Microfracture Orientation in the Douglas Fault Damage Zone: Implications for Past Seismicity and Earthquake Rupture Directivity

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Driven to Discover

Background

The Douglas Fault is located in the US, spans Wisconsin and Minnesota, and is connected to a wider system of faults (Cannon, 1994). The origin for this system began with the Midcontinent rifting events associated with the Laurentian supercontinent, about ~1.1 Ga. During this time, the Chengwatana Volcanics were deposited, and subsequently faulted in a horst and graben system with one of the faults in this system being the Douglas Fault (Cannon, 1994; Manson and Halls, 1993). During this time of extension, the sandstones of the Bayfield Group were deposited over the underlying volcanics (Thwaites, 1912). The Bayfield sandstone is characterized as having highly rounded and dominantly quartz grains and distinct cements (Hogdin et al., 2024). Subsequently, this extensional regime was compressed and is now a reverse fault due to the nature of the Grenville Orogeny (1090 - 980 Ma) (Hodgin et al., 2024; Bjornerud, 2010) occurring thereafter. The Douglas fault has two general trending arms: one striking East and one striking Northeast (Figure 1). Bjornerud (2010) found evidence of seismic activity in the form of pseudotachylyte (Figure 2) along a nearby fault, the Atkins-Lake Marenisco Fault, which is much fault system that has been exhumed from much deeper than the Douglas Fault..

