How Fault Rocks Form and Evolve in the Shallow San Andreas Fault

Randolph T. Williams1,2, Christie D. Rowe3, Kristina Okamoto3, Heather M. Savage1, and Erin Eves3

1Earth & Planetary Sciences Department, McGill University, Montréal, QC, Canada, 2Now at Department of Geoscience, University of Wisconsin-Madison, Madison, WI, USA, 3Earth & Planetary Science, University of California Santa Cruz, Santa Cruz, CA, USA

Abstract

We document the mechanical and geochemical processes of fault rock development in the shallow San Andreas fault (Mojave segment), and quantify their importance in shaping the mineralogy, grain size, fabric, and frictional characteristics of gouge. Through a combination of field and laboratory analysis of an extensive suite of shallow (<150 m) drill cores, we show that fault rocks evolved from a granodiorite protolith via three main processes: distributed microfracturing/pulverization; cataclastic flow and incipient fabric development; and production of authigenic illite/smectite during fluid-rock interaction. The interdependence of these mechanical and geochemical processes results in a diverse suite of fault rocks, and causes significant changes in frictional strength. Spatial variations in the effects of these mechanisms, as manifested in fault-rock mineralogy and geochemistry, indicate marked variations in their relative contribution to fault-rock evolution. These data reveal a complex San Andreas fault with multiple principal slip zones and damaged and altered rock hosting numerous interconnected secondary slip surfaces. The resulting picture of the San Andreas Fault zone suggests a substantial departure from the simple structures envisioned for near-surface seismogenenic faults in numerical models is required, and may inform future efforts to forecast peak ground accelerations during southern California earthquakes.

1. Introduction

The physical properties of fault rocks govern the stability and strength of upper crustal faults in addition to the magnitude and distribution of radiated energy during earthquakes (e.g., Berryman, 2007; Bolton et al., 2017; Colletti et al., 2009; Di Toro et al., 2011; Kirkpatrick et al., 2015; Niemeyer et al., 2012; Peacock et al., 1994; Scudery et al., 2017; Sibson, 1977). These properties change through time as fault rocks evolve and protolith is progressively transformed to fault gouge. The factors governing this transition are vast, and include a combination of mechanical and geochemical processes (Vrolijk & van der Pluim, 1999). The mechanical processes governing fault-rock evolution (i.e., distributed microcracking, granular/cataclastic flow, dilatant fracturing) have been the focus of many laboratory deformation experiments and numerical models (e.g., Hadizadeh et al., 2015; Marone & Scholz, 1989; Nguyen & Einav, 2009; Sammis et al., 1986; Stunitz et al., 2009). The geochemical reactions contributing to gouge formation (i.e., dissolution, alteration, and authigenic mineral growth) have received similarly large amounts of attention, particularly where they lead to the formation of frictionally weak phyllosilicates (e.g., Ikari et al., 2018; Lockner et al., 2011; Moore & Lockner, 2007; Schleicher et al., 2010; Solum & van der Pluim, 2009; Tembe et al., 2010). Both mechanical and geochemical processes are controlled by the mineralogy of the protolith material in addition to the temperature, pressure, fluid availability/composition, and strain rate/magnitude conditions of deformation (Aben et al., 2016; Moore, 2014; Rowe & Griffith, 2015; Schleicher et al., 2015; Tenthorey et al., 2003). Thus, the mechanical and geochemical mechanisms governing the evolution of fault-rock properties are interrelated, and critically, the spatial and temporal scales of their interaction cannot be fully replicated in laboratory experiments.

Although fault rocks throughout the seismogenic crust must exert some effect on earthquake physics, those in the near surface of seismogenic faults are likely of particular importance for seismic hazards. For example, it has long been hypothesized that the velocity-strengthening behavior of shallow fault gouge contributes to the deceleration and arrest of earthquake rupture as it approaches the surface (Scholz, 1998). More recent numerical models also demonstrate that long-period ground motions during large earthquakes...
may be strongly mediated by near-surface plastic yielding within fault zones (Lapusta et al., 2019; Milliner et al., 2015; Roten et al., 2014, 2017, 2018) which is largely dependent on the mechanical properties and distribution of shallow fault rocks. These same mechanical properties may also dictate the propensity for the shallow-slip deficits commonly observed during earthquakes associated with large, strike-slip faults (Kaneko & Fialko, 2011). Although the mechanical properties and structure of seismogenic faults in the near-surface have received increased attention in recent years (e.g., Dorsey et al., 2021; Nevitt et al., 2020; Ponti et al., 2020; Ostermeijer et al., 2020; Share et al., 2020; Upton et al., 2018), they remain poorly understood in comparison to their deeper counterparts. The paucity of data concerning the mechanical properties of such structures in southern California is particularly troubling, given that probabilistic models of peak ground acceleration are an important component of earthquake hazards assessment in that area.

