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BRITTLE FAULT KINEMATICS OF THE SAN JUAN FAULT ZONE, SOUTHERN VANCOUVER ISLAND, BRITISH COLUMBIA

JOHN JAMES BORAH, Colorado College
Research Advisor: Meredith Bush

ABSTRACT

The tectonic interplay at the Cascadia-subduction zone (CSZ) has the potential to produce earthquakes of a massively destructive magnitude and the ability to drench an estimated 1000km of the well-populated western coastline of the United States and Canada in a series of 8m tall tsunami waves. Because of this, the CSZ has been studied at length (Clague, 2002, Wood, 2009, DeMets *et al.,* 2010). What remains overlooked, however, are faults in southwestern British Columbia's crust (Balfour *et al.,* 2012). In fact, the last known earthquake centered upon Vancouver Island, with an estimated magnitude > 7, occurred in 1946 along a still unknown unidentified fault proximal to Courtney, British Columbia (Rogers and Hasegawa, 1978, Balfour *et al.,* 2012).

One fault of interest is the San Juan fault. To date, kinematic data regarding this fault has not been published. With that in mind, brittle kinematic data was collected at six different sites along the San Juan fault inorder to illuminate their Neogene history. 216 fault planes and their associated striations were measured, their slip-sense interpreted, and eight oriented thin samples collected. In the end, the geometry, kinematics, and fault plane solutions of exposures of the San Juan fault and the San Juan fault zone were unearthed.

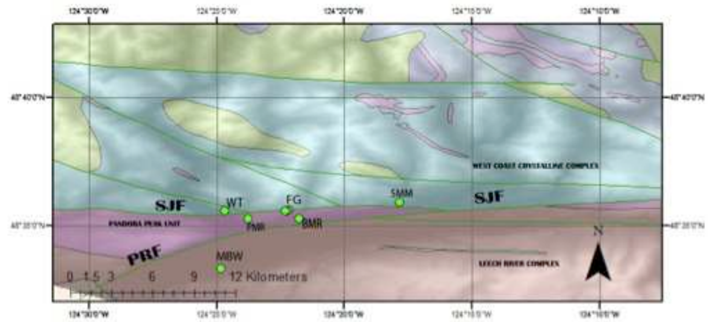


Figure 1. Geological map showing study locations in the Port Renfrew area. PMR (Pacific Main Road quarry), 5MM (Five Mile Main quarry), FG (Fault Gouge quarry), WT (Water Tank quarry), MBW (Marina Blast Wall quarry), and BMR (Browns Main Road quarry) are locations where faults of the San Juan fault zone are exposed. San Juan Fault (SJF), Port Renfrew Fault (PRF) are also illustrated (Geoscience B.C., 2013).

INTRODUCTION

A thorough brittle kinematic analysis of the San Juan fault began during a Keck Consortium-sponsored field investigation last summer led by Dr. Kristin Morell, where extensive fault-slip data, eight oriented samples, and GPS coordinates of sites in the San Juan fault zone were collected. This project, which tests the prevalent interpretation that the San Juan fault is left-lateral fault, contributes to the understanding of the geodynamic context for the San Juan fault and seismic hazard for southern Vancouver Island (Rusmore and Cowan, 1985, Johnston and Acton, 2003). This research is crucial for communities and institutions along the San Juan fault, perhaps contributing to future decisions regarding existing and new infrastructure if indeed the fault is active.

GEOLOGICAL BACKGROUND

The San Juan fault and the Leech River fault to its south are the foremost structures of southern Vancouver Island. The steeply dipping faults run parallel and are the result of regional tectonism in the

