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Stranded: Structural Analysis of the Northern Transition Zone of the Central Creeping Section, San Andreas Fault

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SANTA CRUZ

**STRANDED: STRUCTURAL ANALYSIS OF THE NORTHERN  
TRANSITION ZONE OF THE CENTRAL CREEPING SECTION, SAN  
ANDREAS FAULT**

A thesis submitted in partial satisfaction of  
the requirements for the degree of

MASTER OF SCIENCE

in

EARTH SCIENCES

by

**Jacquelyn Williams**

September 2022

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**Stranded: Structural Analysis of the Northern Transition Zone of the Central  
Creeping Section, San Andreas Fault**  
Jacquelyn Williams

**Abstract:**

The mechanics behind the unusual lateral shift in slip behavior along the northern transition zone of the central creeping section of the San Andreas Fault (SAF) is poorly understood. Previous hypotheses have focused on changing lithology and stress conditions to explain the SAF's creeping section but fail to fully explain this unusual behavior. This thesis focuses on the role of shallow fault zone geometry in controlling slip behavior along the northern transition zone near San Juan Bautista, California. Field mapping of structures exposed in this region, along with microstructural analysis of field samples collected at such exposures were used in conjunction with mapped seismicity and subsurface data to assess how the shallow structure of the SAF influences its slip behavior. Structural data collected suggest that the SAF in the northern transition zone is a complex network of multiple strands that tend to dip to the southwest. Three active creeping strands are observable along Searle Rd (located 5.5 km NW of San Juan Bautista, Ca), which is the northernmost documentation of SAF creep to date. Other strands within the study area show microstructural evidence of pulverization and cyclic failure. The evidence of both aseismic and seismic behavior suggests that the transition from creeping to locked can happen strand by strand, in a piecemeal fashion, along this northern transition zone. This shift in slip behavior is likely unrelated to changes in stress condition or

lithology due to the similar fault orientations and gabbroic lithology seen in both creeping and locked strands.

## **Acknowledgements**

Paramount among the people who have helped me complete this project is my advisor and committee chair, Heather Savage. I am deeply indebted to you for your patience, compassion, and all the hours you spent with me, nose to the grindstone, on the outcrop and in the lab. I cannot express enough thanks to the amazing reading committee for their continued support and encouragement. Emily Brodsky and Hilde Schwartz-You women are a powerhouse of intellectual brawn, and I offer my utmost and sincere appreciation for this learning experience.

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## **Introduction**

The San Andreas fault (SAF) undergoes a lateral transition in slip behavior along its 1300 km length. Whereas the northern and southern sections fail in large earthquakes, the central section- spanning from approximately San Juan Bautista, CA to Parkfield, CA- slips quasi-stably at or near the average slip rate for the SAF. Historically, the 1906 San Francisco earthquake rupture extent ranged from Cape Mendocino to just northwest of San Juan Bautista, CA, with a rupture extent of approximately 477 km (Thatcher et al. 1997). The 1857 Fort Tejon earthquake ruptured from just south of Parkfield, CA southward to Wrightwood, CA, a roughly 360 km long rupture extent (Sieh 1978). The 1989 Loma Prieta earthquake only ruptured the southernmost 40 km of the 1906 rupture extent (Spudich 1996). Despite the lack of large historic earthquakes along the SAF creeping section, recent work has shown that large earthquakes have occurred at least 10 km north of Parkfield in the last few million years (Coffey et al. 2022).

The mechanics behind the SAF's transition from creeping to locked is poorly understood. One hypothesis is that an abundance of frictionally weak mineral phases such as serpentine and its associated products are prevalent in the central SAF, sourced from both the central coast range ophiolite and Franciscan mélange (Irwin 1990). Talc-bearing serpentine and smectites found in cores from the San Andreas Fault Observatory at Depth (SAFOD), located in Parkfield, CA, have been shown to

have friction values around 0.1 and the inability to regain strength when stationary, which is a necessary component of the seismic cycle (Moore and Rymer 2007; Lockner et al. 2011; Carpenter et al. 2011). These frictional strength values are low enough to explain the lack of long-term frictional heat signal around the SAF in this location (Lachenbruch and Sass 1980). However, questions remain regarding whether these conditions can be met along the entire length and depth of the SAF creeping section, as smectite and other weak phases are not stable below about 5-6 km (Holdsworth et al. 2011). A second hypothesis is that creeping faults might have elevated pore pressures, which lower effective stress and stabilize frictional sliding, according to rate and state friction laws (e.g., Scuderi and Collettini 2016). But fluid pressures were hydrostatic at the SAFOD borehole, indicating that the fault should not be extremely weak from this mechanism (Zoback et al. 2010).

More recent work has suggested that fault geometry can also play a role in fault stability as shallow faults will interact with the free surface (Skarbek 2021). The shallow structure of the San Andreas fault may be a missing link to understanding its unusual slip behavior. In an effort to address the relationship between fault zone geometry and slip behavior, I mapped shallow SAF structures along the northern transition zone near San Juan Bautista, CA, where average creep rates drop from ~10mm/yr (Hirao et al. 2021) to presumably zero in the locked segment. I mapped surface outcrops and extended these observations to depth with subsurface data from a drilling project in which I participated as part of my thesis. The purpose of this mapping was to gain a better picture of shallow structure complexity and document

any evidence of creep if possible. Thin sections of gouge samples taken from shallow exposures were analyzed for microstructures to better understand the cycles and mechanics of slip. Relocated seismicity in the area was used to further analyze shallow structure and how it relates to mapped surface exposures. I document fault creep 2-km northwest of the last known creeping section and provide microstructural evidence that other mapped strands may fail in earthquakes.

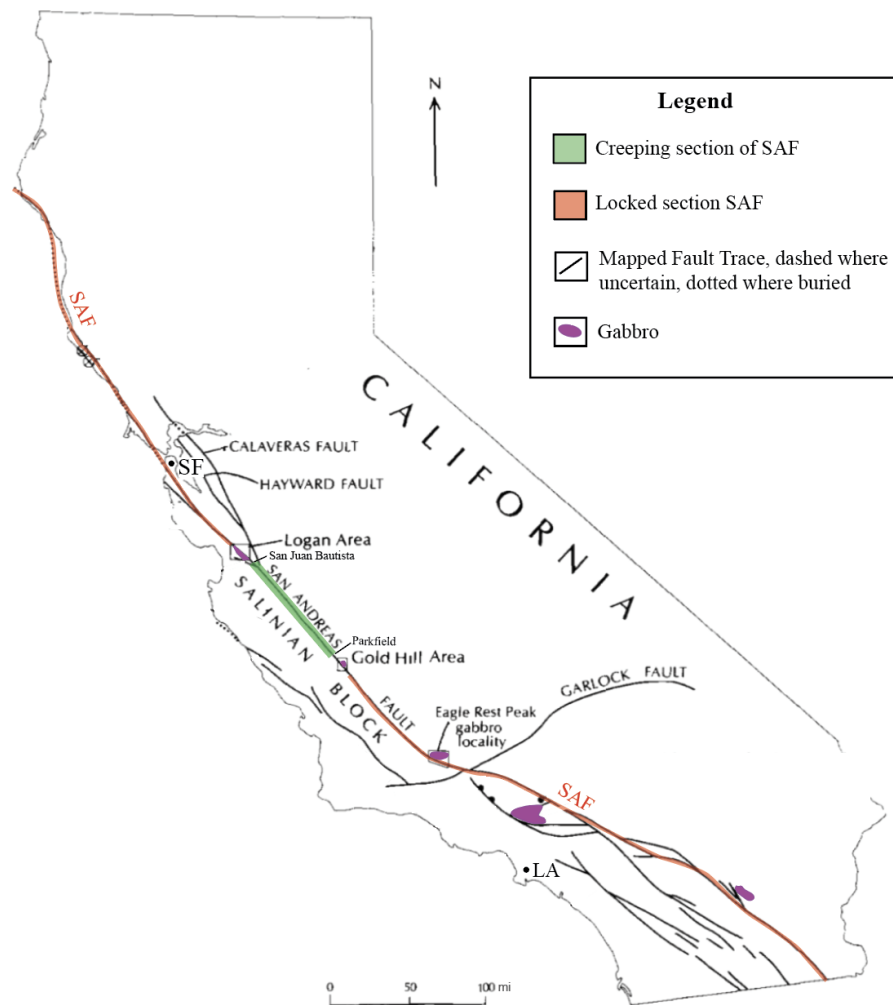
## **Background**

### **Regional Tectonics**

Broad-scale regional tectonics have played an important role in bringing the gabbroic rocks of the subject field area to the surface. The ‘Logan’ type gabbro exposed in the field area have been interpreted to be part of the Coast Range Ophiolite, which is Mesozoic-aged oceanic crust that displays a classic ultramafic-mafic succession upon which the Great Valley Sequence was deposited (Ross 1970; Hopson et al. 1981), it is separated from underlying Franciscan complex via the Coast Range Thrust (Bailey et al. 1970). These ‘Logan’ type gabbros are late Jurassic in age (165-153 Ma) and highly distinctive from younger Salinian (70-90 Ma) granites. They are thought to have been originally deposited in a low latitude equatorial setting before being carried northward and accreted to North America, via oceanic underplating of the continental plate (Ross 1970; Irwin 1990). While the original extent of the Coast Range Thrust is not well constrained, it is surmised that faulting

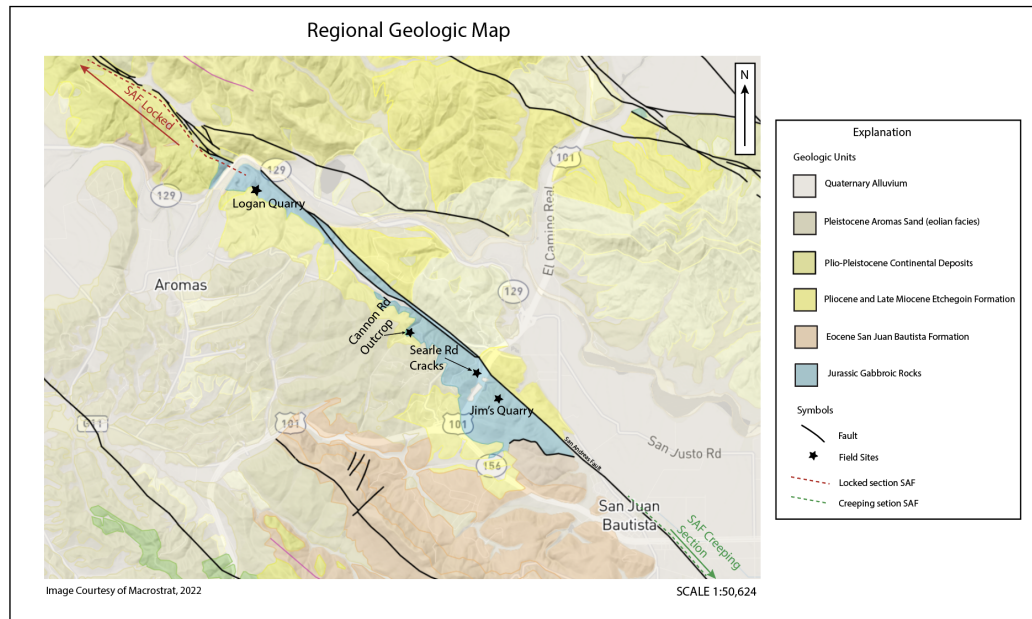
from the Coast Range Thrust has allowed these old seafloor remnants to override younger basement rocks locally (Bailey et al. 1970). During the mid-Cenozoic, a subduction trench lay offshore of the western margin of North America, resulting from the North American plate's westward convergence with the oceanic Farallon plate (Atwater 1970) (Irwin 1990). Eventually, the rate of subduction exceeded the rate of seafloor spreading, such that the spreading center between the Farallon and Pacific plates was consumed by this trench, with subduction terminating no earlier than 30 Ma (Atwater 1970). The subduction of the spreading ridge initiated the San Andreas Fault system, by bringing the Pacific plate into contact with North America and divided the remnant Farallon Plate into its two modern day counterparts, the Juan de Fuca plate and the Cocos Plate. The resulting triple junctions migrated roughly northwest-southeast respectively, as subduction of the Farallon plate continued (Irwin 1990). Movement along the SAF has brought the Logan gabbro body to its present-day location (Ross 1970; Irwin 1990).

Three main exposures of the gabbro bodies are found in modern day California: Logan, Gold Hill, and Eagle Rest Peak (See Figure 1 below). These gabbro bodies include a quartz-diorite gabbro, anorthositic gabbro, pyroxenite and metamorphosed plagioclase-hornblende gabbro, and are consistent with typical ophiolite sequences (Ross 1970).



**Figure 1.** Map of the central creeping section of the San Andreas Fault (in green) and the three main exposures of gabbro bodies: Logan, Gold Hill, and Eagle Rest Peak (gabbro shown in purple). (Modified from Ross 1970).

The subject field area is centered around the Logan gabbro body located along the SAF northern transition from creeping to locked (Figure 2).



**Figure 2.** Regional geologic map showing mapped geologic units in the subject field area, with the Jurassic-aged ‘Logan’ type quartz gabbro body shown in blue. Stars show location of Jim’s Quarry, Logan Quarry, Cannon Rd and Searle Rd field sites located southwest of the mapped SAF trace. Red dashed lines show locked section of the SAF, while green dashed lines show creeping segment of the SAF, with the study area transition zone between. (Modified from Macrostrat, 2022).

### Slip style of the central San Andreas fault

Fault creep is defined as a fault gradually sliding without generating an earthquake or seismic waves and is characterized by a slow slip rate ( $\sim$ cm/yr) (Harris 2017). The present creeping section of the SAF system is an approximately  $\sim$ 175-km long section in central California, that extends from the northern transition zone in San Juan Bautista to the southern terminus in Cholame (Titus et al. 2006). Creep rates are approximately equal to plate rates in the central creeping section ( $\sim$  34 mm/yr), and taper toward zero at both the northern and southern terminuses. Several aseismic slip detection techniques have been employed to measure creep rates along this

section, such as alignment array monuments, continuous GPS, and creepmeters. Based on the data collected from the above means, a lower bound creep rate of 28 mm/year and an upper bound creep rate of 34 mm/year are given for the slip rate along the SAF in central California (Titus et al. 2006). Recent data from the USGS creepmeter stationed outside of San Juan Bautista shows an average creep rate of 10 mm/yr (Hirao et al. 2021). A creepmeter installed at Nyland Ranch, located 1.2 km northwest of the town of San Juan Bautista and within the general area of this study (GPS: 36.8550/-121.5460), has recorded a local creep rate of 8.7 mm/yr from 2004-2011 (Bilham 2011). This area is within the transition zone and the SAF is thought to be locked in the region near Logan Quarry, to the northwest (Figure 1 and 2). Earthquakes in the area around San Juan Bautista are small ( $M_L$  3 and lower), consistent with fault creep. The largest earthquake recorded in this region was a  $M_w$  5.1 on August 12, 1998 (Taira et al. 2014).  $M_w$  4 magnitude earthquakes occur about once per year in this region (Hirao et al. 2021).