In this paper, we take advantage of cores collected through the Mojave segment of the San Andreas fault (SAF) to investigate the processes governing fault-rock evolution and frictional strength in the near-surface (<150 m depth). Through a combination of core and outcrop examination and laboratory analysis, we show how fault rocks evolve from protolith through the inter-dependent mechanisms of mechanical deformation and geochemical alteration. These mechanisms are governed by a variety of processes common to shallow crustal faults which ultimately control the strength of fault gouge, including cataclasis, entrainment, alteration, dissolution, and authigenic mineral growth. We show that spatial variations in the extent of these processes results in a highly complex fault zone: many discrete, micro-to-meter-scale gouge zones grade variably (and repeatedly) into fault-damaged rocks and slivers of largely undeformed protolith over a width of more than 100 m. By sampling across inferred deformation gradients in the cores, and comparing the extent of mechanical and geochemical processes in fault-rock evolution, we quantify the relative importance of these processes in shaping the mechanical properties of shallow fault rocks. We find that the frictional strength of the fault rocks varies from relatively strong pulverized rock (coefficient of friction ~0.75) to exceptionally weak gouges enriched in authigenic, mixed-layer illite-smectite (coefficient of friction ~0.16). These data suggest that fault-rock friction in the shallow SAF is dependent on the type and abundance of phyllosilicates, consistent with that observed in deeper portions of the SAF system (Carpenter et al., 2011, 2015; Lockner et al., 2011; Moore & Rymer, 2012; Tembe et al., 2006). We discuss the implications of these results for efforts to forecast peak ground accelerations during southern California.

2. San Andreas Fault and Elizabeth Tunnel Cores

The Mojave segment of the SAF was cored by the Los Angeles Department of Water and Power (LADWP) during a recent geotechnical investigation surrounding the five-mile-long Elizabeth Tunnel; part of the LA Aqueduct system which cuts through the fault near Elizabeth Lake, California (Figure 1). This segment of the fault has accumulated ~160 km of right-lateral displacement since its inception at ~5 Ma (Darin & Dorsey, 2013). Paleoseismic studies of other locations along the Mojave segment document a history of recurrent ground-rupturing earthquakes with an average recurrence interval of ~100 years (Biasi et al., 2002; Scharer et al., 2010), although more recent work near Elizabeth Lake suggests slightly longer recurrence intervals (~200 years; Bemis et al., 2021). The most recent of these ruptures, the 1857 Fort Tejon event, produced coseismic surface displacements of ~4 m (Mw ~7.7; Zielke et al., 2012).

During drilling, seven holes were advanced obliquely (plunging ~60° northeast) to a depth of ~150 m below ground surface (LADWP, 2019). The fault was intersected in all seven holes which were completely cored (>95% recovery) for logging and sampling (Figure 2). The core was initially described in detail by Amec Foster Wheeler, geotechnical consultants engaged by the LADWP, who identified and correlated several large gouge zones interpreted as the primary, active strands of the SAF in the area (solid bold lines in cross section in Figure 2; LADWP, 2019). The cores are interpreted to span a large portion of the fault zone due to good recovery of both Pacific plate (MzPgn) and North American plate (Kgd; Figure 1) rocks, including a decaying abundance and thickness of gouge zones away from the interpreted main strand (see Section 4.2 of LADWP, 2019). Here, we focus on samples collected from boreholes 1, 2, and 7 due to their generally superior preservation of the inferred primary strands and surrounding rocks (Figure 2). The primary gouge zones observed in these cores are separated by variably deformed rocks including many secondary gouge zones and other deformed rocks. Apatite (U-Th)/He analyses of rocks surrounding the SAF in this area indicate an
exhumation of <2 km over the last 10 Ma (Buscher & Spotila, 2007), suggesting that the near-pristine fault rocks exposed in the Elizabeth Lake cores likely formed near their present depth.

2.1. Description of Fault-Related Rocks

We conducted additional core descriptions of intervals that included the prominent gouge zones interpreted by the original loggers to represent the principal strands of the SAF near Elizabeth Lake (LADWP, 2019). Their report uses the classical fault rock naming scheme of Sibson (1975). We opt for a simpler scheme and broadly classify fault-related rocks into three categories representing increasing degrees of deformation: Protolith, which is wall rock that is largely unaltered and/or undamaged by fault activity; fault-damaged rock, which is pervasively microfractured and/or disaggregated, but with sufficient preservation of primary structure or mineralogy that the protolith can be recognized; and fault gouge, which is typically strongly foliated and altered/deformed to the extent that no macroscopic features are retained from the protolith.

2.2. Protolith

Near Elizabeth Lake, the SAF juxtaposes Cretaceous granodiorites of the North American plate against Cretaceous to lower Proterozoic amphibolite gneiss of the Pacific plate. Cretaceous granodiorites are abundant in core samples and are generally well exposed along the northern walls of the fault valley near the coring locality (Figures 1 and 2). The granodiorites exhibit limited-to-moderate weathering, and are generally coarse grained with variable amounts biotite and amphibole (Figure 3a). Mafic enclaves and xenoliths of amphibolite gneiss are common, and are generally less than 20 cm in diameter when observed in outcrop. Granodiorite samples show equilibrium magmatic textures in thin section with no discernible fabric and little evidence of post-crystallization deformation (Figure 3a).

