



From damage zones to seismic hazard: Systematic variations in off-fault deformation across southern California strike-slip faults and implications for Mmax

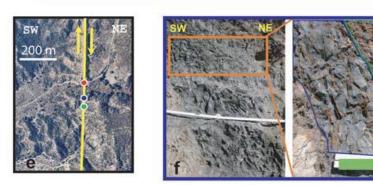
Thomas Rockwell (SDSU) SDSU San Diego State

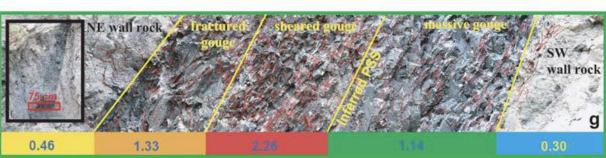
Ashley Griffith (OSU) THE OHIO STATE UNIVERSITY

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Distinguished Lecture, SCEC Annual Meeting
September 7, 2025

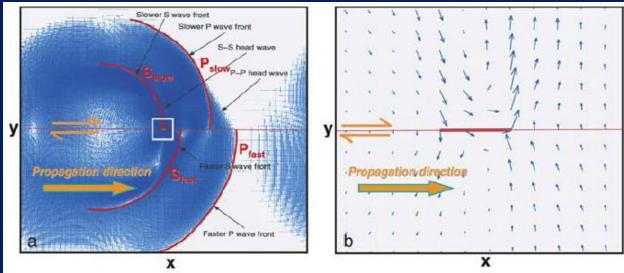




A little background

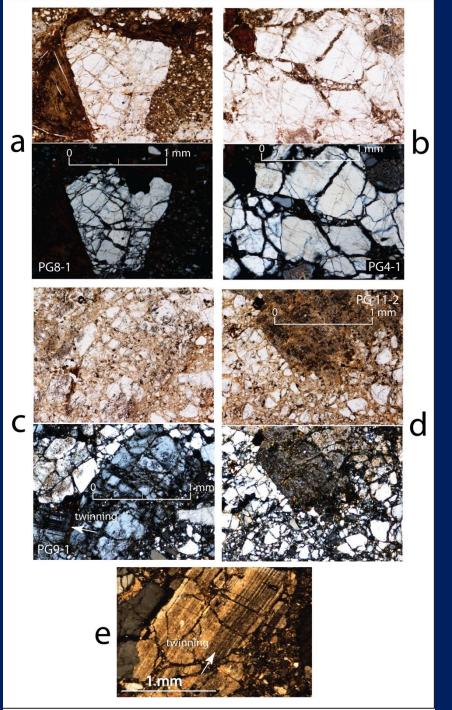
Initial motivation for our studies was to test whether symmetry properties along major crustal faults (SAF, SJF) may affect rupture direction.

Preliminary field studies indicated strong asymmetry in the fault core structure of the San Jacinto fault.



Ben-Zion and Shi, 2005

Dor et al. 2006



This led into observations of intense pulverization (sub-grain fracturing) along the San Andreas and San Jacinto faults

- Pulverized Fault Zone Rocks refers mainly to crystalline metamorphic and plutonic rocks that were mechanically fractured to the micron scale, while preserving most of their original fabric and crystal boundaries (Dor et al., 2006b).
- Little to no grain rotation lack of shear!
- We also recognized sub-grain fragmentation in sandstone and alluvium adjacent to the San Andreas and San Jacinto faults.

Jig-saw puzzle texture: Quartz injections of gouge matrix injections of gouge matrix injections of gouge matrix

Notably, pulverized rocks display dilation with gouge injected between crystal fragment near the fault core, and a lack of sub-grain rotation.

These observations imply dilation under tension rather than compression.

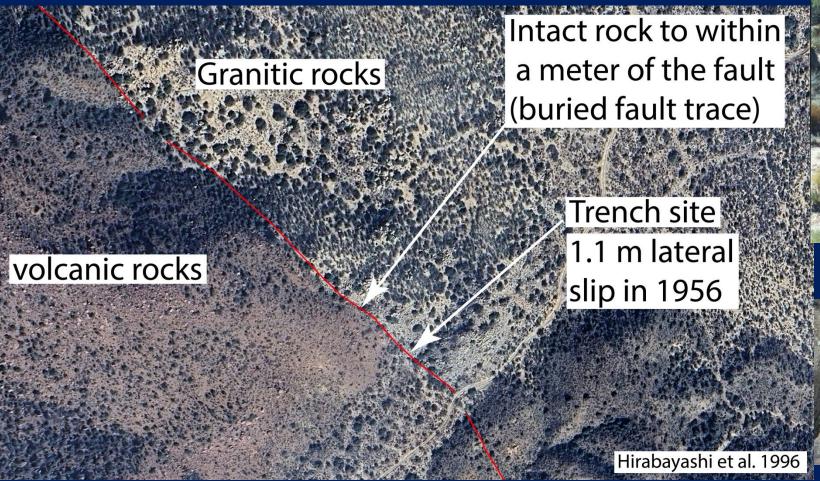


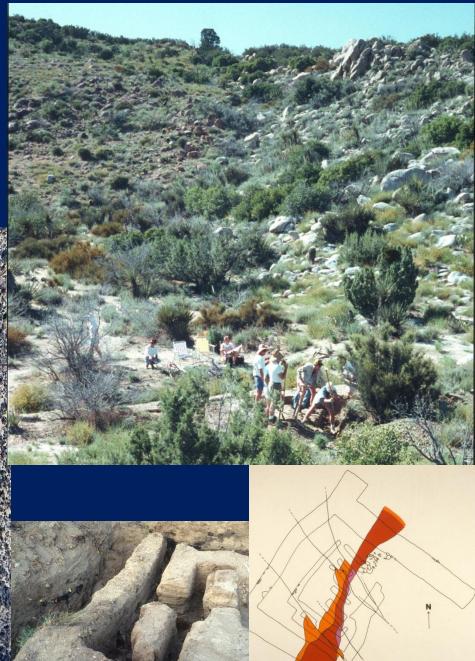
Early work was on the faults that produce large earthquakes

But what about faults that produce moderate earthquakes?

San Miguel Fault, Baja California

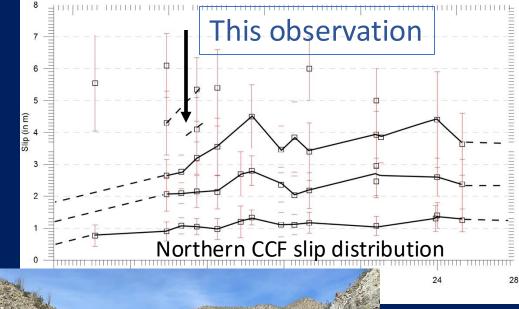
Paleoseismic study in early 1990's: No significant damage zone within 1 m of fault core of 1956 (M6.8) rupture trace with 1.1 m of lateral displacement based on 3D trenching

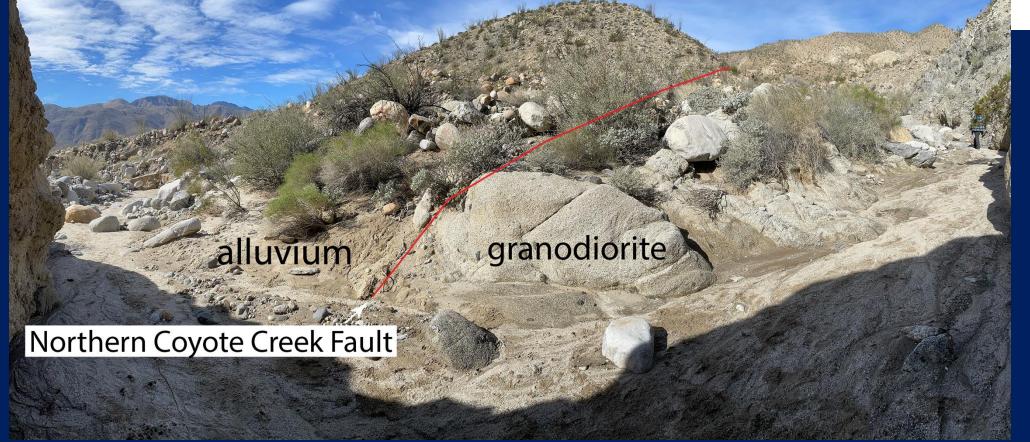


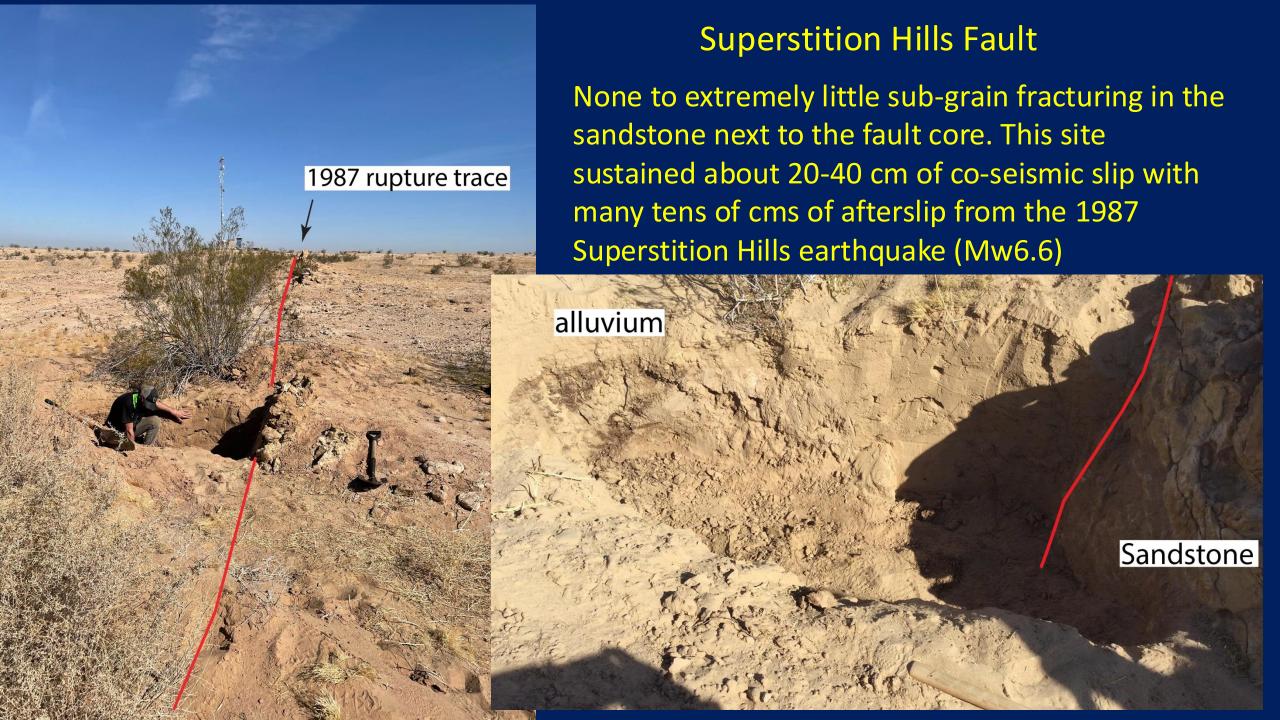


Northern Coyote Creek Fault

Granodiorite with little to no brecciation or evidence of pulverization adjacent to the Coyote Creek fault. Displacement per event estimated at about 1 m based on geomorphic offsets.