### **The San Andreas Fault Observatory at Depth**

As mentioned above, the creeping section of the San Andreas Fault system has plagued researchers with questions surrounding the underlying mechanics of this slip behavior. Many have suggested elevated pore fluid pressures, citing the reduction in effective normal stress (Zoback et al. 1987), as a means to achieve such a weak fault, while others have cited mechanically weak lithologies/minerals in the fault core, and/or as a coating along slip surfaces (Moore and Rymer 2007). The SAFOD

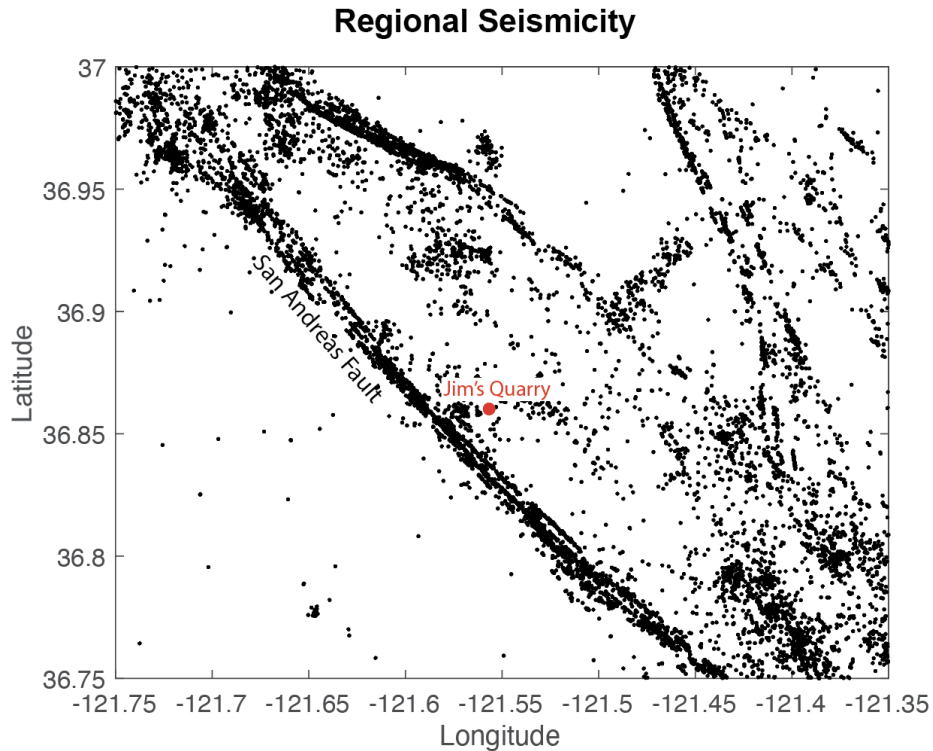
(San Andreas Fault Observatory at Depth) project drilled a borehole into actively slipping strands of the SAF at seismogenic depths along the creeping section of the SAF near Parkfield, CA and provided important insights into the weak fault conundrum and the mechanically unusual creep behavior. Gouge samples taken from SAFOD were found to contain mechanically weak minerals such as saponite (smectite clay) that are by-products of serpentine alteration (Bradbury et al. 2011; Holdsworth et al. 2011). Friction experiments yielded a low strength of such materials, with a coefficient of friction of 0.15, which led the authors to conclude that the SAF is intrinsically weak, in an otherwise strong crust (Lockner et al. 2011). Others have found fault zone materials from SAFOD to yield coefficients of friction closer to 0.21, which would not be low enough to explain the observed fault slip behavior alone (Carpenter et al. 2011). Other friction experiments suggested that the lack of frictional healing, coupled with velocity strengthening frictional behavior, keeps shear stress low throughout the seismic cycle such that it never increases to failure threshold before slip (Carpenter et al. 2011). Pore fluid pressure at SAFOD was near hydrostatic (Zoback et al. 2010), so overpressures cannot explain the creep behavior at least at these depths in the Parkfield area.

### **Seismicity in the San Juan Bautista area**

The San Juan Bautista area has had high seismic coverage for several decades, which supplies a robust earthquake catalog for my field area. Here I plot the double-difference earthquake catalog for Northern California for 1984-2011 (Waldhauser and



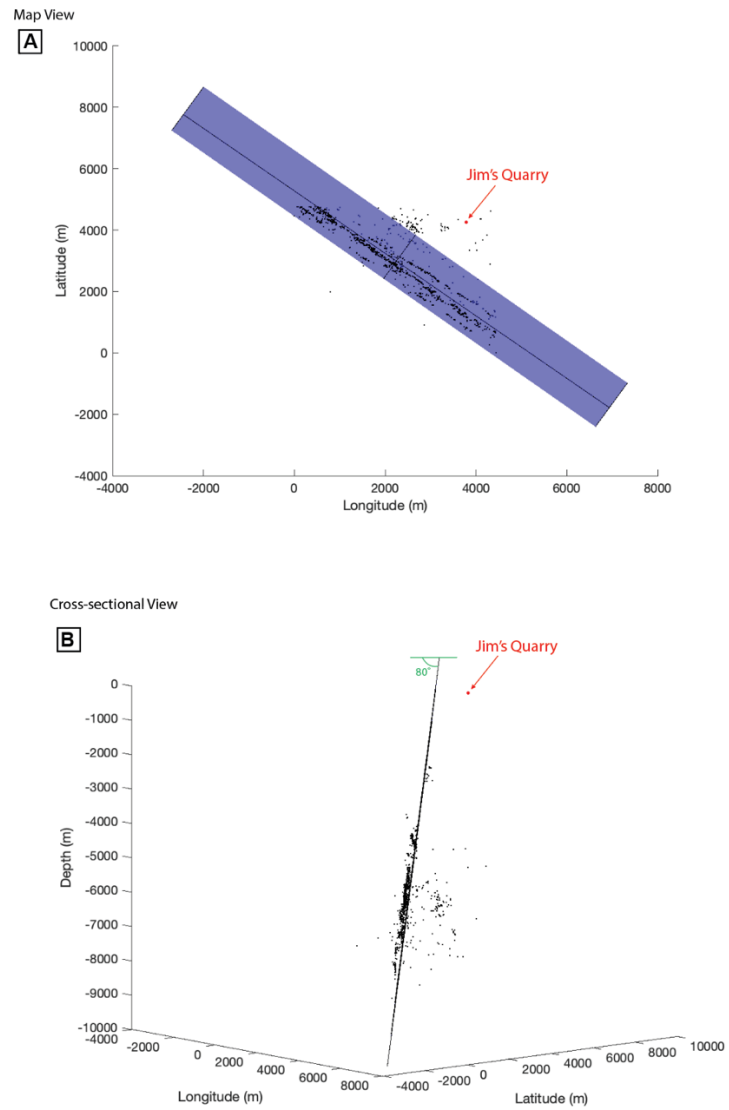
Schaff 2008) to investigate aspects of sub-seismic structure (Figures 3 and 4). As stated above, creeping faults tend to be active generators of small earthquakes, as “sticky spots” within the otherwise creeping fault tend to fail in small ( $M4$ ) events. This is seen in the northern creep transition zone, as the small earthquakes that occur clearly delineate active faults in map view (Figure 4A). I fit a plane to the cloud of seismicity within the SAF using single value decomposition and determine a dip for the SAF of  $\sim 82^\circ$  SW.



**Figure 3.** Regional seismicity map depicting earthquakes from 1984-2011 from USGS Earthquake catalog (USGS 2017). The SAF trace is labeled in black and Jim’s Quarry field site in red (Plot produced in Matlab).

In cross-section, the earthquakes clearly define a dipping fault and there is almost no mapped seismicity shallower than 2 km (Figure 4B). In addition to this, I note that the best-fit plane would place the surface trace of the SAF approximately 1.2 km to the southwest of the surface trace as defined by actively creeping structures. Such a discrepancy would indicate that the non-seismic portion of the fault would need to dip at a shallower angle than the seismic portion. Even taking into consideration that average horizontal (0.2 km) and vertical (0.4 km) absolute error locations in this area (USGS 2017), the SAF cannot dip at 82 degrees SW and daylight at its currently defined surface trace, as the discrepancy is greater than the absolute error locations.

### Local Seismicity in the San Juan Bautista Region

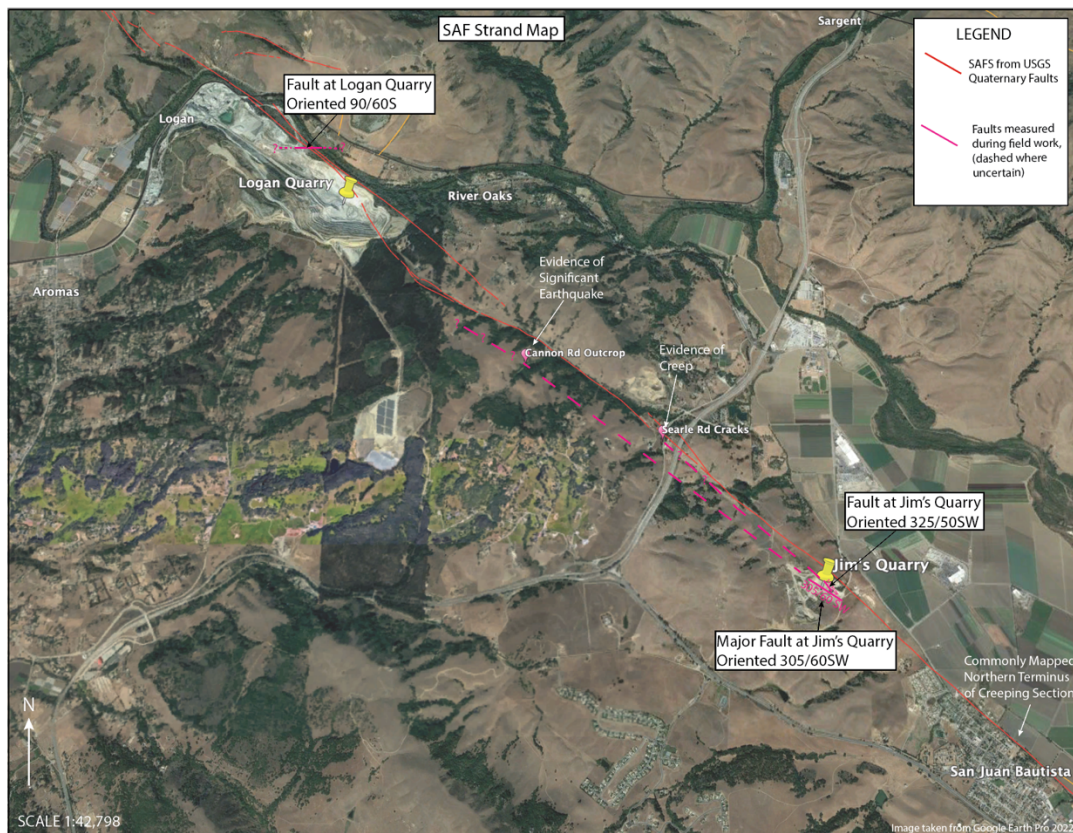


**Figure 4.** Local Seismicity in the SJB region. Figure 4A is map view, while Figure 4B is cross sectional view. Location of Jim's Quarry field site shown in red. (Earthquake data from USGS catalog (USGS 2017), plot produced in Matlab)

## Methods

### Field Mapping

In the locations outlined in the following section, I measured structural features and made lithologic descriptions. When possible, I measured strike and dip of faults and other features with a Brunton compass. Gouge thickness measurements were made with a ruler (see field photos). At each site, we sampled for XRD and thin section analysis when possible (but due to the friable nature of some of the outcrops, intact samples were not possible). Structures measured at Jim's Quarry, Logan Quarry, and Searle Road were overlain on Google Earth Satellite imagery (Figure 5).



**Figure 5.** Google Earth Satellite image depicting the subject field sites NW of San Juan Bautista, CA. Red solid line depicts the USGS mapped SAF trace (USGS Quaternary Faults Database), while the pink lines depict faults mapped during field reconnaissance.

### **X-Ray Diffraction (XRD)**

Bulk rock X-ray diffraction analysis was conducted on field samples collected from Jim's Quarry, Logan Quarry and Cannon Road. The instrument used for the analysis is a PANalytical PW3040/60 X'Pert PRO MPD X-Ray diffractometer, which uses a 3kW ceramic PW3373/10 LFF X-Ray tube with a Cu anode (UCSC). Samples were powdered to roughly 1-10 micrometers and ran for 1-hour spin cycles. Results were analyzed using the PANalytical X'Pert HighScore Plus v2.2b software package (c. PANalytical B.V. 2007).

### **Microscopy**

Field samples collected from Logan Quarry, Jim's Quarry and Cannon Road outcrops were sent to 'Spectrum Petrographics (11406 NE Rosewood Ave Ste.B, Vancouver, WA 98662)' to make thin section slides. Thin sections were analyzed with petrographic and scanning electron microscopes. Images captured from thin section analysis are included below in the results section.

## **Results**

### **Field Site Observations**

All of my field sites are situated on the southwestern side of the SAF, within the northern end of the creeping-locked transition (Figure 5). Previously mapped geologic units near the quarry include Jurassic-aged Logan gabbro and Tertiary

sedimentary units (Butano Fm., and San Juan Bautista Fm.) on the southwestern edge of the SAF, juxtaposed against Tertiary sedimentary rocks of the Etchegoin Formation along northeastern side of the SAF (Dibblee 2006; Wagner et al. 2002; Figure 2). In addition, I document a previously unmapped amphibolite schist, described in more detail in later sections.

### **Jim's Quarry**

The first field site I will describe consists of a non-operational quarry (named Jim's Quarry) located 2.25 km (1.41 miles) northeast of the town of San Juan Bautista, California, encompassing an area of approximately 0.25 km<sup>2</sup> (Figure 5). I observed two major faults at Jim's Quarry during site reconnaissance.





**Figure 6.** Jim's Quarry site location map. Red line in upper right-hand corner depicts the mapped SAF trace from the USGS Quaternary Faults database. Red lines in the quarry body are faults mapped by the author during site reconnaissance on August 13, 2021. Green dots show approximate sample location areas, with S-1, S-2, etc. as abbreviations for sample JQ\_081321\_1, JQ\_081321\_2, etc. (Satellite image from Google Earth Pro 2022).

