which may have been ideal for chemical ore remobilization into the South Prairie fault via the fracture network and hydrothermal fluids.

INTRODUCTION

The South Prairie fault (SPF), a basement-involved backthrust to the Beartooth range-front thrust system, has been exposed via underground mining in the Archean ultramafic-mafic cumulate layered Stillwater Complex, offering a unique opportunity to study an in situ basement fault never exposed to surface weathering processes. As exposed in the underground mine workings, the SPF is observed to intercalate with the Pt-/Pd-rich Johns-Manville (JM) Reef, which is mined by the Stillwater Mining Company. Discernible surface outcrops are rare across the 20 km trace of the SPF (Cox and Holick, 2008), and comprehensive observation is restricted to the subsurface. Paleozoic strata displaced by the SPF at high elevations above the Stillwater River Valley (Jones et al., 1960; Page and Nokleberg, 1974; Segerstrom and Carlson, 1982; Cooper et al., 2002), along with the SPF’s geometry, kinematics, and estimated pressure-temperature (P-T) conditions, strongly suggest its most recent motion occurred during the Laramide orogeny. Therefore, the SPF has allowed analysis of a Laramide basement fault with known geometric and spatial fault zone relationships that has not undergone subsequent alteration by surficial processes.

The purpose of this study is to address the physical-chemical characteristics of the SPF and is condensed into four objectives: (1) the geometry and kinematics of the SPF, (2) the architecture and permeability of the SPF, (3) the mineralogy of the SPF and its spatial variation, and (4) the synkinematic P-T conditions and deformation mechanisms at these conditions. A comparison of Laramide deformation of mafic (layered igneous) rocks and quartzofeldspathic gneisses is also described, providing a field study for mafic fault rocks, which have received little field and experimental research (Rowe and Griffith, 2015). This study is also timely and relevant with respect to results from the San Andreas Fault Observatory at Depth (SAFOD) project (Chester, 2014; Richard et al., 2014; Warr et al., 2014; Bradbury et al., 2015), research on the Alpine fault (Boulton et al., 2012), and the Deep Fault Drilling Project (DFDP) in New Zealand (Sutherland et al., 2012; Toy et al., 2015). Interestingly, these studies have shown similar results concerning fault zone dynamics as a physical-chemical system.

In order to address these objectives, we undertook outcrop and laboratory analyses, stereographic analysis techniques, and a detailed study of a petrographic transect across the SPF at two locations. Possible chemical remobilization of ore into the fault zone by fluid/fault relationships was observed and may have implications for future mining operations. These results are also important for general comprehension of fault zone processes and could have implications for better understanding of seismogenic upper-crustal faults.

GEOLOGIC BACKGROUND

The SPF occurs in the Lower Banded Series of the ultramafic-mafic cumulate layered Stillwater Complex in the Beartooth Mountains of south-central Montana (Figs. 1 and 2). Intrusion of the complex occurred around 2701 Ma (DePaolo and Wasserburg, 1979), following a major crust-forming event (Mueller et al., 2010), into slightly metamorphosed sedimentary rocks in a tectonically quiescent (Page and Zientek, 1985) pull-apart basin (Mogk, 1988). Tectonic juxtaposition of the complex to
Figure 1. Regional map showing allochthonous blocks of the Beartooth arch and the study area at the Stillwater Mine, modified from Wise (2000).

Figure 2. Simplified geologic map of the Stillwater Complex showing major faults discussed in this study and the Stillwater Complex units, modified from McCallum (2002) with data from Geraghty (2013). Figure excludes the inferred Stillwater River Valley fault. Figure 3 cross-section line is shown by A-A’. Red line denotes approximate trace of the Pt/Pd ore-bearing JM Reef.
the main Beartooth massif took place by 2500 Ma (Mogk and Geissman, 1984; Geissman and Mogk, 1986), as suggested by intrusion of the Mout Quartz Monzonite into the Stillwater and Beartooth blocks.

Tectonic activity and/or regional metamorphism after Archean assembly has been described, with regional greenschist metamorphism having occurred around 1700 Ma (Page, 1977; Page and Zientek, 1985). The most recent and evident tectonic activity was during the Cretaceous–Tertiary Laramide orogeny, which arched the Beartooth Range via opposing faults, the Beartooth thrust and the Gardiner thrust to the northeast and southwest, respectively. Locally, Laramide deformation was responsible for the near-vertical and locally overturned nature of the stratiform Stillwater Complex rocks (Page, 1977; Page and Zientek, 1985; Wise, 2000; McCallum, 2002). This stratiform layering is likely responsible for the formation of the SPF, as its orientation is coincident with a less-competent olivine layer within the Lower Banded Series. Laramide motion for the SPF is evidenced by displaced Paleozoic strata at high elevations above the Stillwater River Valley and by Paleozoic strata that are in fault contact with the SPF on the east side of the Stillwater Canyon (Fig. 2; Jones et al., 1960; Page and Nokleberg, 1974; Segerstrom and Carlson, 1982; Cooper et al., 2002). Neogene to recent crustal extension has dropped the western edge of the arch in the Paradise Valley west of the range (Fig. 1), though this has not affected the study area.

**METHODS**

**Outcrop and Fracture Analyses**

Five exposures were analyzed and sampled at three different levels in the Stillwater Mine (Fig. 3). Mine locations are described as a twodigit abbreviation for elevation in feet above sea level, followed by distance west of the mine’s initial marker, in feet (e.g.: 48w8400). Mines in the United States traditionally use English units, and mine data are not recorded in metric units. However, all other measurements used for this study are in metric units. A fault zone description was taken at each location; wet and dry descriptions were taken where a water source was available. For the purpose of this publication, fault rocks are described according to the classification of Woodcock and Mort (2008).