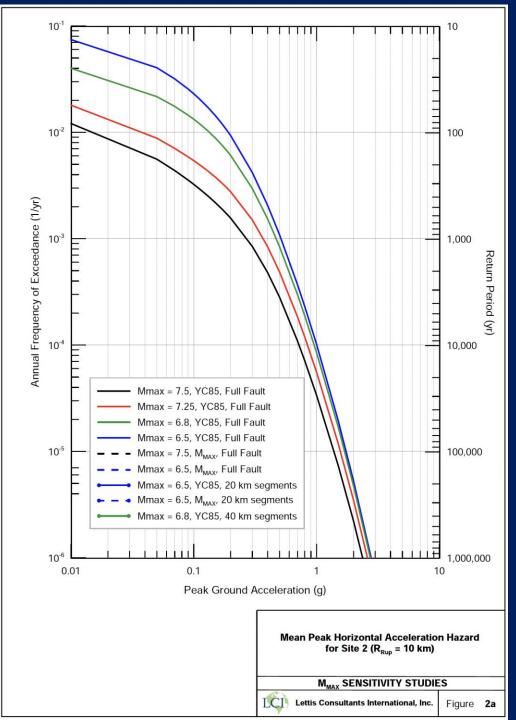




This led to the question: Are there thresholds in rupture size that control the type and extent of damage?

And the topic of my presentation: Can we define the typical size, and perhaps the largest size (Mmax) earthquakes that typically occur along a fault based on their physical and chemical characteristics?

Mmax – the maximum size of an earthquake that can occur on a specific fault



Mmax is used in PSHA studies and affects hazard calculations, and although a bit counter-intuitive, the larger the Mmax for a fault, the lower the hazard in general because some of the long-term motion is used by the rarer, very large earthquakes.

If the fault typically ruptures in smaller, moderate events, the hazard is actually higher than if it typically ruptures end-to-end

Test case: 160 km-long x 13 km-wide fault with 4 mm/yr slip rate. This example uses Bruce Shaw's Mag-LogA to yield a best-fit Mw7.5

Superstition Hills Fault

Relatively young element of the southern San Jacinto fault zone with <8 km of total RL slip

None to extremely little sub-grain fracturing in the sandstone next to the fault core. This site sustained about ~20-40 cm of co-seismic slip with many tens of cms of afterslip from the 1987 Superstition Hills earthquake (Mw6.6)





Much of final displacement was after-slip, and it still sustains some creep

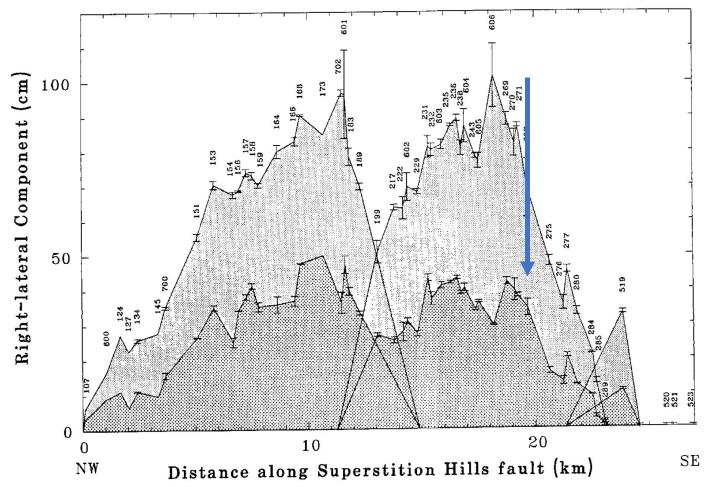


Fig. 8. Longitudinal profiles of right-lateral component of slip along the Superstition Hills fault zone. Site numbers from Plate 1 are indicated. Lower line indicates displacement at one day; upper line is final displacement predicted from power-law fit to observed displacements.

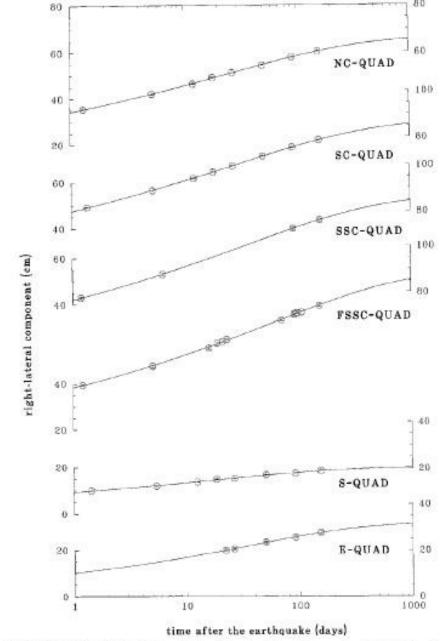


Fig. 2. Growth of right-lateral components with postearthquake (second main shock) time. The quadsite is indicated by letters. Circles with error bars inside are observed data points. Line is power-law rajectory fitted to the data points. Values of the constants for each trajectory are given in Appendix.

Superstition Hills Fault

1987 surface rupture was highly localized along the fault



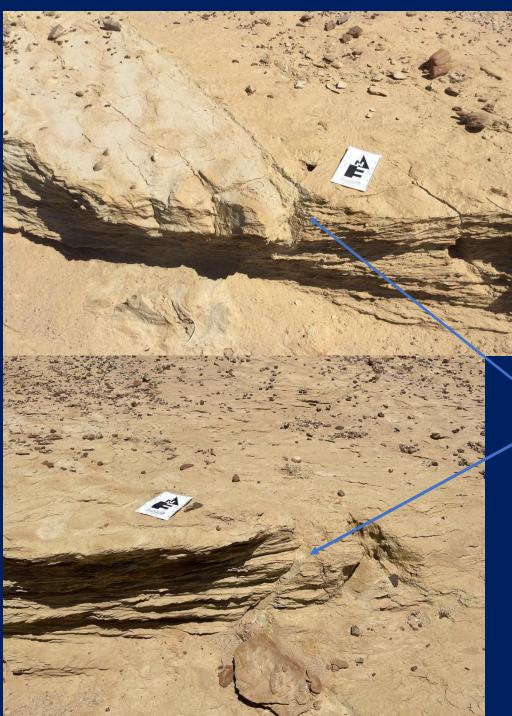




Superstition Hills Fault

Deformation bands are extensive out to at least 100 m from the fault core, and are generally subparallel to the SHF

Gaston, Griffith, Rockwell in prep.



Shear surfaces exposed in 3D

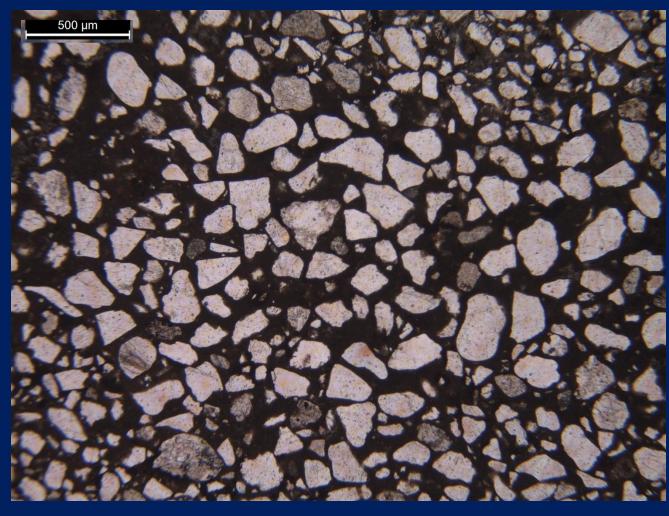
Small sand channels show right-lateral slip



Superstition Hills fault

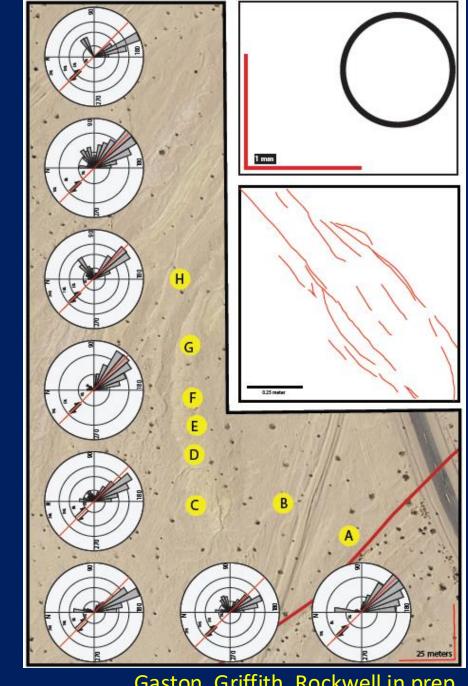
Gaston, Griffith, Rockwell in prep.

Superstition Hills Fault Zone Summary



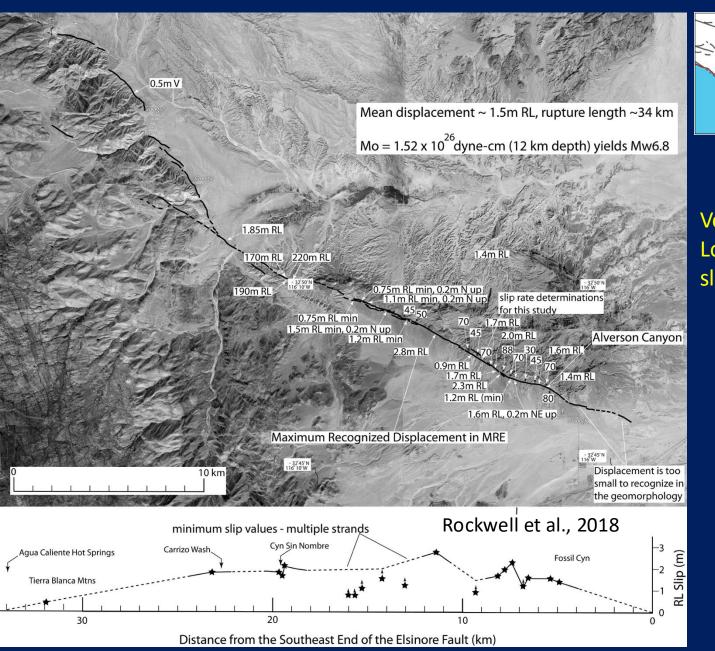
Little to no sub-grain fracturing immediately adjacent to fault in cemented sandstone

Shear bands to at least 100 m from the SHF have a consistent orientation sub-parallel to the fault, with RL shear clear on some, indicating off-fault yielding



Gaston, Griffith, Rockwell in prep.

