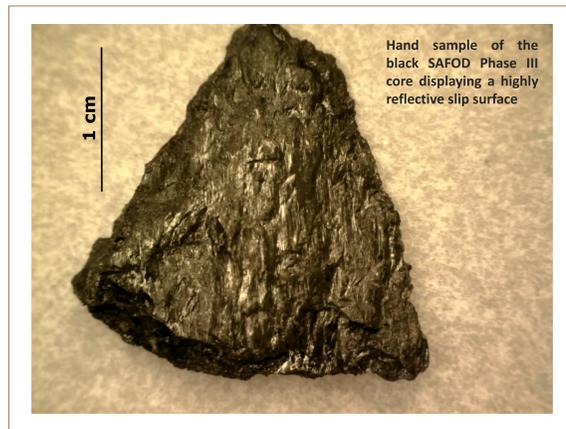


Carbonaceous fault-related rocks in the San Andreas Fault Observatory at Depth (SAFOD) Phase III core: Indicators of fluid-rock interactions and structural diagenesis during slip

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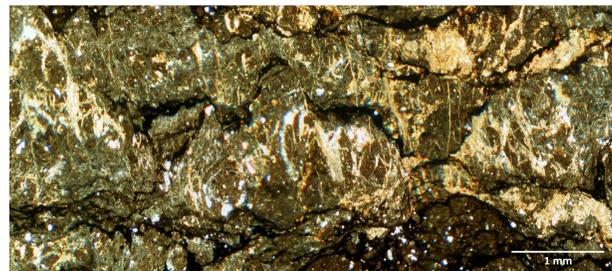


Hand sample of the black SAFOD Phase III core displaying a highly reflective slip surface

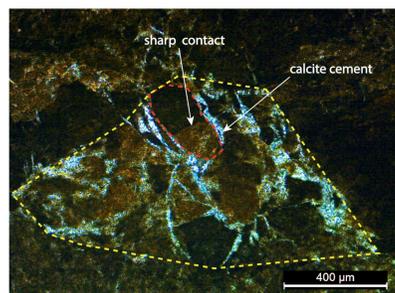
Overview

- At elevated temperatures, many carbon-rich fault zones are subjected to thermal maturation, fluid-rock interactions, and/or shear-induced phase transformations, often yielding various fault weakening agents.
- Black carbonaceous material documented by Bradbury et al. (2011; 2015) in SAFOD Phase III core exhibits intense comminution, shear-induced slip localization, fragmented shear zones, stylolites, calcite-cemented breccia, calcite veins of varying trace element chemistry, and calcite vein fragments in the wall rock.
- Presence of calcite-cemented carbonaceous ultracataclasites in creeping segments of the Central Deforming Zone (CDZ) and Southwest Deforming Zone (SDZ) of the San Andreas Fault raises questions regarding the source of the carbonaceous material, and the nature of thermochemical reactions and fluid-rock interactions that promote dynamic weakening and strength recovery in carbon-bearing fault gouges during the seismic cycle.

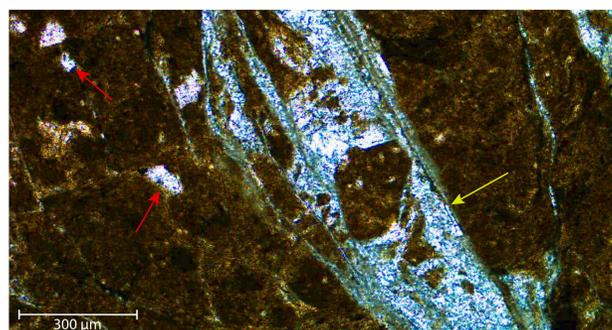
Fault microstructures and geochemistry



Microstructures in carbonaceous material (CM) of SAFOD Phase III core (cross-polarized light) consist of a network of stylolites at (primarily) calcite interfaces. Note the fine-grained, fibrous nature of (re-precipitated?) calcite – diffusive material transport.



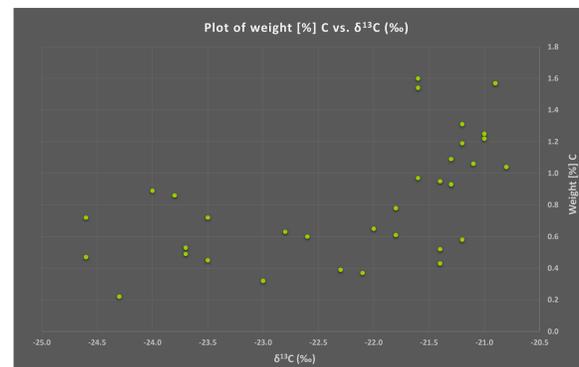
Left: (plane-polarized light). Microstructures in CM-bearing material of SAFOD Phase III core indicate multiple episodes of brittle deformation. The yellow dashed polygon delineates edges of a single brecciated fragment consisting of numerous smaller brecciated fragments cemented by fine-grained calcite. The red dashed polygon delineates a single brecciated fragment composed of two smaller fragments separated by a sharp contact.