Amphibolite gneiss is encountered only in the uppermost portions of Elizabeth Lake cores where it is highly weathered and often incoherent, and generally does not appear in the vicinity of major gouge strands found at greater depths (discussed below). Outcrops of amphibolite gneiss are common south of the fault valley, but are similarly weathered and incoherent, disaggregating readily by hand.
2.3. Fault Damaged Rock

The character of fault-damaged rocks changes across inferred strain gradients in core samples (Figures 2, 3b, and 3c). Samples broadly similar to “pulverized rock” described previously along this segment of the SAF (e.g., Dor et al., 2006; Rockwell et al., 2009; Wechsler et al., 2011) are inferred to have experienced little to no shear. Original granodiorite textures are still visible at the outcrop/core scale, but samples disaggregate readily into fine dust by hand. Microstructural examination of these samples reveals dense microfracture arrays with little or no preferred orientation, but original grain boundaries are still visible (Figure 3b). No apparent evidence of grain rotation, cataclastic flow, or fabric development is visible in these samples. Some

Figure 2. (a) Photo showing Elizabeth Lake in the San Andreas fault valley in the study area. View is to the south. (b) Cross section showing inferred strands of the San Andreas fault in the subsurface as determined by correlation of major gouge zones (modified from LADWP, 2019). Thin solid lines show the orientation of seven bore holes across the fault zone. Thick solid lines show the location of the inferred primary strands of the San Andreas. Thick dashed lines show location of potential secondary faults. The extension between each of the identified strands to the surface is unknown, and therefore not displayed. Yellow stars show the location of collected samples. Depth to bedrock was determined by preliminary cone penetration testing conducted by Amec Foster Wheeler (see section 2.1.2 of LADWP, 2019). The locations of samples with microstructural imagery in Figure 3 is also shown. (c) Example cores recovered during drilling exhibiting end-member fault-rock types discussed in text. Cores are approximately 6 cm in diameter and 60 cm in length. See Figures 3 and 4 for corresponding microstructural images of fault-rock types.
of these fault rocks exhibit minor zeolite formation in fracture networks, but little other discernible alteration. In contrast, samples of fault-damaged rock that record shear are almost entirely disaggregated relative to their original protolith grain structure, and exhibit evidence of particle rotation and cataclastic flow (Figure 3c). Original protolith textures are often no longer recognizable and grain size is significantly reduced in comparison to protolith, although original protolith mineralogies are still discernible. These fault rocks may also exhibit evidence of initial fabric formation with increasing shear, where discrete bands of sheared biotite anastamose around clasts of deformed protolith material (Figure 3c).

2.4. Gouge

Gouge samples represent the most advanced stage of fault-rock development in the Elizabeth Lake cores. The markedly reduced grain size and fabric development of these samples generally prevents recognition of original protolith type/mineralogy (Figures 2 and 3d). Nearly all gouge samples exhibit pervasive fabrics defined by a combination of color/compositional banding and survivor clast alignment. Foliations are also
visible in preferred orientations of desiccation cracks when samples are dried, and are generally oriented ~30° from the core axis. Most gouge samples appear clay-rich, and are sticky and malleable when wet. High-resolution electron microscopy confirms a significant quantity of phyllosilicates in the μm -to-nm matrix (Figures 4a and 4b), which are generally aligned parallel to the foliations observed in hand samples. Contacts between gouge and surrounding rocks range from sharp to gradational. The geometry of gouge zones ranges from densely arranged, anastomosing clay shear bands sub-mm in thickness to more prominent zones of continuous gouge up to 30 cm in thickness. The latter are interpreted to represent the principal slip zones of the SAF in this area, and can be correlated between boreholes (Figure 2; LADWP, 2019). Most gouge zones observed in core are flanked by rocks with an identifiable granodiorite protolith, suggesting that they may have developed preferentially from the rocks on the North American plate side of the fault.

3. Analytical Methods

Full details regarding the methods used to collect the data are also available in the Supporting Information S1.

3.1. X-Ray Diffraction

We conducted both bulk-rock and clay grain-size separated X-ray diffraction (XRD) analyses on fault-rock samples from the Elizabeth Lake cores and surrounding protolith materials. Average modal mineralogies of protolith samples were determined quantitatively using Rietveld refinement. This approach, however, could not be conducted on fault-rock samples due to the combined presence of smectite and chlorite (see “Results”), whose primary peaks overlap in air-dried samples. To provide a semi-quantitative metric for comparing the bulk mineralogy of fault-rocks, we adopt a peak-area ratio approach where the integrated intensity of each phase is given normalized to the integrated intensity of the quartz peak (a stable phase that is unlikely to undergo significant dissolution or precipitation in the shallow crust; e.g., Solum et al., 2003). Peaks were selected to minimize interference with other phases, and include: oligoclase 201–3.25 Å; quartz 1004.26 Å; potassium feldspar 040–3.25 Å; and biotite 100–10.0 Å. To assess differences in peak-area ratios between fault rocks, we conducted a simple bootstrapping hypothesis test as outlined in Efron and Tibshirani (1994). Bootstrapping is a common statistical method that uses resampling to generate confidence bounds around a statistic of interest, and critically requires no assumptions on the nature of the underlying distribution (e.g., normal, skewed, etc.; see Supporting Information S1 for complete statistical description).
Clay grain-size (<4, <2, and <1 μm) fractions were separated by centrifugation from a subset of gouge samples for more detailed XRD analysis of phyllosilicate type and relative abundance. To further constrain the mineralogy of fault-rock phyllosilicates and estimate their relative abundances, we used NEWmod for Clays (Reynolds, 1985) to model XRD spectra for each sample and grain size.

