Architecture of the Douglas Fault damage zone, northwest Wisconsin

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Background

Fault damage zones are tabular regions of fractured and deformed rock that develop adjacent to fault cores during displacement. These zones have elevated fracture density, brecciation, and alteration of the host rock.

Previous studies suggest fault damage zone width scales with fault diaplacement (Savage & Brodsky, 2011; Faulkner et al., 2011).

Fault damage zones critically influence fault permeability structure, affect fluid-rock interaction, and modulate seismic wave propagation.

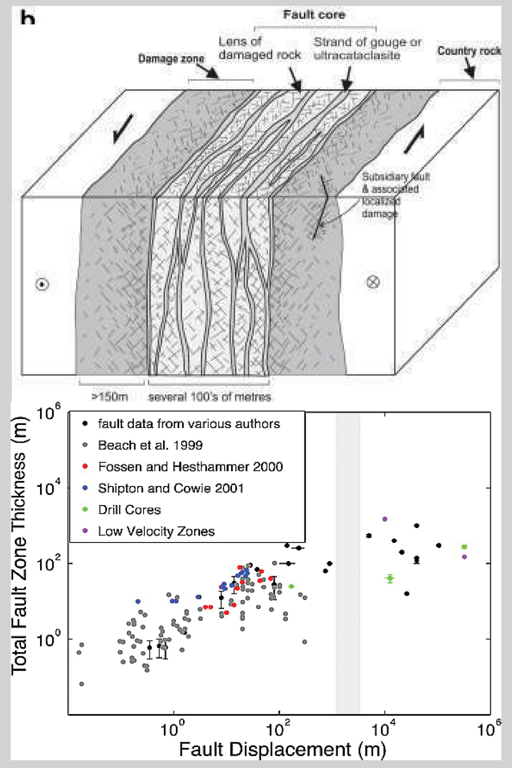


Figure 1. Top: Illustration of a fault damage zone (from Mitchell & Faulkner, 2009). Bottom: Direct relationship between fault displacement and total fault zone thickness (from Savage & Brodsky, 2011).

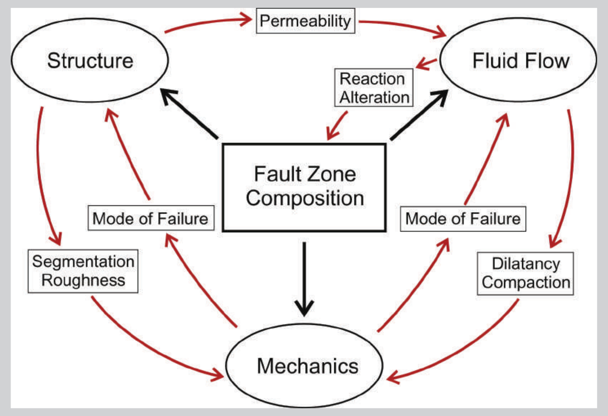


Figure 2. Flow diagram showing interrelationships among fault structure (including the damage zone), seismicity and mechanics and fluid flow (from Faulkner et al., 2008).

Quantifying their mechanical and hydraulic properties is essential for realistic models of fault zone evolution, earthquake rupture dynamics, and subsurface resource management.

