2017 SCEC AWARD #17207 PROJECT SUMMARY REPORT
Co-seismic Weakening Mechanisms within the San Andreas Fault System at SAFOD, California: The roles of Carbon and Focused Alteration on the Strength of Faults (*Research priorities addressed: P3.b., P3.d., P3.f., 5.1.2. (FARM)***)** By Kelly K. Bradbury (PI) and Krishna Borhara (Ph.D. Student), Department of Geology, Utah State University, Logan, UT 84322-4505, Email: kelly.bradbury@usu.edu

PROJECT OBJECTIVES

Previous examination of the lithology and microstructures in the San Andreas Fault Observatory at Depth (SAFOD) Phase 3 core revealed distinct intervals of sheared black carbonaceous rocks (Bradbury et al., 2011; 2015) in various locations throughout the ~ 40 m length of core. Several studies have also documented the presence of black carbonaceous material (e.g. amorphous carbon, graphite) in natural fault zones of varying protolith composition (Zulauf et al., 1990; Arai et al., 2002; Rowe et al., 2005; Oohashi et al., 2012; Craw and Upton, 2014; Liu et al., 2016; Kuo et 2017; 2018), suggesting carbon enrichment during shear due to creation of permeability pathways and/or *in situ* chemical reactions. Recent experiments on simulated carbonaceous fault gouge attribute dynamic weakening to tribological properties of carbon during shear-induced slip localization (Oohashi et al., 2011; 2013; 2014; Kuo et al., 2014). Although faults with amorphous carbon are not mechanically weak at low slip rates, they can effectively lubricate the fault surface and promote dramatic dynamic weakening at near seismic slip rates by coseismic graphitization (Oohashi et al., 2011; Kuo et al., 2018). Thermal decomposition and nanoparticle lubrication in carbon-rich faults have also been reported to dramatically reduce frictional strength due to phase transformations and crystal-plastic processes (De Paola et al., 2011; Rowe et al., 2012; Fondriest et al., 2013; Han et al., 2014). Carbonaceous materials are often foreign to many host rocks and thus carbon and/or carbonization to graphitization reactions may occur as a result of the migration of fluids and/or fluid-rock interactions during deformation (Mathez et al., 1995; Mathez et al., 2008; Buseck and Beyssac, 2014).

Listed below are the key questions we focused on addressing for this project, which are specific to understanding the nature of carbonaceous material in SAFOD, and more broadly, to understanding the evolving structural and permeability architecture of active fault zones. While there are still some unanswered questions related to this project, we continue to develop these as part of our broader research efforts.

1. *What is the source of carbonaceous matter in SAFOD and the San Andreas Fault?*
2. *What are the mechanical and chemical effects of carbonaceous-rich fault zones and their potential evolution over both seismic and interseismic periods?*
3. *What are the effects of temperature, composition and degree of shear localization on dynamic fault weakening of carbon-rich fault zones?*
4. *How do carbonaceous faults weaken? What mechano-chemical reactions occur during weakening? What mineralogy and microstructures indicate this? Is there evidence of thermal decomposition of the carbonaceous material?*

METHODOLOGY AND RESULTS (*Project still in progress to 12/31/18*)

Discerning the nature and extent of physiochemical processes associated with fine carbonaceous matter and the role of fluids in mature fault zones or during fault zone weakening requires high-resolution microscopy and geochemical techniques. We use an integrated micro-structural and micro-geochemical approach to identify the zones enriched in carbonaceous matter and any potential evidence for weakening or alteration in these carbon-rich zones in SAFOD Phase 3 Core. Methods include optical and high-resolution Scanning Electron Microscopy (SEM), Synchrotron Radiation, Total Organic Carbon (TOC) Analysis, X-Ray Diffraction Analysis, and Raman Microspectroscopy. This project is part of our broader research efforts and the next phase will include a comparison of our observations of the SAFOD samples with observations from experimentally produced slip surfaces (De Paola et al., 2011; Oohashi et al., 2011; 2013; 2014; Fondriest et al., 2013; Kuo et al., 2014; Nakamura et al., 2015; Spagnuolo et al., 2015), as well as other natural faults (Oohashi et al., 2012; Rowe et al., 2012; Liu et al., 2016; Sánchez-Roa et al., 2016; Kuo et al., 2018), to identify evidence of weakening and physiochemical processes associated with the presence or alteration of carbonaceous material in the San Andreas Fault at depth **(Figs. 1)**.