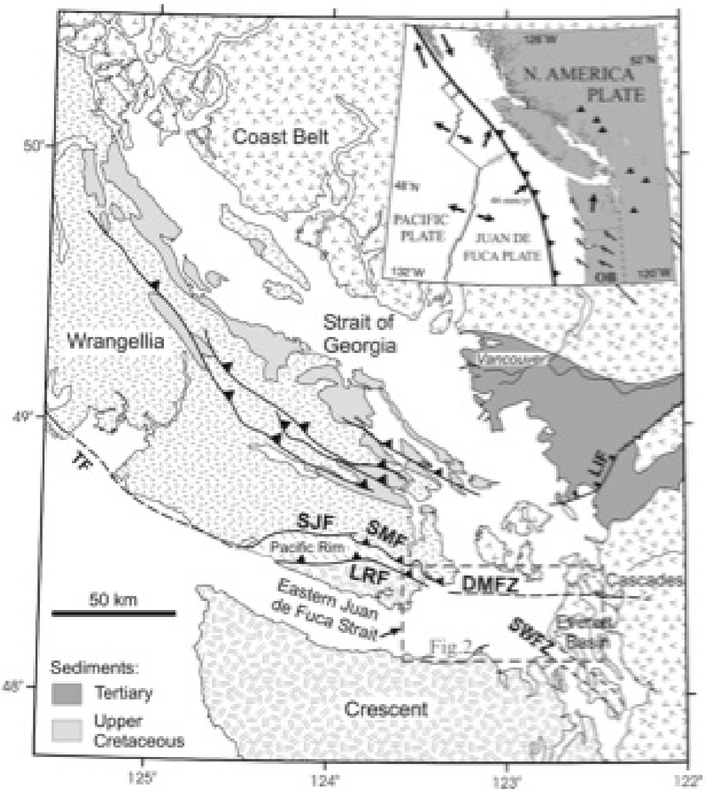


Figure 2. Map of the terranes and crustal faults near the Juan de Fuca Strait. San Juan (SJF), Leech River (LRF) and Survey Mountain (SMF) faults pictured, along with the Devil's Mountain and Southern Widbey Island (SWFZ) fault zones. Notice how SJF is illustrated without movement sense. Inset on the top right corner of the figure illustrates tectonics of the Cascadian Subduction Zone. Inset in the middle of the figure outlines general locations of figures 2 and 3 (Hayward et al., 2006).

Late Oligocene (Mayers and Bennet, 1973). Though the San Juan fault is poorly exposed, it is assumed that it is the boundary between the Wrangellia and Pacific Rim terranes (Fairchild and Cowan, 1982).

The San Juan fault system is interpreted as a left-lateral fault based on the sinistral offset of the West Coast Crystalline complex (a component of the Wrangellia terrane) and unpublished kinematic data (Rusmore and Cowan, 1985, Johnston and Acton, 2003). There are, however, opposing interpretations claiming the San Juan fault is a thrust fault, especially when interpreted in the context of the Cowichan Fold and Thrust System (CFTS) (England and Calon, 1991, England *et al.,* 1997), or a normal fault (Mayers and Bennett, 1973).

Regardless of the kinematic interpretation, the San Juan fault is widely assumed to be inactive (Muller, 1977, Johnson *et al.,* 2001). Morell *et al.'s* findings however, suggest that the San Juan fault may be apart of an active network of faults permeating Vancouver Inland's crust.

METHODS

A full fault slip-dataset was collected at six sites proximal to the San Juan fault. Included in the dataset are 216 fault plane and striation orientation measurements. Kinematic indicators— which, in this study, are either reidel shears or mineral fibers— were used to interpret slip-sense (Petit, 1987).

Principally, kinematics are spatially homogenous. This tendency towards spatial homogeneity requires selectivity in interpreting data in isolating the most prevalent fault-slip data at each site. Failing to separate heterogeneous data leads to averaging distinct subgroups, which muddles the kinematic results (Marret and Allmendinger, 1990). Thus, data was procedurally divided into these subgroups with help from the softwares Faultkin and Stereonet9 (Marret and Allmendinger, 1990, Allmendinger *et* al., 2011). An additional component of this study was microstructural analysis. Microstructural analysis was conducted to elucidate the slip-senses and deformation history of oriented samples (Passchier and Trouw, 1996, Blenkinsop, 2007).

DATA

Pacific Main Road Quarry, located approximately 500m south of the San Juan fault, is an outcrop of Leech River Schist, a member of the Leech River Complex. Sample SJ16JB01 was collected at this location and its hand sample exhibit two-three crosscutting veins. The mineral assemblage is roughly 84% quartz, 13% plagioclase, 2% olivine, and 1% opaque minerals. The rock is cohesive, has a random, non-foliated fabric, and a 75% proportion of matrix to clasts and can thus be classified as a cataclasite.

The dominant fault plane at Pacific Main road is represented by eight south-southeast faults with normal slip-sense. The resulting kinematic axis of shortening gathered from the mean average of the fault-slip data trends 125.5° and plunges 60.6° and the extension axis trends 276.6° and plunges 16.2°.

The outcrop along Five Mile Main Road is situated along an east-west striking portion of the fault and is the eastern most studied outcrop and composed of West Coast Crystalline rock, a constituent of the Wrangellia terrane. This cohesive sample has a non-foliated fabric and contains <10% matrix, making it a protocataclasite.