Width measurements were taken perpendicular to strike and categorized by fault architecture into the severely comminuted core zone (CZ), composed chiefly of clay-rich gouge, and the fractured and brecciated damage zone (DZ), which exhibited abundant veining. These units are in accordance with Caine et al.’s (1996) designations, except that we use the term “host rock” instead of protolith for unfractured rock surrounding the SPF. Damage zones were described as the hanging-wall damage zone (HW-DZ) and footwall damage zone (FW-DZ). Exposed fault zone thicknesses were measured at nonideal locations due to limited exposures in adits. These limited exposures made it difficult to determine the exact extent of the DZ, and, therefore, estimated permeability could not be averaged for the three locations visited.

Fracture measurements were taken using the selection and inventory method (Van der Pluijm and Marshak, 2004). A 1 m² grid was used for the inventory method. Limited exposure and time constraints for underground work based on mining schedules made it difficult to conduct a comprehensive analysis of fracture patterns, thus limiting the amount of data collected.

**Geometric and Kinematic Analyses**

**South Prairie Fault and Fracture Data**

Fracture and fault orientation data were plotted on equal-area, lower-hemisphere stereonets and rose diagrams using Rockware Stereostat. These data were then Kamb-contoured to deduce any dominant fracture patterns in the SPF architecture.

**Regional Geometric Analysis**

Trends of structures along the Beartooth front near Nye were measured on the Montana Bureau of Mines and Geology Red Lodge 1:100,000 geologic map (Lopez, 2001). These data were then plotted on rose diagrams to test the consistency of the SPF’s geometry with respect to other known Laramide structures. Resultant vectors from these Rose diagrams were then plotted on a stereonet (Fig. 4), similar to Brown’s (1993) model. Dip values on the resultant stereonet are given as 90° on structures to show the general strike of the feature being considered; thrust faults are shown with a 30° dip solely for the purpose of visual reference.

**Balanced Cross Section**

A cross section (Fig. 3) was constructed using data from U.S. Geological Survey (USGS; Page and Nokleberg, 1974; Segerstrom and Carlson, 1982) and Montana Bureau of Mines and Geology (Lopez, 2001; Geraghty, 2013) maps and reports, as well as subsurface and surface data collected during this study. Drill data from Geraghty (2013) were also utilized. Consistent bed thicknesses were used during construction, and an assumption was made via rake measurements that out-of-plane motion was minimal enough for the cross section to be line-length balanced (Fig. 3; Marshak and Mitra, 1988).

**Sampling**

Sampling of vein-filled fractures, HW-DZs, FW-DZs, CZs, and unaltered host rock was dependent upon each location’s exposure quality. Three of the five exposures (26w8000A, 26w8000B, and 29w10200) were along strike and only offered exposure of less than half of the entire fault zone. Exposure 26w8000B did offer a partial cross-sectional view and was sampled from HW-DZ to FW-DZ. Two locations at the 48w8400 access offered cross-sectional views, though only one was transect-sampled and analyzed due to subsequent shotcreting of the first access. This location allowed comprehensive sampling from undamaged footwall host rock to the HW-DZ.

**X-Ray Diffraction**

Eleven samples were processed by X-ray diffraction (XRD) at Montana State University’s Imaging and Chemical Analysis Laboratory (ICAL). Three samples were from the core provided by Stillwater Mining Company, four gouge samples were from the shotcreted 48w8400 location, and another four CZ gouge samples were from the sampling transect at 48w8400. Random and oriented mounts were made following USGS Open File-Report 01–041 (Poppe et al., 2002). Random mounts were scanned in increments of 2° per minute from 3° to 73°. Oriented mounts were scanned at 2° per minute from 2° to 22°. Samples were analyzed with the program DMSNT.

**Petrographic Analysis**

Twenty-five thin sections from the sampling transects at 26w8000B and 48w8400 were used for petrographic analysis to study how deformation and mineralogy changed across the fault zone. Orientation data were marked for kinematic interpretations. Where orientation markings proved unsuccessful (incohesive gouge), nonoriented samples were made perpendicular to foliation, though the general absence of slickensides within the gouge made it impossible to determine if the cut was parallel to the displacement vector of the SPF.
Figure 3. (Top) Balanced cross section of the Beartooth front near Nye, Montana. A complex system of splay faulting partitioned the total heave of the Beartoth massif. Stillwater Mine locations visited in this study are indicated. Stillwater Mine Complex layering is concordant with the SPF in the cross-section area. JM Reef is coincident with SPF; SWC—Stillwater Mine Complex rocks (undifferentiated for simplicity); Pzu—Mississippian Madison Formation through Permian Amsden Formation; Pzl—Triassic Chugwater Formation through Jurassic Morrison Formation; K—Cretaceous Kootenai Formation through Cretaceous Telegraph Creek Formation; LK—Cretaceous Sliderock Mountain member of Livingston Group; Q—Quaternary landslide deposits. (Bottom) Line-length restoration shows an accurate and restorable geometry of the cross section prior to Laramide deformation. H/V—Horizontal/Vertical.
Whole thin-section images were taken using a Nikon photonegative scanner in plane-polarized and cross-polarized light. Photomicrographs were taken at mineral alteration zones and within fractures. Anorthite concentrations were estimated using the Michel Levy lamellae twinning extinction angle method; a minimum of six grains were examined per slide.

RESULTS

Structural Analysis

Geometry and Kinematics

Measurements collected in this study give an average orientation of 286, 63N for the SPF. This strike is consistent with other major Laramide structures along the Beartooth front (Figs. 3 and 4), and it compares well with Brown’s (1993) model for Laramide structures. Abundant slickenlines were measured at the 26w8000A location, showing an average rake of R = 78°W (n = 17), thus documenting that the SPF is dominantly dip-slip, with a slight component of dextral slip.