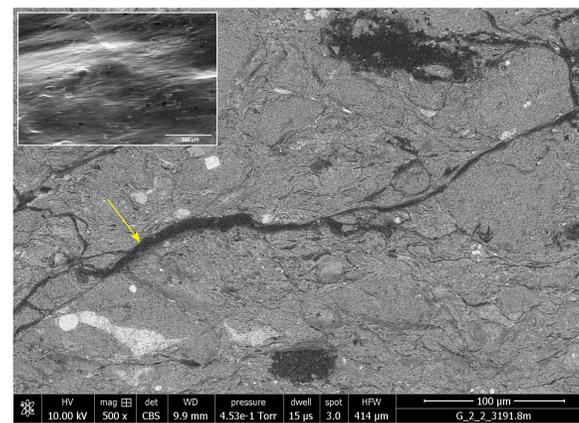
Microstructures in CM-bearing SAFOD Phase III core (plane-polarized light) suggest multiple generations of calcite precipitation. Yellow arrow points to a fine-grained calcite vein cementing wall rock breccia. Red arrows show calcite vein fragments in the wall rock – likely exhibit different trace element chemistry than the adjacent intact vein.

SAMPLE (m MD)	Weight [%] C	$\delta^{13}C$ (‰)	SAMPLE (m MD)	Weight [%] C	$\delta^{13}C$ (‰)
E-1-4-3144.8	0.45	-23.5	G-2-2-3192.7	0.43	-21.4
E-1-5-3145	0.47	-24.6	G-2-2-3192.7B	0.61	-21.8
G-1-1-3186.7	0.78	-21.8	G-2-3-3192.7	0.58	-21.2
G-1-2-3178.5	1.04	-20.8	G-2-3-3192.8	0.52	-21.4
G-1-2-3187.9	1.57	-20.9	G-2-5-3194.8	0.37	-22.1
G-1-3-3189	1.54	-21.6	G-2-5-3195.3	0.39	-22.3
G-1-4-3189.2	1.60	-21.6	G-2-6-3195.8	0.60	-22.6
G-1-4-3189.3	0.97	-21.6	G-2-6-3196	0.63	-22.8
G-1-4-B-3190.1	1.31	-21.2	G-2-8-3197.72	0.53	-23.7
G-1-5-3190.6	1.25	-21.0	G-3-2-3199.2	0.32	-23.0
G-1-6-3190.9	1.09	-21.3	G-4-1-3295.3	0.22	-24.3
G-2-1-3191.5	1.19	-21.2	G-5-3-3303.87	0.49	-23.7
G-2-2-3191.8	1.22	-21.0	G-5-6-3305.2	0.72	-23.5
G-2-2-3192.4A	0.95	-21.4	G-6-1-3307.9	0.86	-23.8
G-2-2-3192.4A	1.06	-21.1	G-6-2-3308.8	0.89	-24.0
G-2-2-3192.4A	0.93	-21.3	G-6-3-3309.7	0.72	-24.6
G-2-2-3192.4-B-Clast	0.65	-22.0			

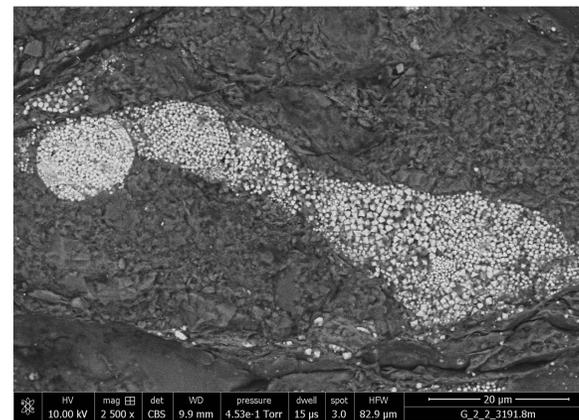
Weight [%] C and $\delta^{13}C$ (‰) values of total organic carbon in gouges in SAFOD Phase III core range from 0.22% to 1.60%, and -24.6‰ to -20.8‰, respectively. $\delta^{13}C$ (vs. PDB) values near that characteristic of organic matter. Presence of ^{12}C -enriched material within local fractures and shear zones in the core suggests the possibility of hydrocarbon migration along the fault, consistent with previous mud-gas analyses^[1]. $\delta^{13}C$ data are reported to precision ± 0.1 .