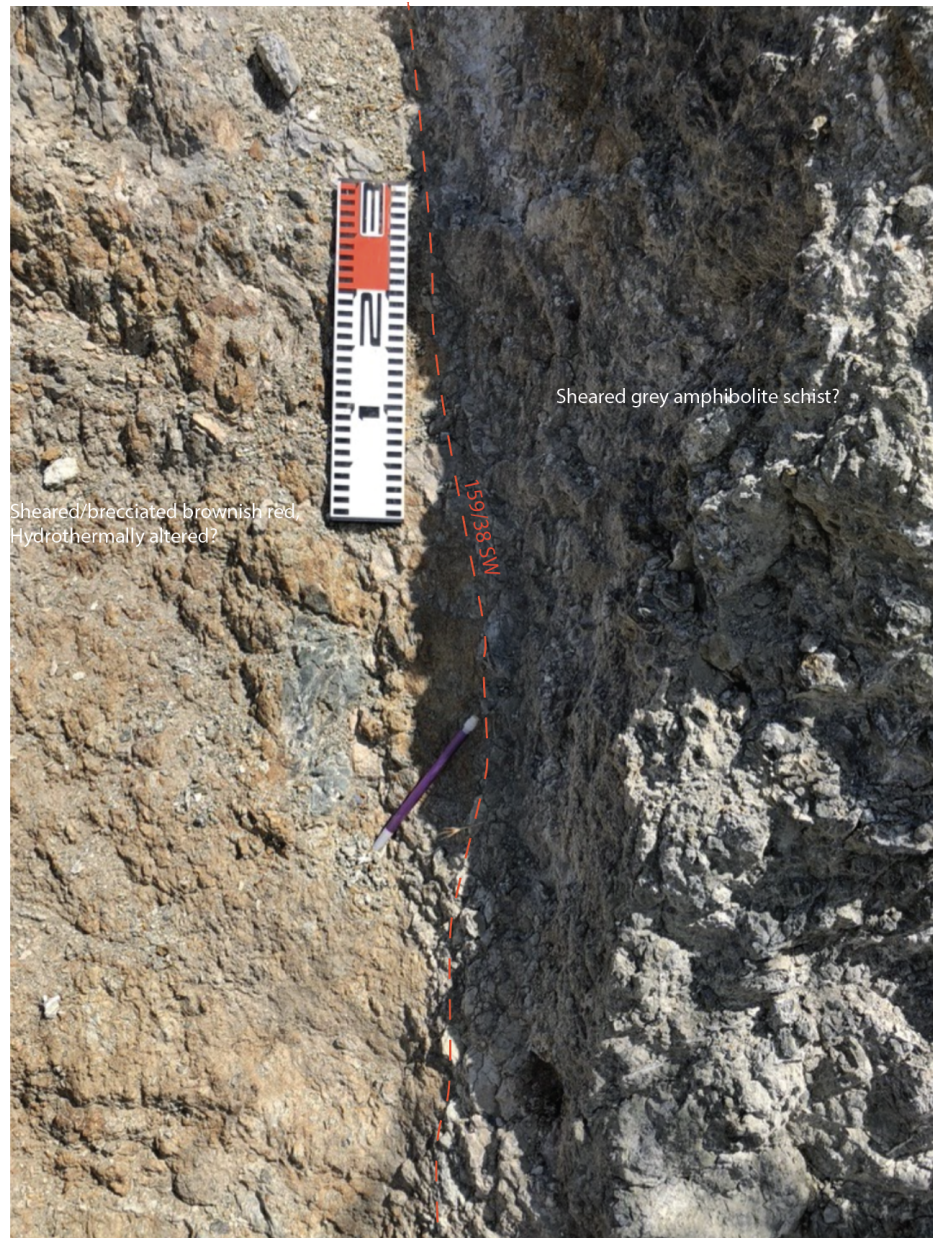
A northwest trending fault was observed crossing the main body of the quarry (fault orientation 125/60 SW: Figure 7). This fault forms a sharp, planar contact between two distinctive lithologies, a greenish, friable gouge and a reddish-brown, slightly more indurated gouge. The host rocks on either side of this fault appear hydrothermally altered and fractured. Although no clear sense of motion or total offset could be measured, with a 6-8 meter-wide damage zone that encompasses the main fault zone and several lateral, parallel strands to the northeast, the apparent scale of this fault is notable.





**Figure 7.** Major fault exposed on the northwest side of Jim's Quarry, oriented approximately 125/60SW, with apparent en echelon faulting to the northeast dashed in red.

Another fault exposed along the south-eastern region of Jim's Quarry, measured 160/38 SW, and also juxtaposed a reddish hydrothermally altered gouge against a greenish-gray, friable gouge (which is possibly deformed amphibolite schist; Figure 8). The fault core along this fault was narrower, approximately 1-2 m wide, however the host rocks on either side display a significant amount of deformation. The deformed greenish-gray host rock appeared to have large, rotated blocks and zones of what appears to be localized breccia. Large cobble sized angular clasts of the green rock can be seen floating in the deformed red gouge bed as well. It is possible that the two faults mentioned above are acting in one system. They both appear to juxtapose greenish gouge against reddish-brown gouge, and both dip shallowly to the southwest. Given the strike of the first fault, it would be expected to outcrop on the southeastern quarry wall exactly where the second fault outcrops. However, the more southerly fault is 35 degrees off strike (to the west), and dips more steeply by 22 degrees than the more northern fault. Due to lack of access to the quarry after summer 2021, I could not go back and check measurements, but hypothesize that these outcrops are the same fault and that I measured a fault surface within the fault zone that had a slightly different orientation (old faults can be deformed).

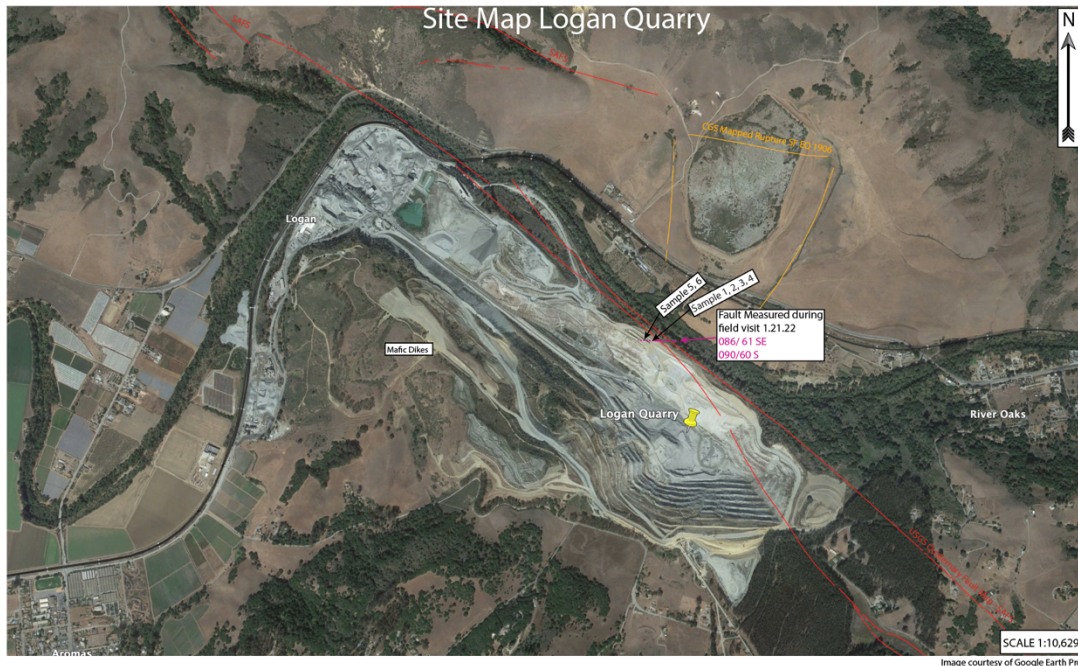


**Figure 8.** Jim's Quarry fault from southeast side of the quarry oriented 159/38 SW.

### **Logan Quarry**

The Logan Quarry is an active Graniterock-owned quarry located approximately 1.6 miles northeast of the town of Aromas, CA, encompassing an

approximate area of 2 km<sup>2</sup>. The SAF system lies along the northeastern border of Logan Quarry, with one strand extending into the southeastern section of the quarry before joining with the main strand of the SAF along the northeastern boundary of the quarry (Figure 9). Geologic units mapped within Logan Quarry include Jurassic-aged gabbroic rocks (including hornblende quartz gabbro of the ‘Logan’ type) and Plio-Pleistocene-aged sedimentary units (the unnamed ‘continental deposits’ of Wagner et al. 2002).



**Figure 9.** Google Earth satellite image depicting the Logan Quarry field site, sample locations, and structural data recorded during field reconnaissance 1/21/2022.

Three faults total were observed at Logan Quarry, including a large wedge-shaped gouge zone ranging in thickness from 20mm to 80mm, and featuring anastomosing clay-rich branches averaging 40 mm thick, crops out near the quarry



road (Figures 10.1 and 10.2). Highly sheared gabbroic rocks flank either side of the main gouge layer. Measurements taken along the gouge-gabbro contact yield a fault orientation of 90/60 S to 86/61 SE. It is noteworthy that the E-W orientation of this fault is somewhat unusual, as most of the SAF system is predominantly oriented NW/SE. However, given that two fault strands come together in this region of the quarry, it's not unreasonable to encounter complex structural geometry.

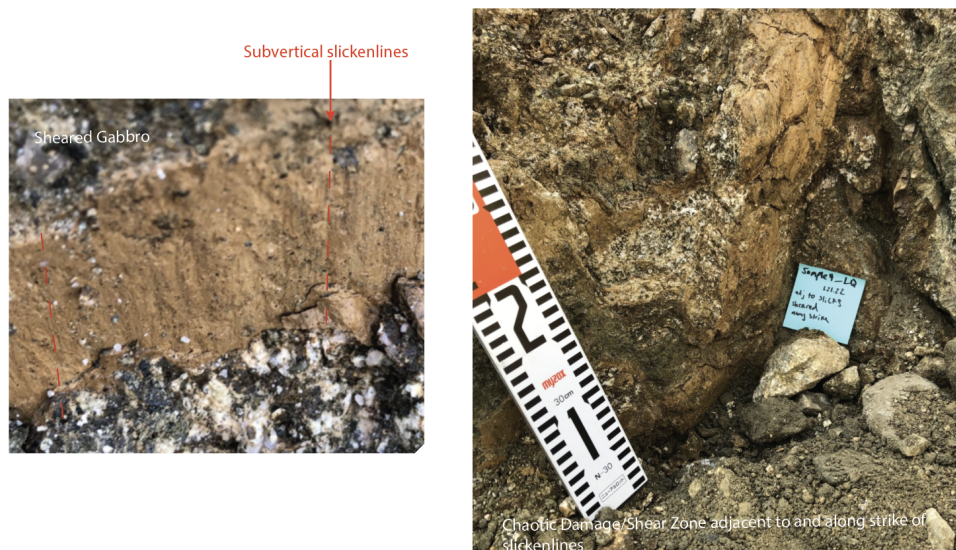


**Figure 10.1** Images display anastomosing gouge bed in Logan Quarry road with fault oriented 086/61 SE to 090/60 S. Image on left is an overview image outlining the zone of anastomosing gouge in red dashed lines. Gold colored box outlines area where image on the right is captured. Image on the right depicts the approximate width of gouge bed, with sheared Logan gabbro host rock on either side.



**Figure 10.2** Gouge bed located in quarry road floor: fault oriented 090/60 S- 086/61 SE.

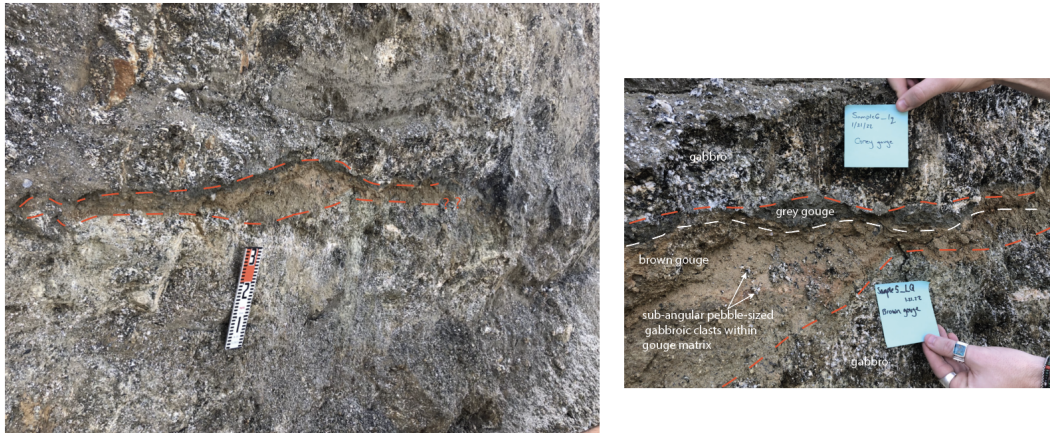
Four hundred meters southeast from the fault mentioned above, sub-vertical slickenlines on a fault plane oriented 100/60 SW (with slicks parallel to dip, i.e., rake approximately  $\sim 90^\circ$ ) were observed along the edge of an upper quarry road cut, within a zone of highly sheared, chaotically oriented gabbroic rocks (Figure 11). While there was no indication of absolute movement, the sub-vertical slicks parallel to dip indicate pure dip-slip motion.



**Figure 11.** Left image depicts subvertical slickenlines parallel to dip on fault oriented 100/60 SW, approximate field of view is 4 inches. Right image displays adjacent damage zone, scale bar shown.

Another wedge-shaped fault zone was observed in a road cut along the upper quarry road, with gouge thickness ranging from approximately 10 cm to 65 cm (Figure 12). The upper host rock-gouge contact is sharp and planar in some areas and wavy in others. The gouge consists of an upper thin gray layer and a thicker lower, brown colored layer. The lower gouge-host rock contact is less distinctive, and more diffuse. A few sub-angular pebble-sized clasts of gabbro were observed within the gouge matrix.





**Figure 12.** Wedge-shaped fault on upper Logan quarry road cut. Dashed red lines outline gouge bed. Right image is a close up of gouge matrix with sub-angular gabbro clasts visible.

### Cannon Road

Cannon Road is located off Anzar Road in San Benito County, approximately 5 miles southeast of Logan Quarry. The road cut outcrop on Cannon Road is located 0.15 miles southwest from the intersection with Anzar Rd, on the northwestern side of Cannon Road. Rocks exposed at this outcrop are heavily weathered and fractured, with fractures oriented 21/55 SE. The exposed rock is gabbroic in composition (see XRD/TS results below). A 1-2 meter-wide zone that is shattered/pulverized to white powder occurs on the eastern margin of the outcrop (Figure 13), but no clear fault trace is observable. Angular, pebble to small cobble sized gabbroic clasts occur within the white powder matrix.