3.2. Fault-Rock Geochemistry

Fusion X-ray fluorescence (XRF) analyses were also conducted on bulk fault-rock and protolith samples to assess potential changes in elemental geochemistry during fault-rock evolution. To provide mineralogical context for XRF analyses, rock chips obtained from core or outcrop were homogenized into a single powder and used for both XRD and XRF analyses. Powder samples were then sent to Act Labs (www.actlabs.com) for XRF analysis. Loss on ignition was used to assess volatile content prior to sample preparation and analysis. To provide a more quantitative examination of changes in elemental geochemistry during fault-rock development, we compared the composition of fault-damaged rock and gouge to the composition of the granodiorite protolith from which they apparently formed. For this comparison, elemental concentrations were normalized to a presumed immobile element via the following equation:

$$\Delta C_x = \left( \frac{C_{F_x}}{C_{P_x}} \right) / \left( \frac{C_{F_i}}{C_{P_i}} \right)$$

where $\Delta C_x$ is the change in concentration of element $x$ relative to protolith, $C_{F_x}$ and $C_{P_x}$ are the concentrations of element $x$ in the fault-rock and protolith, respectively, and $C_{F_i}$ and $C_{P_i}$ are the concentrations of the immobile element in the fault-rock and protolith, respectively. In this way, fault-rock elemental concentrations are expressed as a factor of enrichment or depletion relative to the average protolith concentration. This analysis is commonly employed to assess mass flux in both fault rocks and soils (e.g., Medaris et al., 2017, 2018; Morton et al., 2012). In the shallow crust, Al, Ti, and/or Zr are typically assumed to be immobile elements (Medaris et al., 2018). Our fusion-XRF analysis did not measure the concentration of Zr, however, and the concentration of TiO$_2$ in the protolith is low (<1 wt%) and variable (standard deviation ~41%). Thus, our calculations assume Al is immobile during fault-rock development. The values $C_{P_x}$ and $C_{P_i}$ were calculated as the mean composition of 9 samples of unaltered protolith granodiorite for each element $x$ and Al$_2$O$_3$, respectively.

3.3. Laser-Diffraction Granulometry

Samples selected for laser-diffraction granulometry were extracted directly from core or outcrop samples and lightly disaggregated in a mortar and pestle. As this analysis requires disaggregating samples without significant additional grain breakage, protolith granodiorites were not analyzed. Samples were then loaded in 15 mL centrifuge tubes with a solution of distilled water and sodium-hexametaphosphate (a dispersant). Samples were left to hydrate over a period of several days, after which they were repeatedly subjected to 30 s treatments with a probe ultrasonicating device. Quantification of particle-size distributions was conducted with a laser-diffractometer particle-size analyzer with an operational range of 0.02–2800 μm.

3.4. Friction Experiments

A subset of samples from the Elizabeth Lake cores (1 protolith, 2 fault-damaged rocks, and 2 gouges) was selected to determine how frictional strength evolved as fault rocks matured. Samples were crushed by mortar and pestle until the entire sample mass passed through a 40 μm sieve. Experiments were conducted in a triaxial deformation apparatus with servo-controlled axial displacement and confining and pore fluid pressures. A more complete description of the experimental apparatus and methodologies is available in the Supporting Information S1. Samples were placed between L-shape steel holders (e.g., Samuelson & Spikers, 2012) so that the sample was vertical and the applied confining pressure was equal to the normal stress on the fault. The sample assembly was then jacketed in polyolefin tubing. The void spaces between the L-blocks were filled with polydimethylsiloxane (silly putty™), which has low strength and can squeeze outward when compressed (e.g., Verberne et al., 2014). These experiments employed a 25 MPa normal stress with a 10 MPa pore-fluid pressure to mimic approximately 1 km burial depth under hydrostatic conditions. Displacement occurred at a constant rate of 8.6 μm/s up to a total of ~2–6 mm. We also ran a smectite-rich
gouge sample at a slower rate of 0.3 μm/s due to the potential for smectite to locally trap fluids leading to overpressured conditions (Faulkner et al., 2018; Morrow et al., 2017). Sample thickness perpendicular to the shear direction was \( \sim 2 \) mm prior to shearing in all experiments. Axial force was measured on two load cells, one internal and one external to the pressure vessel. Shear stress was calculated by dividing the axial force by the sample area. Generally, the friction coefficient was calculated with the internal load cell to avoid the influence of seal friction. However, in two experiments (230E-FDR; 210B-G at 0.3 μm/s; see “Analytical Results”), the internal load cell malfunctioned and we use the external load cell as an upper bound on the friction coefficient in that case.

4. Analytical Results

4.1. Fault-Rock Mineralogy

XRD spectra from granodiorite protolith are dominated by plagioclase (oligoclase) and quartz with subordinate potassium feldspar (orthoclase) and biotite. Minor amphibole and/or chlorite are also present. Average modal mineralogies determined by Reitveld refinement for protolith granodiorites are: plagioclase = 41%; quartz = 25%; biotite = 11%; potassium feldspar = 10%; chlorite = 7%; amphibole = 6%. Thin section examination indicates that chlorite is present locally as a replacement phase after biotite and amphibole. Amphibolite gneisses are considerably more mafic in composition: hornblende = 47.0%; plagioclase = 33.0%; chlorite = 8.0%; with accessory hematite, biotite, clinopyroxene, and quartz (<2%). Smectite was not detected in either granodiorite or amphibolite gneiss protolith samples. The mineralogy of fault-damaged rock and gouge samples from the Elizabeth Lake cores are nearly identical to those of granodiorite protolith samples, but with variable additions of smectite and chlorite, minor additions of laumontite and calcite, and a reduction in biotite (Figure 5a).