New measurements of Total Organic Carbon (TOC in wt.%) were completed on 60 samples of SAFOD Phase 3 whole-rock core as part of this work (**Fig. 2**). Notable increases occur both in the SDZ and CDZ, the actively deforming creeping shear zones of the SAF in SAFOD (Hickman and Zoback, 2005). A 0.76 with a 1.6% max wt% TOC occurs in samples southwest and across the SDZ. The region surrounding and within the CDZ records a 1.12 avg wt% to 4.0 % max TOC, with the highest values observed immediately adjacent or within the CDZ (**Fig. 2**). X-Ray diffraction Analysis shows the presence of Carbon in some samples, however, it does not indicate that this material is graphite, however, XRD will only pick up mineral concentrations > 3-5% of the sample. The carbonaceous matter is variable in texture across the core and may form continuous highly-reflective glassy thin films on slip surfaces or discontinuous and irregular patchy marks on fracture surfaces or as black, dull, opaque fracture in-fillings (**Fig. 1**). Based on the composition and distribution of this material, we interpret this material to reflect hydrocarbon migration along the San Andreas Fault near SAFOD and are not formed directly through the process of graphitization. However, the textural, mineralogical, and geochemical variations at the meso- to micro-scale may record signatures of deformation, thermal alteration (including graphitization and/or carbonization of the carbonaceous matter) and fluid conditions and provide a unique tool for understanding physiochemical processes and weakening across the SAFOD core during active slip or aseismic creep.

To identify shifts or temperature-related changes in the carbonaceous material, Raman spectroscopy was conducted on ~ 30 samples that were selected based on the identification of this material in the sample using SEM-EDS analyses. This analyses confirmed our findings from meso- to micro-scale observations that this material is indeed some form of carbonaceous matter (microcrystalline graphite, amorphous carbon, or graphitic oxides) due to the presence of both D and G peaks and that the signatures are significantly different across the thin bounding slip surface and into the zone of foliated cataclasite (**Figs. 1, 3**). Measurements were made in early November 2018 and data is currently being processed to examine variations in the degree of crystallinity. We are using Raman Spectra to search for indicators of elevated temperatures through the conversion of amorphous carbonaceous material to more ordered phases and increased crystallinity of carbon (Buseck and Bo-Jun, 1985; Beyssac et al., 2002; Oohashi et al. 2011; 2013; 2014; Buseck and Beyssac, 2014; Kuo et al., 2014, 2017; 2018; Nakamura et al., 2015; Spagnuolo et al., 2015 etc.). The degree of organization of carbonaceous material in graphite is unaffected by retrogression i.e., it is irreversible (Beyssac et al., 2002). The amount of shift in Raman spectra will provide insight into maximum temperatures reached across the area sampled by Phase 3 core. Temperatures inferred from Raman spectra will also be used to as a proxy for maximum temperatures likely experienced by slip zones in adjacent lithologies along the trace.

The use of bright high-energy x-rays from synchrotron radiation introduces a powerful method to extract unique chemical signatures from fault zones. High-resolution μXRF maps can be used to trace and correlate element distribution with textures. Transition metals are common trace elements in geologic materials and most exhibit multiple redox states sensitive to changes in environmental conditions. Redox potential of an environment controls paragenesis of minerals, as it governs which reactions are most likely to occur. Fe is ubiquitous in minerals and is the most abundant redox-sensitive element in nature. The redox states of Fe reportedly affect the frictional properties of clays (Stucki et al., 1996), and may be used to study mechanical behavior of smectites that comprise shallow portions of the San Andreas Fault trace. A systematic approach to extract chemical information from mature faults of composition and microstructures that vary with depth is required to further understanding of how structural diagenesis affects the frictional properties of fault zones. **(Fig. 4)**