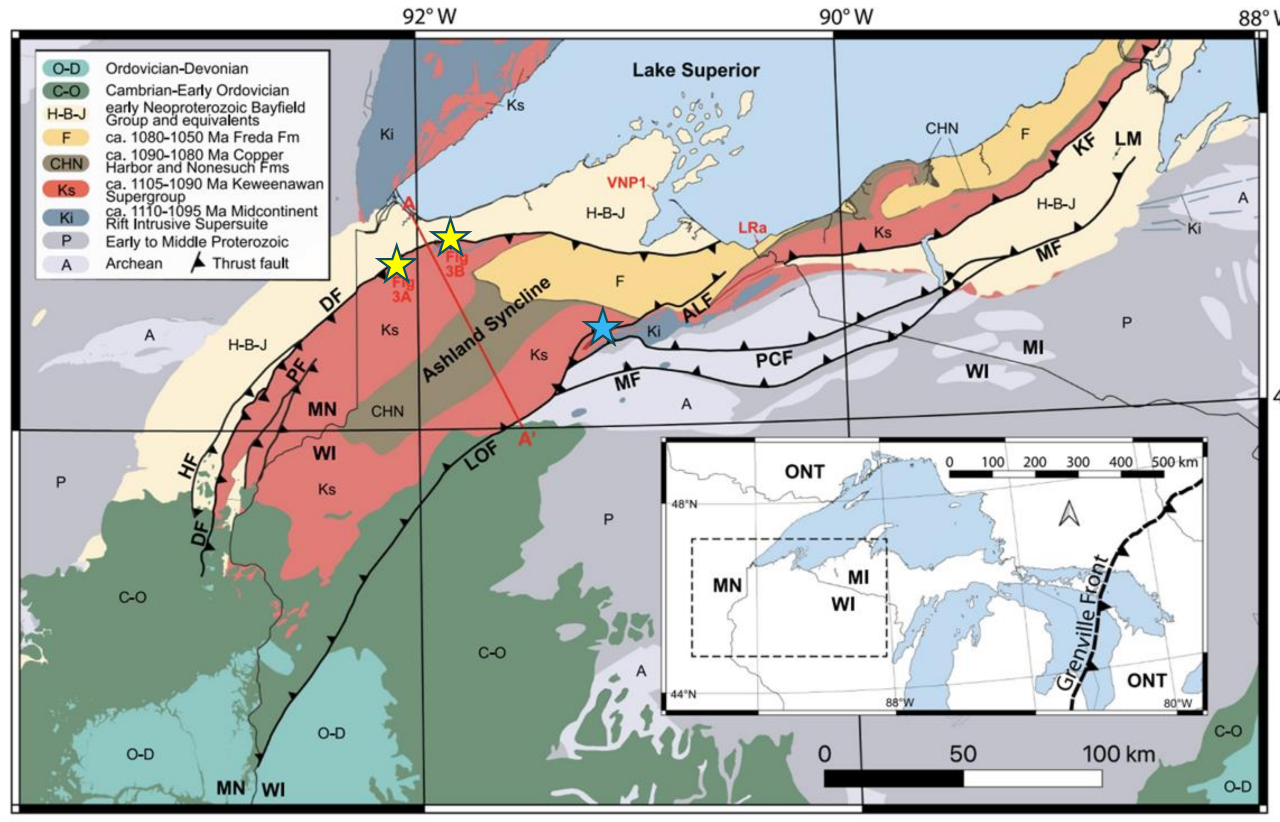

Figure 1. Geologic map displaying the Douglas Fault (DF) and the Atkins-Lake Marenisco Fault (ALF); blue star notating where pseudotachylyte was identified by Bjornerud (2010), yellow stars notating the locations of the two sample collection sites of this study (Amnicon Falls and Pattison Park); Figure modified from Hodgin et al. (2024)

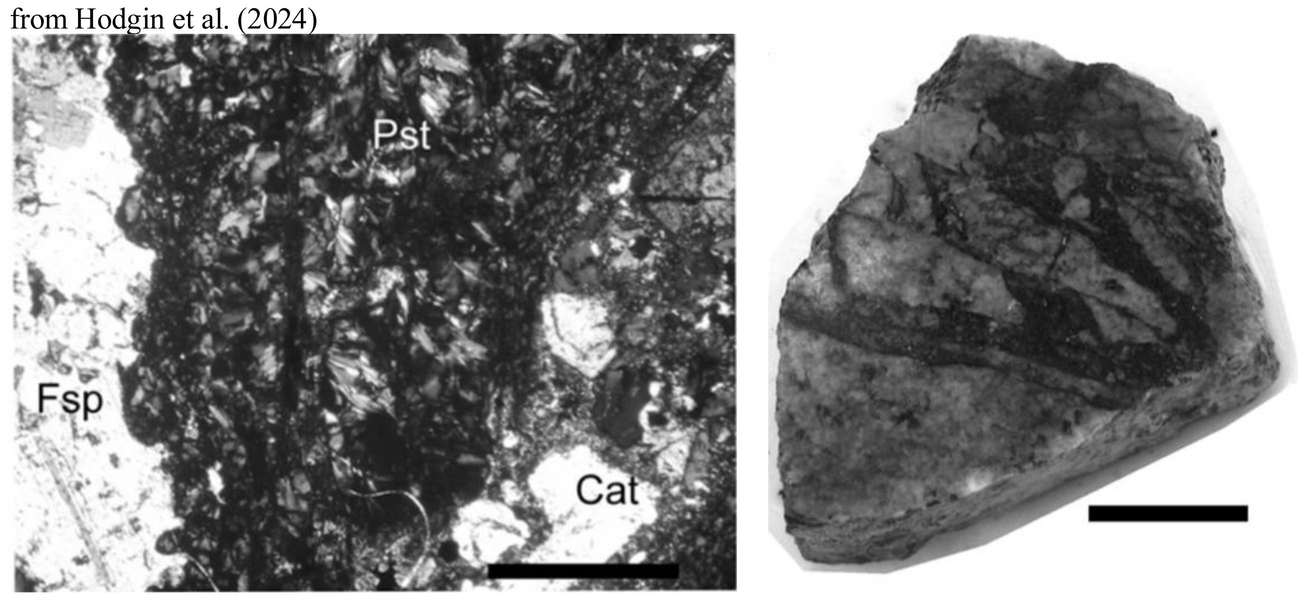

Figure 2. (left) Thin section in cross polarized light of pseudotachylyte (Pst) in contact with Feldspar (Fsp) and Cataclasite (Cat), scale bar is 0.5 mm; (right) hand specimen of pseudotachylyte in Puritan quartz monzonite, scale bar is 2 cm; Bjornerud (2010)

Problem Statement

Due to the presence of pseudotachylyte on a similarly located and oriented fault, we have reason to suspect that the Douglas Fault also has experienced seismic events during its past. For that reason, this study aims to:

1. Identify microstructural density and compare to damage textures of rocks in known seismogenic fault zones (Weigandt 2023; Rowe & Griffith 2015)
2. Determine overall microfracture orientations to evaluate preferred rupture orientations