Bootstrapping the results of fault-rock peak-area ratios shows that there are no significant differences between the K-feldspar:quartz and plagioclase:quartz intensity ratios between protolith, fault-damaged rock, and gouge. In comparison, gouge samples exhibit significantly lower (95% confidence) biotite:quartz intensity ratios than do fault-damaged rocks, which are themselves significantly lower than protolith granodiorites (95% confidence). Differences in K-feldspar:quartz and plagioclase:quartz ratios between fault-rock types are not statistically significant.

Figure 5. (a) Bulk X-ray diffraction spectra of representative samples of protolith granodiorite, fault-damaged rock, and gouge. Letters denote mineral phases: (b) biotite; (a) amphibole; Sm - smectite; chl - chlorite; L - laumontite; Q - quartz; P - plagioclase; K - potassium feldspar; (c) calcite. Gouge data represents a sample from the primary fault strand interpreted by the original core loggers. (b) Peak intensity ratios calculated for protolith granodiorite, fault-damaged rock, and gouge. Bootstrap analyses show that gouge samples from the Elizabeth Lake cores have significantly lower biotite:quartz ratios than do fault-damaged rocks, which are themselves significantly lower than protolith granodiorites (95% confidence). Differences in K-feldspar:quartz and plagioclase:quartz ratios between fault-rock types are not statistically significant.
Phyllosilicates are the primary phases observed in grain-size separated samples. NEWmod modeling of clay-grain size fraction results from a subset of samples show that the smectite phase identified in bulk XRD results is a randomly-interstratified, mixed-layer illite/smectite (I/S $\sim$20%/80%; hereafter “I/S”). Chlorite is Fe-rich as evidenced by dominant 002 and subordinate 001 basal reflections. Model results show that the abundance of I/S relative to other phyllosilicates increases with decreasing grain size in each gouge sample, while the relative abundance of chlorite and biotite decreases. Thus, I/S is preferentially concentrated within the finest grain-size fractions, whilst chlorite and biotite are concentrated in the coarser fractions. This inference is consistent with electron microscopy and microprobe analyses where phyllosilicates in excess of $\sim$4 $\mu$m appear to be exclusively biotite and chlorite (Figure 4).

4.2. Fault-Rock Geochemistry

Fusion XRF results reveal that granodiorite protolith, fault-damaged rock, and gouge samples each exhibit a distinct elemental composition of Mg/Si, Fe/Si, and Na/Si ratio, where the evolution from protolith to gouge is typified by a relative increase in Mg and Fe and decreases in Na and Si (Figure 7). Loss on ignition (a proxy for sample volatile content) is also well correlated with Mg, Fe, and Si concentrations. Collectively, these trends could arise from two potential mechanisms: mechanical incorporation of more (Fe + Mg)-rich and Na- and Si-poor phases (e.g., amphibole, biotite, chlorite) from amphibolite gneiss or mafic enclaves during shear and cataclasis, or mass flux during fluid-rock interaction and I/S authigenesis. To assess the first possibility, a suite of representative amphibolite gneiss and mafic enclave samples were analyzed by fusion XRF. Results from mafic enclaves samples were then used to define a mechanical mixing line with granodiorite protolith (Figure 7e). This mixing line does not include the composition of fault-damaged rock and gouge samples, indicating that fault-rock elemental composition cannot be explained by mixing of granodiorite protolith and mafic enclave rocks alone.

Results of mass-flux calculations show that fault-damaged rocks are broadly similar in composition to granodiorite protolith, with the exception of slight enrichments in Fe and Mg (Figure 8). Gouge samples from the Elizabeth Lake cores exhibit slight depletions in Si and Na concentration, with relative enrichments in Fe, Mn, Mg, Ca, Ti, and P. The largest enrichments occur in Mg and Fe, which high-resolution electron microprobe analysis reveal to be concentrated preferentially within the sub-micron matrix (Figure 4).

4.3. Grain Size Distributions

Laser-diffraction granulometry results (Figure 9) show that fault-damaged rocks are generally coarser grained (average median value $\sim$38 $\mu$m, $n = 20$ samples) when compared to gouge (average median value $\sim$6 $\mu$m, $n = 20$). Similarly, the clay-sized (<2 $\mu$m) fraction of fault-damaged rocks accounts for an average of $\sim$11% of the total sample volume, while clay-sized grains account for $\sim$35% of the total volume of gouge samples. Notably, four ($\sim$20%) of the analyzed gouge samples exhibit distinct grain-size peaks at $\sim$0.1 $\mu$m range that were never detected in fault-damaged rocks. Although protolith granodiorites were not analyzed using laser diffraction, field and microstructural observations reveal that individual grains in those samples are generally millimetric in scale (e.g., Figure 3a).