Drill data from Geraghty (2013) show a duplex fault zone beneath the Horseman thrust (Fig. 3). Intricate series of faults make up the Beartooth front near Nye, in which the SPF is a minor part of the frontal system, concordant with layering in the Stillwater Complex. This concordant geometric relationship has made estimates of slip on the SPF difficult, though estimates from duplexed JM Reef strata suggest ≥750 m (Cox and Holick, 2008).

Architecture

At the floor of 26w8000, the CZ was coincident with a single vein, 6 cm wide, that abruptly ended as the CZ widened to 1 m. CZ material consisted of dark-green clay-rich gouge that was breakable into granules at the outcrop (Woodcock and Mort, 2008). Abundant anastomosing fractures were observed within the CZ (Fig. 5A). The FW-DZ/CZ and CZ/HW-DZ contacts were sharp, and no through-going fractures penetrated into either zone from the other. There was no presence of the JM Reef within the SPF at 26w8000.

Only a fraction of the 26w8000 HW-DZ was visible, thus precluding accurate width measurements. Where visible, the HW-DZ showed a visibly altered appearance, and fracture sets were noted (Fig. 5A). Likewise, drilling of the access parallel with the SPF strike allowed limited observation of the FW-DZ immediately proximal to the CZ. The FW-DZ here was observed to be competent relative to the comminuted CZ and also exhibited a visibly altered appearance. Extensive wire mesh on the ceiling restricted observation, but a FW-DZ of <3 m was estimated given the competent, nonbrecciated nature of host rock on the south side of the access.

The 48w8400 FW-DZ and HW-DZ (Fig. 5B) displayed a similar appearance and was almost entirely visible due to a cross-sectional cut. The FW-DZ was ~2.36 m wide and was competent with minimal fracturing. A single fracture at the south end of the FW was interpreted to be the start of the FW-DZ. Similar to 26w8000, there were sharp contacts at the FW-DZ/CZ and CZ/HW-DZ.

Figure 4. Schmidt stereonet plot of resultant vectors of major structures at the Beartooth front as measured from Lopez (2001); compare with Brown (1993). Dips of features are given as 90°, except for a 30° dip on thrust faults for the purpose of visual reference. An approximate regional Laramide shortening direction is shown here as 050, though it likely ranged between 040 and 065.

Figure 5. (A) 26w8000B location, rock hammer for scale. Orange flags show sampling locations used for petrographic analysis. Note vein at footwall damage zone (FW-DZ)/core zone (CZ) contact beneath hammer and anastomosing fractures within core zone. Competent nature of footwall compared to hanging wall is also visible, along with systematic footwall fractures and “bleached” appearance of hanging wall. (Continued on following page.)
The HW-DZ was heavily brecciated and extended to ≥2.63 m from the CZ/HW-DZ contact. The end of the access obscured a measurement of the complete extent of the HW-DZ. HW-DZ rock exhibited a visibly altered and “bleached” appearance when compared to the FW-DZ (Fig. 5B) and was extensively brecciated. According to Woodcock and Mort (2008), the 48w8400 HW-DZ exhibited a crackle breccia.

At 48w8400, the CZ was 2.51 m wide and composed of dark-green fine-grained incohesive gouge that was easily broken into granules by hand. A lens of leucocratic troctolite, probably from the JM Reef, was observed within the CZ. A 4-cm-wide vein was noted at the FW-DZ/CZ contact and was in contact with a dark zone of foliated gouge, 4 cm wide, at the HW-DZ contact within the CZ. Similarly, a 1.5-cm-wide zone of foliated gouge was observed within the CZ at the FW-DZ/CZ contact, but it was not as abrupt at the mesoscopic scale.

Fractures

Systematic fractures occur in the 26w8000 hanging wall and footwall and dip south in both zones. Footwall fractures dip 32–56°S with a spacing of 6–10 cm, but were up to 20 cm apart. CZ fractures are anastomosing, dipping similar to the main fault zone. A single sighted-dip measurement in the hanging wall was 44°S.

In the 48w8400 footwall, fractures were nonsystematic (Fig. 5B). Hanging-wall fractures were dominantly systematic, with two sets dipping ~60°N and 60°S. The south-dipping set had 14–16 cm spacing and an average strike of 085° (n = 4). Fractures dipping 60°N had an approximate spacing of 15 cm and displaced south-dipping fractures up to 3 cm, suggesting these fractures are younger. The extent of the north-dipping fracture set occurred up to 53 cm from the CZ/HW-DZ contact and did not persist further than this.

Fractures are shown plotted on lower-hemisphere, equal-area stereonets in Figure 6. Kamb contouring of the plots reveals three populations of fractures, two of which are consistent with the strike of the SPF (Fig. 6). One set dips northerly, while the second set dips southerly. The third population appears anomalous with the strike and dip of the SPF. Fractures were then plotted by fault architecture. FW-DZ fractures are shown to be more erratic, though one population is shown consistent with the strike and dip of the SPF. HW-DZ fractures are relatively bimodal, showing the north- and south-dipping fractures clearly. CZ fractures are dominantly consistent with the strike and dip of the SPF.

South Prairie Fault Mineralogy

The following results are a synthesis of petrographic and XRD analyses. Abbreviations for orthopyroxene and clinopyroxene follow mineral abbreviations in Whitney and Evans (2010).

Host Rock

Rocks 60 m stratigraphically below the JM Reef typically consist of gabbronorite, norite, and minor anorthosite and troctolite, while the JM Reef and units 35 m stratigraphically above contain anorthosite and troctolite (Geraghty, 2013). A sample of gabbronorite host rock from 26w8000 was taken at the southern end of the access across from the footwall exposure, giving a modal composition of 50% plagioclase, 38% orthopyroxene (Opx), and 12% clinopyroxene (Cpx). Plagioclase compositions were estimated at An 68–88. Oikocrystic anorthosite was observed in the 48w8400 hanging wall, a common hanging-wall feature stratigraphically above the JM Reef. Only altered hanging wall was able to be sampled. Relic host rock minerals were interpreted, giving a modal percentage of 63% plagioclase, 33% Opx, and 4% Cpx.