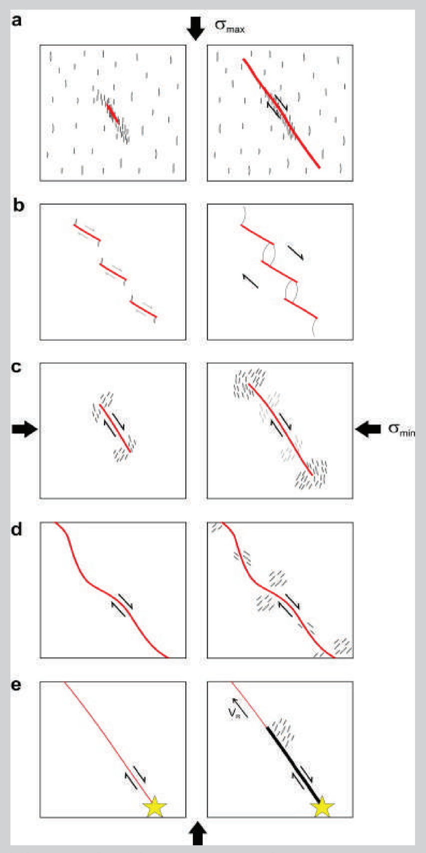


Figure 3. Processes that create off-fault inelastic damage within fault damage zones (from Mitchell and Faulkner, 2009).

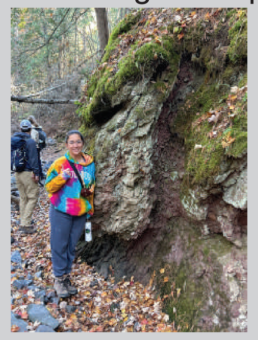
Problem Statement

Fault damage zones form through a combination of dynamic rupture propagation, stress concentration, and off-fault deformation during fault slip. The geometry and asymmetry of damage zones thus reflect fault maturity, lithology, and slip history.

Research Goals

Characterize the extent and geometry of the damage zone adjacent to the Douglas Fault of northwestern Wisconsin.

- How do fracture orientation, density, and connectivity vary across the damage zone?
- Are there multiple generations of fractures and what are their relative age relationships?
- How has the damage zone evolved through multiple tectonic phases?



Field Observations & Measurements

The Douglas Fault is a prominent mid-continental rift bounding structure extending from Ashland, Wisconsin, to near the Twin Cities, Minnesota. Field observations and geophysical studies indicate reverse-sense displacement of approximately 11,000 feet, which places older basaltic rocks of the Chengwatana Volcanics over younger sedimentary units of the Bayfield Group (Grant, 1901; Chandler et al., 1989; Cannon, 1994; Hodgin et al., 2024).

The fault and surrounding damage zone are well exposed at Amnicon and Pattison State Parks in northwest Wisconsin, which were the sites selected for this study.

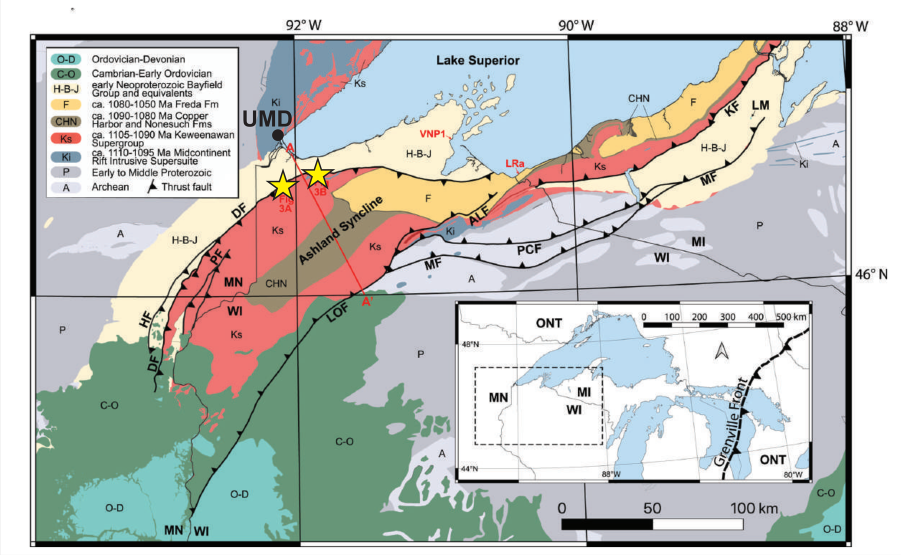


Figure 4. Regional geologic map of the southwestern Lake Superior region (from Hodgin et al., 2024). Our two study sites are shown by yellow stars.