Elsinore Fault in the Coyote Mountains







Very Localized slip

1.5-2.7 m displacements at Fossil Cyn



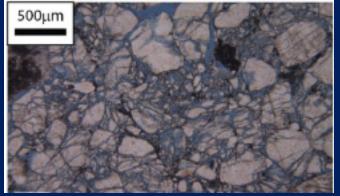
Fault core is ~20 cm fault gouge

Elsinore Fault

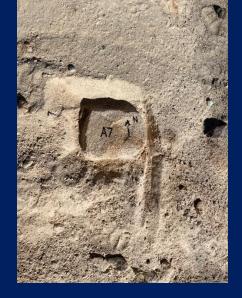




Oriented block recovered ~50-70 cm from fault core

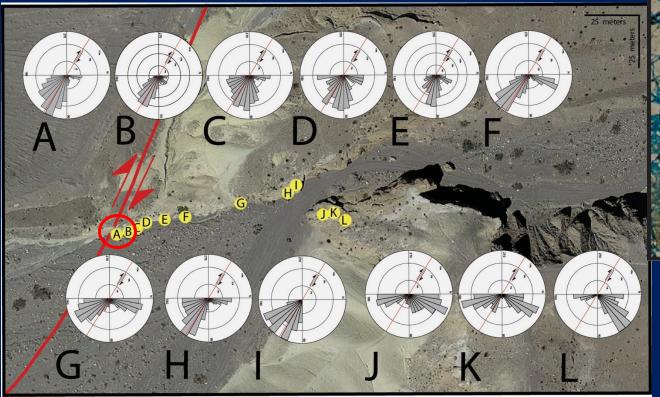


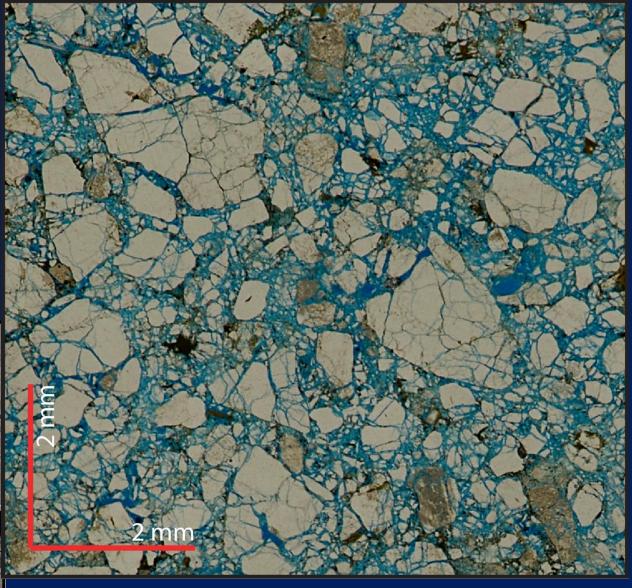
Sub-grain fracturing



Sampling transect in exposed rock along active channel margin

Intense sub-grain fracturing adjacent to the fault core and PSS (A)



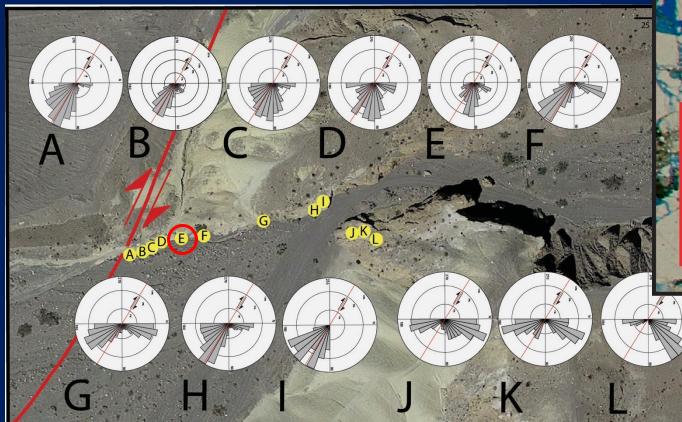


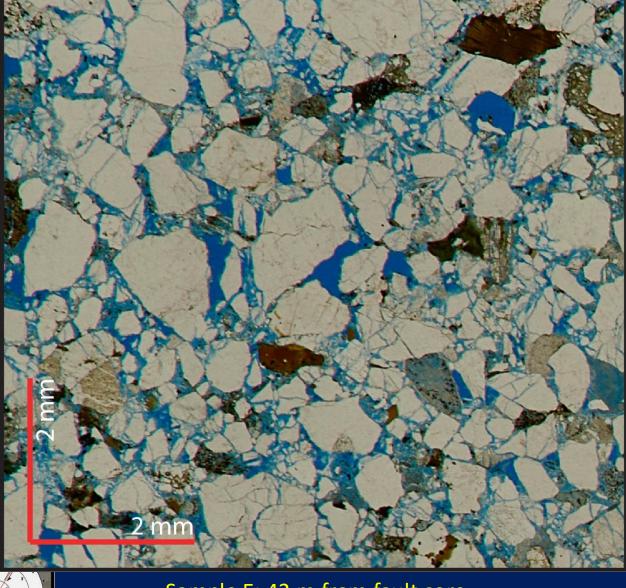
Griffith, Gaston, Rockwell (in review)

Elsinore Fault Zone

Much less sub-grain fracturing in host sandstone. Grain comminution in deformation bands

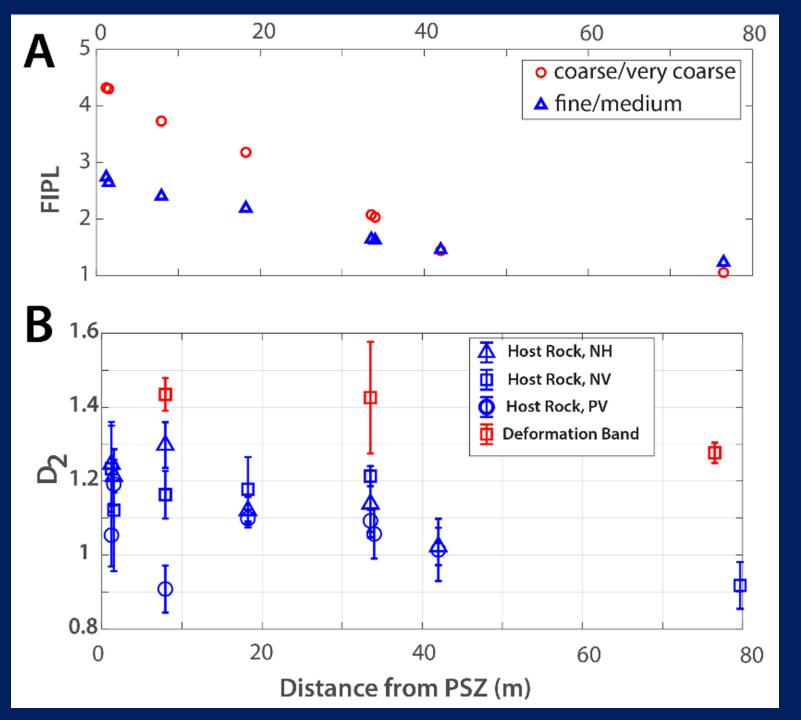
Deformation bands are sub-parallel to the fault near the fault





Sample E: 42 m from fault core

Griffith et al., in review



Elsinore Fault

Quantitative measures of brittle deformation in damage zone rocks.

- (A) Factor of Increase in Perimeter Length (FIPL) in grains in background rocks as a function of distance from the PSZ. FIPL is generally elevated in coarse and very coarse grains (red) relative to fine or medium grains (blue), but both approach a horizontal asymptote at ~40m from the PSZ.
- (B) Exponent D_2 as measured from particle size distributions as a function of distance from the PSZ. D_2 is elevated in deformation bands (red) compared to background rocks (blue). Trend in background rocks decays with distance from the PSZ, like FIPL trend.

NH = normal horiz., NV = normal vert., PV = perpendicular vert.



Pulverized granite on the SW side of the fault (to be quantified)

Pulverization influenced by rock type, with maximum brecciation in granitic rocks

Sections in basement rock on both sides of fault: on the docket for next year

Elsinore Summary

Sub-grain fracturing adjacent to fault core on NE side extends out 40-60 m, and is most intense adjacent to the fault core. Pulverized granite on the SW side extends out at least several meters (to be further studied).

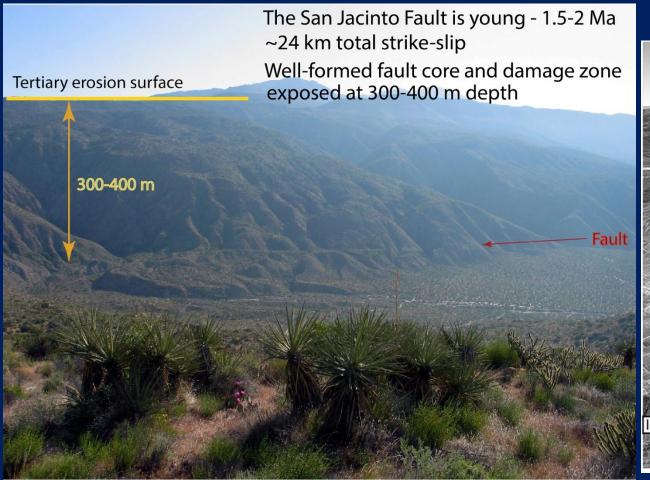
Fracture damage on NW side of the fault is ~40-50 m in width based on factor of increase in perimeter length (FIPL), but is most intense next to the fault

Deformation bands extend out ~100 m from the fault core, but increase in density adjacent to secondary fault strands. Grain comminution in deformation bands indicates distributed shear across the damage zone in discrete subsidiary faults