The dominant fault plane strikes east-northeast (67.5° ± 35°), has a lineation trending east (90° ± 40°), and has a normal slip sense. The shortening kinematic axis trends 130.8° and plunges 13.9° and the extension axis trends 028.2° and plunges 41.4°. Both oriented thin sections from this quarry come from a fault plane striking 88, dipping 69° with a lineation trending 254.9° and plunging 30.6°.

Fault Gouge quarry is the name given to a collection of outcrops along an east-west striking portion of the San Juan fault. In Fault Gouge Quarry proper, there are two strata of rock separated by extremely faulted, deformed, sub-vertically dipping, black-orange fault gouge. Both these rocks are interpreted as the Pandora Peak Unit of the Pacific Rim terrane. The dominant fault plane of Fault Gouge quarry strikes 89°, dips 64.6°, trends 253.1°, and plunges 28.4° and exhibit thrust slip-sense. The resulting shortening axis trends 033.0° and plunges 04.3° and the extension axis trends 298.8° and plunges 04.3°.

Samples SJ16JB03 and SJ16JB04 are from this Fault Gouge quarry road. SJJB03 is a cohesive, matrix-dominated, weekly-foliated rock with crosscutting veins. The foliation is spaced, rough, and parallel schistoicity. The foliation composes 20% of the fabric. The groundmass is extremely fine and the proportion of matrix to clast (>90%) suggest that SJ16JB03 is a ultramylonite. The matrix is approximately 90% quartz, with the remaining 10% composing of graphite. SJJB04, on the other hand, is felsic, extremely brittle, though cohesive, with a random fabric and contains 80% matrix— a cataclasite. This thin section is derived from a sampled fault plane striking 33°, dipping 84° with mineral fibers and reidels fractures trending 113.5° and plunging 83.9°. The field interpreted shear sense from these indicators was thrust. The thin section of SJ16JB04 displays altered potassium feldspar grains, staircase

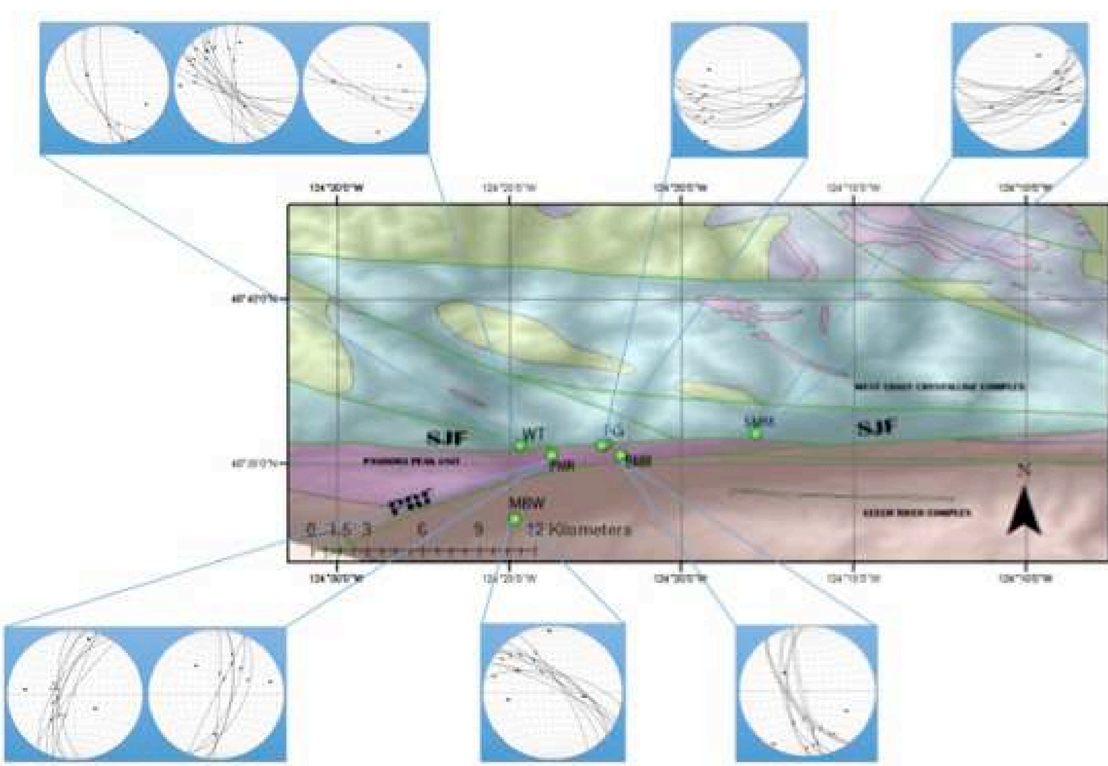


Figure 3. Stereonet plots of the study sites and their dominant fault-slip data subgroups (Geoscience B.C., 2013).

porphyroblasts, indenting potassium feldspar grain boundaries, and microveins.