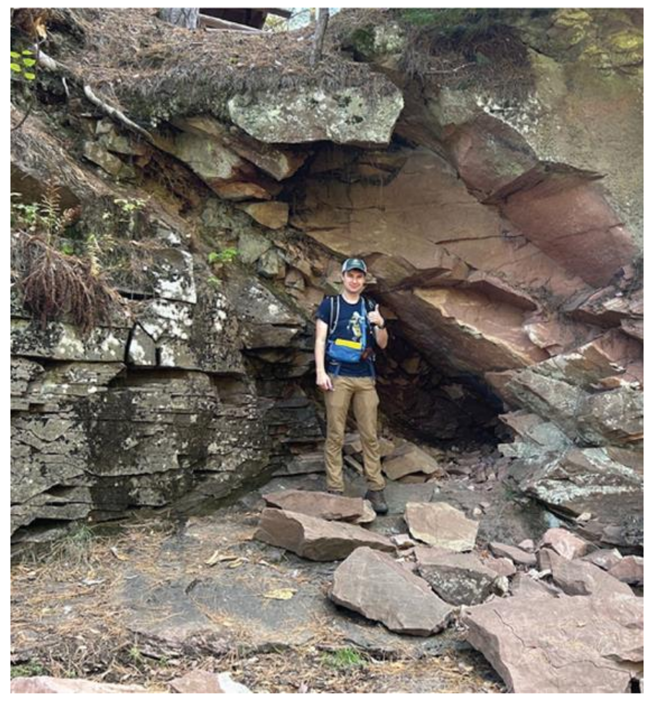

Figure 3. Field photo of the CV placed on the BS by the Douglas Fault at Amnicon Falls behind N. Daniels

Observations

Figure 4. (left) Field photo showing the Bayfield Sandstone, located in the footwall, mildly deformed with multiple joint sets marked by the yellow books. (right) Thin section of the Bayfield Sandstone (AFBS - 1P) with deformation bands either displaying compressional deformation. Field of view is 4.5 cm by 2.5 cm.

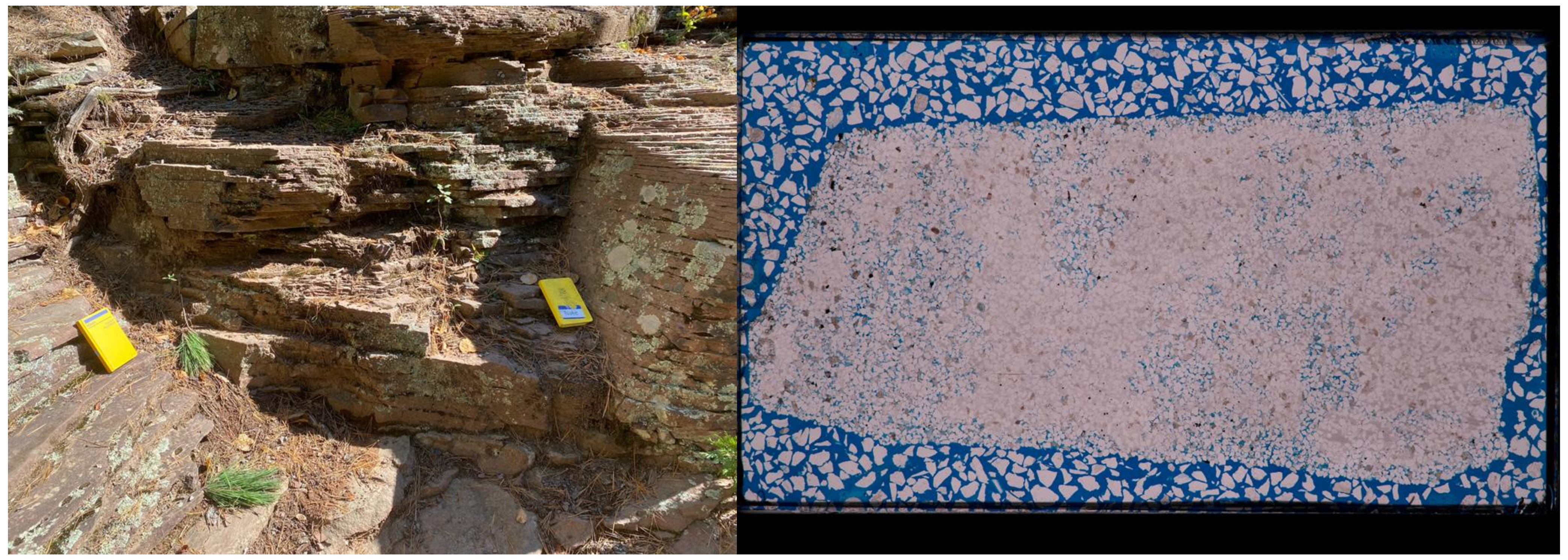

Figure 5. (left) Field photo showing the Chengwatana Volcanics , located in the hanging wall, deformed and displaying columnar jointing. (right) Thin section of the Chengwatana Volcanics (PPCV - 1P) with veins of calcite and microfractures. Field of view is 4.5 cm by 2.5 cm.