Damage Zone

It was observed through petrographic analysis that characteristic alteration products formed by replacement of the igneous host-rock mineralogy. Alteration increased toward the heavily comminuted and altered CZ. Grains within the DZ failed by unstable (transgranular) and stable (intragranular) fracturing (Fig. 7E; Mitra, 1984; Miller, 1987; Smith, 1991). Furthest from the CZ, stable fractures were observed within different mineral grains. Unstable fractures were typically only present in grains of the same phase, showing their similar rheological behavior. Given these observations, the following results are presented by individual phase.

Plagioclase. Plagioclase was the second most resilient phase to alteration. Fracturing was observed up to 2.5 m from the CZ in the 48w8400 FW-DZ, though alteration did not readily occur until more pervasive fracturing nearer the CZ. Fracturing occurred as both stable and unstable...
Figure 6. Stereonet and Kamb contoured plots of fractures and veins measured at all five locations. Bold red great circle represents average SPF strike and dip. (A) All fractures and veins. (B) Footwall damage zone (FW-DZ) fractures. Anomalous concentration at left of Kamb plot represents 29w10200 fractures that are likely the result of blasting. (C) Core zone (CZ) fractures, note strong concentration of data in line with SPF strike and dip. (D) Hanging-wall damage zone (HW-DZ) fractures, showing a bimodal geometry that is interpreted to represent Riedel R and R’ fractures. CI—contour interval.
Figure 7. Photomicrographs of SPF mineralogy. All photos shown with cross-polarized light. (A) Clinzoitization of plagioclase from footwall damage zone (FW-DZ) sample 26w80008-5. Note preferred alteration near grain boundaries. (B) Serpentinitization of orthopyroxene (Opx) from hanging-wall damage zone (HW-DZ) sample 48w8400-16HW. Note plagioclase at left of grain that remains mostly free from alteration, though heavily fractured. (C) Talc-tremolite-chlorite-serpentine assemblage from hydrothermal, possibly metasomatic, fluid flow. Undulose extinct quartz (Qtz) also visible. Trem—tremolite. (D) Vein-fill material from FW-DZ sample 48w8400-5. Euhedral nature indicates postkinematic formation. Later-stage carbonate and talc fill interstices. (E) Stable fractures within plagioclase grains and unstable fractures between plagioclase and orthopyroxene from 48w8400 HW. (F) Sigma structure porphyroclast of vein-fill material within sample 48w8400–7 at the FW-DZ/core zone (CZ) contact. Relic zeolite, carbonate, and talc are visible within porphyroclast. This is suggestive of recurring fluid flow at zeolite conditions, possibly interseismically, with eventual entrainment of vein-fill material into the SPF core zone.
fractures (Figs. 7A and 7E). Footwall samples consisted dominantly of stable fractures, though monophase unstable fractures between grains were observed. No unstable fractures were observed between plagioclase and Opx/Cpx 1.55 m into the fault zone (≈0.8 m south of the CZ) at 48w8400. Polyphase unstable fractures were observed in the more brecciated 48w8400 HW-DZ (Fig. 7E).

Alteration of plagioclase was to the Ca-/Al-epidote variety clinozoisite and occurred initially at the grain boundaries (Fig. 7A). More advanced alteration exhibited patchy internal alteration and occurred as anhedral granules. In addition, 48w8400 hanging-wall samples appeared more intensely altered to clinozoisite than footwall samples. Anorthite concentrations were observed to decrease toward the CZ, though this relationship was irregular and not uniform amongst all grains. No grains of albite were observed petrographically, although XRD analysis suggested its presence. The alteration of plagioclase to clinozoisite in extensively fractured grains suggests its formation was strictly tectonic, and it did not appear to result from postkinematic (i.e., postfaulting) fluid flow.

Orthopyroxene (Opx). Opx altered most readily, though more complexly, showing extensive alteration in the FW-DZ as far as 1.5 m south from the CZ. Alteration appeared to be by pseudomorphic replacement to serpentine (Fig. 7B). Talc was also present within some Opx grains within twins, as well as tremolite at the grain boundaries. This relationship was not consistent for all Opx grains, however. Irregular fracturing of Opx was noted in all grains. This trend is commonly observed in Opx of the Lower Banded Series in the Stillwater Complex.

Clinopyroxene (Cpx). Cpx was the most resistant phase, often remaining mostly free from alteration, while plagioclase was heavily fractured and altered to clinozoisite, and Opx was fully serpentinized. Direct observation of Cpx alteration could not be made given its minor modal percentage and this resistance to alteration. No extensive shear fractures deviating from cleavage planes were observed.

Alteration material. Various minerals occurred within alteration zones in the SPF and were not directly observed within distinct grains as described above. At 26w8000, quartz was observed and exhibited undulose extinction. These alteration zones at 26w8000 also included small grains of talc, tremolite, and serpentine-chlorite (Fig. 7C). Minor amounts of tremolite were also observed in the 48w8400 HW-DZ.

Veins

Zeolites were the most prevalent vein-fill material within the CZ and DZ and occurred as euhedral grains with slight undulose extinction. Ca-stilbite is the likely variety of zeolite within SPF veins, as detected by XRD and determined petrographically by a tabular nature and one plane of cleavage (Fig. 7D).

Carbonate appears to have formed during late-stage vein mineralization, typically filling interstices between zeolites that lined fracture walls (Fig. 7D). Talc also was found, appearing to have formed later than carbonate by filling the interstices of carbonate.

Core Zone

The most comminuted and altered areas of the CZ occurred at the FW-DZ/CZ and CZ/HW-DZ contacts. Gouge at the contacts was foliated and exhibited a strong mesoscopic preferred orientation. Internally, CZ gouge was incohesive and pervasively altered. Mineral phases within the CZ were extensively serpentinized/chloritized. Microscopically, CZ gouge appeared to have deformed from cataclasis (Sibson, 1977). XRD of Stillwater Mine core and CZ gouge samples identified clinocoherence-chlorite, serpentine, and mixed-layer serpentine-chlorite as the major phases.