Water Tank quarry is the western most San Juan fault study area dominated by cohesive, black, brittle cataclasite belonging to West Coast Cystalline Complex of the Wrangellia terrane. Sample SJ16JB05 displays boudinages and schistocity. The fabric of the thin section is random and contains 65% clasts to matrix. This Sample strikes 108°, dips 80° and its reidel shear lineation trends 114.0° and plunges 30.5°. The interpreted movement sense is left lateral. Two orientated thin sections, SJ16JB05a & SJ16JB05b, were prepared.

The dominant fault plane at this site has an average strike of 140.9°, dip 77.1°, trend 315.1°, and plunge 22.6°. The field-interpreted slip-sense on all 14 planes, which compose the dominant fault plane dataset, was thrust. As such, this plane has a shortening kinematic axis of trending 268.3° and plunging 10.3°, while the extension axis trends 04.3° and plunges 30.1°.

Marina Blast Wall Quarry sits approximately 3km south of the Port Renfrew fault. This rock was interpreted as Leech River schist of the Pacific Rim terrane. Sample SJ16JB08 is composed of 85% quartz and 15% plagioclase, not including the secondary pyrite mineralization. Boudins, crosscutting veins, mineralization and the occasional preferential alignment of grains are found in this cohesive, non-foliated cataclasite hand sample. The sample is derived from a right lateral fault striking 301°, dipping 69° with mineral fibers trending 117.8° and plunging 08.4°.

The dominant fault plane, represented by nine out of the 23 measurements, strike and trend northwest (270-360°). They all exhibit a thrust, right-lateral slip-sense. The resulting shortening axis trends 356.5° and plunges 08.0° while the extension axes trends 260.8° and plunges 35.0°.

The outcrop along Browns Main Road Quarry, which is located less than 1km southeast from Fault Gouge Quarry, consists of white, brittle rock. This rock belongs to the Pandora Peak Unit of the Pacific Rim terrane. Foliations are sub-vertical and permeated with quartz veins.

The dominant fault plane at this location has an average strike of 160.3°, dip of 70.1°, trend of 172.2° and plunge of 27.5°. The field-interpreted slip-sense is thrust, dextral. The shortening axis trends 212.4° and plunges 05.4° and the extension axis trends 118.3° and plunges 36.4°. Unfortunately, no sample, oriented or otherwise associated with this outcrop exists.

INTERPRETATIONS

The data suggests that the San Juan fault is a left-lateral, thrust oblique-slip fault at Water Tank, Fault Gouge, and Five Mile Main quarries. These are the study sites most proximal to the fault. The geometries of the faults, however, are variable. Fault Gouge and Five Mile Main quarry faults share similar kinematic orientations and remarkably in-sync movement planes, which leads to interpreting their kinematics in conjunction with one another. The result is shortening occurring from the north-northeast to south-southwest and extension from east-southeast to west-northwest. It appears feasible, then, to interpret these two faults as constituents of the San Juan fault. Disparities in their relative geometry may be the product of their differing terranes' rheologies.

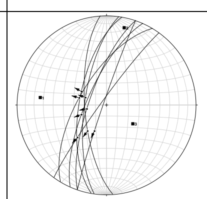
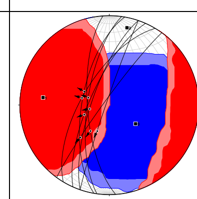
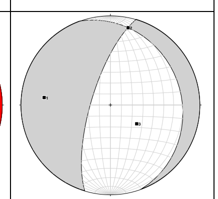
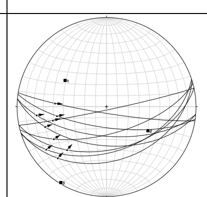
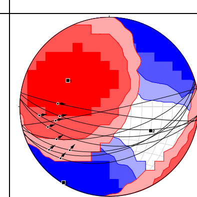
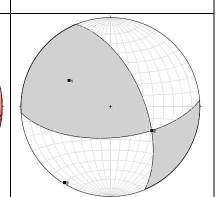
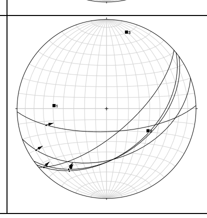
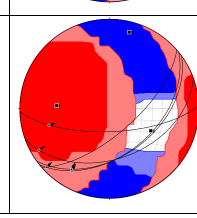
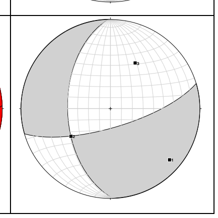
Location	Geometry	Kinematics	Fault Plane Solution
Pacific Main Road			
Fault Gouge			
Five Mile Main			

*Table 1. The dominant fault plane data for each site and their resulting kinematics and fault plane solution illustrated using Stereonet9. Kinematic data visualizes P (blue) and T (red) contours (*Marret and Allmendinger, 1990, Allmendinger et al., 2012).