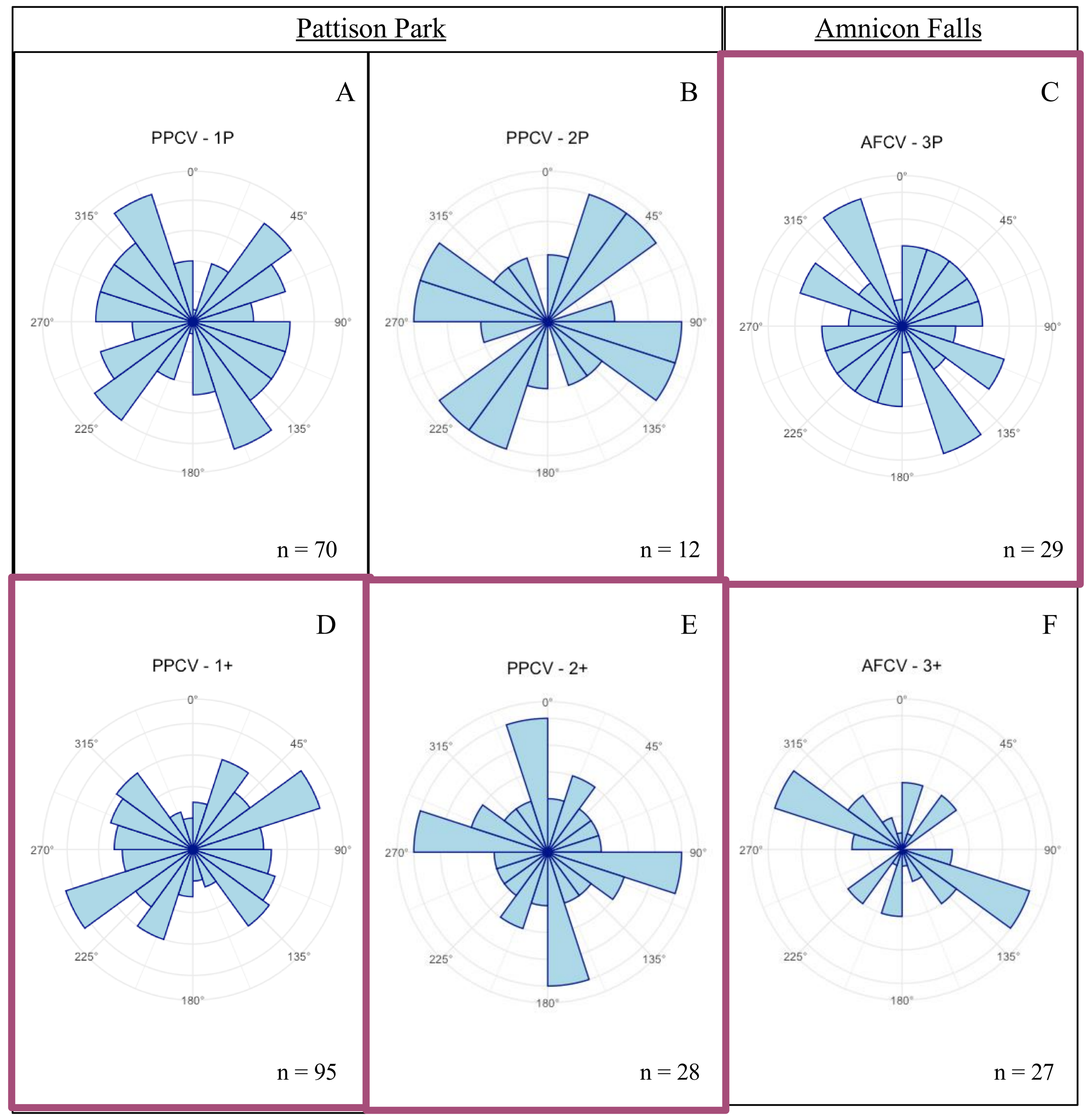

Figure 6. Rose diagram depicting microfracture orientation in the Chengwatana Volcanics (CV) from multiple samples. Samples beginning with PP are from Pattison, samples beginning with AF are from Amnicon Falls. Samples with a P at the end are parallel to the fault plane, samples ending with + are perpendicular to the fault plane. Number of fractures = n.