4.4. Fault-Rock Friction

Measured friction coefficients reveal marked differences between protolith and gouge (Figure 10). A sample of undeformed and unaltered granodiorite yielded coefficient of friction of 0.69–0.75 (EL-07). Two fault-damaged rocks yielded coefficients of friction of 0.66–0.70 (230E-FDR; pulverized fault-damaged rock) and 0.25–0.30 (117-FDR; moderately sheared fault-damaged rock). One sample from a secondary gouge zone (225D-G) yielded a slightly lower coefficient of friction of 0.20–0.24. An I/S-rich gouge sample collected from inferred primary strand of the SAF in core (210B-G) yielded still lower values of 0.14–0.16. This sample was sheared at a displacement rate of 0.3 $\mu$m/s to account for the potential to induce excess pore-fluid pressures in smectite-rich samples when sheared at faster rates (Faulkner et al., 2018; Morrow et al., 2017). For completeness, we also deformed sample 210B-G at the higher displacement rate of 8.6 $\mu$m/s, which yielded friction coefficients $\sim$35% lower than those measured at 0.3 $\mu$m/s, consistent with the predictions of Morrow et al. (2017) and Faulkner et al. (2018). The relatively low friction coefficients
5. Discussion

5.1. Phases of Fault-Rock Evolution

We propose a general evolution for the examined fault-rocks that occurred by three main mechanisms: distributed microfracturing/pulverization (Figure 3b); cataclastic flow and incipient fabric development exploiting protolith phyllosilicates (i.e., alignment of protolith biotite and chlorite; Figure 3c); and production of authigenic illite/smectite during fluid-rock interaction. The core and microstructural observations of fault rocks (e.g., Figures 2 and 3), show that these processes were variably active throughout the fault zone, and may have facilitated each other. Pulverized rocks disaggregated along a gradient in to a gouge zone (e.g., Figures 2 and 3c), for example, suggest that pulverization facilitates subsequent cataclastic flow. We infer that both pulverization and cataclastic flow provide permeable pathways for fluid infiltration and subsequent alteration and clay authigenesis. In pulverized or otherwise moderately fractured rock, however, alteration is primarily in the form of precipitation of laumontite, within only limited formation of I/S (Figure 5). Thus, I/S formation in gouge with finer grains and increased surface area may represent the symbiotic relationship between fluid-rock interaction and cataclasis, where substantial grain-size reduction is required to facilitate the formation of large quantities of I/S. Frictional weakening associated with the production of I/S may encourage subsequent strain localization and in turn facilitate additional disaggregation and granular flow.

5.2. Origins of Fault-Rock Phyllosilicates

Core observations, XRD, and XRF data collectively indicate that gouge zones representing both the primary and (presumably) secondary strands of the SAF in core samples developed from granodiorite protolith on the North American plate side of the fault. Illite/smectite, chlorite, and biotite are the major phyllosilicate components of these gouge zones. Of these, chlorite and biotite are present in granodiorite protolith in broadly similar abundance (chlorite $\approx$ 7%; biotite $\approx$ 12%) and with identical spectral characteristics to that observed in gouge samples. Thus, we infer that the origin of chlorite and biotite in the gouge zones is mechanical, and reflects incorporation of each phase from the protolith during cataclasis and granular flow. This inference is supported by increased concentrations of chlorite and biotite in relatively coarser grain-size fractions of the gouge (Figure 6).

Illite/smectite, however, is not detected in protolith granodiorites, suggesting an authigenic origin during fluid-rock interaction. This interpretation is supported by apparent increases in I/S concentration with decreasing grain size in gouge samples (Figure 6; cf. Boles et al., 2015; Schleicher et al., 2010), and suggests growth of sub-$\mu$m clay grains during alteration of less stable phases. It is also consistent with increases in Mg and Fe content with fault-rock development (Harder, 1972), which cannot be explained by mechanical mixing with mafic enclaves alone (Figure 7e). The marked decrease in biotite/quartz peak-intensity ratios from granodiorite to fault-damaged rock and gouge (Figure 5b) indicates that I/S formation proceeded predominately by breakdown and alteration of biotite during fluid-rock interaction. The depletion of Na in gouge relative to protolith suggests that alteration of plagioclase may also have contributed to I/S authigenesis, but this could not be confirmed in XRD peak-area ratio data, which show no significant differences in feldspar/quartz ratios between protolith and gouge. This lack of differentiation, however, may be due to the lower sensitivity of this method and higher inter-sample variability (Figure 5b).

5.3. Effects of Mechanical and Geochemical Processes

Our data show that the evolution of fault rocks in the shallow Mojave segment of the SAF was dictated by a combination of mechanical and geochemical processes. In the following sections, we consider the relative magnitude of each in shaping the character of fault rocks.
5.3.1. Production and/or Incorporation of Fault-Rock Phyllosilicates