XRD analysis of samples collected along a transect of the 48w8400 CZ (Figs. 5B and 7) suggests the highest alteration occurred at the FW-DZ/CZ contact (Fig. 8A), where gouge consists of only serpentine-chlorite. Samples toward the center of the CZ still contain zeolite, plagioclase, and clininozoisite, determined both by petrographic and XRD analysis (Figs. 8B and 8C). Serpentine-chlorite was also the dominant phase at the CZ/HW-DZ contact, but minor amounts of zeolite and tremolite were also detected (Figs. 8D and 9B).

 Sigma structure porphyroclasts were abundant within foliated gouge at the FW-DZ/CZ contact, with 93.4% of all porphyroclasts between samples 48w8400–7a and –7b identifiable as relic vein-fill material (zeolite >> carbonate > talc; Figs. 7F and 9A). These clasts varied in size and texture.

Deformation Mechanisms

Microscopically, fracturing and cataclasis, cataclastic flow, and pressure solution/dissolution were observed within DZ material. Cataclasism, cataclastic flow, and pressure solution were all observed within the CZ of the SPF. Unlike the DZ, the CZ consisted of anastomosing serpentine-chlorite, which encompassed pervasively altered relic grains within the central CZ. Some of the most comminuted samples of gouge at the CZ boundaries exhibited cataclastic flow at the microscopic scale with evident Riedel fabrics, resulting in a fine-grained foliated gouge (Figs. 9A and 9B). At the CZ/HW-DZ contact, an interpreted S-C fabric was cut by brittle fractures (Fig. 9B), suggesting both brittle and brittle-plastic conditions during the motion history of the SPF.

As mentioned, stable and unstable fractures were observed. Polyphase unstable fracturing was only observed in the HW-DZ closest to the CZ. Some grains showed stable fracturing and microfaulting, dying out into a ductile matrix.

DISCUSSION

Geometry and Kinematics of the South Prairie Fault

Laramide contractile structures correlate with an approximately NE-SW regional shortening direction (Blackstone, 1986; Brown, 1993; Bird, 1998; Neely and Erslev, 2009), resulting in numerous NW-SE–trending Laramide structures across southern Montana and northern Wyoming. As shown in Figure 4, the SPF correlates well with this regional shortening direction. In addition, contractile and extensional structures at and near the Beartooth front also correlate with these published estimates of Laramide shortening in the direction 040–065 (Fig. 4).

Given the well-documented contractile model of Brown (1993) and others, it is postulated that the Beartooth frontal thrust from Red Lodge to Livingston had a slight sinistral oblique slip dip to its minimal deviation from normal to the regional shortening direction (Fig. 4). En echelon structures of the Nye-Bowler lineament (Wilson, 1936; Foose et al., 1961) also suggest this sinistral component of deformation near the Beartooth front. South of Red Lodge, the Beartooth front has a NNE-SSW trend and has been interpreted to have dextral oblique slip (O’Connell, 1996). Cross sections constructed north (Fig. 5) and south (Neely and Erslev, 2009) of Red Lodge show decreasing amounts of dip separation, while cross sections at Red Lodge (Lopez, 2001; Wise, 2000) show the greatest amount of dip separation with ≥5 km of heave (O’Connell, 1996). These observations are interpreted to be consistent with sinistral oblique slip on the northern Beartooth frontal system.

Sinistral motion for the Beartooth front is counterintuitive for the slight component of dextral motion on the SPF. This may be explained by the SPF’s north-dipping, rather than south-dipping geometry. Backthrusting of the SPF during the Laramide orogeny may have resulted from contraction of the fault block between the Horseman thrust to the northeast and
Figure 8. X-ray diffraction spectra of 48w8400 CZ transect. Locations of samples are shown in Figure 5B. Footwall- and hanging-wall (HW) damage zone (DZ) contacts (A and D, respectively) show higher-grade conditions by nearly complete absence of damage zone phases such as zeolite, clinozoisite, and host-rock material and a dominance of serpentine/chlorite. Minor tremolite in the HW-DZ is suggestive of the hydrothermal conditions observed at 26w8000. The interior of the core zone (CZ; B and C) shows less alteration and deformation by presence of DZ and host-rock material. These observations suggest hotter conditions and localized slip at the CZ/DZ contacts and a more passive tumbling (see Fig. 12, inset B) of gouge zone material within the CZ. Opx—orthopyroxene, Cpx—clinopyroxene.
Bluebird and Lake thrusts to the southwest, causing the SPF block to “pop up” and be extruded to the east from slight transpression in a direction consistent with the local tectonic transport of the Beartooth arch, but slipping obliquely in an opposite sense to the Beartooth front (Fig. 10). This relationship can be visualized by considering that south-dipping thrusts with sinistral oblique slip would display rake measurements from the west as well, pushing the block toward the east and giving the Horsemen thrust a sinistral motion and the SPF a dextral motion (Fig. 10). However, more kinematic evidence is required to evaluate this kinematic model.

Balanced Cross Section

Intricate series of faults are observed along the Beartooth front near Nye, in which the SPF is a minor part of the frontal system (Fig. 3). Cross-section balancing supports the interpretation of the SPF as a back-thrust. This range-front geometric relationship is also consistent with work by Erslev (1993) and fits into Geraghty’s triangle zone geometry at the Beartooth front (Geraghty, 2013). Drill data (Geraghty, 2013) also suggest a complex duplex fault zone beneath the Horseman thrust that substantially partitioned heave on the Beartooth front.