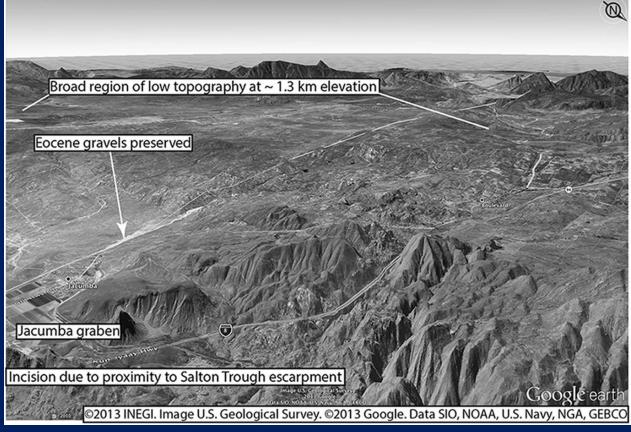
San Jacinto Fault

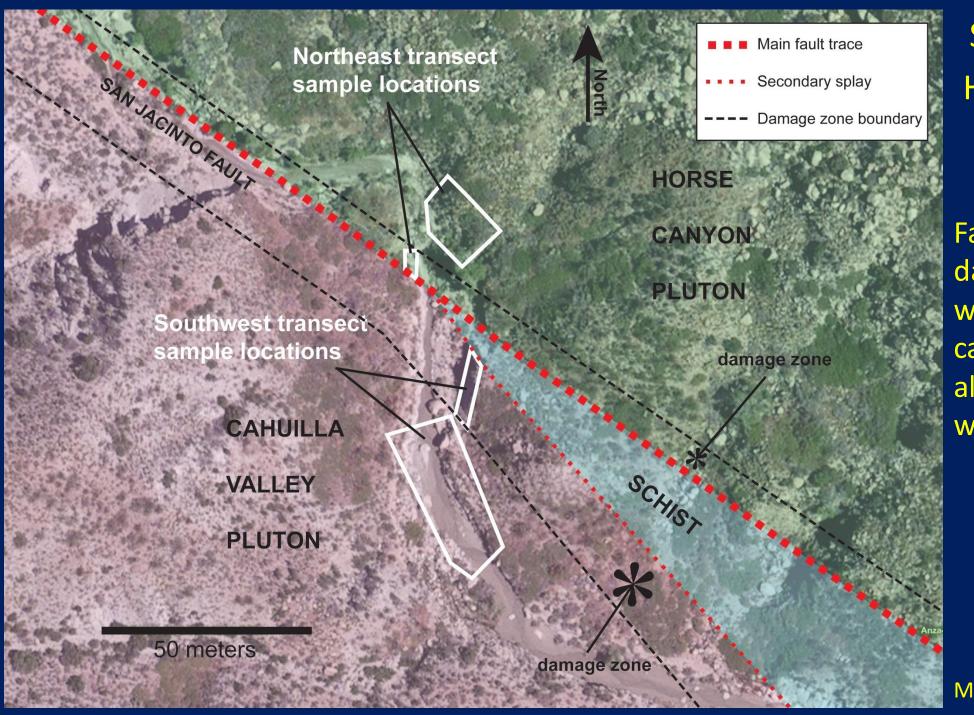
Young fault (~2 Ma) with 24-26 km of total displacement

A Tertiary erosion surface limits the total depth of exhumation of fault exposures









San Jacinto Fault Horse Canyon Site

Fault core and damage zone are well-exposed in a canyon bottom and along the canyon walls.

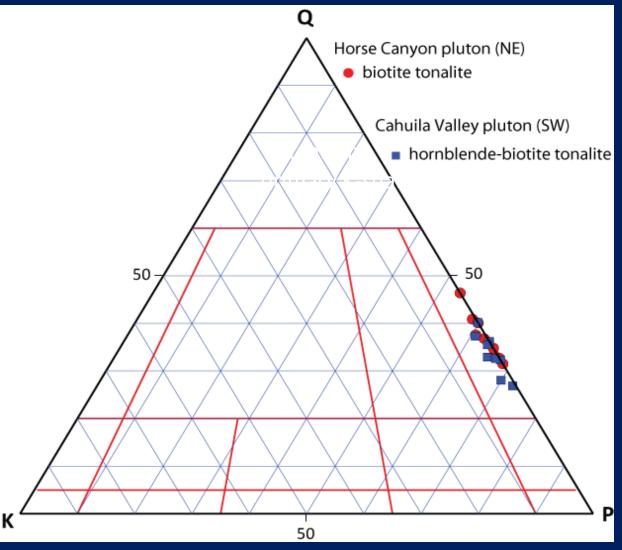


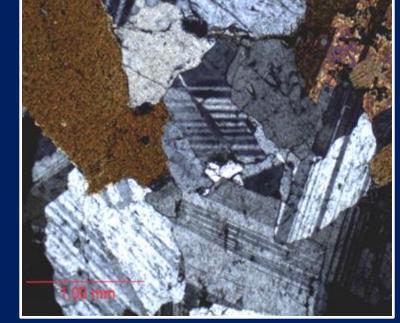
Horse Canyon pluton

The fault separates two distinct plutonic bodies by ~24 km



Wall rocks are tonalites (<10% K-spar)

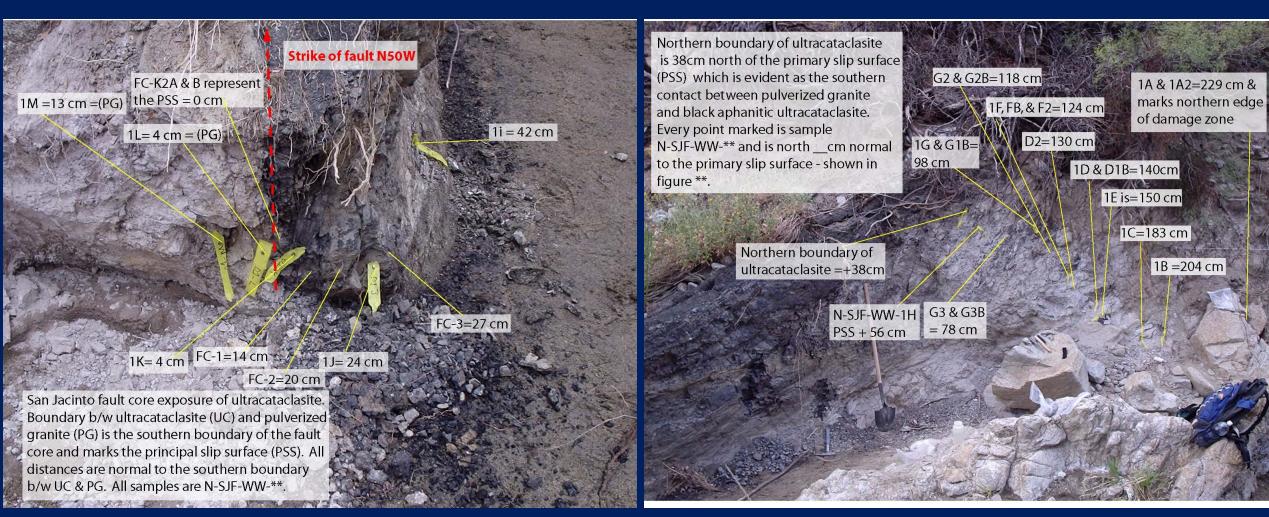




Cahuilla Valley pluton

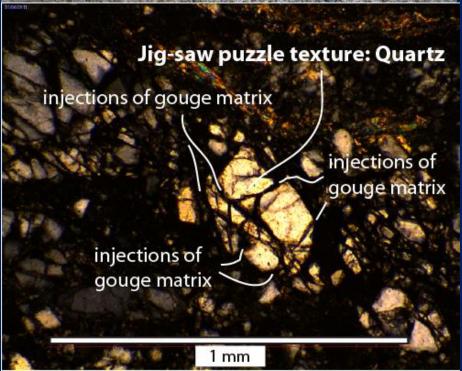
San Jacinto Fault, Horse Canyon

Ultracataclasite fault core with 1-2 cm-thick gouge zone containing the PSS. Dense sampling from the PSS into the wall rock to the NE and SW.



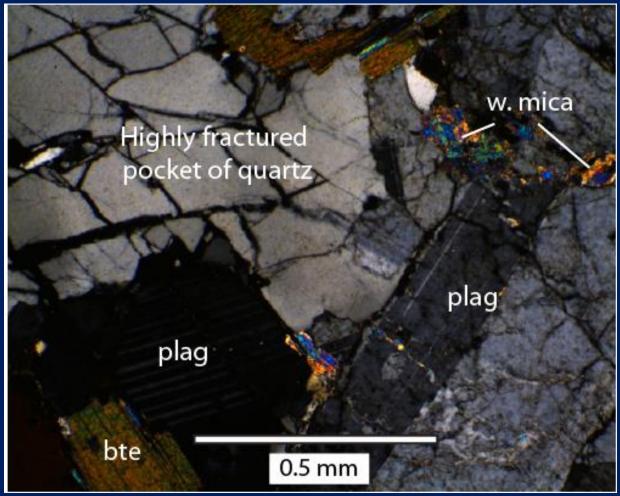
SW side NE side





San Jacinto Fault, Horse Canyon Damage Zone:

Pulverized tonalite with gouge seams and rock fragments



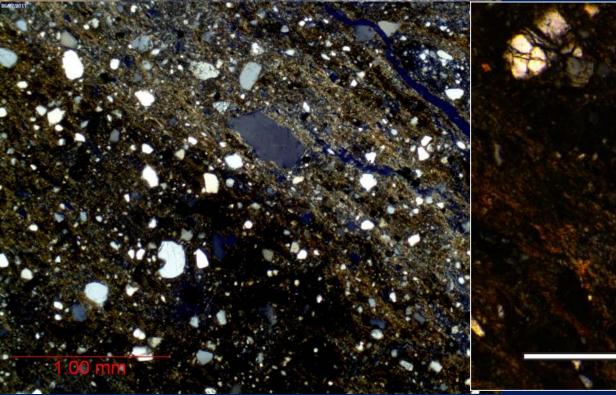


San Jacinto Fault, Horse Canyon Transition Zone

trace of foliation

1 mm

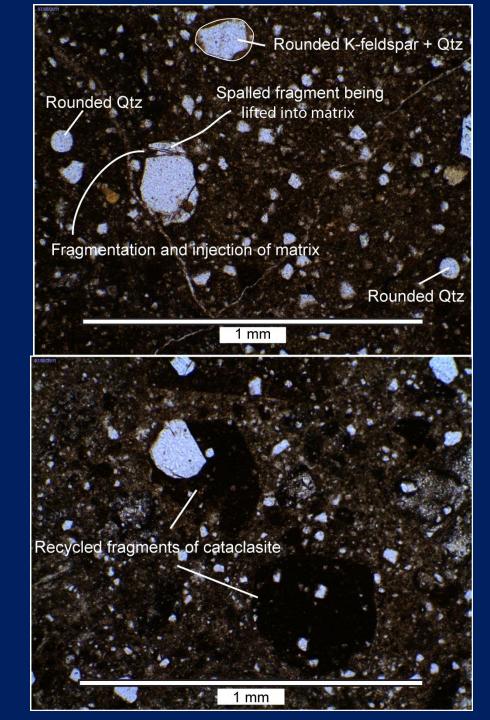
Brittle fragmentation with substantial shear