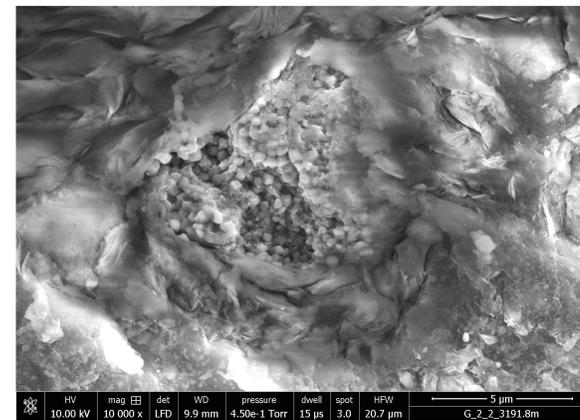
Plot of weight [%] C vs. $\delta^{13}C$ (‰) of SAFOD Phase III samples showing variation in isotopic composition with total organic carbon (TOC) content.



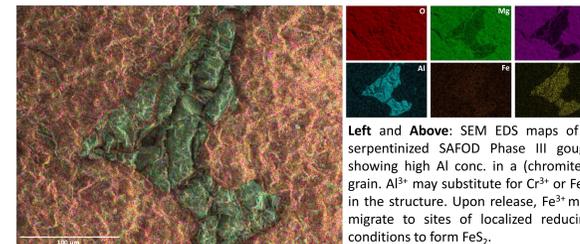
SEM photomicrograph showing textures and phases in SAFOD Phase III gouge. Yellow arrow points to localized carbon 'injections' surrounded by flow features. Note the presence of framboidal pyrite (brighter regions) in the gouge. (Inset: slip surface in G-5-6-3305.2)



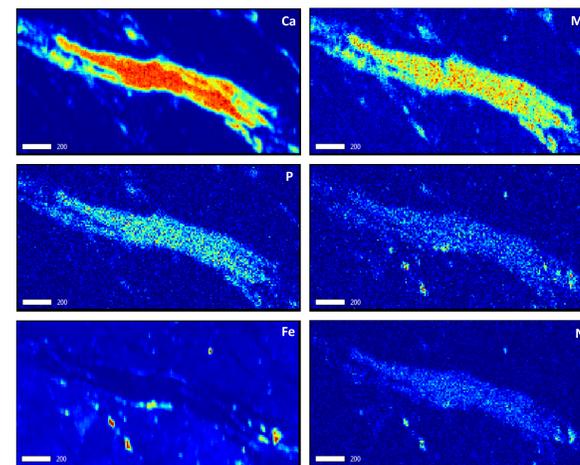
SEM photomicrograph of framboidal pyrite (FeS_2) – indicators of (localized?) reducing conditions in the gouge. Formation of framboidal pyrite requires migration of dissolved Fe to zones of accumulation – which requires a localized sulfide source^[2]. Framboid size distributions may reflect availability of dissolved iron in the surroundings during formation.



SEM photomicrograph showing framboidal pyrite aggregates in phyllosilicate cavities. Alteration of phyllosilicates during fluid-rock interactions may release Fe along cleavage planes, and subsequently form pyrite close to sites of release, in presence of H_2S -enriched aqueous solutions^[2]. During decomposition of organic matter, colonies of sulfate reducing bacteria release H_2S , that may serve as a localized sulfide source for dissolved Fe to form pyrite. Fe and other metal sulfides form through multiple reaction pathways depending on the physicochemical conditions and availability of ions in solution. Transition element chemistry and distribution may be used to constrain evolution of environmental conditions in the gouge.



Left and Above: SEM EDS maps of a serpentinized SAFOD Phase III gouge showing high Al conc. in a (chromite?) grain. Al^{3+} may substitute for Cr^{3+} or Fe^{3+} in the structure. Upon release, Fe^{3+} may migrate to sites of localized reducing conditions to form FeS_2 .



Micro X-ray fluorescence (μXRF) maps of a calcite vein in CM-bearing SAFOD Phase III gouge using synchrotron radiation. Fe, Mn, P, S, Ni are trace elements in the vein. Scale bar is in μm .

Ongoing work

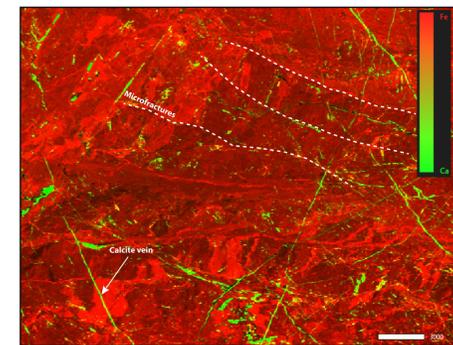
Additional SAFOD Phase III core sample acquisition is in progress. Work in progress includes:

- Cathodoluminescence (CL) microscopy to delineate different generations of fill material in the gouge
- Raman spectroscopy to detect changes in degree of crystallinity of carbonaceous material in the gouge
- Further micro X-ray fluorescence (μXRF) mapping of the gouge using synchrotron radiation to target specific trace elements and reconstruct reaction pathways
- X-ray Near Edge Spectroscopy (XANES) will be used to infer environmental conditions (redox state, pH, temperatures ranges, precipitation rates etc.)
- $\delta^{18}O$ and $\delta^{13}C$ isotope analysis of veins which will be used to trace the source of fluids during deformation

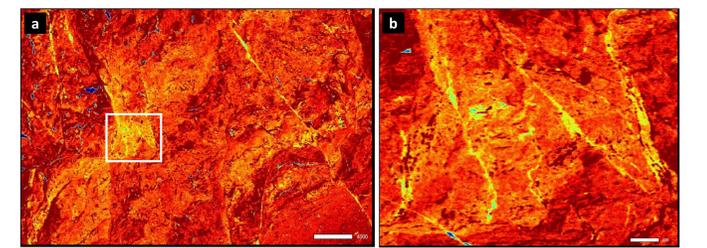
In future, microstructural observations and geochemical data from this work will be used to constrain experimental conditions to study deformation processes and fluid-rock interactions in faults.

Implications

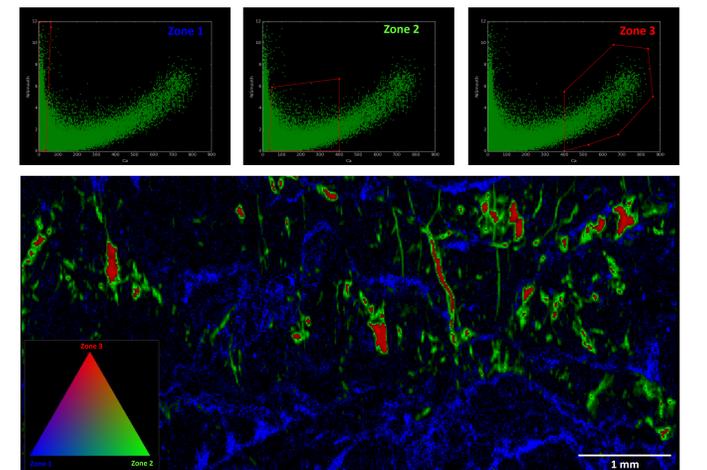
Preliminary work suggests reducing conditions in carbon-bearing zones of SAFOD Phase III core. The nature of physicochemical reactions resulting from changes in environmental conditions in the gouge may contribute to dynamic weakening and strength recovery in faults. As majority of displacement in faults is accommodated on extremely narrow (μm scale) principal slip surfaces, constraining physicochemical processes at the microscopic scale may provide insight into the nature of fluid-rock interactions, and how distribution and alteration of carbonaceous material in faults may affect frictional properties of the gouge.



Left: Micro X-ray fluorescence (μXRF) map of carbonaceous SAFOD Phase III gouge using synchrotron radiation. Variations in Fe (red) concentration illuminate microfractures and crenulation cleavages in the gouge. Variations in Ca (green) concentration illuminate calcite veins and cement intersecting shear zones and microfractures. Varying Ca concentrations in calcite veins may indicate varying degrees of Ca^{2+} substitution by one or more trace elements in aqueous solutions – multiple generations of fluid phases? Scale bar is in μm . (Inset: color legend)



Micro X-ray fluorescence (μXRF) map of carbonaceous SAFOD Phase III gouge using synchrotron radiation. (a) Deformation-related microtextures illuminated by variations in Fe concentration in the gouge. (b) Close-up of boxed area in (a). Yellow zones represent calcite veins (Fe-depleted relative to the adjacent matrix). Note the undulatory form (precipitation during shear?) and incremental growth of calcite veins (different growth stages from a single fluid phase?). Scale bar is in μm .



Top: Ni vs. Ca concentration plots masking three chemically different zones of SAFOD Phase III gouge. Ca concentration increases from **Zone 1** \rightarrow **Zone 2** \rightarrow **Zone 3**. Ni concentration peak is highest in **Zone 1**, decreases to lowest values in **Zone 2**, and increases in **Zone 3**.
Bottom: Micro X-ray fluorescence (μXRF) mapping of **Zone 1**, **Zone 2** and **Zone 3** in SAFOD Phase III gouge. Ni concentration in calcite veins is highest in the vein center (**Zone 3**) and decreases towards the edges (**Zone 2**). Dissolution of calcite during pressure solution accumulated Ni-rich stylolites (**Zone 1**) – gouge becomes progressively enriched in Ni (insoluble). Trace element chemistry and distribution in the gouge may be used to infer environmental conditions and dynamics at fluid-mineral interfaces during deformation. (Inset: color legend)

Acknowledgements

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[2] Scheiber, J., 2011. Iron sulfide formation. Encyclopedia of Geobiology, Springer Verlag, J. Rettner & V. Thiel (Eds.) 486-502.