Approximately 7 km of overlying Phanerozoic rocks have been cited for the Beartooth region (Neely and Erslev, 2009, and references therein), with a minimum overburden of ≈4 km likely during the latest stages of uplift (Fig. 3) as a result of protracted unroofing of the Phanerozoic sedimentary cover during deformation. Assuming a geothermal gradient of 30 °C/km (Beaudoin et al., 2011), this yields \(T \approx 250\) °C during maximum burial of the SPF at the start of the Laramide orogeny and \(T \geq 120\) °C during later stages of movement.

South Prairie Fault Architecture and Fractures

Architecture

Observations at 26w8000 and 48w8400 suggest slip localization within the CZ, as evidenced by comminution and alteration of the incohesive CZ gouge. Furthermore, slip localization at 48w8400 appears to have occurred at the FW-DZ/CZ and CZ/HW-DZ contacts, apparent by the 4-cm-wide and 1.5-cm-wide dark foliated gouge bounding the CZ. These principal slip zones are herein termed the footwall-localized shear zone and hanging-wall-localized shear zone (FW- and HW-LS in Fig. 5B). These characteristics are similar to observations by Sutherland et al. (2012) and Toy et al. (2015) on the Alpine fault, which they also interpreted to represent higher strain accommodation. Microscopic observation shows more comminution at the FW-LS. These results are suggestive of significant mechanical differences at the CZ/DZ contacts, consistent with observations by Chester and Logan (1986).

Mechanically, it appears that the presence of the JM Reef dictated the width of the CZ. At 48w8400, the CZ hosts the JM Reef and is 2.51 m wide, whereas the CZ at 26w8000 is only 0.3–1 m wide and does not contain a section of the olivine-rich JM Reef. Rather, the SPF here is hosted in harder gabbronorites. This suggests a propensity for the CZ to be wider in areas where the SPF is hosted within olivine-rich units, and it attests to the formation of the SPF due to a competency contrast within the Lower Banded Series.

Fractures

Three populations of fractures are observed in the Kamb contoured plots, two of which are consistent with the strike of the SPF (Fig. 6). The bimodal nature of these two populations is interpreted to represent Riedel R (north-dipping) and R′ (south-dipping) fractures (Scholz, 1990), and these were best observed in the 48w8400 hanging wall (Fig. 5B). The third population of fractures was recorded at 29w10200, where nonsystematic fractures were sourced from a single fracture. These splays were conspicuously oriented perpendicular to 29w10200, suggesting these formed during blasting of the access and are therefore not considered in the following discussion.

Analyzing the data by fault architecture shows distinct patterns, namely in the CZ (Figs. 6B, 6C, and 6D). All fractures exhibit the interpreted geometry of R and R′ fractures. FW-DZ (Fig. 6B) and HW-DZ (Fig. 6D) fractures are bimodal, while fractures measured in the 26w8000 and 48w8400 CZ (Fig. 6C) are dominantly subparallel to the SPF. This is interpreted to represent the anastomosing behavior of the CZ fractures, which may have acted to partition slip during movement. Similar textural

Figure 9. Whole thin-section scans of footwall- and hanging-wall-localized shear zones. (A) S-C fabrics and sigma structure porphyroclasts of relic vein-fill material within a matrix of serpentine/chlorite from sample 48w8400–7 at footwall-localized shear zone. Note heavy comminution. Cross-polarized light. Field of view is ~36 mm across. (B) Hanging-wall-localized shear zone of 48w8400 showing later-stage brittle fractures crosscutting earlier brittle-plastic S-C fabrics (bottom-left corner). Note lesser comminution of material than at footwall-localized shear zone. Plane polarized light, some color correction applied. Field of view is 45 mm across.
observations have been made in the actively creeping section of the San Andreas fault’s serpentine-rich gouge (Bradbury et al., 2015).

**South Prairie Fault Mineralogy**

**Damage Zone**

Observations from the SPF suggest that damage zones behave as intermediate zones of alteration and consequently record the partial physical-chemical alteration history of the fault. Progressive deformation in the form of fracturing behaved differently in various mineral phases, as expected, and alteration products appeared consistent with the chemical composition of each mineral species. It appears a system of progressive alteration aided in deformation closer toward the CZ, as minerals were observed to have both higher alteration and deformation closer to the CZ.

Quartzofeldspathic basement rocks in other Laramide fault studies have been shown to concomitantly exhibit brittle and plastic deformation at the grain scale (Miller, 1987). This relationship was also observed in the heterogeneous mafic mineralogy of this study. Some grains showed fractures dissipating into cataclasized material. This may be explained by grain-boundary alteration phases altering to more ductile material, as shown with feldspar deformation (Janecke and Evans, 1988).

Evidence of fluid-flow alteration was observed in the 48w8400 hanging wall by the presence of fully serpenitized Opx grains. The 26w8000 hanging wall and footwall displayed hydrothermal fluid-flow characteristics by the mineral assemblage tremolite-chlorite-serpentine-talc (Fig. 7C; Polovina et al., 2004; Boschi et al., 2006; Winter, 2010). This characteristic assemblage was most pervasive at 26w8000. It was observed that phases in the DZ consistently altered to specific alteration phases at both levels, and these are discussed individually in order of prevalence.

**Plagioclase.** Clinopyroxene, the Ca-/Al-rich variety of epidote, was the characteristic alteration product of plagioclase, and occurred initially at the grain boundaries. The formation of epidote is expected, because it commonly occurs from the hydration of tectonically fractured plagioclase (Miller, 1987; Miller and Lageson, 1993). Miller (1987) found epidote to be the most common alteration phase associated with Laramide deformation of plagioclases (An<sub>50</sub>) in quartzofeldspathic rocks from the Bridger and Gallatin Ranges in southwest Montana. Conditions in his study were T ≥ 200°C, similar to this study.