SIGNIFICANCE

This interdisciplinary approach spans a wide range of scales and methods used in earthquake mechanics to understand the evolution of strength and slip behavior of major tectonic faults for seismic hazard assessment. Faults are dynamic structures capable of accommodating large crustal stresses and frequent fluid influxes that incorporate compositionally diverse materials. Mechanical and chemical processes in fault zones often increase the reactivity of constituent minerals and produce complex microstructural changes. As faults experience frequent changes in environmental conditions, evidence of earlier physiochemical processes may over-printed by late-stage processes, and only be preserved as microscopic remnants. Geochemically significant elements may be present in dilute concentrations not detectable by conventional analytical methods. This approach is particularly useful for studying fluid-rock interactions and resolving the evolution of major and trace element chemistry with microstructural changes at the micro- to nano-scale.

BROADER IMPACTS

Project funding supported a summer stipend for Krishna Borhara (USU PhD student) and provided travel funding to attend and present her work at both the 2017 SCEC Annual Meeting and the 2018 Gordon Research Conference. Funds have also provided 2 annual SEM memberships and direct training and experience in SEM imaging and analysis at the USU Microscopy Core Facility for the PhD student and an undergraduate student. The PhD student gained new expertise in preparing and analyzing rock samples through the geochemical work at USU's Stable Isotope Laboratory and in examining rock samples as a visiting scientist at the Stanford Synchrotron Radiation Lightsource (SLAC) lab. Project funding also enabled the PI to foster a new research direction in microscopy of fault rocks by conducting analyses at the Raman Micro-spectroscopy Lab in Geological Sciences at the University of Colorado-Boulder. This work is currently in preparation for publication by the PI, and will be co-authored by the PhD student and the 2 undergraduate students.

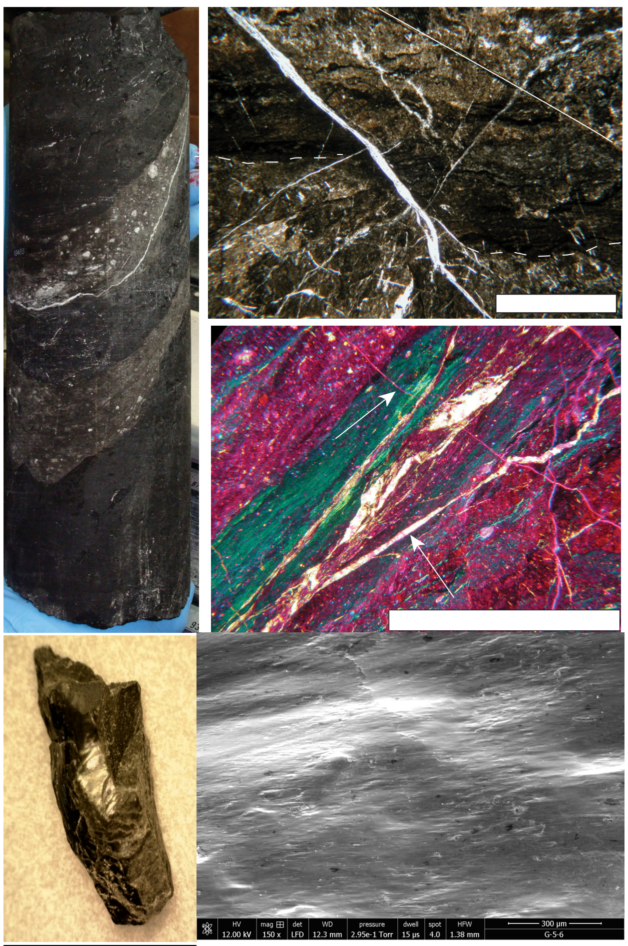

Figure 1. Meso- to micro-scale nature of black, carbonaceous –bearing fault rocks in SAFOD Phase 3 Core. Black sheared rocks west of the SDZ at 3194. 8 m MD (upper left). Micro-scale observations show this rock consists of multi-layered fine- to ultra-fine grained cataclasite and ultracataclasite (the two upper right photos). At the meso-scale numerous black, highly reflective surfaces are observed across numerous intervals within the core (G-5-6-3305.2 m MD in lower left image). Using SEM (lower right image) to image and map these surface, the carbonaceous matter appears discontinuous and irregular across the slip surfaces.