Fault Core Cataclasite to ultracataclasite

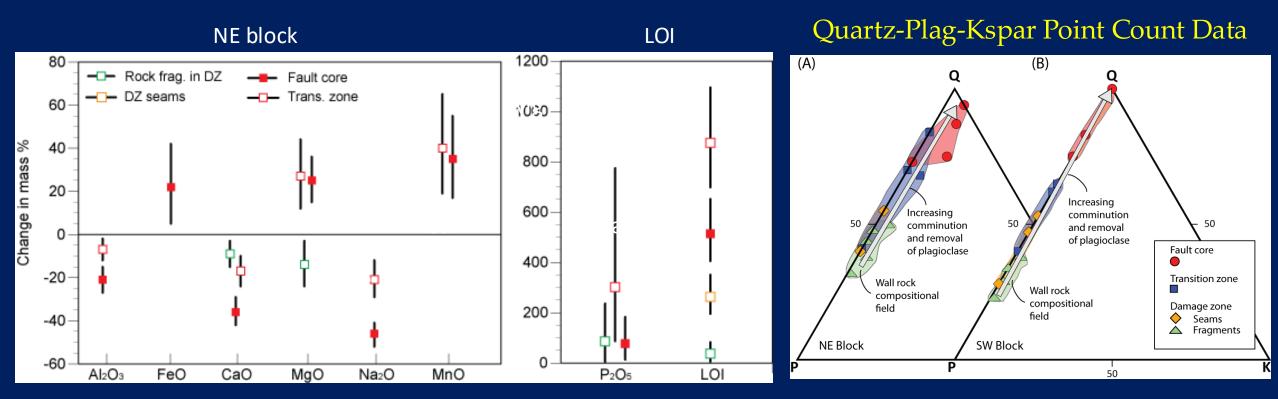


1-2 cm clay gouge PSS



San Jacinto Fault, Horse Canyon

Elemental Mass Change

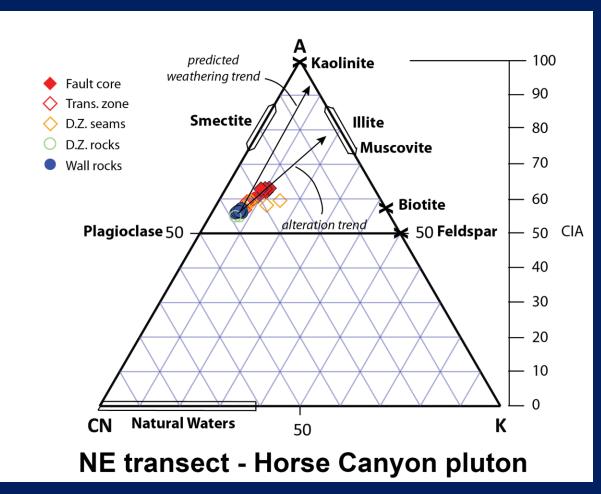


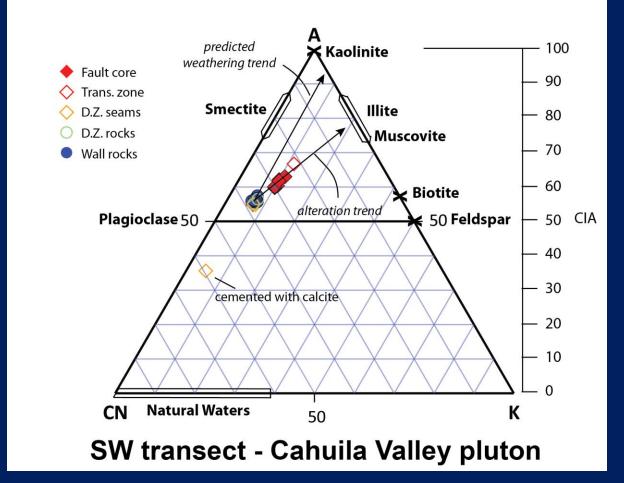
XRF analysis shows dissolution of plagioclase which results in decrease in elemental mass of Al, Ca, Na, enrichment of Mg, Mn, P, and volatile components in the fault core and transition zone, and enrichment of Fe and Si in the fault core. Requires the interaction of a fluid phase within the transition zone and fault core

Chemical Index of Alteration (CIA): $CIA = 100 \times [Al_2O_3/(Al_2O_3 + K_2O + Na_2O + CaO^*)]$

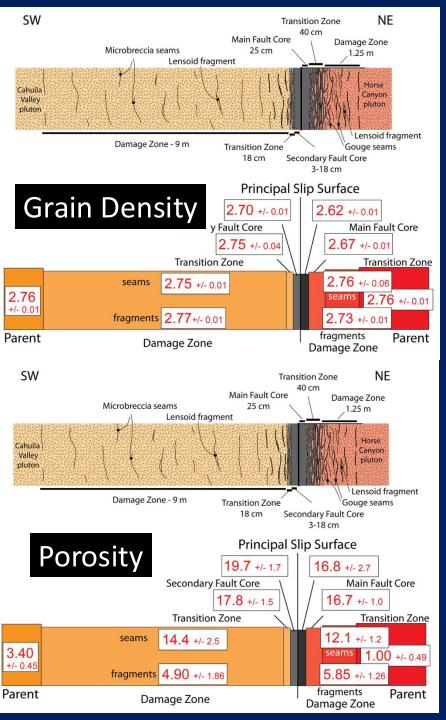
Unweathered igneous rocks: CIA = \sim 50

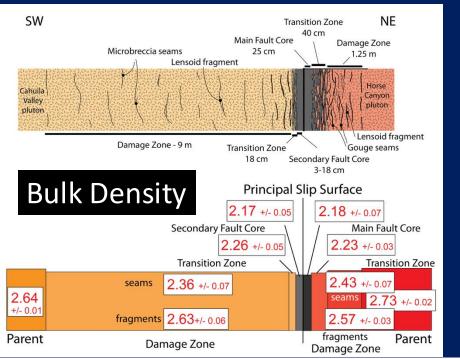
Weathered to clay: CIA = 70-100





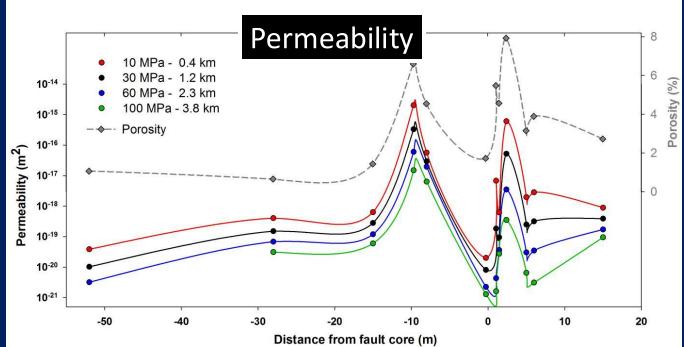
Clear trend towards crystalline Illite –requires elevated heat





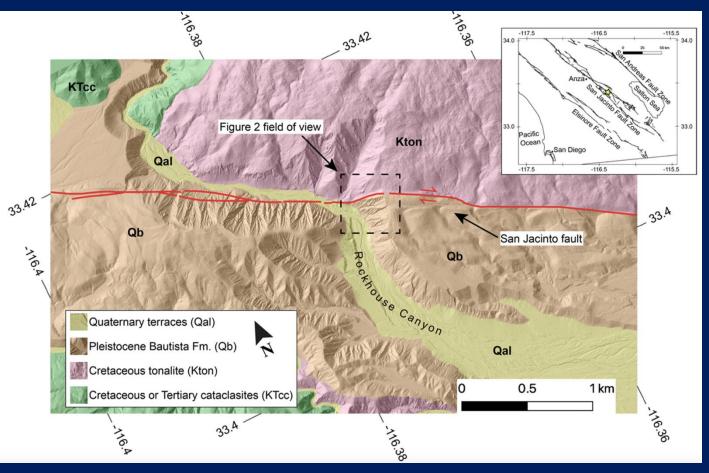
San Jacinto Fault Horse Canyon

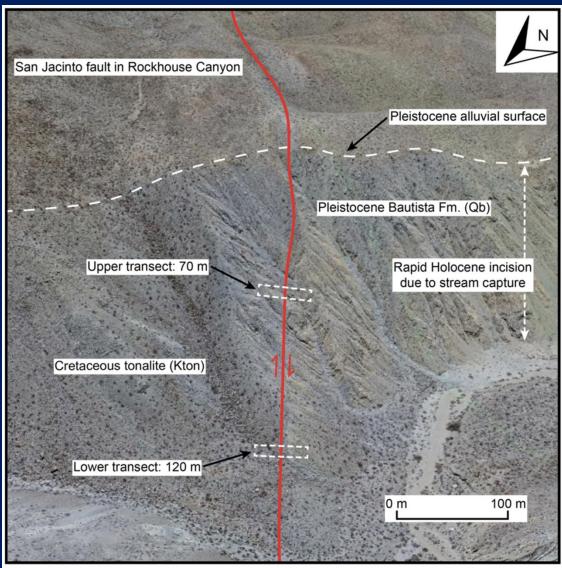
Chemical transformations require fluid-driven alterations, which are facilitated by the increase in porosity and permeability in the damage zone



San Jacinto Fault, Rockhouse Canyon

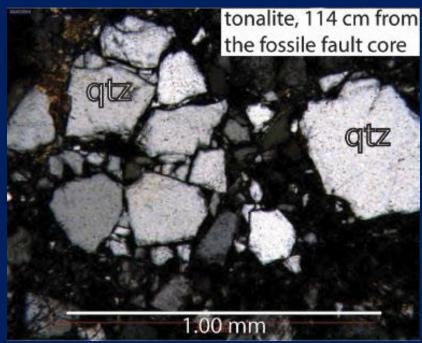
Analysis of damage in Cretaceous tonalite wall rock (NE side) and unconsolidated Pleistocene Bautista Formation (SW side) as a function of confining stress. Average displacement ~2.5 m/event (Salisbury et al., 2012)





Whearty et al., 2017; Weigandt et al., 2023





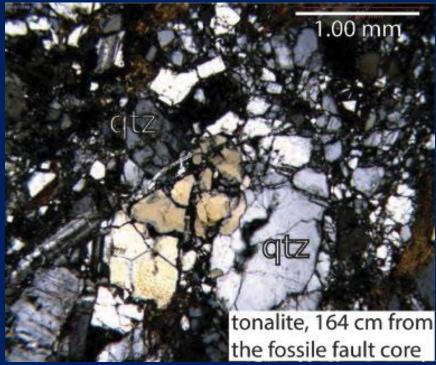
San Jacinto Fault Rock House Canyon

NE side of fault is pulverized tonalite out to at least 10 m from the fault core

Very clear dilation of fragmented crystals

Evidence of shear in Inner damage zone next to core





Whearty et al., 2016



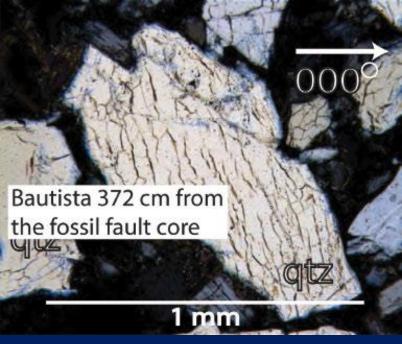
1 mm OOO Qtz Bautista 240 cm from the fossil fault core