Anorthite concentration was observed to decrease toward the CZ. The term albitionization is herein used to describe decreasing An content to more sodic compositions. We interpret the coincident albitionization of plagioclase in relation to increased clinzoitization to be directly related to the release and remobilization of Ca<sup>2+</sup> and Al<sup>3+</sup> from plagioclase to clinzoisite. Clinzoisite formation from labradorite by albitionization can be shown by the reaction:

\[
5(Ca_{0.60}Na_{0.40}Al_{1.60}Si_{2.40}O_{8}) + Ca^{2+} + H_2O \\
= 2Ca_2AlSi_3O_9(OH)_2 + 2NaAlSi_3O_9
\]

as modified from Moody et al. (1985), showing a starting composition of labradorite and assuming a constant Al concentration and a positive or negative influx of Ca/Si as needed. Similar reactions for the albitionization of labradorite to clinzoisite have been shown through experimental methods by Moody et al. (1985). Though discernible crystals of albite were absent, its presence from XRD could suggest that albite precipitated within the fine-grained groundmass of alteration material.

This alteration material in deformed plagioclases is consistent with studies by both Moody et al. (1985) and Miller (1987, 1993). Based on Miller’s results, we postulate that sodic plagioclases are expected to form Ca-/Al-deficient epidote varieties, as observed in his study, since there is not an excess of Ca<sup>2+</sup> and Al<sup>3+</sup> as seen in the calcic plagioclases of our study. This observation shows a clear physical-chemical relationship between fault zone processes and the formation of particular fault zone material, whereby host-rock composition dictates the alteration products formed (disregarding influence from external fluids).

**Orthopyroxene (Opt).** Irregular fracturing of Opx may have been the source for much of the synkinematic fracturing and the likely cause for prevalent fluid-assisted alteration. Alteration appeared to be by pseudomorphic replacement to serpentine (Fig. 7B) from liberation of SiO<sub>2</sub> and hydration of Opx, shown by the reaction:

\[
3Mg_2Si_2O_6 + 4H_2O = 2Mg_2Si_2O_5(OH)_4 + 2SiO_2.
\]

This reaction assumes a starting composition of enstatite per McCallum (2002). Release of SiO<sub>2</sub> was observed in the form of quartz with undulose extinction (Fig. 7C). The presence of quartz in these mafic rocks suggests its formation as an alteration product prior to the latest stages of deformation. Talc was also present in some Opx grains within twins, as well as tremolite at grain boundaries. This relationship was not consistent in all Opx grains and may represent a partial reaction prior to serpentinization.

**Clinopixene (Cpx).** Alteration of Cpx was likely to serpentine, though its low modal percentage did not allow substantial observation. Alteration may have progressed along cleavage plane fractures. Interestingly,
the observed resistance of Cpx within the SPF is also observed in Stillwater Mine core, as augite-rich units often preclude visible alteration amidst surrounding units that have succumbed to substantial visible alteration.

Veins

Zeolites were the most prevalent vein-fill material within the CZ and DZ. Evidence of repeated interseismic mineralization was observed by broken clasts of vein material within CZ gouge porphyroclasts (Figs. 7F and 9A). These clasts varied in size and texture, perhaps suggesting a protracted fluid-flow history within the SPF due to their varying degrees of comminution.

Lower-grade subhedral-euhedral mineral assemblages compared to higher-grade assemblages in the CZ suggest that vein-filling minerals precipitated at ambient (nonkinematic) fault zone conditions (discussed in the following section). Some euhedral zeolite grains exhibited slight undulose extinction, indicating that not much strain accumulation or recovery had taken place since their formation, and may suggest that mineralization was interseismic and/or postdated the latest stages of SPF deformation.

Core Zone

Mineral phases within the CZ were extensively serpentinized/chloritized. Given the general lack of mobility of Al$^{3+}$, this material may have formed from the continual release of Al$^{3+}$ from plagioclase, giving way from clinzoitization to chloritization, though no evidence of this was observed directly. The presence of pervasively altered DZ phases within the CZ suggests its formation through further comminution of DZ material. The presence of tremolite in CZ alteration material is suggestive of pervasive fluid flow in the hanging wall and likely formed from hydrothermal conditions (discussed in the following section).

Incorporation of vein material into gouge suggests it was proximal and easily brecciated into the CZ’s plane of localized slip, and this is perhaps suggestive of a fluid-flow/fault-slip relationship. Veins were observed in contact with the CZ at 26w8000 and 48w8400 (Figs. 5A and 5B), further suggesting this relationship. Identification of porphyroclasts containing vein-fill material (Figs. 7F and 9A) attests to a protracted fluid-flow history within the SPF.

Role of Fluids within the South Prairie Fault

DZ rock had a distinctly bleached appearance compared to host rock at 26w8000 and 48w8400, with the 48w8400 HW-DZ having the most defined bleaching. This appearance may be in part from alteration and fluid flow and is suggestive of buoyant fluid permeation consistent with hanging-wall hydraulic brecciation as proposed by Phillips (1972). According to Phillips (1972), a pressure gradient may be established between hydrothermal fluids in the fault and pore water in the adjacent damage zone (or host rock in noncrystalline rocks), causing lower-density hydrothermal fluids to rise and permeate into the hanging wall. The presence of hydrothermal fluids is supported by observation of the 26w8000 DZ, which shows the assemblage tremolite-chlorite-serpentinite-talc (Winter, 2010), and could be indicative of metasomatism (Boschi et al., 2006). Likewise, the 48w8400 HW-DZ, unlike the FW-DZ, shows extensive serpentinization of pyroxenes, a process that requires 50% water/pyroxene concentrations (Eq. 18 in Frost and Beard, 2007). These results suggest that fluids played a considerable role in alteration of the fault zone, possibly synkinematically (at the time of faulting). Furthermore, the presence of talc within alteration material and Opx could be suggestive of the role of fluids in alteration and deformation, as talc has been shown to require hydrothermal fluids for formation (Anderson et al., 1990).