Quantitative phyllosilicate abundance data permits examination of the relative magnitude of mechanical and geochemical processes in the production and/or incorporation of these frictionally-weak phases during fault-rock evolution. Biotite and chlorite are abundant in the granodiorite, greatly reduced in the fault-damaged rock, and partially replaced by I/S in the fault gouge (Figure 5). Within the gouge, the relative abundance of I/S relative to chlorite and biotite changes with different size fractions. In the <1 μm grain-size fractions, I/S and chlorite + biotite are present in approximately equal proportions. In the <4 μm fractions, chlorite + biotite are dominant and account for ∼70% of phyllosilicate volume (Figure 6b). We did not analyze coarser grain size fractions in the gouge, but >4 μm grains are observable in SEM images, where they are dominated by chlorite and biotite (Figure 4). Thus, mechanical incorporation of these phyllosilicates from protolith appears to be a more volumetrically significant (≥70%) source of phyllosilicates than in situ authigenic growth at this shallow depth in the San Andreas fault. This observation is counter to observations from faults at greater than ∼2 km, where geochemical/authigenic sources of phyllosilicate formation appear to be more dominant (e.g., Boles et al., 2015; Scheiber et al., 2019; Solum et al., 2005; although wall rock lithology may be a factor). It is clear, however, that even in the shallow subsurface precipitation/alteration exerts a substantial effect on phyllosilicate content of fault rocks, in this case contributing as much as ∼30% of the total phyllosilicate budget.

The production and/or incorporation of phyllosilicates during fault-rock evolution also influences particle-size distributions. Fault-damaged rocks and gouge exhibit marked decreases in median particle size when compared to granodiorite protolith, with clay-sized (<2 μm) particles accounting for ~11 of fault-damaged rock and ~35% of gouge, by volume (Figure 9). The clay-sized matrix of the gouge is dominated by phyllosilicates (Figure 6). Authigenesis of I/S is linked to Mg-enrichment in the fault-rocks when compared to protolith (Figure 7), consistent with electron microprobe analysis which shows that the the sub-micron matrix of gouge is enriched in Mg (Figure 4), providing further evidence that I/S precipitation drove a relative increase in sub-micron particles. It is therefore possible that the anomalous peaks near ~0.1 μm diameter in some gouge samples (Figure 9) record the authigenic growth of mixed-layer I/S during fluid-rock interaction.

5.3.2. Development of Fabric

Qualitative microstructural analysis indicates that fault-rock fabric is defined by the preferred alignment of biotite and chlorite grains in the ~5–20 μm size range, it appears that mechanical processes (e.g., grain rotation) were mostly responsible for fabric development in the Lake Elizabeth core fault gouges (Figure 4).
Laboratory deformation experiments have shown that fabrics formed in this way can arise even after small shear strains ($\gamma \sim <10$) in phyllosilicate-rich samples (Ikari et al., 2011). If the San Andreas fault gouge fabric also developed at small strains, it was probably early in fault-rock formation. The authigenic I/S does not reach coarse enough grain size to be individually identified in the SEM images, but is present in the foliated, Mg-bearing groundmass (Figure 4). It is not clear at the scale of our observations whether the alignment of coarser phyllosilicates, and the development of the foliation, pre- or post-dates the development of authigenic matrix I/S.
5.3.3. Fault-Rock Friction

The profound difference in the friction coefficient of protolith granodiorite and gouge reflects the larger abundance of frictionally-weak phyllosilicates in the gouge. Thus, the frictional strength of the fault rocks was controlled by the same combination of mechanical and chemical processes that govern phyllosilicate addition: entrainment and/or authigenesis. The friction coefficients of the protolith granodiorite (EL-07) and a fault-damaged rock (pulverized granodiorite; 230E-FDR) are consistent with that predicted for most lithologies during brittle failure ($\mu = 0.66–0.75$; Byerlee, 1978). In contrast, samples of moderately sheared fault-damaged rock (117-FDR) and gouge (225D-G and 210B-G) yielded considerably lower friction coefficients ($\mu = 0.16–0.30$). As mentioned above, chlorite and biotite (mechanically incorporated from the protolith) account for at least $\sim 70\%$ of the phyllosilicate budget in these fault rocks (Figure 6). Previous experimental work documenting the friction coefficient of chlorite-rich gouge revealed values of $\sim 0.20–0.35$ (Ikari et al., 2007; Okamoto et al., 2019). In contrast, authigenic I/S (formed during fluid-rock interaction) accounts for less than $\sim 30\%$ of the phyllosilicate budget in these fault rocks. Smectite-group minerals, however, often exhibit extreme frictional weakness ($\mu = \sim 0.2$; Ikari et al., 2007; Tembe et al., 2010; Behnsen & Faulkner, 2013; Morrow et al., 2017), particularly when sheared under low normal stress conditions such as we employ here (Moore & Lockner, 2008). Unfortunately, the bulk abundance of the end-member phyllosilicates in our samples cannot be reliably determined using the data available, as the relative abundances of phyllosilicates shown in Figure 6 are specific to the clay grain-size fraction, and these values cannot be projected to coarser grain-size fractions (see Section 6.2). Thus, we cannot quantify the relative contributions of mechanical versus geochemical processes in modifying fault-rock mechanical properties. However, the lowest coefficient of friction observed in our data set ($\mu = 0.14–0.16$), was measured on a gouge sample from the inferred primary strand of the SAF (sample 210B-G). This suggests that authigenic clay formation is an important mechanism of fault-rock weakening, even if mechanical incorporation of chlorite and biotite from the wall rock is more volumetrically dominant, consistent with previous studies showing that only a few % of a weakening phase in a foliated fault rock can dominate the frictional strength (Colletini et al., 2009; Niemeyer et al., 2010).