**Figure 13.** Cannon Road Outcrop. Left image shows largely intact, fractured quartz gabbro. Right image shows pulverized damage zone with angular gabbro clasts floating within white powder matrix.

## Searle Road

Searle Road runs parallel to Highway 101 just north of the Highway 101-Highway 156 intersection in San Benito County, California (as seen on Figures 2 and 5). Approximately 244 meters south of the Anzar-Searle Road intersection, three en echelon road cracks trace across Searle Road (Figure 14).



**Figure 14.** Three en echelon cracks located along Searle Road trend NW/SE showing repeated road repair.



The road cracks are all sub-parallel with a NW/SE orientation ( $317\text{--}336^\circ$ ), and are roughly 55-60 meters apart, with the northernmost road crack roughly 17 meters south of the closest USGS mapped SAF trace (Figure 15).

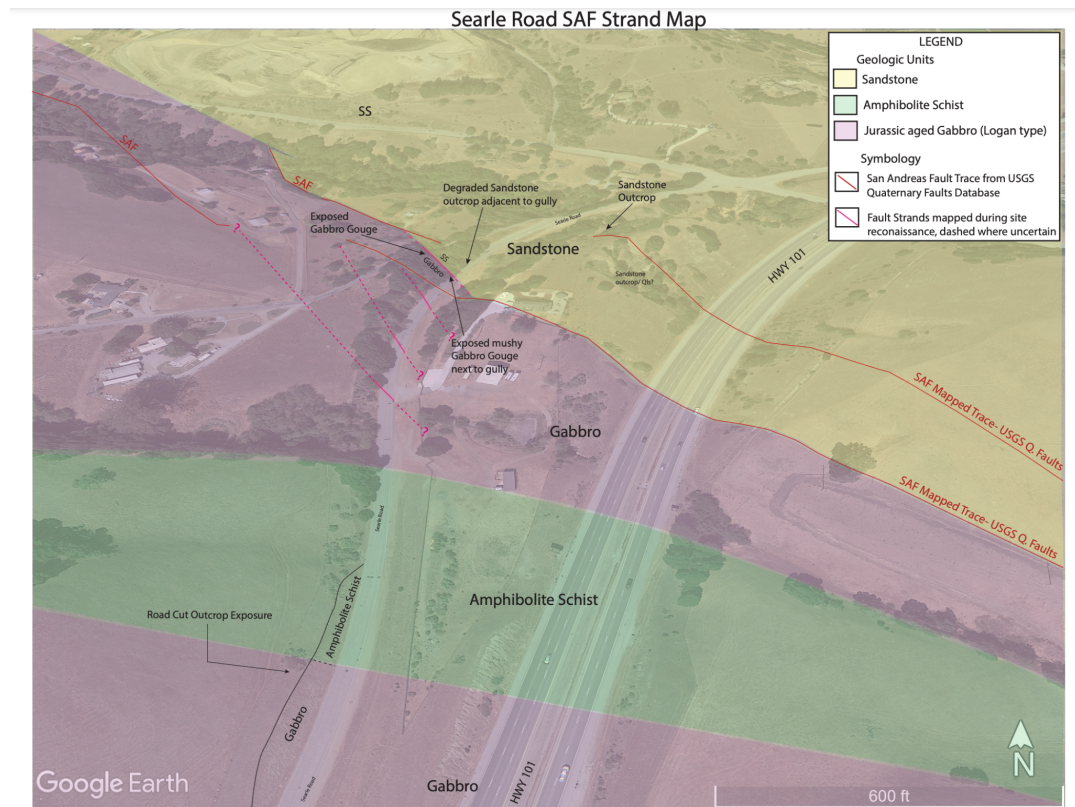


**Figure 15.** Searle Road site map showing USGS mapped SAF trace in solid red, and three en echelon NW/SE trending road cracks in dashed red lines.

Additionally, an exposed outcrop located in a drainage gully southwest of the Searle-Merrill Road intersection, located at  $36.874615, -121.572977$  shows degraded gabbro gouge adjacent to degraded sandstone (Figure 16). Following Searle Road, a quarter mile to the southwest, a road cut exposure displays an amphibolite schist- gabbro contact at  $38.871217, -121.573065$  (Figure 16). The amphibolite schist exposed along Searle Rd appears to be the same schist that is observed at Jim's Quarry. Extending

the schist gabbro contact from Jim's Quarry along strike, it does not align with the observed Searle Rd schist-gabbro contact, however a shear zone does not have to be straight.

The USGS Quaternary faults database shows several mapped San Andreas faults in the vicinity of Searle Rd (Figure 16). The potential fault strands mapped in this study do not coincide with these previously mapped faults (See pink strands mapped on Figure 16) and suggest greater complexity in the SAF structure in this area, or a need to revisit the fault locations in the Quaternary fault database.



**Figure 16.** Searle Road site map with geology and potential SAF strands (in pink). USGS mapped faults are shown in red. Outcrops observed during field reconnaissance are shown with black arrows. (Satellite Base Image from Google Earth Pro 2022).

## Sample Analyses

At each location described above, samples were collected for thin section and mineral analyses. Table 1 is a complete list of the samples and analyses performed.

| Sample ID    | GPS Coordinates       | Field Site   | Description                                                                                           | Analysis     |
|--------------|-----------------------|--------------|-------------------------------------------------------------------------------------------------------|--------------|
| JQ_081321_1  | 36.857670/-121.557390 | Jim's Quarry | Black stained, with, stretched Gabbro?                                                                | XRD          |
| JQ_081321_2  | 36.857540/-122.557400 | Jim's Quarry | Foliated gouge, sheety, orange, fine grained, friable                                                 | XRD          |
| JQ_081321_3  | 36.857700/-122.557460 | Jim's Quarry | More solidified than above, uniform, blocky dark stretched Gabbro, below gouge                        | XRD          |
| JQ_081321_4  | 36.857700/-121.557460 | Jim's Quarry | Gouge above 3, foliated, friable, clay, v.f.g., continues from sample 2                               | XRD          |
| JQ_081321_5  | 36.857731/-121.556950 | Jim's Quarry | Brecciated, white gray damage zone, W side of contact                                                 | XRD          |
| JQ_081321_6  | 36.857731/-121.556980 | Jim's Quarry | Damage zone, NE side of contact, brown/red breccia/gouge, (damage zone width~30m)                     | XRD          |
| JQ_081321_7  | 36.857780/-121.556810 | Jim's Quarry | Dark black, intact, E side of thin sub-vert fault zone                                                | XRD          |
| JQ_081321_8  | 36.857851/-121.556911 | Jim's Quarry | Reddish brown, weird clasty like intact but deformed, further east of sample 7                        | XRD          |
| JQ_081321_9  | 36.857820/-121.556840 | Jim's Quarry | White chalk like stuff, Fizzed under HCl, end of upper quarry samples                                 | XRD          |
| JQ_081321_10 | 36.858020/-121.557910 | Jim's Quarry | Greenish, w of carpark face, 'intact', beneath sheared nose                                           | XRD          |
| JQ_081321_11 | 36.858060/-121.557820 | Jim's Quarry | Brown, hydrothermal/red, altered rock, SW adjacent to 10, loose, crumbled, unconsolidated             | XRD          |
| JQ_081321_12 | 36.857811/-121.557870 | Jim's Quarry | Green with serp looking rock, w. of carpark, sw of hydrothermal sample 11                             | XRD          |
| JQ_081321_13 | 36.857980/-121.557471 | Jim's Quarry | Core of fault, maybe continuous from top to car park?, S end                                          | XRD          |
| JQ_081321_14 | 36.857980/-121.557471 | Jim's Quarry | Brown gouge E of fault, hydrotherm?                                                                   | XRD          |
| JQ_081321_15 | 36.857980/-121.557470 | Jim's Quarry | Grey gouge W of fault, serp?                                                                          | XRD          |
| JQ_081321_16 | 36.857911/-121.557530 | Jim's Quarry | Stretched hornblende                                                                                  | XRD          |
| JQ_081321_17 | 36.858290/-121.557311 | Jim's Quarry | Meta sed rocks? Veined, hi clay (green), soft, friable, old rd cut, chlorite withg?/loc. chlor. pods? | XRD          |
| JQ_081321_18 | 36.858970/-121.558840 | Jim's Quarry | White withd gabbro?, friable, clays                                                                   | XRD          |
| JQ_081321_19 | 36.858900/-121.558780 | Jim's Quarry | Red (hydrotherm.) altd rock, en echelon faulting                                                      | XRD          |
| JQ_081321_20 | 36.858900/-121.558650 | Jim's Quarry | Wedge of dark green, non gabbroic?                                                                    | XRD          |
| JQ_HS_1      | 36.858251/-121.558495 | Jim's Quarry | Logan type gabbro collected by HS                                                                     | TS           |
| JQ_HS_2      | 36.858251/-121.558495 | Jim's Quarry | Logan type gabbro with green rinde collected by HS                                                    | TS           |
| JQ_HS_3      | 36.858251/-121.558495 | Jim's Quarry | Chlorite schist or sepr polytype? cut perpend. to fabric collected by HS                              | TS           |
| JQ_HS_4      | 36.858251/-121.558495 | Jim's Quarry | Chlorite schist? cut perpendicular to fabric collected by HS                                          | TS           |
| JQ_HS_5      | 36.858251/-121.558495 | Jim's Quarry | Chlorite schist? cut perpend. to fabric collected by HS                                               | TS           |
| LQ_1         | 36.902101/-121.614318 | Logan Quarry | Gouge at LQ, 86/61 SW, 20 mm to 80 mm thick at widest, anastomosing, wedge shaped                     | n/a          |
| LQ_2_Perp    | 36.902101/-121.614318 | Logan Quarry | Oriented Gouge (same gouge bed as LQ_1) 90/60 SW, intact gouge, Perpendicular to strike               | XRD, TS, SEM |
| LQ_2_Par     | 36.902101/-121.614318 | Logan Quarry | Oriented Gouge (same gouge bed as LQ_1) 90/60 SW, intact gouge, Parallel to strike                    | XRD, TS, SEM |
| LQ_3         | 36.902101/-121.614318 | Logan Quarry | Sheared/fractured/ chewed up qtz gabbro adjacent to gouge from samples LQ_1&2                         | XRD, TS      |
| LQ_4         | 36.901831/-121.613085 | Logan Quarry | Adjacent to slickenlines, on strike, gouge mess/sheared                                               | XRD, TS      |
| LQ_5         | 36.901610/-121.613228 | Logan Quarry | Brown gouge from wedge shaped fault                                                                   | n/a          |
| LQ_6         | 36.901610/-121.613228 | Logan Quarry | Upper grey gouge in wedge shaped fault, above sample 5, sheared gabbro                                | n/a          |
| LQ_7         | 36.864310/-121.588532 | Cannon Road  | Host rock off Cannon Road, withd gabbro?                                                              | XRD, TS      |
| LQ_8         | 36.880883/-121.588495 | Cannon Road  | White powdered breccia/gouge? (ang. clasts, poss. gabbro, 2" diam., w/in white powder matrix          | XRD          |
| LQ_9         | 36.902101/-121.614318 | Logan Quarry | Host gabbro- Logan type- crystalline, competent                                                       | XRD, TS      |

**Table 1.** Complete sample list showing all samples collected during field reconnaissance activities, sample description, and relevant sample collection location. Final column indicates which samples were subject to X-Ray Diffraction (XRD), Thin Section (TS), and Scanning Electron Microscope (SEM) analysis.

## XRD Results

Bulk rock XRD analysis was performed on samples collected from Jim's Quarry, Logan Quarry, and Cannon Road. Samples from Jim's Quarry yielded

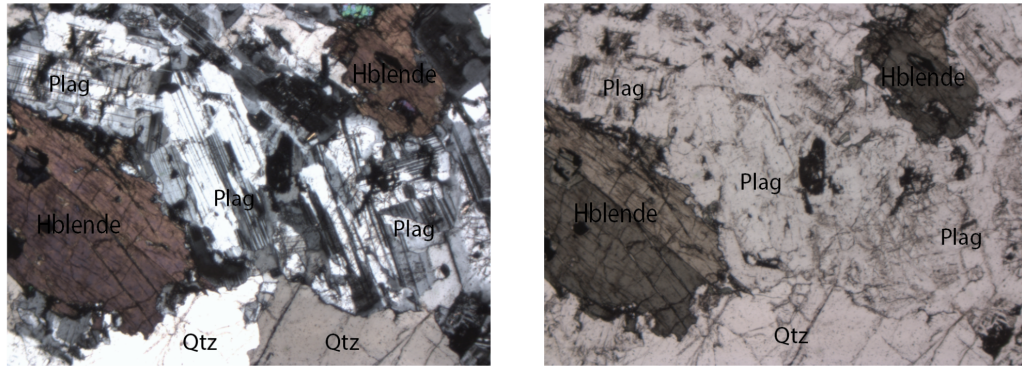
complex XRD patterns that suggested samples were subject to hydrothermal alteration and/or significant weathering. Many samples displayed distinctive low 2-Theta peaks associated with smectite clays, as well as signatures of chlorite group minerals. Traces of gabbroic host rocks with fingerprints of hornblende, plagioclase, and quartz were also observed in Jim's Quarry samples. Samples from Logan Quarry displayed less complex XRD patterns, likely due to the fresh nature of exposures (as Logan Quarry is an active, operational quarry), as well as the lack of any amphibole schist. Host rock gabbro samples from Logan Quarry displayed distinctive gabbroic mineralogy with clear amphibole (primarily as hornblende to Mg-rich hornblende), plagioclase (bytownite, labradorite, and anorthite), and quartz signatures, as well as minor pyroxene (wollastonite, diopside), olivine, and biotite signatures. A semi-quantitative analysis of the Logan gabbro (Sample LQ\_9) yielded a mineral composition of approximately 50% plagioclase, 30% hornblende, 15% quartz, with minor amounts of pyroxene, biotite, and olivine making up the remaining 5%. Gouge samples collected from Logan Quarry also displayed gabbroic mineralogy patterns, likely reflecting the composition of the angular gravel sized clasts of host gabbro observed within the gouge beds. However, the Logan Quarry gouge samples also showed distinctive low 2-theta peaks associated with smectite clays. The Cannon road samples displayed a similar XRD pattern with a gabbroic mineral composition (hornblende, plagioclase, quartz, and minor pyroxene/olivine) as well as phyllosilicate signatures (likely smectite and lepidolite). (There was no significant difference in the mineralogy of the fractured gabbro outcrop and the pulverized to

white powder outcrop at Cannon Road, except for small smectite peaks on the Cannon Road sample, suggesting that the pulverized rock is more altered but still most likely sourced from gabbro. There were also noticeable gabbroic clasts within the white powder, so this may have influenced the XRD results).