Hand samples were collected from two parks, Amnicon Falls, WI and Pattison Park, WI at varying distances from the fault. These were cut into thin sections to be optically analyzed. After viewing in thin section, it was determined that the Bayfield Sandstone (BS) was not deformed enough to make hertzian microfractures to be interpreted, similar to observations of Weigandt et al. (2023) in the seismogenic transpressive San Jacinto Fault in southern California. For the remainder of the study, the sandstone won't be utilized for analysis.

From the Chengwatana Volcanics (CV) thin sections, microfracture and vein orientations were mapped and orientations were collected in order to make rose diagrams (Figure 6), coded using R. These diagrams were to be compared to our expected orientations in order to determine earthquake rupture activity and directivity (Figure 7). To interpret these diagrams, they need to be visualized within a 3D environment, with the 90° - 270° line parallel to the strike of the fault, and the 0° - 180° line parallel to the dip direction of the fault.

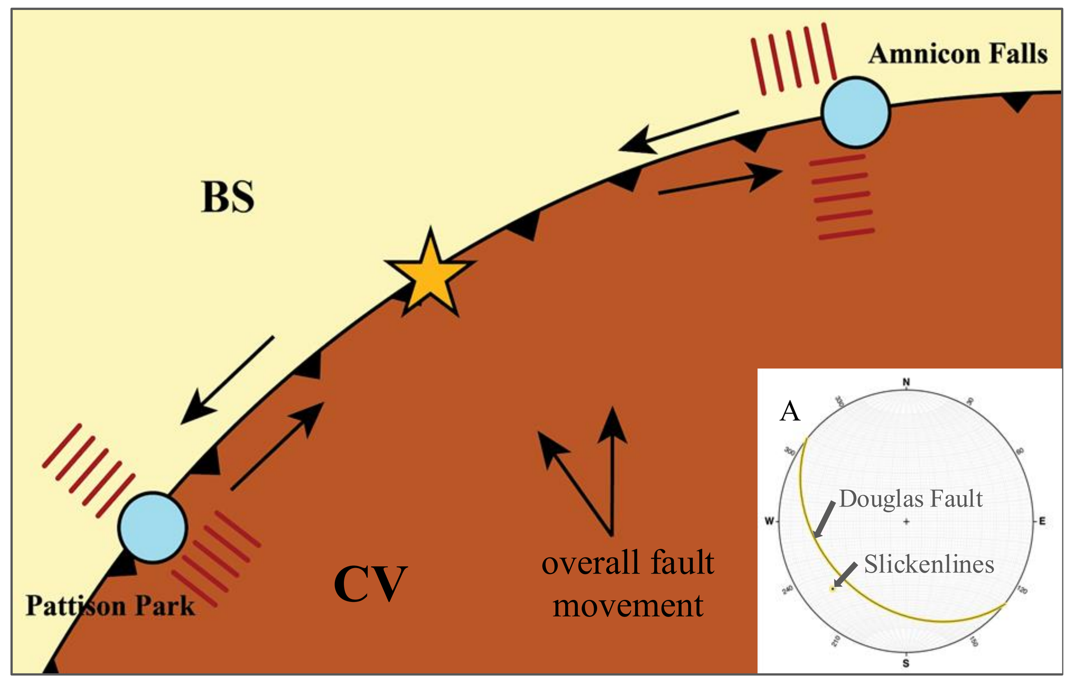

Figure 7. Image depicting expected microfracture orientation (dark red lines) based on the orientation and geometry of the Douglas Fault. Earthquakes are expected to rupture at the star, because of the stress concentrations at the "bend" of the fault, and move outward along the fault, causing deformation fractures at the margins of the fault. Arrows indicate the fault's general north - northwestern oblique movement. Arrows on the fault point at the hanging wall (the CV). 7A. (bottom right) Stereonet showing the orientation of the Douglas Fault in comparison to the slickenline orientation identified on the fault surface in the field.

Discussion

Based our hypothesized orientation of the microfractures (Figure 7), special attention is paid to the samples boldly outlined in Figure 6 (C, D, and E). At Pattison Park, the hanging wall's overall movement is up and to the northeast, which should create an extensional regime within the Chengwatana Volcanics (CV). Because of this, these rocks should form tensile fractures at a high angle to the fault plane (Figure 6D & 6E).