San Jacinto Fault Rock House Canyon

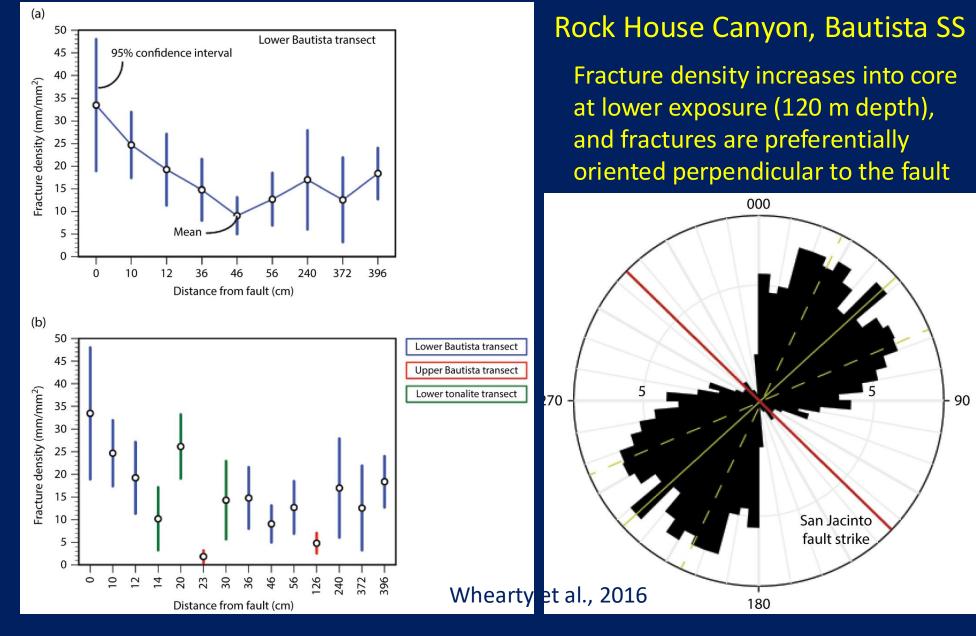
Low confining stress (~1.4 Mpa at upper exposure, ~2.4 Mpa at lower exposure)

Bautista sandstone at 70 cm depth shows little to no subgrain fractures whereas at 120 m depth, sub-grain fracturing is clearly evident but without dilation, and with a preferred fracture orientation





Whearty et al., 2017

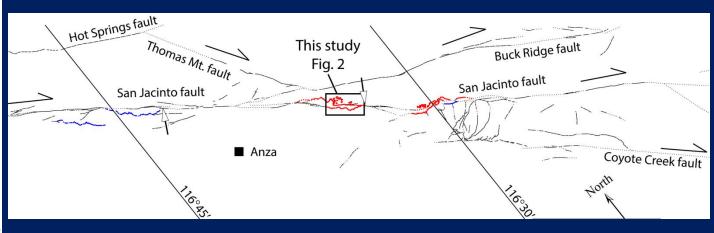


Not a result from an instantaneous decrease in normal stress! Interpreted as a result of compressive stress during rupture

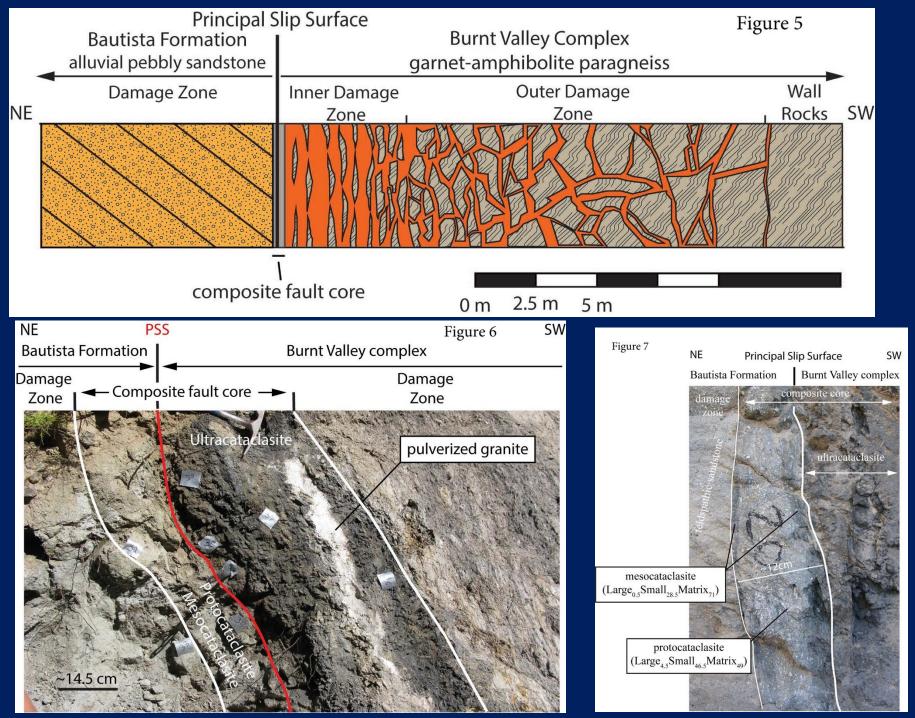
Study Area and Fig. Pleistocene Cretaceous ~305 ~610 meters sands and gravels Horse Canyon pluton 2000 feet Bautista Fm. Coahuila Valley pluton pre-middle Cretacous main trace Burnt Valley complex (B) San Jacinto fault feet meters thrust fault 5000 teeth on dip direction hanging wall and value (C) aluvial sediments main fault that 4000 ~1219 dismembers flower Study Area and Fig. 3 3000 2000 plutonic \ metatmorphic rock 0 no vertical exaggeration

San Jacinto Fault, Alkali Wash Site

Exhumation depth ~220 m Located up the canyon from the Horse Canyon exposure



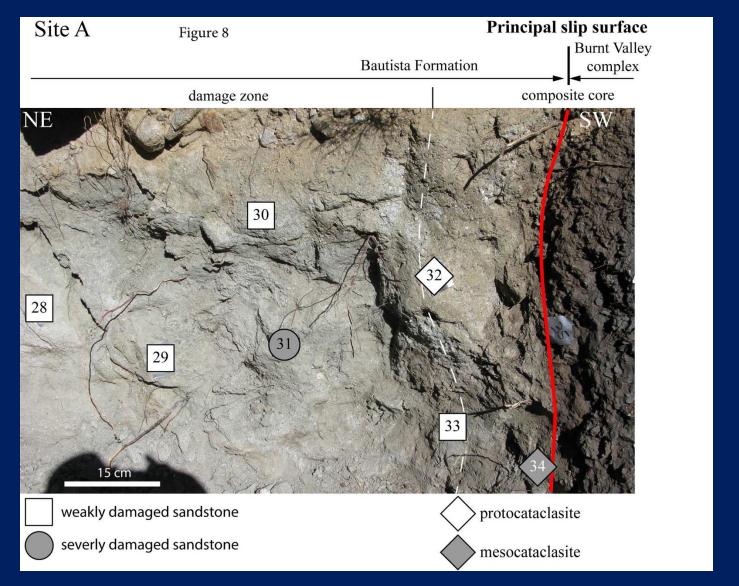
Peppard et al., 2018

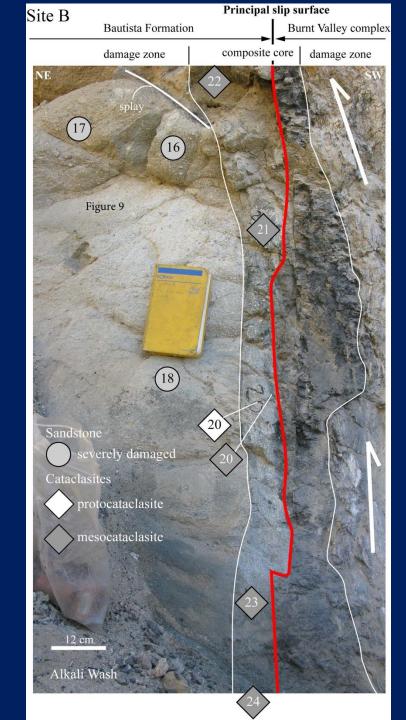


San Jacinto Fault, Alkali Wash Site

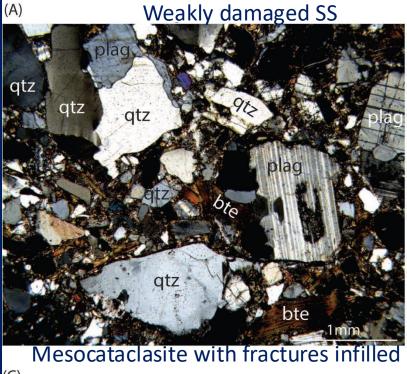
San Jacinto Fault, Alkali Wash Site

Heterogeneous damage of the Bautista Sandstone extending out >20 m on the NE side





San Jacinto Fault, Alkali Wash Site



plag

Mesocataclasite with fractures infilled with calcite and lesser amount of clay

Severely damaged SS

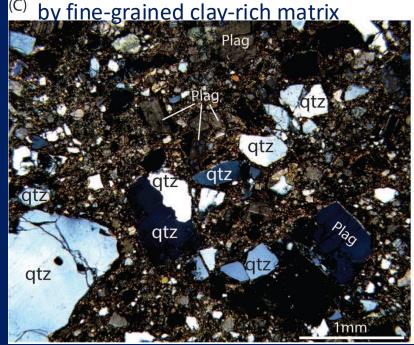
plag

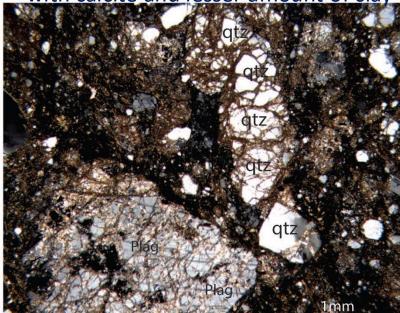
1mm

plag

Fragmented crystals show dilation without shear

Fault core





Adjacent to fault core

San Jacinto Summary - Physical damage

At Horse Canyon, the fault core that formed at no more than 300-400 m depth is ultracataclasite. The active PSS is 1-2 cm thick gouge embedded with the ultracataclasite. Increases in porosity and permeability extend out 40-60 m from the fault core. At Alkali Wash with an exhumation depth of 220 m or less, the fault core is a mesocataclasite but displays the intense fracturing of sand grains.

In general, the San Jacinto fault exhibits a zone of pulverized granitic rocks that extends out meters to ten meters from the fault core. The inner damage zone exhibits crystal fragmentation and shear.

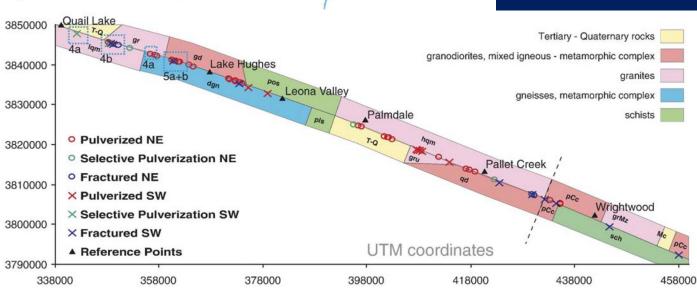
Chemical transformations in fault core and damage zone at Horse Canyon exposure (300-400 m maximum depth of exhumation) require fluids with elevated temperature.