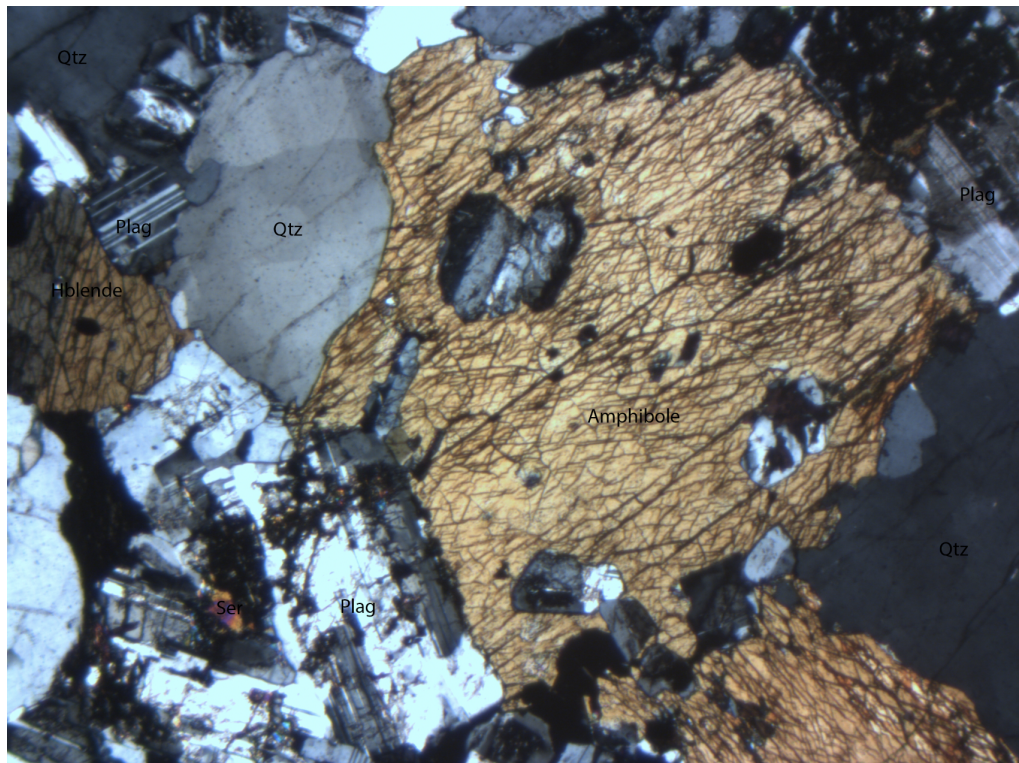
### **Host Rock Microstructural Observations**

Thin sections from Logan Quarry, Jim's Quarry and Cannon Road outcrops displayed distinctive mineralogies. As noted in the Background section, all of the field sites described here are mapped as being within a pod of quartz gabbro (Dibblee et al. 2006; Wagner et al. 2002), but as I noted, there is considerable lithologic complexity due to faulting, hydrothermal alteration, and a previously undescribed amphibole schist. Figures 17.1 and 17.2 below show the dominant mineralogy of Logan-type gabbro observed in samples consisting mainly of plagioclase, hornblende, and quartz. The textures and mineralogy of these samples, which appear unaltered in hand sample, are very similar to previously described samples of Logan gabbro (Ross 1970).



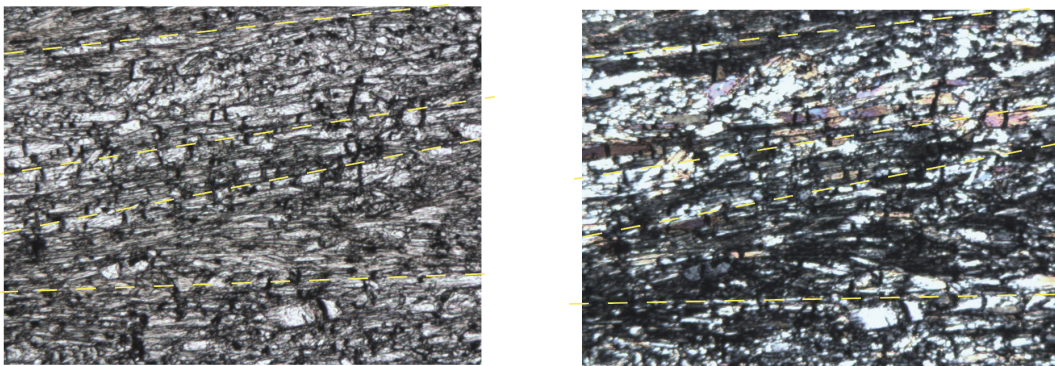


**Figure 17.1** Logan type gabbro in thin section showing plagioclase, amphibole (hornblende), and quartz grains. Image on left is XPL, image on right is PPL. Field of view is approximately 2mm viewed at 1.6X magnification (Sample ID LQ\_9).



**Figure 17.2.** Logan type gabbro (Sample ID LQ\_9) in thin section showing amphibole (hornblende), quartz, and plagioclase grains, as well as localized sericitization of feldspar grains. Field of view is approximately 4mm (3.80 x 2.85 mm) viewed at 1.6X magnification in XPL. Logan type gabbro overall is dominated by plagioclase and amphibole grains with lesser amounts of quartz, and sparse amounts of biotite, pyroxene, and olivine grains.

Figures 18.1 and 18.2 depict the mineralogy and strong foliation fabric of the amphibole schist. To my knowledge, no previous description of a rock like this exists in the literature for the San Juan Bautista region, although an amphibolite unit that has been correlated to a possibly related gabbro body has been documented in the San Emigdio mountains (Nilsen 1984). The amphibole schist is mineralogically similar to the Logan gabbro, with a dominant composition of plagioclase and hornblende. Unlike the gabbro, this incompetent highly friable rock displays a distinct schistose foliation (Figure 18.1 and 18.2). In thin section, the amphibole schist displays highly birefringent grains (hornblende +/- biotite) which appear to display rectangular-tabular boudinage, with clear extensional cracks between grains. Dark fine grains display finer, almost mylonitic fabric, and appear to be flattened plagioclase. As I will return to in the discussion, the mineralogy suggests that the schist is most likely sheared gabbro.

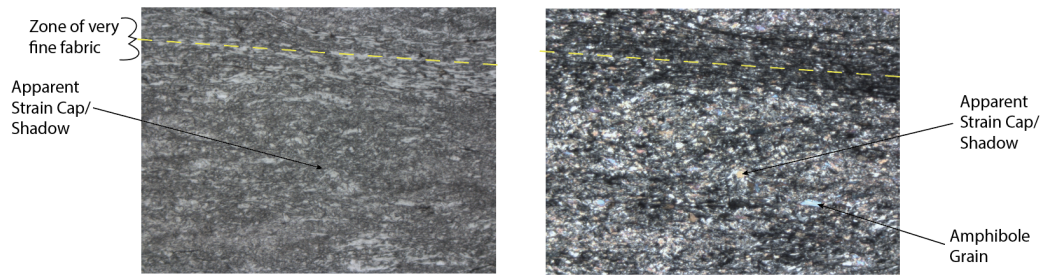


**Figure 18.1.** Amphibole schist from Jim's Quarry in thin section (Sample ID JQ\_HS\_5). PPL on left, XPL on right. Field of view is approximately 0.5 mm in each image, viewed at 5X magnification.

Dashed yellow lines show strong fabric on grain scale. Highly birefringent grains (amphibole or biotite) appear to display rectangular-tabular boudinage, with clear extensional cracks between grains.

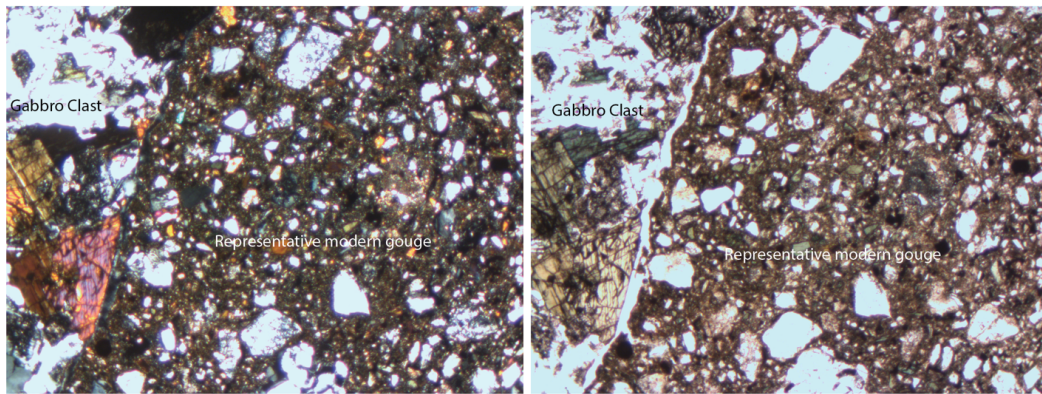
Dark fine grains display finer fabric and appear to be flattened plagioclase.





**Figure 18.2.** Amphibole schist from Jim's Quarry in thin section (Sample ID JQ HS 4). PPL on left, XPL on right. Field of view is approximately 2 mm, viewed at 1.6X magnification. Upper fine fabric of densely aligned smaller grains shows well developed linear fabric, with dashed yellow line showing trend of fabric. Below this zone grains are larger, less well aligned, and show evidence of ductile shear with apparent strain caps and shadows.

Thin sections were also made of intact fault samples from Logan Quarry (LQ2\_Perp, LQ2\_Par). Figure 19 displays a representative gouge sample with poorly sorted sub-angular gabbroic clasts in a matrix composed of clay and comminuted particles of gabbro. Gouge samples also displayed several characteristic microstructures including relic gouge clasts, clay-clast aggregates, micro-grain alignment around larger grains, and brecciation and pulverization of grains. These microstructures will be discussed in more detail in the subsequent section.

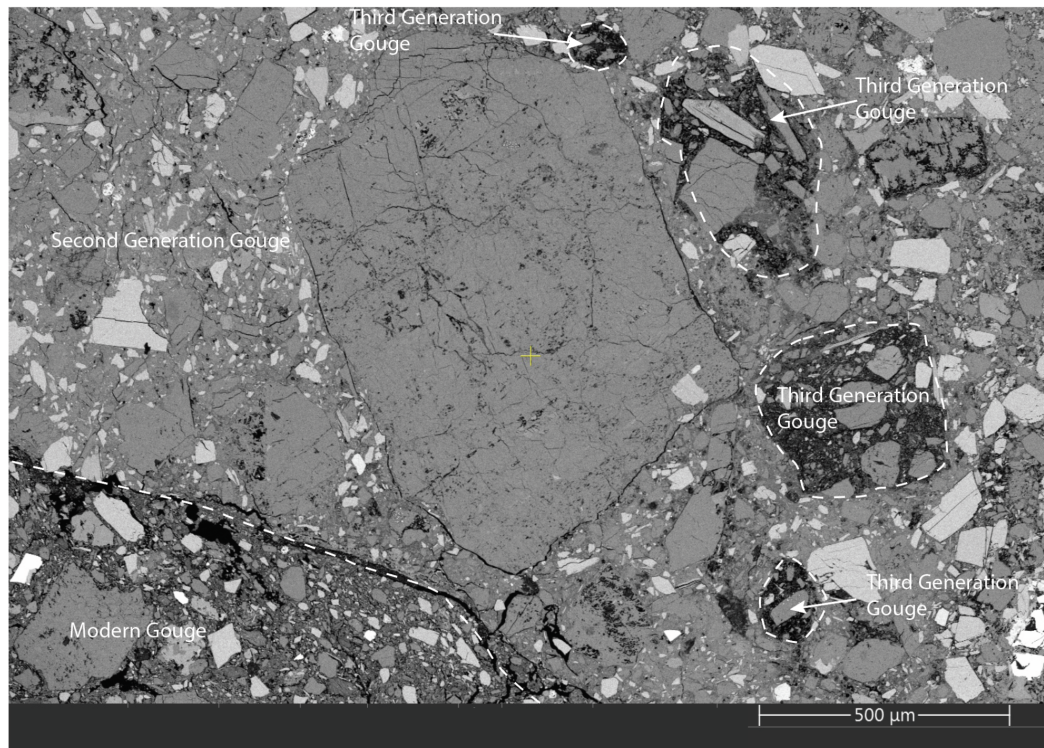


**Figure 19.** Photomicrograph of Logan Quarry gouge displaying a large gabbro clast and a representative modern gouge. XPL on left; PPL on right; viewed at 1.6X magnification. Field of view is approximately 2 mm. (Sample ID LQ2\_Par).

## Fault Gouge Microstructural Observations

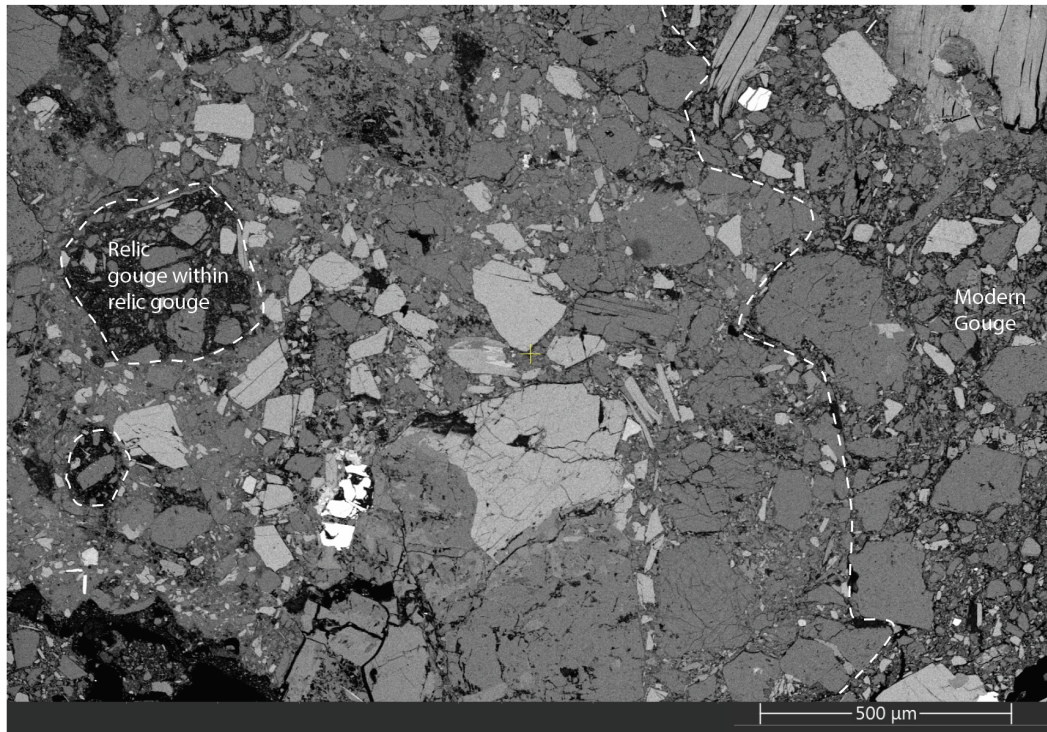
### Generations of gouge

Multiple generations of gouge were observed in the Logan Quarry gouge samples, identified by their variable matrix: clast composition. Within the modern gouge, distinct clasts composed of gouge were noted. In some samples, relict gouge clasts were observed within relict gouge clasts, within the modern gouge, connoting at least three distinct generations of gouge (See SEM Figs. 20.1 and 20.2 and thin section images Figs. 21.1 and 21.2 below). Modern gouge was identified by immature grains and lack of weathering and/or alteration products. Within the modern gouge, clast fragments are angular, poorly sorted, and the matrix clay content is less well developed. Within older relict gouge, clay content is more mature, grains are smaller, and weathering and/or alteration products (e.g., chlorite, smectite, sericite) are present.