Conversely, Amnicon Falls CV is in a compressional regime due to the resulting strain gradient. This movement would create compressional fractures that should parallel the fault plane (Figure 6C).

On the rose diagrams,

- Compressional microfractures occur at orientations of ~ 0° and 180° on the parallel face and ~90° and 270° on the perpendicular face.
- Tension microfractures occur at orientations of ~0° and 180° on the perpendicular face and ~90° and 270° on the parallel face.

Comparing expectations to collected data, the microfractures generally match the orientations mentioned above. One key difference between expected and observed is exemplified in the Pattison Park samples with a second strong orientation of microfractures. PPCV - 1P should have an overall fracture density from 90° to 270°, but instead we see two main orientations that are more oriented 0° to 180°. This data suggests two things: the Douglas Fault is a reactivated fault, aligning with observations from Hodgin et al. (2024) and the fault has transpressional movement (both convergent and strike-slip) as opposed to the overall convergent movement or the locally strike-slip movement surrounding the area of the parks.

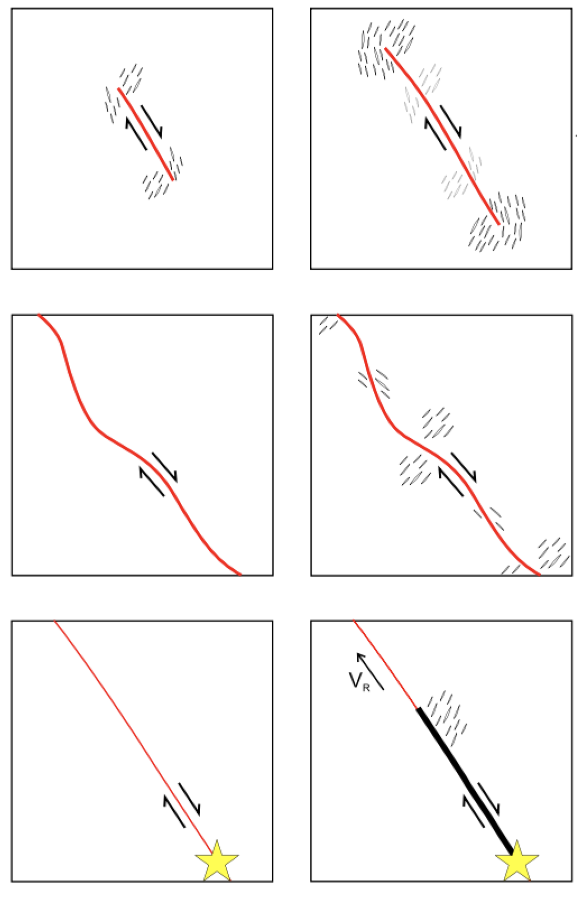

Figure 8. Diagram illustrating fault damage zone formation and seismic activity, maximum compressive stress in the vertical direction; Mitchell and Faulkner (2009)

Conclusions and Further Work

- Approximate orientation of expected deformation fractures were found to match expectations while also being indicative of oblique fault movement
- Microfracture orientations are indicative of seismic activity along the fault
- Further work in the Bayfield Sandstone should focus on undeformed samples, collected a greater distance from the fault surface than in the present study.
- The BS is remarkably undeformed compared to the CV (Wiegandt et al., 2023) in similar lithologies, results suggest that the BS was no deeper than 130 m below the surface during deformation (consistent with Hodgin et al., 2024)

Sources: Bjørnerud, M. G. (2010) *Journal of Geology*; Cannon, W. F. (1994) *Geology*; Hodgin, E. B. et al. (2024) *Tectonics;* Manson, M. L., & Halls, H. C. (1994) *Canadian Journal of Earth Sciences;* Mitchell, T. M., & Faulkner, D. R. (2009) *Journal of Structural Geology;* Rowe, C. D., & Griffith, W. A. (2015) *Journal of Structural Geology;* Shipton, Z. K., & Cowie, P. A. (2003) *Journal of Structural Geology;* Thwaites, F. (1913) *The Journal of Geology;* Weigandt, C. K., Griffith, W. A., & Rockwell, T. K. (2023) *Journal of Structural Geology.*

Acknowledgements: This work was supported by funding from the University of Minnesota Duluth Undergraduate Research Opportunities Program and completed within their framework. Thank you to my advisor, Dr. Braunagel, and my fellow researchers, R. Vogel, N. Daniels, and H. Gerfen for your help and guidance.