Figure 5. South-dipping subsidiary thrust fault within the Bayfield Sandstone, exposed at Amnicon Falls State Park.

Field Data collection included:

- Mapping and orientation of the fault plane, splay faults, veins, and kinematic indicators,
- Fracture counts along scanlines perpendicular to the main fault plane,
- Bedding orientation in the folded Bayfield Sandstone,
- Oriented samples for thin section and ultrasonic pulse velocity measurements,
- Photographs for fracture connectivity analysis.

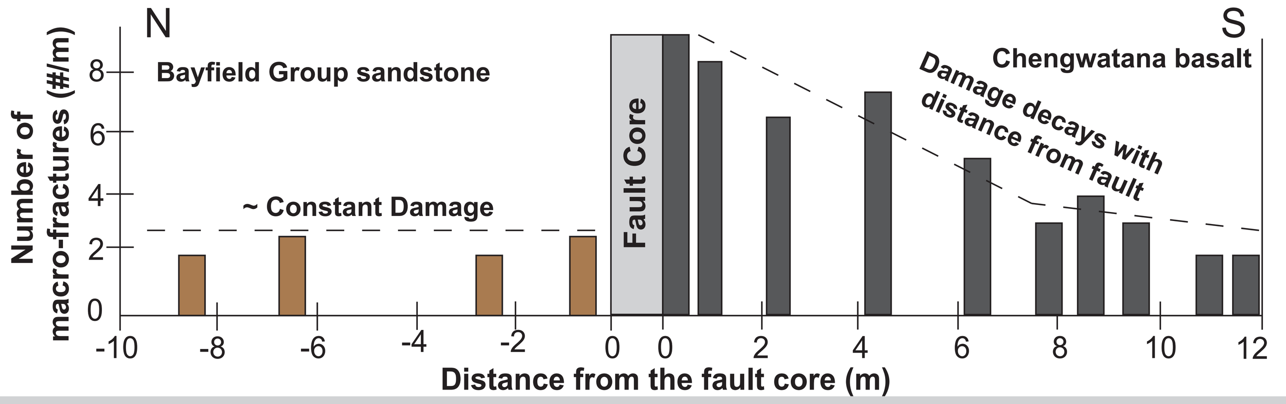


Figure 6. Damage intensity measured as number of macro-fractures normalized by scan line length in Bayfield Sandstone and Chengwatana volcanics with distance from the fault core. Stereonet shows macrofracture and vein orientations in the Chengwatana volcanics.

Figure 7. Representative sample and field photographs of the Bayfield Sandstone (left), fault core (center), and Chengwatana Volcanics (right). In hand sample, the Bayfield Sandstone displays little to no macroscopic damage while the Chengwatana basalt contains multiple generations of cross-cutting calcite veins. The fault core contains a 5 - 6 cm thick clay-rich gouge and slickenlines oriented at 24 →228.

Key Findings

Hanging Wall Chengwatana Volcanics -

- Greater fracture density at the outcrop and micro-scale.
- Multiple mode I and mode II cross-cutting calcite veins.
- Grain size reduction in thin section.

Footwall Bayfield Group strata -

- Systematic, regularly spaced joint sets
- Deformation bands exhibiting porosity loss.
- No evidence for grain size reduction at the thin section scale.
- Fault propagation folding