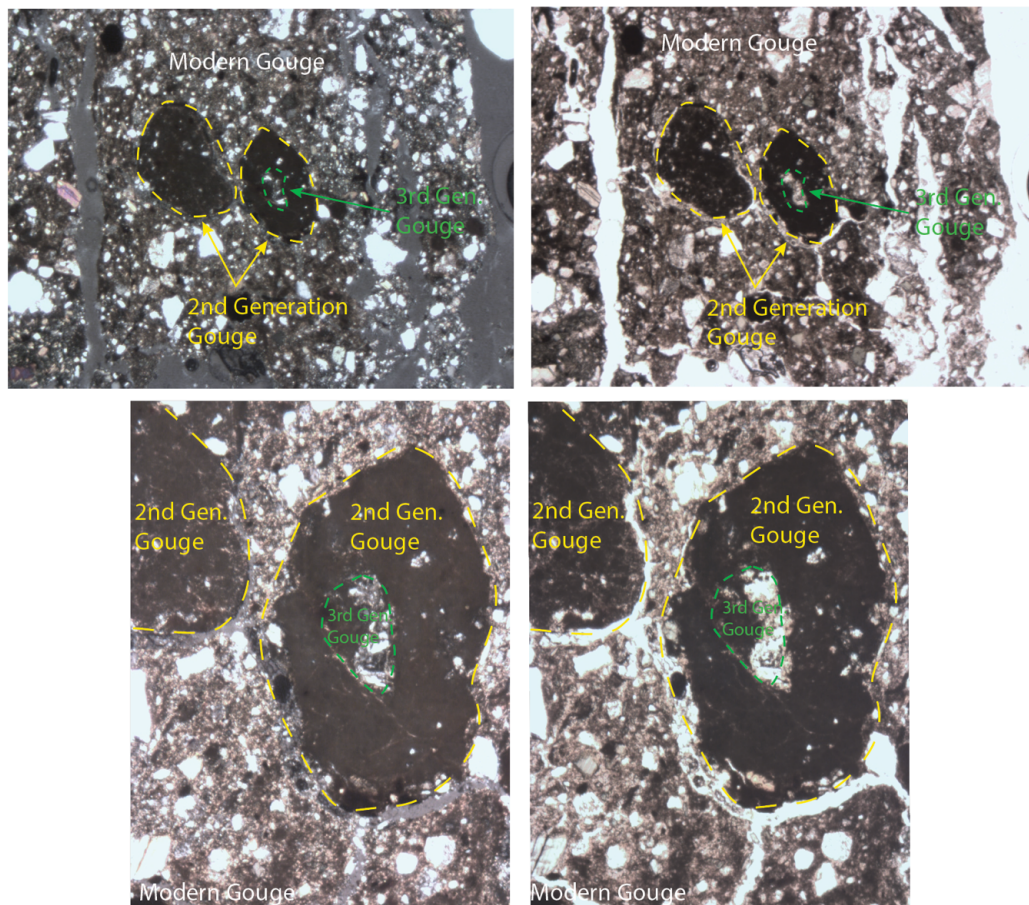


**Figure 20.1** SEM backscatter image of Logan Quarry fault gouge displaying 3 generations of gouge. White dashed lines outline different gouge bodies (Sample ID LQ\_2\_Perp).



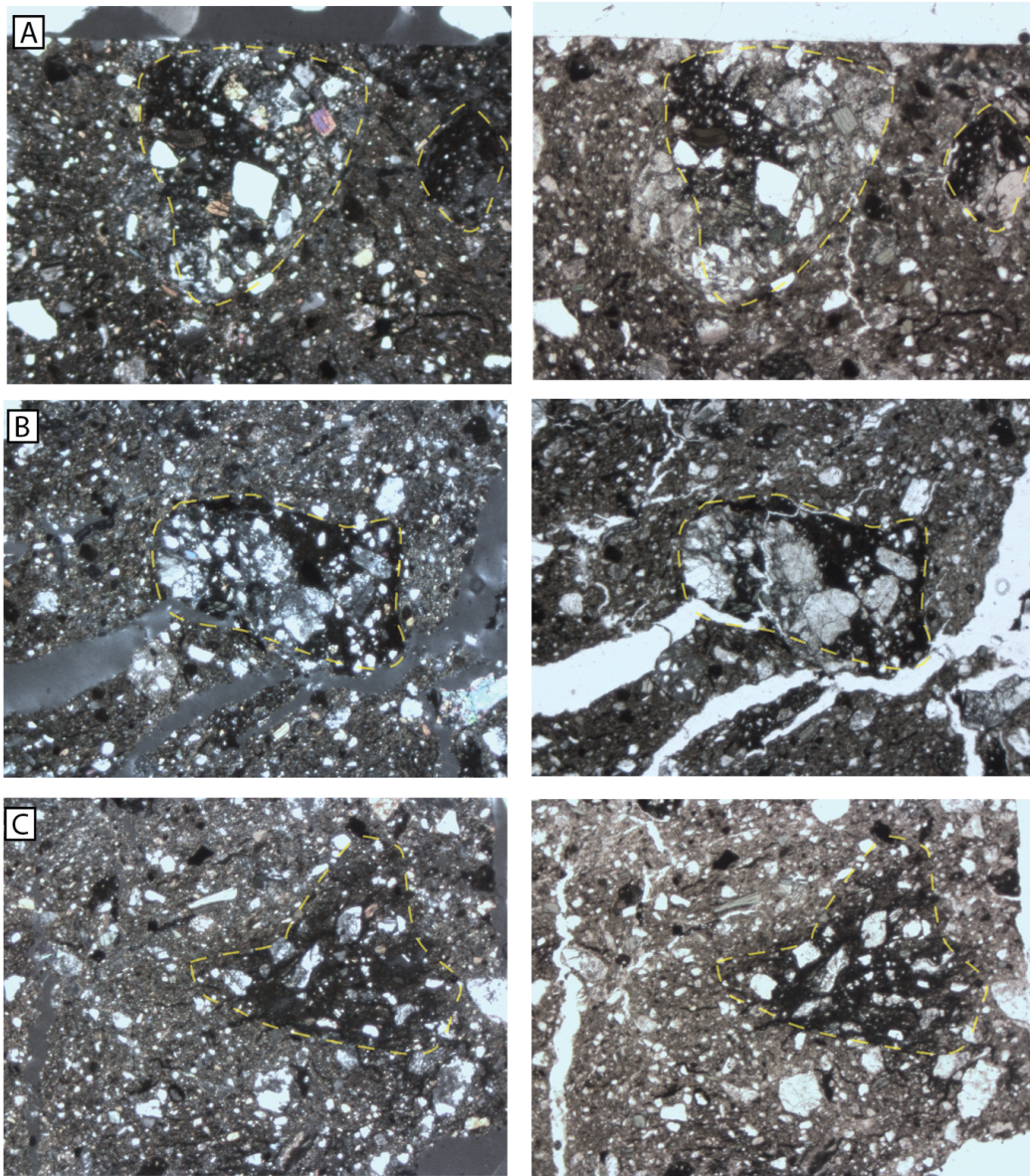


**Figure 20.2** Backscatter SEM Image depicting multiple gouge generations (Sample ID LQ\_2\_Par).



**Figure 21.1** Photomicrograph of Logan Quarry gouge sample showing 3 generations of fault gouge. XPL on left; PPL on right. Upper images are viewed at 1.6X magnification, with approximately 2mm field of view. Lower images are viewed at 5X magnification, with an approximate 0.5mm field of view. (Sample ID LQ2\_Par).



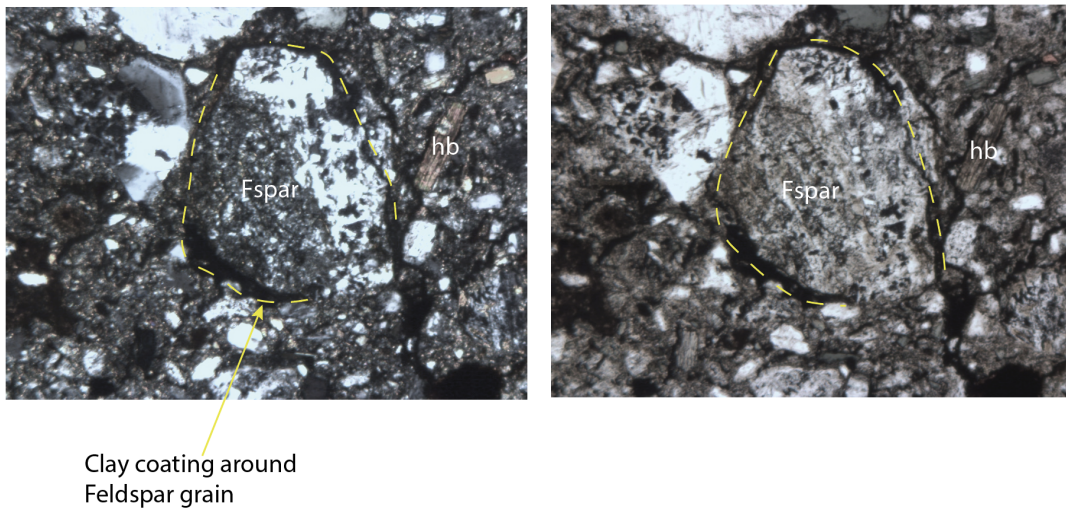


**Figure 21.2** Photomicrograph of Logan Quarry gouge depicting several examples of relict gouge clasts outlined in yellow dashed lines. Image A and B appear to be a similar or contemporaneous relict gouge, while Image C possibly depicts a separate generation of gouge due to greater fine-grained matrix content. XPL on left; PPL on right; viewed at 1.6X magnification. Field of view is approximately 2 mm. (Sample ID LQ2\_Perp).

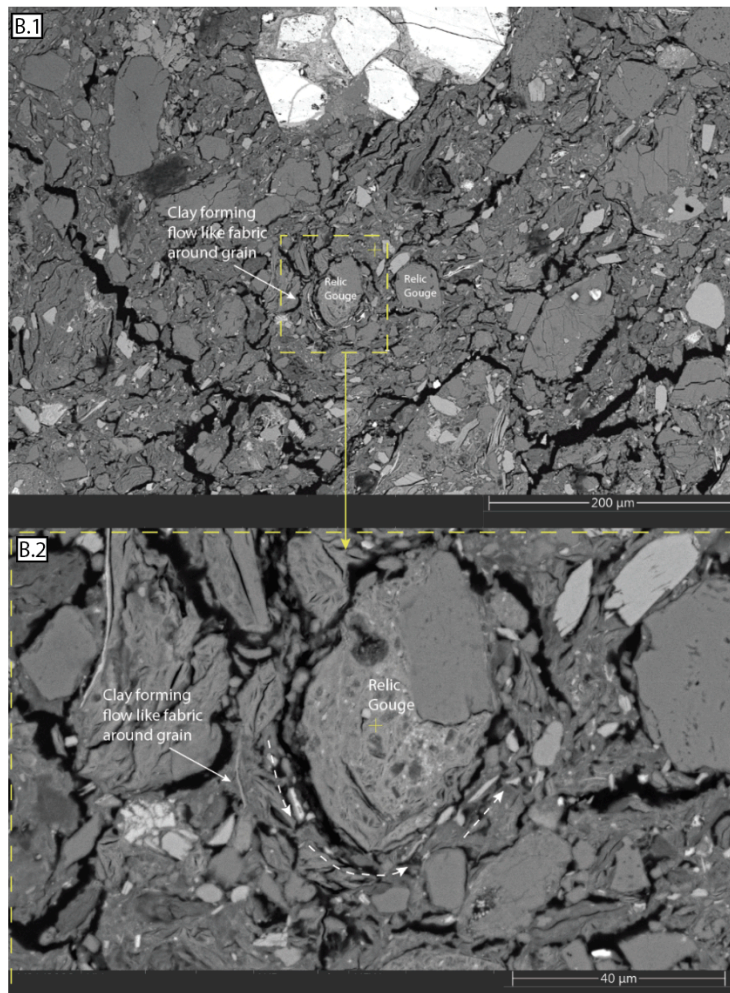
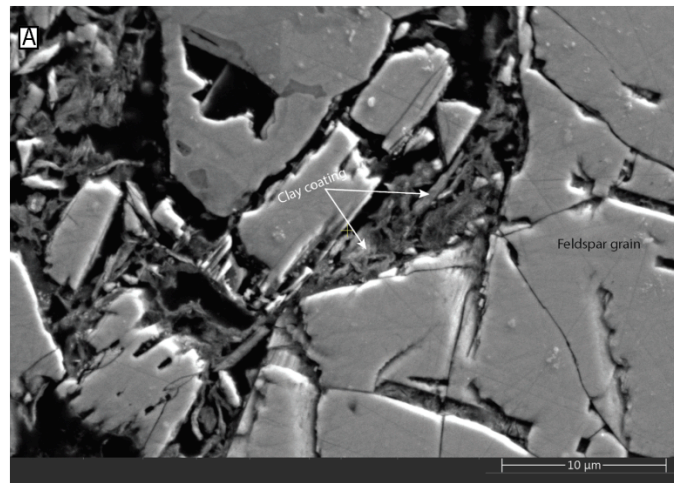


### Clay coatings around grains (aka Clay Clast Aggregates (CCA))

Clay coatings around grains are present in several of the Logan Quarry gouge samples (See Figures 22 and 23 below). Clay (smectite) peaks were recorded in the XRD analysis of the gouge samples, consistent with petrographic observations. Individual clay particles are too small to observe in thin sections, while some clay particles are observable in the SEM backscatter images. Previous work (Boutareaud et al. 2008; Rempe et al. 2014; Han and Hirose 2012) has noted similar structures and attributed the formation of clay coatings to rolling during granular flow.