The dissimilar geometry of the fault at Water Tank quarry (fault plane strike differs by 55°) make it difficult to interpret it as a primary fault of the San Juan fault, though it is a left-lateral, thrust oblique-slip fault. However, the acute angle of this fault relative to the San Juan fault and its identical shear sense leads to the interpretation that this is an H-splay fault (Scholz *et al.,* 2010), secondary to the San Juan fault. There is also evidence for multiple stages of deformation in two sets of striae— one that trends south, the other east. This site's high degree of deformity, exhibited by these multiple deformation events and its intracystalline-platicity microstructures, are holdovers from the Wrangellia terrane's history of deformation. This history of deformation also controlled the geometry of this splay fault, making it a product of anisotropy reactivation (Marret and Allmendinger, 1990).

The remaining faults, which are further removed, have geometries that are considerably distinct. Brown's Main Road quarry, namely, hosts a fault striking south-southeast with striation trending south. Despite this geometry, this fault also observes north-northwest to south-southeast shortening and east-southeast to west-northwest extension and is left-lateral, thrust oblique-slip — not unlike what is observed at the San Juan fault proper.

The fault at Marina Blast Wall is also left-lateral, thrust oblique-slip fault. It is another example of shortening being applied from the north-northwest to south-southeast and extension in the east-southeast to west-northwest.

The fault at Pacific Main Road is one of two normal faults in this study. Extension occurs east to west and shortening is mostly vertical. With a shortening axes trending 123.8° and plunging 60.0°, there is no slight strike-slip component with an influence of shortening in the north-south direction. This fault's dissimilar kinematics makes it a viable candidate for its own fault.

Though the faults from these sites seem quite dissimilar, they, along with every other fault in this study, save for the splay fault at Water Tank quarry, have a degree of shortening from north-south, and extension east-west. The consistency of these kinematic orientations suggests that the San Juan fault is a part of a larger fault zone expressing a compressional regime— the San Juan fault zone.

DISCUSSION

Several of these faults can be examined within the context of the Southern Vancouver Island Orocline. Some models suggest that this orocline is the response of the accretion of the Pacific Rim and Crescent terranes via the Kula plate onto Vancouver Island, which is believed to have rotated the Vancouver Island Southern Crustal Block (SCB). Models of this orocline predict northwest-striking dextral faults and northeast-striking sinistral faults as a response to shortening incurred by the accretion (Johnston and Acton, 2002). While the latter is not observed in the San Juan fault zone, northwest-striking faults at the Marina Blast Wall and Browns Main Road quarry are both oblique faults with right-lateral shear sense.

The SCB is not the only culprit responsible for shortening in the area. The Devil's Mountain fault is proposed to be the result of the active northward migration of the Oregon coast block (Lewis *et al.,* 2003, Hayward *et al.,* 2006). Additionally, this northward migration is believed to be the impetus behind nine oblique left-lateral faults off the coast of Washington and Oregon (Goldfinger *et al.,* 1997, Hayward *et al.,* 2006). Within this context, it is reasonable to conclude that the San Juan fault, an east-west striking, oblique left-lateral fault, and the San Juan fault zone, an expression of a north-south compressional regime, originally developed from the accretion of the Pacific Rim and Crescent terranes, like the CFTS, and is still accommodating strain today from Cascadian subduction zone strain partitioning, not unlike that experienced by Devil's Mountain fault and the nine oblique, left-lateral faults southwest of Vancouver Island (Goldfinger *et al.,* 1997, Hayward *et al.,* 2006).

CONCLUSION

The San Juan fault proper is a left-lateral, thrust oblique-slip fault, which experiences shortening from north to south. The San Juan fault zone is also an expression of north-south shortening, though faults in this zone have geometries and kinematics that do not mimic the San Juan fault proper. The accretionary history of Vancouver Island terranes and the active Cascadia subduction zone are responsible for the development and current kinematic orientations on the San Juan fault and the San Juan fault zone at large.

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