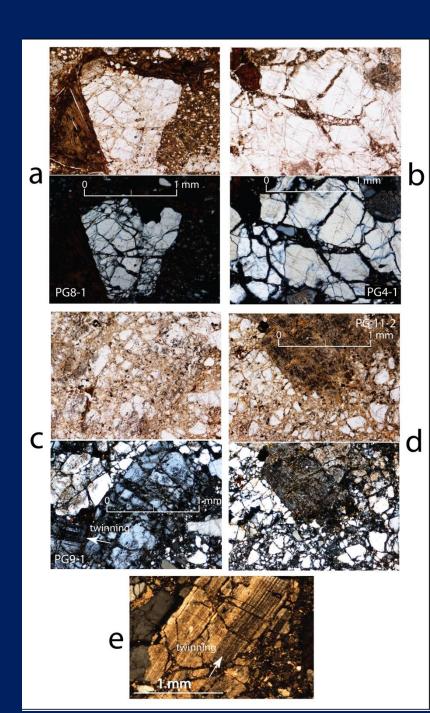
At Rockhouse Canyon, dilation of pulverized granitic rock on the NE side vs evidence of compressionally fractured sediments on the SW suggests NW-directed rupture direction. A minimum confining stress of ~2 MPa seems to be required to fracture the unconsolidated Bautista sediments.

Elizabeth Lake Lake Hughes Little Rock Paleoseismicity site Little Rock Creek Jackson Lake Homogeneous pulverization Marble (fractured) Hwy 15, Cajon Pass > Pulverized sedimentary rock 3840000

San Andreas Fault

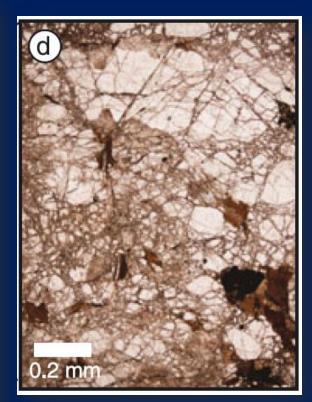
Initial studies on the San Andreas fault focused on grain-size reduction (pulverization) of the plutonic rocks adjacent to the fault core (Wilson et al., 2005, Dor et al., 2006).





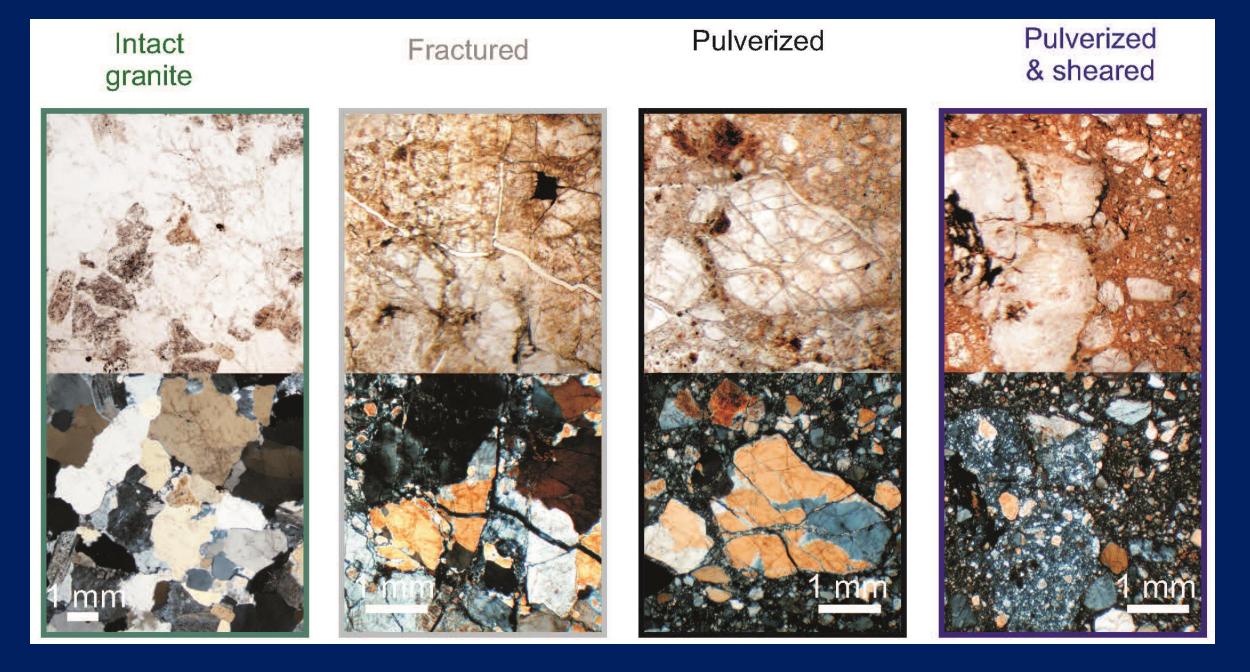
Little Rock site (south)



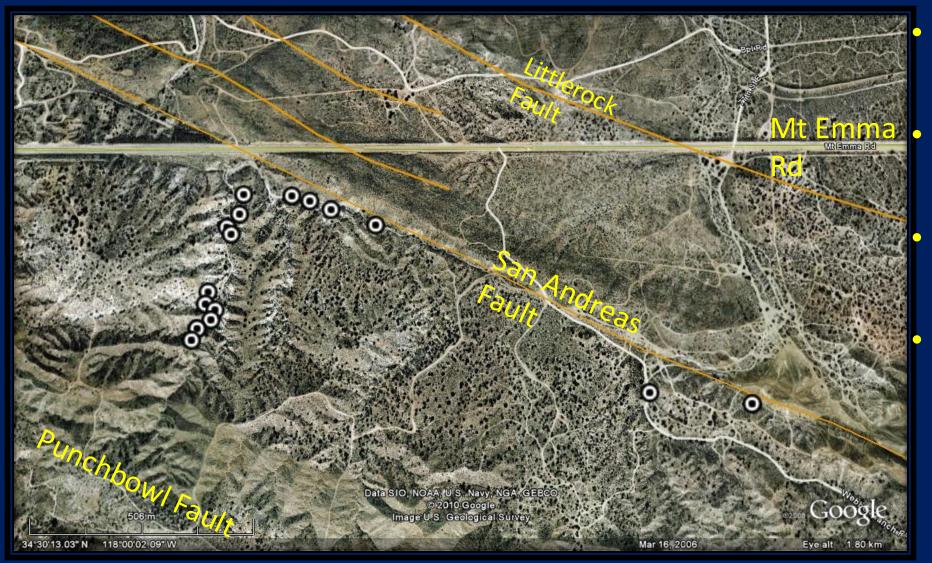


Rempe, et al., 2013

Pulverized Fault Zone Rocks (e.g., Brune, 2001; Dor et al., 2006; Mitchell et al., 2011; Rempe et al., 2013) ~100m from major faults are too far away to be caused by stress perturbations due to sub-Rayleigh ruptures

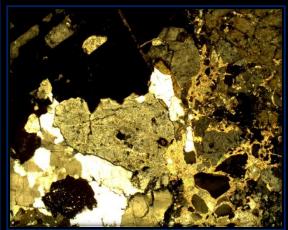


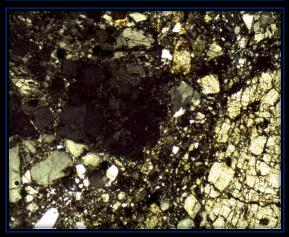
NW Littlerock transect in fossil releasing step



- 26 samples in a 400 m traverse on the San Gabriel block
- Once part of step-over basin between the SAF and Punchbowl F.
- Relatively young strand with accumulated slip only a few tens of kms
- Pulverization within 100 m of the principal slip surface, with damage extending hundreds of meters to the SW







NW Littlerock

Parent Rock

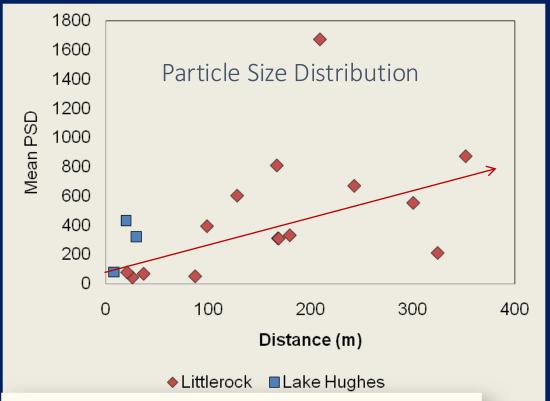
Unweathered granodiorite

Damage Zone

Extends from about 100-400 m from fault core, with damage progressively decreasing outward

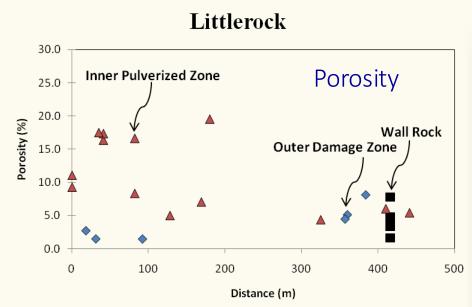
Pulverized Zone

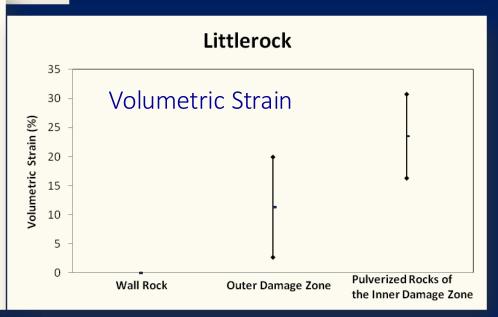
Nearly 100 m wide zone of pulverized Granite, with some secondary shear zones



NW Littlerock physical damage data

But the San Andreas fault has experienced a long and complex History. How much of the observed damage occurred near the surface vs. at depth?