**Figure 22.** Photomicrograph of Logan Quarry gouge sample depicting clay coating around central large sub-round feldspar grain. XPL on left; PPL on right; viewed at 5X magnification. Field of view is approximately 0.5 mm. (Sample ID LQ2\_Perp).



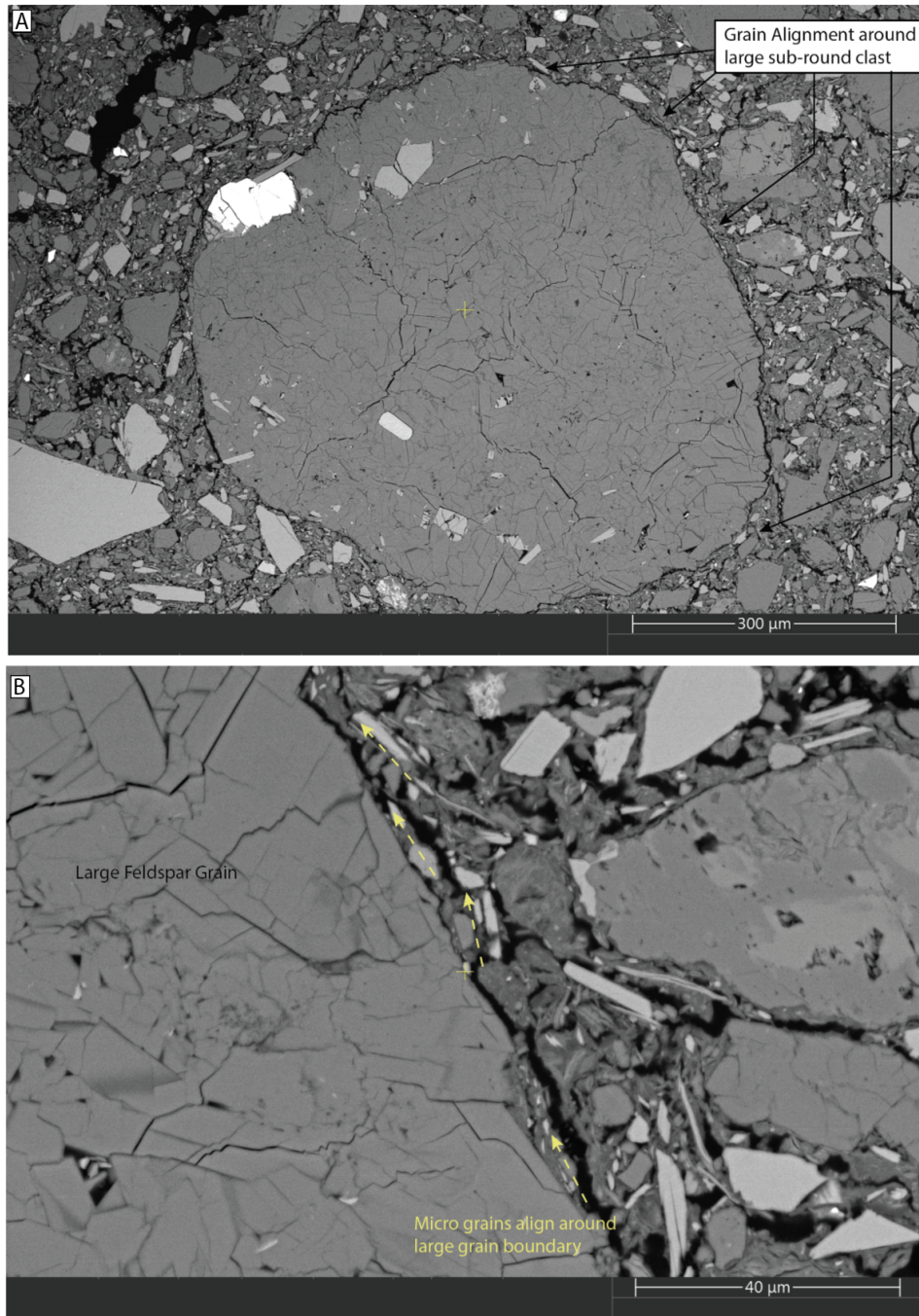
**Figure 23.** Two examples of CCA in SEM. Image A is a backscatter image showing platy clay grains coating large angular feldspar grain. Image B shows clay forming a swirl fabric around relict gouge

grains. B.1 is an overview image, with a yellow dashed box showing the area of focus in B.2 image (Both images from Sample ID LQ\_2\_Par).

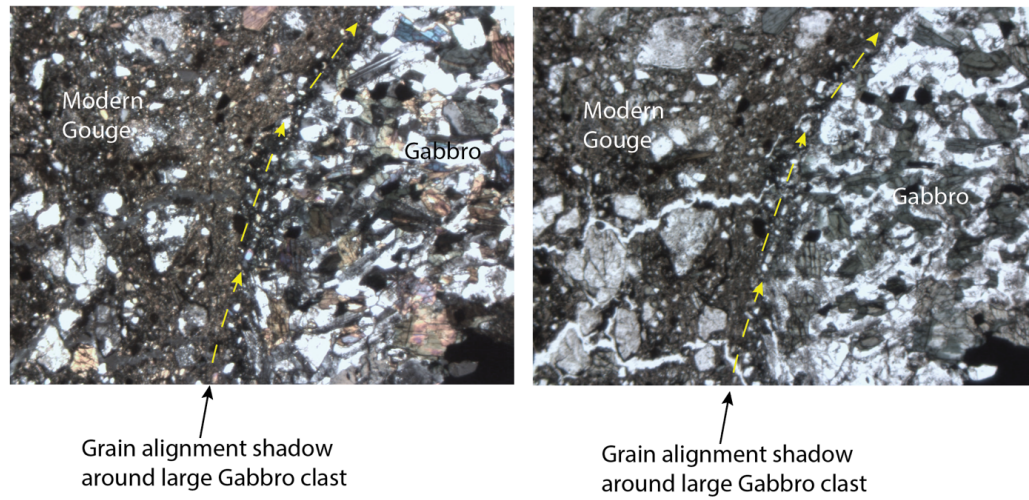
### **Grain alignment**

Micro-grain alignments were observed surrounding larger grains in several of the Logan Quarry gouge samples (Figures 24 and 25 below). This is a more subtle feature than the CCAs. Finer, angular to sub-angular grains can be seen aligning with the edges of larger grain boundaries, as shown in the figures below. Grain alignment has been suggested to occur during grain rotation during shearing (Vrolijk and van der Pluijm 1999). The alignment around clasts suggests that clast rolling during shearing is creating the grain alignment.





**Figure 24.** Backscatter SEM images showing examples of grain alignment. Image A depicts alignment of smaller angular gouge grains around large sub-round grain. Image B depicts matrix micro-grain alignment along a large feldspar grain boundary. Yellow dashed lines show grain alignment (Sample ID LQ\_2\_Perp).

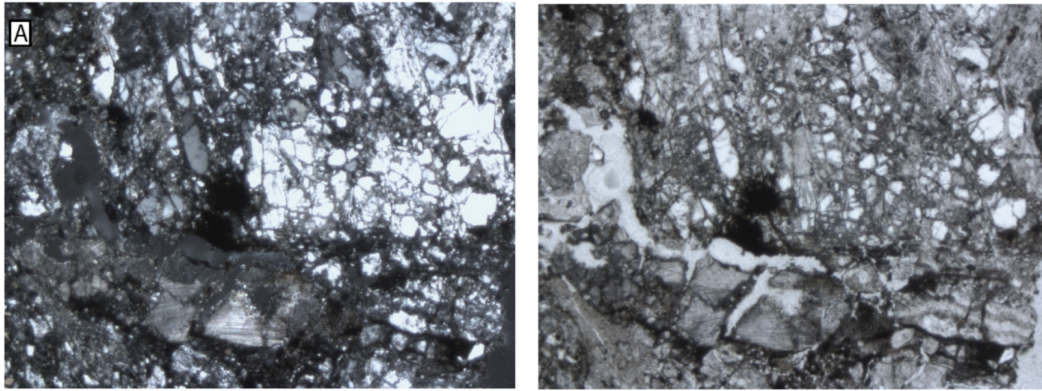


**Figure 25.** Photomicrograph of Logan Quarry gouge showing grain alignment around a large gabbro clast. XPL on left; PPL on right; viewed at 1.6X magnification. Field of view is approximately 2 mm. (Sample ID LQ2\_Par).

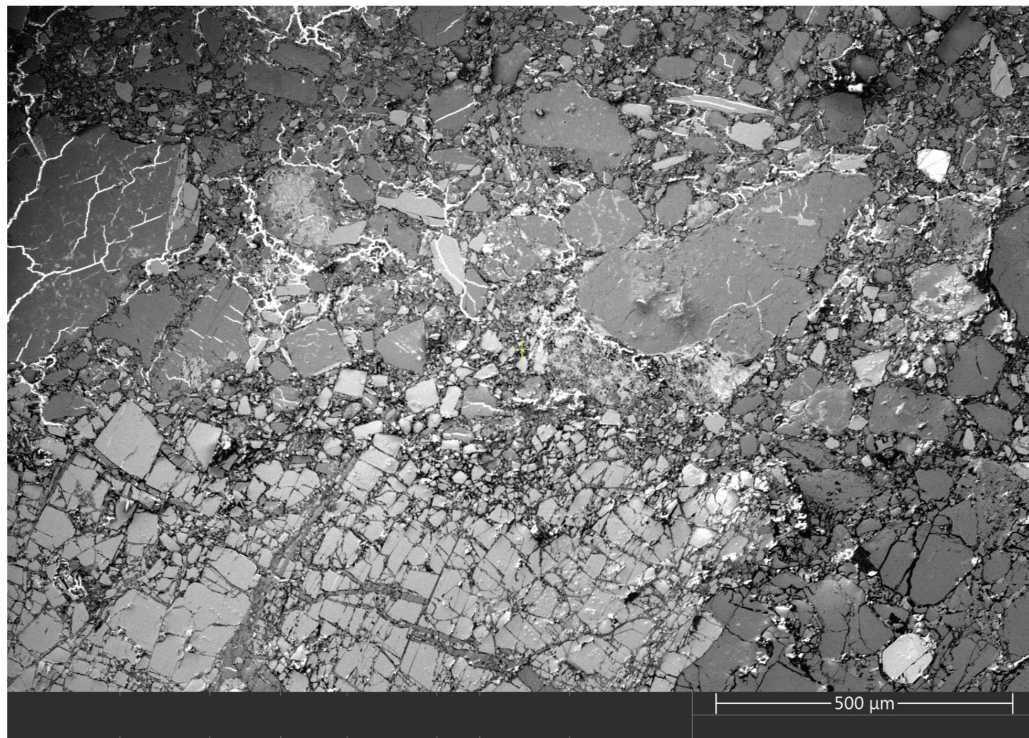
### **Brecciation/Pulverization**

Several instances of grain-scale brecciation occur in the Logan Quarry gouge samples. Grains are shattered into angular small fragments and rotated (Figures 26 and 27). In some cases, the clasts have been pervasively shattered into pieces less than 100  $\mu\text{m}$ , but have not rotated much, i.e., the “puzzle pieces” can be put back together (Figure 27). Such microstructure can be indicative of fault rock pulverization, where the rock is shattered in place due to near wrinkle-like pulses during earthquake propagation (Dor et al. 2006).





**Figure 26.** Photomicrograph of Logan Quarry gouge depicting brecciated grains. Image A depicts brecciated to almost pulverized quartz and feldspar grains. XPL on left; PPL on right; viewed at 1.6X magnification. Field of view is approximately 2 mm\*. (Sample ID LQ2\_Perp).



**Figure 27.** Backscatter SEM image showing brecciated amphibole grain, possibly pulverized? From Logan Quarry gouge (Sample ID LQ2\_Par).

## **Discussion**

### **Shallow fault structure exposed near San Juan Bautista**

Fault structure observed at the various field sites in the SJB vicinity provide potential evidence for both seismic and aseismic activity along the SAF system. Surface exposures observed at both Jim's Quarry and Logan Quarry suggest that many fault strands dip at around  $\sim 60^\circ\text{SW}$ , whereas the main strand at depth is thought to dip closer to  $80^\circ\text{SW}$ . Shallowly dipping fault strands could be parts of a flower structure in a strike-slip regime such as the SAF (Sylvester 1988). However, in the case of the faults exposed in the quarries, the faults are dipping away rather than towards the mapped main strands of the SAF. Subsurface data from a recent drilling project indicate that the creeping SAF faults along Searle Rd. also dip to the southwest at approximately  $50\text{-}55^\circ$ . In a classic transpressional or transtensional flower structure, faults would dip northeast back toward the main mapped SAF traces. As these documented faults dip SW, sub-parallel to the main SAF trace, they cannot be part of a flower structure.

### **Microstructural Evidence of Seismic Slip**

Several faults in this study show microstructures that suggest seismic slip. Pulverized gabbro observed at Cannon Road displays intense shattering that could be due to propagating earthquake slip, as seen along the southern San Andreas fault near Fort Tejon (Dor et al. 2006). The pulverization seen here is more likely to occur in crystalline rocks with high seismic velocities (Mitchell et al. 2011; Dor et al. 2006),

such as would be expected in the unaltered quartz gabbro in this area. Because the pulverized rock is not highly weathered, this texture could be related to the 1906 rupture.

Microstructures observed in gouge samples from Logan Quarry also suggest cyclic fracturing behavior, which is also more indicative of earthquake slip and healing phases. The multiple distinct generations of gouge observed in thin section and SEM imagery record multiple cycles of gouge formation, lithification, and cataclasis. Observations of clay coatings around grains (CCA) also suggest that these faults failed seismically. These spherical clay-clast aggregates have been shown to form in crustal clayey fault gouges and suggest relatively fast slip, as grains and clay were tumbling around at a significant speed for the clay to wrap around the grain (Boutareaud et al. 2008). However, subsequent experiments have shown that CCAs can be formed at sub-seismic velocities when faults are dry and at very low normal stresses ( $<5$  MPa; Han and Hirose 2012; Rempe et al. 2014), but these experiments might not apply to the faults discussed here for several reasons. Taking into the constraints from above, without the presence of water to create lower effective normal stress, this would suggest that CCAs could only form at slower velocities in the top 200 m of a fault. Furthermore, documented experiments were conducted at  $100\text{ }\mu\text{m/s}$  and faster, which although far from earthquake slip rates, is still faster than transient slow slip events in most cases. Finally, the regional water table at Logan Quarry is located within the sediments above the crystalline gabbro basement rocks, meaning that water is most likely present in the fault zone. Therefore, I suggest that

CCAs in this case are related to granular flow of the fault gouge during earthquakes that rolled grains allowing them to build a clay coating. Although I do not have direct evidence of earthquake slip along these faults from frictional heating (e.g., pseudotachylyte; Cowan 1999), the microstructural evidence presented here points towards the Logan Quarry and Cannon Rd. faults behaving seismically: There is no evidence of current creep (fractured roads, offset features) at these faults.