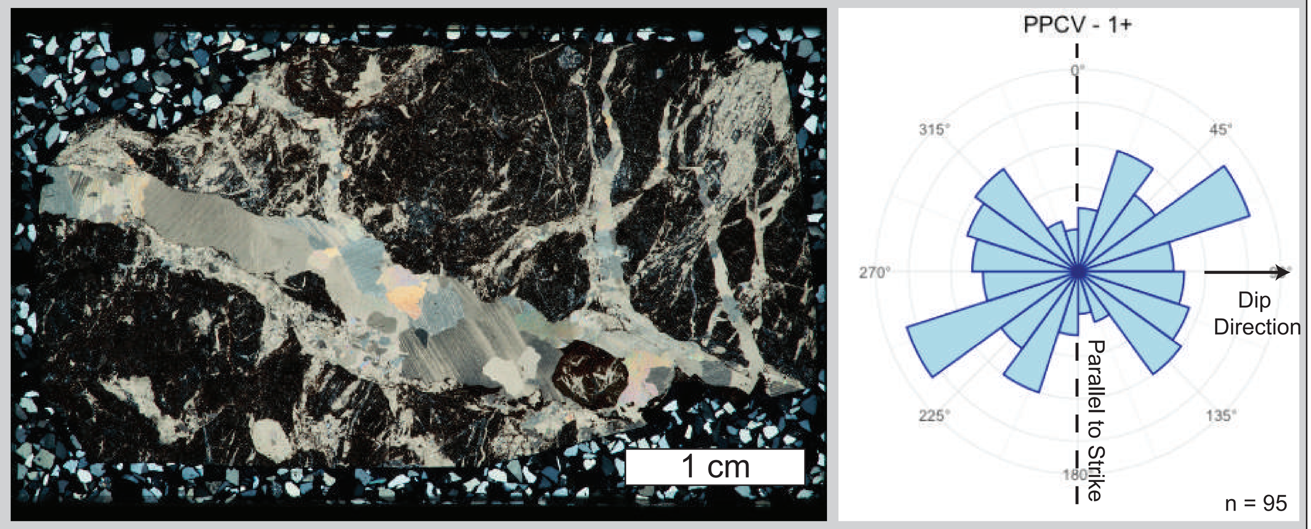
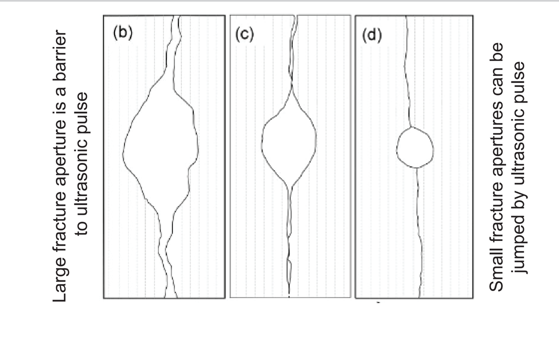


Figure 8. Representative cross section of the Chengwatana Volcanics in cross-polarized light (left). Thin sections were used to measure micro-fracture density and orientations using Adobe Illustrator and FracPaq (Healy et al., 2017). These data were then plotted as a polar histogram shown on the right. n = # Fractures.

Lab Analysis

An **ultrasonic pulse velocity** (UPV) meter measures damage in rock or concrete by detecting changes in the velocity of high-frequency sound waves traveling through the material. In intact, dense, and well-consolidated rocks, UPV is high because sound waves travel efficiently. In damaged, fractured, or weathered zones, UPV drops due to:

- Increased path tortuosity.
- Energy loss at crack tips.
- Scattering and mode conversion.