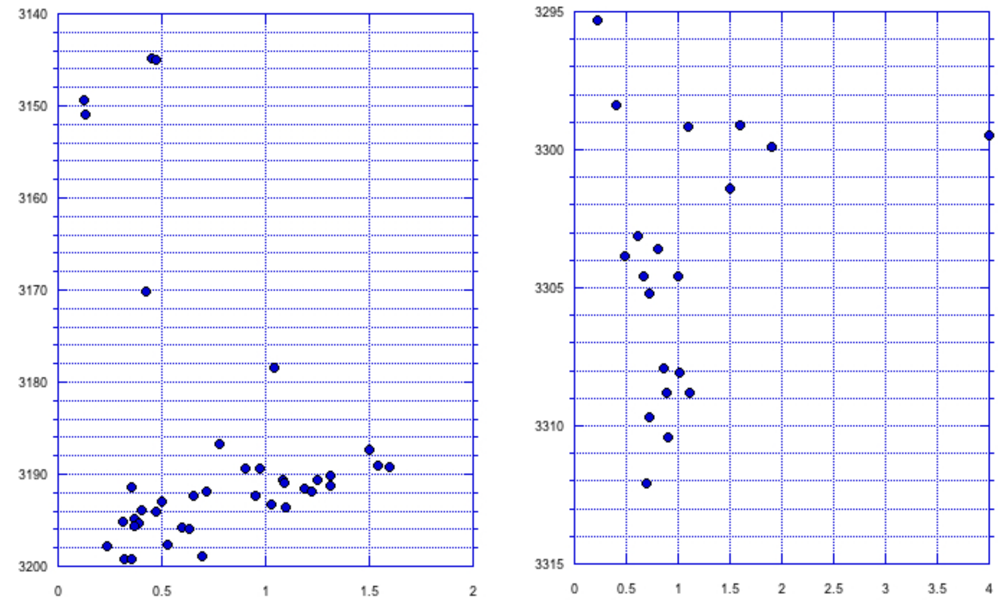

Figure 2. Total Organic Carbon measurements on SAFOD Phase 3 whole rock core. Left: Results from 40 measurements taken to 3200 m MD; Right: Results from 20 measurements taken between 3295 – 3312 m MD. Significant increases occur surrounding the SDZ (~ 3189 – 3191 m MD) and within the CDZ (~ 3300 m MD).