5.3.4. Implications for the Mechanics and Architecture of the Shallow San Andreas Fault

Recent work has shown that the magnitude and distribution of peak ground velocities and shallow slip deficits during earthquakes are strongly mediated by the potential for near-surface plastic yielding in and
around fault zones (e.g., Milliner et al., 2015; Roten et al., 2017, 2018, 2014). In the absence of direct constraints on the frictional characteristics and architecture of the SAF in the shallow subsurface, much of this work has assumed values consistent with prior laboratory experiments on jointed rock surrounding a discrete principal slip surface (e.g., Roten et al., 2018). The shallow SAF near Elizabeth Lake, however, consists of discrete, meter-to-mm-scale gouge zones that grade variably into fault-damaged rocks and slivers of largely undeformed protolith over a width of more than 100 m, implying that the near-surface geometry of the fault is a compliant or inelastic zone (cf. Duan, 2010; Kurzon et al., 2014).

The frictional strength of these fault rocks ranges from relatively strong pulverized rock (coefficient of friction $\sim 0.75$) to profoundly weak I/S-rich gouges (coefficient of friction $\sim 0.16$). The variation in friction coefficient is correlated to the type and abundance of phyllosilicates, and therefore the relative contribution of mechanical (incorporation of biotite and chlorite from wallrock) and chemical (production of I/S during fluid-rock interaction) mechanisms contributing to fault-rock formation. Geochemical and XRD results indicate that the relative efficacy of these mechanisms varies throughout the observed fault zone, suggesting substantial spatial variations in frictional strength. These observations contrast starkly with the simplified mechanical configurations utilized in previous models simulating rupture through the near surface (cf. Roten et al., 2018).

Simplified conceptual models of fault structure may arise in part as a result of mechanical models arguing that fault evolution should proceed toward a single slip surface that is both smooth and weak, implying that delocalization by initiation of and/or slip on other subparallel faults is unlikely (e.g., Scholz et al., 1993; Vermilye & Scholz, 1998). This expectation does not seem to be born out by the fault structure at Elizabeth Lake, with gouge strands of varying thickness and complexity, which appear to branch along strike (Figure 2; LADWP, 2019). One possibility that could resolve the paradox is that the gouge strands may have developed sequentially through time. This hypothesis implies that slip periodically migrates from earlier-formed, presumably weak fault strands in favor of initiation of and/or slip on others. This trend toward delocalization could be caused by strengthening of individual fault strands through a variety of slip-catalyzed healing processes (e.g., cementation, compaction) or through geometric rearrangement within the fault zone (e.g., rotation which misaligns previously favorable fault strands as displacement accumulates;
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Tarling & Rowe, 2016). Although our inspection of the Elizabeth Lake cores in the vicinity of the interpreted primary gouge strands revealed no widespread evidence of healing in the form of cementation or consolidation, we note that other sections of the core distal to the primary gouge strands do exhibit evidence of cementation (Studnicky, 2021). A second, not mutually exclusive, possibility is that initial complexity in fracture patterns associated with early development of the Mojave Segment gave rise to a network of fault strands forming a large-scale anastomosing fault zone, and that these strands have been simultaneously active since their creation. Finally, the broad network of discrete gouge zones may be related in part to the repeated surface rupturing earthquakes, as mapping of the distribution of seismic slip surfaces within fault zones shows that ruptures do not always occur on the exact same fault surfaces (e.g., Coffey et al., 2021; Rabinoiwitz et al., 2020; Rowe et al., 2018; Savage & Polissar, 2019). All of these interpretations are supported by other research demonstrating that the number of strands within a fault zone increases with increasing displacement (e.g., Rowe et al., 2013; Savage & Brodsky, 2011), although there does appear to be an upper bound beyond which fault zone growth in width/complexity tapers off with increasing displacement (McK- ay et al., 2021; Savage & Brodsky, 2011). In fault zones of this style, individual earthquake ruptures may take different pathways through a network of anastomosing principal slip zones (e.g., Rowe et al., 2018; Shigematsu et al., 2012). Post- and inter-seismic creep may similarly be accommodated by an individual strand, or alternatively, multiple strands simultaneously, as is evident in SAFOD cores through the creeping section of the SAF to the North of the Mojave segment (Zoback et al., 2011). As such, there may be no single persistent fault core which becomes permanently dominant. This paradigm is a good fit to the architecture of the shallow San Andreas in the Elizabeth Lake drill core.

6. Conclusions

In summary, the structure and physical properties of the near-surface Mojave segment near Elizabeth Lake is considerably more complex than that envisioned by previous physical models simulating near-surface rupture phenomena. This complexity is likely manifest in part by significant spatial variations in fault rocks with strongly contrasting mechanical properties. Moreover, the Cretaceous granodiorite protolith from which the examined fault rocks formed extends over ∼40 km along strike in Mojave segment near Elizabeth Lake (Dibblee, 2002, 2003). Thus, the fault-zone structure and fault-rock properties we document here may be typical of a large portion of this seismogenic segment of the SAF in the near surface, and may necessitate re-examination of current models forecasting peak ground acceleration during southern California earthquakes.

Data Availability Statement

A complete data set including tables of derived data and raw data files from instruments is available at the Open Science Foundation (https://doi.org/10.17605/OSF.IO/XPCE8). Reviews by Bart Verberne, Diane Moore, Jim Evans, and three anonymous reviewers significantly improved this manuscript.
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