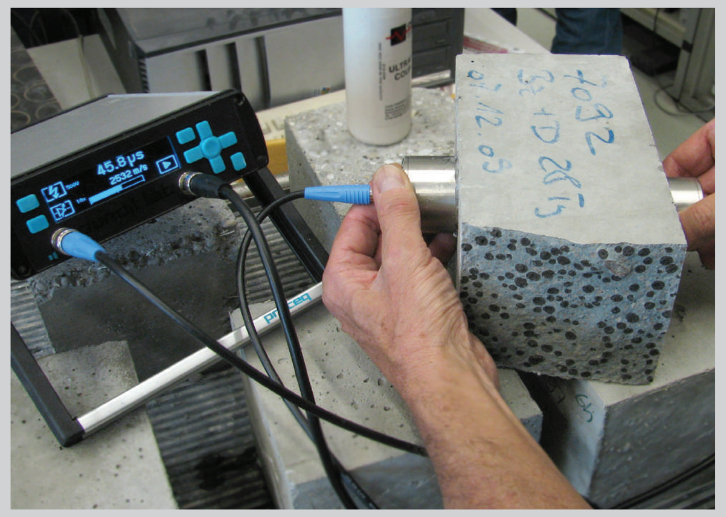
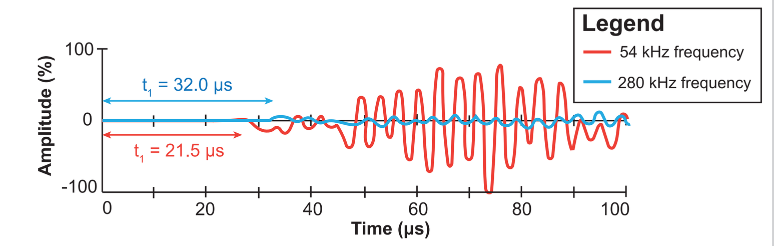
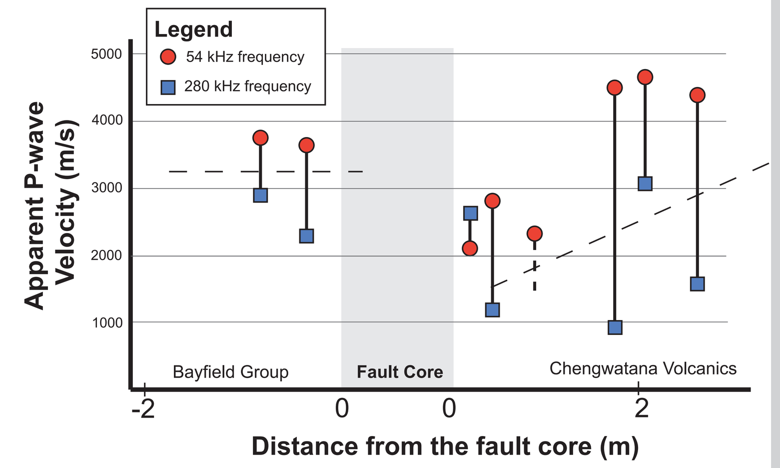


Figure 9. Photo of ultrasonic pulse velocity test in concrete (right) using a Proceq Pundit Lab system and effect of fracture aperture on ultrasonic pulses (figure modified from Pandey et al., 2023).





We tested pulse velocities at 54 kHz and 280 kHz frequencies. Lower frequencies are able to "jump" wider aperture fractures than higher frequency pulses and experience less attenuation.

Two samples of Bayfield sandstone exhibited velocities consistent with intact sandstones. Samples of Chengwatana Volcanics show decreasing velocity with proximity to the fault core.

Conclusions and Future Work

The damage zone surrounding the Douglas Fault is highly asymmetric, with greater damage intensity observed in the hanging wall Chengwatana volcanics compared to the footwall Bayfield Group sandstones. This may suggest low confining pressures during deformation of the Bayfield Group, consistent with interpretations of syntectonic deposition by Hodgin et al. (2024).

Our measurements indicate an extensive damage zone developed in the Chengwatana volcanics, consistent with previous work of Grant (1901) and Hodgin et al. (2024). An inner damage zone characterized by greater damage intensity was osberved to extend ~10 m from the fault core in the Chengwatana volcanics, which contained multiple cross-cutting orientations of fractures. These may record earlier tectonic phases, but more analysis is needed to understand mechanisms of fracture formation.

Preliminary measurements show UPV can be used as a proxy for damage state in the inner damage zone, though more measurements are needed to define a correlation between apparent wave velocity and damage intensity and evaluate the entirety of the damage zone.

References & Acknowledgements

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