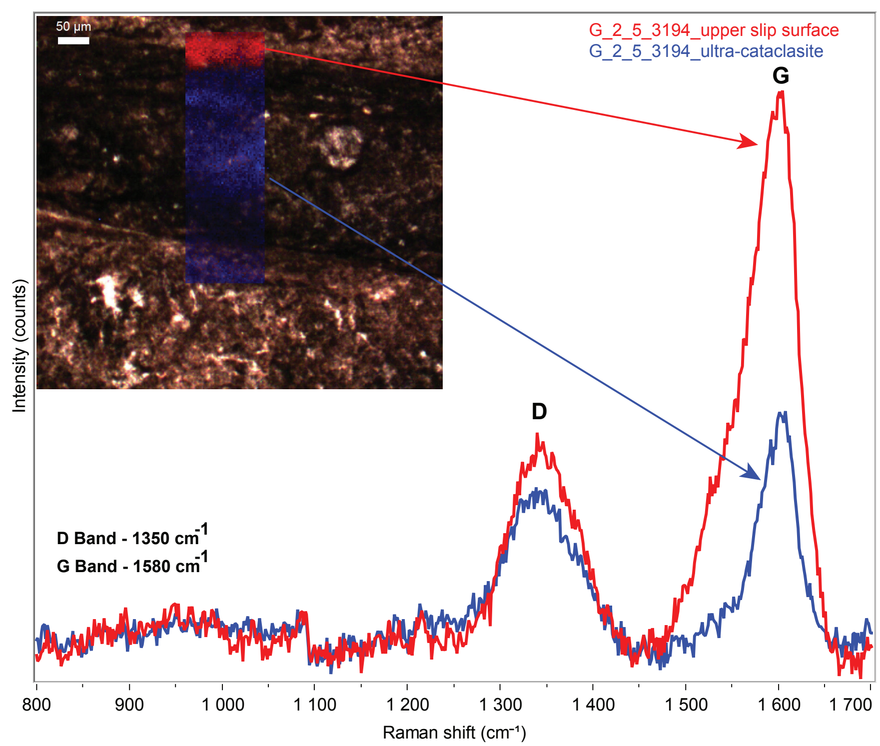

Figure 3. Example results from Raman Spectra on a Sample from the Black Fault Rock at G-2-5-3194.8 m MD (**See Fig. 1**). The red line represents measurements across a bounding slip surface in the black fault rock that is < 50 µm thick (see red region in image). The blue line represents measurements within a zone of ultracataclasite that is ~ 2 mm thick. D represents the defect-activated peaks and G is the graphite activated peak (Buseck and Beyssac, 2014). The Raman signatures between the two regions examined show an increase to a more ordered form of carbonaceous matter within the bounding slip surface relative to the cataclasite zone, indicating an increase in temperature localized to an extremely thin zone. Based on the shape profiles shifts of the characteristic peaks in the first-order region, the change in temperature is on the order of 50 – 100 °C with peak temperatures up to 300° or greenschist facies.

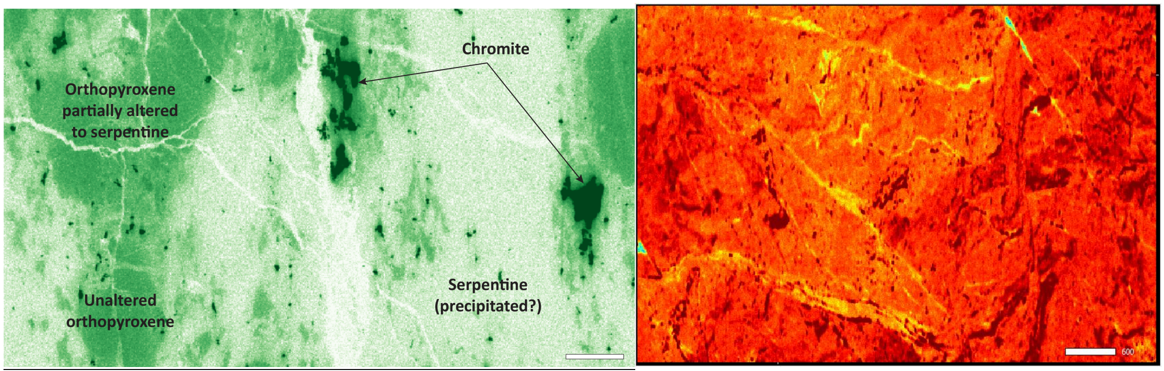

Figure 4. Left: μXRF map showing distribution of Cr in sheared serpentinite-bearing gouge of the SDZ. Darker green zones represent higher concentrations. Serpentine occurs as veinlets and altered remnants. Traces of Cr in serpentinized minerals in the gouge derive from alteration of orthopyroxenes; Right: μXRF map showing distribution of Fe the fault gouge in G-2-4-3193.9. Darker red regions represent high Fe concentrations. Yellow regions represent calcite veins and are depleted in Fe relative to the matrix. Undulatory nature of calcite veins indicates that precipitation occurs during shear. Scale bar is in μm.

Presentations and Abstracts related to this Project:

Borhara, K. Bradbury, K.K., and Evans, J.P., 2017, Carbonaceous fault-related rocks in SAFOD Phase III core: Indicators of fluid-rock interaction and structural diagenesis during slip, SCEC Annual Meeting.

Borhara, K., Webb, S., Edwards, N.P, Bradbury, K.K., and Evans, J.P., 2018, Applications of Synchrotron Radiation to Structural Diagenesis in Mature Faults, 2018 Rock Deformation - Gordon Research Conference.

Bradbury, K.K. and Evans, J.P., 2018, SAFOD Synthesis - Earthscope Workshop, Structural and Geochemical Analyses of SAFOD core.

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