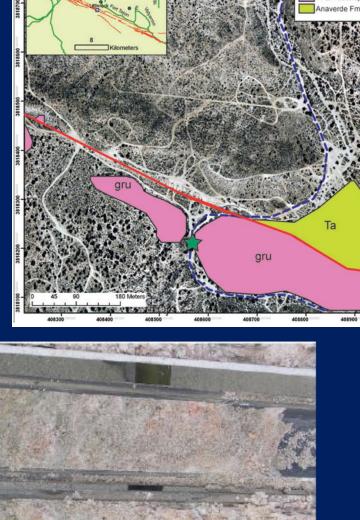




Wechsler et al. 2011

The Littlerock Core

- •Recovered core from 2m to 42m depth at a distance of about 80 m from the current main trace of the San Andreas fault
- •Excellent recovery of oriented core
- •Cored through secondary faults and shears
- •Three rock types all pulverized

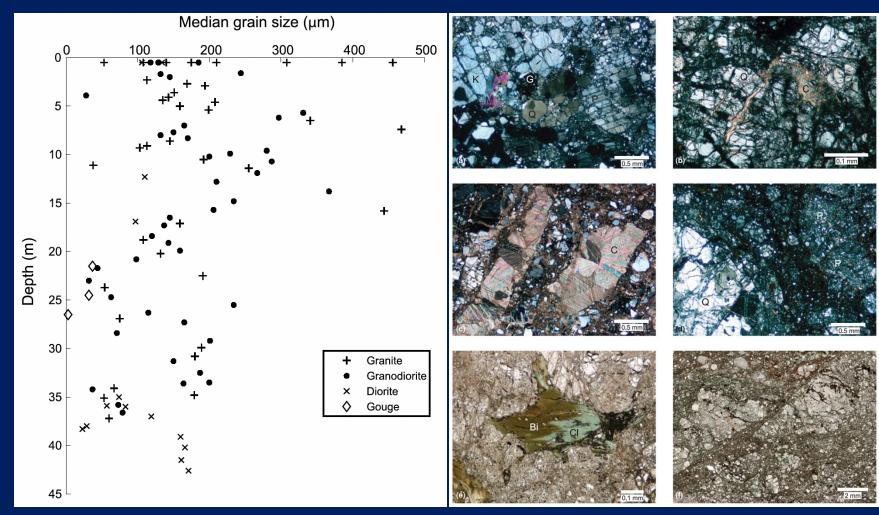




Littlerock Core

Assess the significance of weathering on the pulverization signal by drilling below the weathering zone

Mean grain size averaged between 50-600 µm, in concurrence to ~1% of energy budget for dynamic shattering



Wechsler et al., 2011





Deformation Bands on the San Andreas Fault

Extend out >>100 m from the fault core, and much greater density than along the San Jacinto or Elsinore faults





Geological and Frictional Characterization of Damage Zone Structure of the Southern San Andreas Fault at Ferrum and Implications for Coseismic Off-Fault Deformation

SCEC Contribution #14479, 2025 SCEC Annual Meeting Poster #TBD

Griffith, Fullriede, Rockwell, Torma



General Summary of Physical Damage

Faults with:

Small Displacement (<1m) (SHF, CCF, SMF)

No appreciable sub-grain fracturing (pulverization) in the wall rock Deformation bands extend out 10's of meters showing minor off-fault shear

Moderate Displacement (1.5-2.7m) (EF, soSJF)

Intense sub-grain fracturing (pulverization) within meters of the fault core, dilatational sub-grain fracturing along with increases in porosity and permeability out to ~60 m, deformation bands (some with shear) extend out ~100 m, influenced by secondary fault splays

Large Displacement (3-6m) (SJF, SAF)

Pulverization extends out many tens of meters, broader in fossil stepovers with sub-grain fracturing to hundreds of meters. Deformation bands extends out many hundreds of meters from the fault

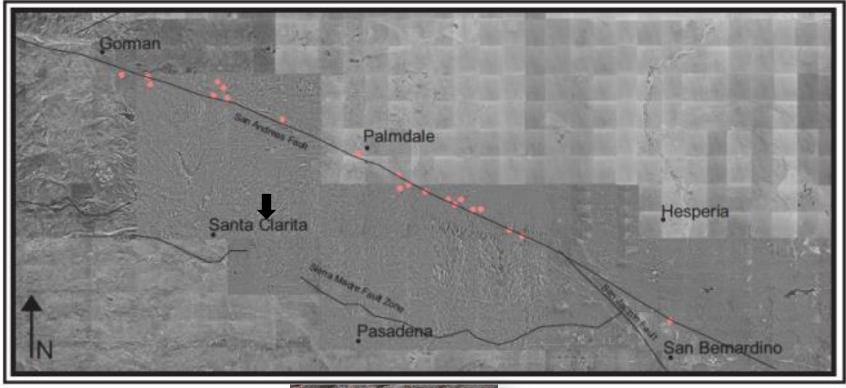
Note: The Superstition Hills, Elsinore, Coyote Creek and southern San Jacinto faults all have similar total displacements whereas the central San Jacinto and San Andreas fault displacements are larger.

But Wait – There's More!

Another signature of fluid
alterations in the San Andreas

Fault Zone

Pink granite









Pink granite is found within about 1-2 km of the San Andreas fault along the Mojave section

Burial depth 1-3 km

Anderson, 2011

Lake Hughes Transect



- 34 samples along an 800 m traverse
- On the Mojave block
- Relatively long and straight
- No major steps or bends
- Accumulated most of the long-term slip
- Pulverization within ~50 m of the principal slip surface

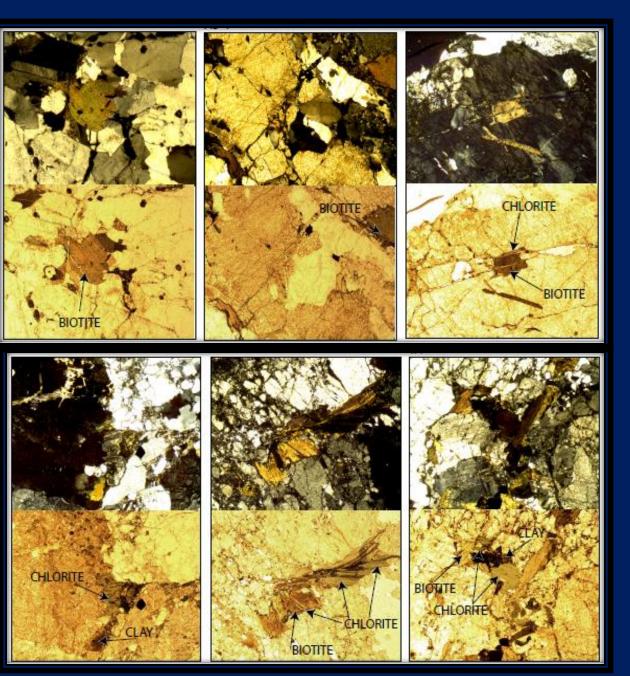
Littlerock Transect



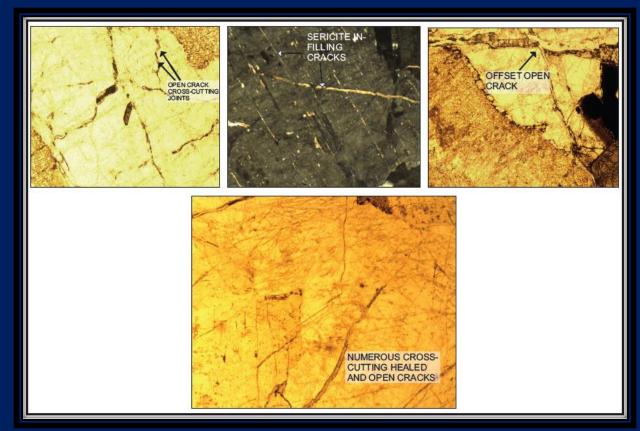
- 26 samples along a 400 m traverse on the San Gabriel block
- Once part of step over basin
- Relatively young strand
- Accumulated only a few tens of kms of slip
- Pulverization within 100 m of the principal slip surface. With damage out 400 m

Tonalite and granodiorite converted to granite with chlorite near the fault

Littlerock biotite alteration to chlorite



- Both transects contain alteration minerals associated with hydrothermal alteration
 - Sericite, laumontite, chlorite
- Lake Hughes has slight increase in alteration minerals towards the fault core, although it is unclear whether it is related to the San Andreas
- Littlerock has a definite increase in alteration minerals toward the principal slip surface



Granodiorite wall rock becomes progressively more granitic towards the fault core

(potassium replacing calcium)



• SiO2 65.6

Al2O3 18.74

• <u>Fe2O3 0.15</u>

• <u>CaO 0.44</u>

• MgO 0.02

• K2O 10.6

• Na2O 4.02

• MnO 0.00

• <u>TiO2 0.01</u>

• P2O5 0.03

Pink

K-feldspar

chemical

composition

Fe content is

the same as

host rock K-

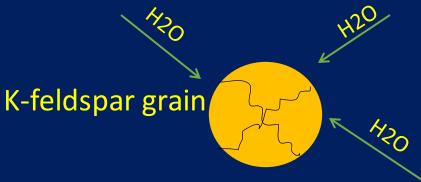
feldspars

Metasomatism of K-feldspar (pinkness) and chlorite alteration are related:

Conversion of biotite to chlorite releases potassium

Fracturing of feldspars allows for oxidation of the iron and replacement of calcium with potassium

Calcium combines with carbonate to fill veins and fractures, which are abundant



Supported by:

- Increase in porosity
- •Increase in precipitated minerals
- •Increase in LOI
- •Changes in elemental mass

Only observed along the San Andreas Fault!

General Summary of Physical Damage and Changes in Chemistry

Faults with:

Small Displacement (<1m) (SHF, CCF, SMF)

No appreciable sub-grain fracturing (pulverization) in the wall rock Deformation bands extend out 10's of meters showing minor off-fault shear No observable changes in chemistry (but those studies are just starting) or evidence of fluid interactions

Moderate Displacement (1.5-2.5m) (EF, soSJF)

Sub-grain fracturing (pulverization) within meters of the fault core Deformation bands (some with shear) extend out ~100 m, influenced by secondary fault splays. Chemical alterations within the core and damage zone, with elemental losses and gains, require fluids-driven interactions with some heat

Large Displacement (3-6m) (SJF, SAF)

Intense sub-grain fracturing extends out tens of meters, broader in fossil step-overs. Deformation bands extends out many hundreds of meters from the fault. Chloritization and metasomatic alteration in feldspars along the San Andreas fault require fluids and heat – 150-300 C. Probably aided by increased porosity and permeability in the damage zone. Not observed along the San Jacinto fault, possibly due to lack of exhumation.

Mmax = 6.5, YC85, Full Fault 100,000 Mmax = 7.5, MMAX, Full Fault Mmax = 6.5, MMAY, Full Fault Mmax = 6.5, YC85, 20 km segments Mmax = 6.5, M_{Max} , 20 km segments Mmax = 6.8, YC85, 40 km segments 0.01 Peak Ground Acceleration (g) Mean Peak Horizontal Acceleration Hazard for Site 2 (R_{Run} = 10 km) M_{MAX} SENSITIVITY STUDIES

A bridge to Engineering

There are characteristics that appear uniquely associated with the size of earthquakes generated along faults of the southern San Andreas fault system. More specifically, rather than earthquake size, these signals may be mostly related to the magnitude of displacement along that section of fault.

Mmax, as used in PSHA studies, affects hazard calculations. Our goal is to better understand which characteristics in fault cores and damage zones relate specifically to the size of displacement, and therefore magnitude, to test whether a set of field and laboratory data can be used to assess Mmax on individual faults.

Along with the field work and chemistry, we are conducting a series of laboratory experiments (Split Hopkinson Pressure Bar experiments, Tom Mitchell's fancy new true triaxial rig and rapid decompression chamber at UCL) to reproduce the features we identify in the field and understand the conditions for their formation.

More to come! (Stay tuned)