Additionally, evidence suggests recurrent flow within the SPF at and near the CZ/DZ contacts. The 26w8000 vein (Fig. 5A) appears to be the result of two stages of growth, possibly representing crack-seal processes. The 26w8000 and 48w8400 veins occur at the contact between the FW-DZ and the FW-LS. As mentioned, the location of these veins may be suggestive of a fluid-flow/fault slip relationship, perhaps through stick-slip by fluid overpressure (Scholz, 1990, 1992; Snoke et al., 1998). Interseismic vein mineralization may have been taking place, possibly cyclically, similar to that proposed by Toy et al. (2015), as suggested by the presence of broken-up low-temperature vein-fill material within the high-temperature FW-LS. Though it is likely that these mechanisms occurred within the SPF, consequential evidence of stick-slip was never identified (pseudotachylite, etc.; Rowe and Griffith, 2015).

Permeability Estimate

It was initially assumed that fluids were present within the SPF, and therefore an estimate of permeability was conducted using the method of Caine et al. (1996). This method assumes disparate hydrologic properties for the CZ (barrier) and DZ (conduit) and is shown by the simple relationship:

\[
F_p = \frac{DZ}{fault \ zone \ width}, \tag{3}
\]

\[
= \frac{DZ}{(CZ + DZ)}, \tag{4}
\]

\[
F_m = \text{mean of } F_p \text{ values}, \tag{5}
\]

where \(F_p\) is the fault zone architectural index and is essentially a percentage of permeability between 0 (barrier) and 1 (conduit). The mean of \(F_p\) values is then calculated, giving \(F_m\). Given the constraints of observation in this study, only 48w8400 could be measured from footwall to hanging wall, and \(F_m\) was not calculated. An estimated permeability of \(F_p = 0.67\) was calculated and plotted as a combined conduit-barrier system according to Caine et al. (1996), further suggesting the role of fluids within the SPF. How the SPF relates to other faults is shown in Figure 11.

P-T Conditions

Multiple lines of evidence suggest two disparate conditions during the motion history on the SPF, interpreted here to represent synkinematic
Conclusions

Subsurface analysis of the SPF has allowed a unique comprehensive look at the physical-chemical characteristics of a basement-hosted fault zone with known spatial relationships. Fault zone processes and fluid flow have been interpreted from the geometric, kinematic, and mineralogical observations presented herein and show that the SPF was likely a Laramide backthrust to the Beartooth range-front system. Faulting was localized along the relatively less-competent olivine-rich JM Reef and produced footwall and hanging-wall damage zones with a central CZ. Damage zones exhibited bimodal Riedel R and R′ fractures, while the CZ exhibited dip-parallel fractures that suggest partitioned slip. At 48w8400, two principal slip zones were identified within the CZ by more advanced comminution and higher-grade mineralogy. These were termed the hanging-wall-localized shear zone and footwall-localized shear zone.

Evidence for fluids was observed in petrographic, XRD, and outcrop analyses. Fluids likely permeated through the CZ fracture networks and ranged from hydrothermal (possibly metasomatic) synkinematic fluids to ambient postkinematic or interseismic fluids. A possible metasomatic mineral assemblage of tremolite-chlorite-serpentinite-talc (Boschi et al., 2006) was pervasive in the 26w8000 HW-DZ (Fig. 7C) and minor at the 48w8400 CZ/HW-DZ contact, suggesting hydrothermal fluids at the time of faulting.

Ambient conditions were likely T ≥150 °C, as evidenced by zeolite veins. The presence of clinzoisite suggests synkinematic conditions of T ≥200 °C, while serpentine-chlorite, the metasomatic assemblage, and undulose extinction quartz suggest a synkinematic upper limit of lower-greenschist conditions at T ≤300 °C. These faulting conditions were
Figure 12. Schematic diagram of possible nonkinematic and synkinematic fault zone processes within the SPF based on the 26w8000 and 48w8400 locations. (Top) Postkinematic/interseismic or ambient: Fluids (blue arrows) permeate through the subsurface via the SPF fracture network and breccia, precipitating low-temperature zeolite veins (Fig. 7D). Conspicuous fractures within the core zone (CZ) allow fluids to migrate locally. Inset A shows the footwall damage zone (FW-DZ)/CZ vein at 48w8400 and the pronounced footwall-localized shear zone (FW-LS). Inset B shows a photomicrograph (from sample 48w8400–13) of the internal CZ where the damage zone (DZ) phases are still apparent (noticeably plagioclase here), though heavily fractured and altered. Low-temperature zeolite veins cut the high-temperature alteration phases present. This attests to slip localization at the FW-LS and hanging-wall-localized shear zone and suggests that the internal CZ gouge behaved more passively during faulting, perhaps by “tumbling” (Rudy Wenk, 2012, personal commun.). (Bottom) Synkinematic: Heat produced from faulting causes buoyant hydrothermal fluids (orange arrows) within the SPF CZ and DZ to permeate into the hanging wall (HW), causing extensive alteration and aiding in brecciation. The FW-DZ here is shown to have a slight alteration zone associated with faulting and fluids, as observed at 26w8000. Inset C shows ripped-up clasts of vein material, likely from the FW-DZ/CZ vein, given its close proximity. These porphyroclasts of low-temperature vein-fill within higher-temperature CZ material show two distinct phases of mineral growth at low-temperature (zeolite) and high-temperature (serpentine-chlorite) conditions. It is postulated that low-temperature conditions occurred interseismically and persisted for some time during the latest stages of motion on the SPF, as evidenced by their inclusion into CZ material as well as by euhedral veins elsewhere in the SPF.
possibly favorable for remobilization of Pt/Pd. Sulfides may have formed Pt/bisulfide compounds that dissolved and remobilized into the SPF near T ≈ 300 °C (Lechler et al., 1988; Hsu et al., 1991; Barnes and Liu, 2012).

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