XRD analysis confirmed the presence of smectite clays in the gouge samples. The smectite CCA coating, as well as the micrograin-alignment around larger grains suggest that clays were forming as the fault was active. If the clays were growing authigenically without the fault moving, the clays would not show a preferential alignment around grains. The presence of smectite participating in deformation is indicative of active shallow faulting, as it generally only remains stable at low temperature conditions associated with the shallow crust (Ahn and Peacor 1986) (Huang et al. 1993) (Vrolijk and van der Pluijm 1999).

### **Seismicity**

Frequent earthquakes of M3 or less define the main fault strand in this region, and suggest that at depth, the SAF dips more steeply than the strands we observe at the surface. Figure 4 shows that the best-fit plane dips  $\sim 80^\circ$ . However, the projected surface trace from this plane is mis-located west of Jim's Quarry by about 1 km from the mapped surface trace. The absolute horizontal and vertical errors on the earthquakes in this region are  $\sim 0.2$  and 0.4 km, respectively, which could improve the

trace location but not quite explain this discrepancy. It is possible that the large gabbro body pulls apparent locations to the west, as velocities are faster in crystalline rock, however velocity structure may not be adequately captured in 3D in such a complexly faulted area, and absolute location errors could be larger than what is reported. Shallower dipping faults like those I map at the field area would align more closely with the trace location. In the relocated catalog, there have been very few shallow earthquakes (above 2 km) so this region cannot be delineated through earthquakes.

## **Conclusion**

Structural observations in the northern transition zone of the SAF show that the fault is a complex zone of multiple strands that mostly tend to dip to the southwest. Three strands show evidence of fault creep at Searle Rd, which is the northernmost evidence of fault creep along the San Andreas fault documented to date. Other SAF strands within the study area show no evidence of current (or recent) creep and microstructurally suggest pulverization and cyclic failure, which points to these faults more likely being seismic. Such observations support the conclusion that the transition from creeping to locking can happen in piecemeal along faults, and at least in the case here, does not seem to be related to changes in lithology or stress conditions, since most of the faults have similar orientations and the same lithology is seen in both creeping and locked strands.



## References

- Ahn, J.H., and D.R. Peacor, 1986. Transmission and Analytical Electron Microscopy of the Smectite-To-Illite Transition. *Clays Clay Miner.* 34, 165–179.
- Atwater, Tanya, 1970. Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of Western North America. *GSA Bulletin*; 81 (12): 3513–3536.
- Bailey, E. H., Blake M.C., Jr., and Jones, D. L. (1970). “On-land Mesozoic oceanic crust in California Coast Ranges”. *U.S. Geological Survey Professional Paper*. 700-C: C70-C81.
- Billham, Roger. 2007. "Continued Measurement of Fault Creep in the San Francisco Bay Area, and Continued Measurement of Creep and Long-Baseline Deformation in Southern and Northern California". USGS Award 04HQAG0008, Final Technical Report. doi/10.1.1.590.7302.
- Billham, Roger. (2011). ‘Nyland Ranch, San Andreas Fault Creepmeter Data’. Department of Geological Sciences, University of Colorado, Boulder. <[http://cires1.colorado.edu/~bilham/CREEPDATA/coNR\\_NylandRanch/Nyland.html](http://cires1.colorado.edu/~bilham/CREEPDATA/coNR_NylandRanch/Nyland.html)>
- Boutareaud, S., D.-G. Calugaru, R. Han, O. Fabbri, K. Mizoguchi, A. Tsutsumi, and T. Shimamoto (2008), ‘Clay-clast aggregates: A new textural evidence for seismic fault sliding?’, *Geophys. Res. Lett.*, 35, L05302, doi:10.1029/2007GL032554.
- Bradbury, Kelly K., James P. Evans, Judith S. Chester, Frederick M. Chester, and David L. Kirschner, 2011. ‘Lithology and internal structure of the San Andreas fault at depth based on characterization of Phase 3 whole-rock core in the San Andreas Fault Observatory at Depth (SAFOD) borehole.’, *Earth and Planetary Science Letters*, Volume 310, Issues 1–2, Pages 131-144, ISSN 0012-821X, <https://doi.org/10.1016/j.epsl.2011.07.020>.
- Carpenter, B., Marone, C. & Saffer, D. (2011). Weakness of the San Andreas Fault revealed by samples from the active fault zone. *Nature Geosci* 4, 251–254 (2011). <<https://doi.org/10.1038/ngeo1089>>.
- Coffey, Genevieve L., Heather M. Savage, Pratigya J. Polissar, Stephen E. Cox, Sidney R. Hemming, Gisela Winckler, and Kelly K. Bradbury. 2022. History of earthquakes along the creeping section of the San Andreas fault, California, USA. *Geology*; 50 (4): 516–521. doi: <https://doi.org/10.1130/G49451.1>

- Cowan, Darrel S. (1999). "Do faults preserve a record of seismic slip? A field geologist's opinion." *Journal of Structural Geology*, Volume 21, Issues 8–9, Pages 995-1001, ISSN 0191-8141, [https://doi.org/10.1016/S0191-8141\(99\)00046-2](https://doi.org/10.1016/S0191-8141(99)00046-2).
- Dibblee, T. W. (Thomas Wilson), et al. *Geologic Map of the Prunedale & San Juan Bautista Quadrangles, Monterey & San Benito Counties, California*. Santa Barbara Museum of Natural History, 2006.
- Dickinson, W. R., and Snyder, W. S. (1979), Geometry of triple junctions related to San Andreas Transform, *J. Geophys. Res.*, 84(B2), 561– 572, doi:10.1029/JB084iB02p00561.
- Dor, Ory, Yehuda Ben-Zion, Thomas K. Rockwell, and Jim Brune. (2006). "Pulverized rocks in the Mojave section of the San Andreas Fault Zone." *Earth and Planetary Science Letters*, Volume 245, Issues 3–4, Pages 642-654, ISSN 0012-821X, <https://doi.org/10.1016/j.epsl.2006.03.034>.
- Han, Raehee and Takehiro Hirose (2012). "Clay–clast aggregates in fault gouge: An unequivocal indicator of seismic faulting at shallow depths?" *Journal of Structural Geology*, Volume 43, Pages 92-99, ISSN 0191-8141, <https://doi.org/10.1016/j.jsg.2012.07.008>.
- Harris, R. A. (2017), Large earthquakes and creeping faults, *Rev. Geophys.*, 55, 169-198, doi:10.1002/2016RG000539.
- Hirao, B., Savage, H., & Brodsky, E. E. (2021). Communication between the northern and southern central San Andreas Fault via dynamically triggered creep. *Geophysical Research Letters*, 48, e2021GL092530. <https://doi.org/10.1029/2021GL092530>.
- Holdsworth, R.E., E.W.E. van Diggelen, C.J. Spiers, J.H.P. de Bresser, R.J. Walker, L. Bowen (2011). Fault rocks from the SAFOD core samples: Implications for weakening at shallow depths along the San Andreas Fault, California. *Journal of Structural Geology*, Vol. 33, Iss. 2: p. 132-144, ISSN 0191-8141, <<https://doi.org/10.1016/j.jsg.2010.11.010>>.
- Hopson, C.A., Mattinson, J.M., and Pessagno, E.A., Jr., 1981, Coast Range ophiolite, western California, in Ernst, W.G., ed., *The geotectonic development of California* (Rubey volume I): Englewood Cliffs, N.J. Prentice-Hall. 418-510.

- Huang, W.L., J.M. Longo, & D.R. Pevear, 1999. An Experimentally Derived Kinetic Model for Smectite-to-Illite Conversion and Its Use as a Geothermometer. *Clays Clay Miner.* 41, 162–177.
- Irwin, William P. and Ivan Barnes (1975). Effect of geologic structure and metamorphic fluids on seismic behavior of the San Andreas fault system in central and northern California. *Geology*, 3 (12): 713–716. doi: <https://doi.org/10.1130/0091-7>.
- Irwin, W.P., 1990. “Geology and Plate-Tectonic Development”. *U.S. Geological Survey Professional Paper*. Vol. 1515. 61-77.
- Lachenbruch, A. H., and Sass, J. H. (1980), Heat flow and energetics of the San Andreas Fault Zone, *J. Geophys. Res.*, 85( B11), 6185– 6222, doi:10.1029/JB085iB11p06185.
- Larson, Roger L., H.W. Menard, and S.M. Smith, 1968. “Gulf of California: A Result of Ocean-Floor Spreading and Transform Faulting”. *Science*. Vol. 161 Iss. 3843: 781-784. doi:10.1126/science.161.3843.781.
- Lockner, D., Morrow, C., Moore, D. *et al.* (2011). Low strength of deep San Andreas fault gouge from SAFOD core. *Nature* 472, 82–85. <https://doi.org/10.1038/nature09927>
- Mitchell, T.M., Y. Ben-Zion, and T. Shimamoto, 2011. Pulverized fault rocks and damage asymmetry along the Arima-Takatsuki Tectonic Line, Japan. *Earth and Planetary Science Letters*, 308, 284-297. doi:10.1016/j.epsl.2011.04.023
- Moore, Diane & Rymer, Michael. (2007). Talc-bearing serpentinite and the creeping section of San Andreas Fault. *Nature*. 448. 795-7. 10.1038/nature06064.
- Nilsen, Tor H., 1984. Offset along the San Andreas fault of Eocene strata from the San Juan Bautista area and western San Emigdio Mountains, California. *GSA Bulletin* 1984; 95 (5): 599–609. doi: <https://doi.org/10.1130/0016-7606>.
- Rempe, Marieke, Steven A.F. Smith, Fabio Ferri, Thomas M. Mitchell, and Giulio Di Toro (2014). “Clast-cortex aggregates in experimental and natural calcite-bearing fault zones.” *Journal of Structural Geology*, Volume 68, Part A, Pages 142-157, ISSN 0191-8141, <https://doi.org/10.1016/j.jsg.2014.09.007>.
- Ross, Donald C., 1970. Quartz Gabbro and Anorthositic Gabbro: Markers of Offset along the San Andreas Fault in the California Coast Ranges. *GSA Bulletin*; Vol. 81 Iss. 12: 3647-3662.

- Scuderi, M., and Collettini, C. 2016. ‘The role of fluid pressure in induced vs. triggered seismicity: insights from rock deformation experiments on carbonates’. *Sci Rep* 6, 24852. <https://doi.org/10.1038/srep24852>
- Sieh, K., 1978. ‘Slip along the San Andreas Fault associated with the great 1857 earthquake.’ *Bulletin of the Seismological Society of America*, Vol. 68. No. 5, pp.1421-1428. doi:<https://doi.org/10.1785/BSSA0680051421>.
- Skarbek, R. (2021), Shallow slow slip events can nucleate on velocity-strengthening thrust faults, Abstract MR35A-0095, AGU 2021 Fall Meeting, 13 - 14 Dec., doi: 10.1002/essoar.10509521.1.
- Spudich, P., 1996. The Loma Prieta, California, Earthquake of October 17, 1989- Main Shock Characteristics. USGS Professional Paper 1550-A. Denver, CO. p. A1-A7.
- Sylvester, Arthur G. (1988). Strike-slip faults. *GSA Bulletin*, Vol.100 No.11, pp.1666-1703. doi: [https://doi.org/10.1130/0016-7606\(1988\)100<1666:SSF>2.3.CO;2](https://doi.org/10.1130/0016-7606(1988)100<1666:SSF>2.3.CO;2)
- Taira, T., Bürgmann, R., Nadeau, R. M., and Dreger, D. S. (2014), Variability of fault slip behavior along the San Andreas Fault in the San Juan Bautista Region, *J. Geophys. Res. Solid Earth*, 119, 8827– 8844, doi:10.1002/2014JB011427.
- Thatcher, W., Marshall, G., and Lisowski, M. (1997), Resolution of fault slip along the 470-km-long rupture of the great 1906 San Francisco earthquake and its implications, *J. Geophys. Res.*, 102 (B3), 5353– 5367, doi:10.1029/96JB03486.
- Titus, Sarah J., Charles DeMets, Basil Tikoff (2006). Thirty-Five-Year Creep Rates for the Creeping Segment of the San Andreas Fault and the Effects of the 2004 Parkfield Earthquake: Constraints from Alignment Arrays, Continuous Global Positioning System, and Creepmeters. *Bulletin of the Seismological Society of America* 2006; 96 (4B): S250–S268. doi: <https://doi.org/10.1785/0120050811>.
- University of California, Santa Cruz (UCSC). “Geochemical and Rock Analysis: X-Ray Diffraction.” *UCSC Earth and Planetary Sciences*. Accessed September 2021. <<https://eps.ucsc.edu/research/facilities/geochem-rock.html>>.
- U.S. Geological Survey (USGS), Earthquake Hazards Program, 2017, Advanced National Seismic System (ANSS) Comprehensive Catalog of Earthquake Events and Products: Various, <https://doi.org/10.5066/F7MS3QZH>.

United States Geological Survey (USGS), 'Quaternary fault and fold database of the United States' USGS Earthquake Hazards. Accessed May 2022.

<https://earthquakes.usgs.gov/hazards/qfaults>.

Vrolijk, Peter and Ben A. van der Pluijm, 1999. "Clay Gouge." *Journal of Structural Geology*, Vol. 21, Iss. 8–9, pp.1039-1048.

Waldhauser, F. and D.P. Schaff (2008), Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res.*, 113, B08311, doi:10.1029/2007JB005479. Catalog accessed July 2022. <<https://www.ldeo.columbia.edu/~felixw/NCAeqDD/>>

Wagner, D.L., H.G. Greene, G.J. Saucedo, C.L. Pridmore, 2002, *Geologic map of the Monterey 30' x 60' quadrangle, California*: California Geological Survey. 3051960.

Watt, J. T., Ponce, D. A., Graymer, R. W., Jachens, R. C., and Simpson, R. W. (2014), Subsurface geometry of the San Andreas-Calaveras fault junction: Influence of serpentinite and the Coast Range Ophiolite, *Tectonics*, 33, 2025–2044, doi:10.1002/2014TC003561.

Zoback, M. D., Zoback, M. L., Mount, V. S., Suppe, J., Eaton, J. P., Healy, J. H., Oppenheimer, D., Reasenber, P., Jones, L., Raleigh, C. B., Wong, I. G., Scotti, O., & Wentworth, C. (1987). New Evidence on the State of Stress of the San Andreas Fault System. *Science*, 238(4830), 1105–1111.

Zoback, Mark, Stephen, Hickman, & William Hickman. (2010). Scientific Drilling into the San Andreas Fault Zone. *Eos, Transactions American Geophysical Union*. 91. 197-199. 10.1029/2010EO220001.