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Inelastic off-fault deformation and pulverization in the lab: Tensile fragmentation of crystalline vs. granular sedimentary rocks in response to isotropic tension

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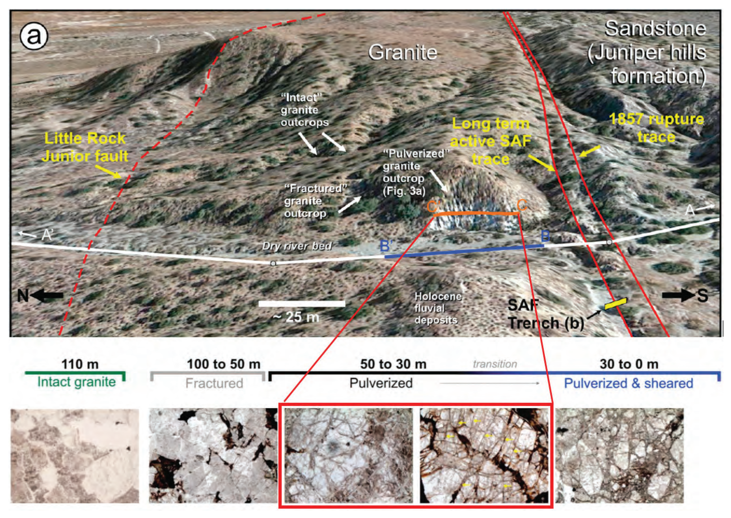
ABSTRACT

The presence of pulverized (highly fragmented, but weakly strained) zones extending 100-200 m from major strike slip faults, including the San Andreas Fault, have been attributed to impulsive compressive stresses associated with propagating earthquake rupture tips. However, theoretical and experimental evidence suggests that such zones may be formed on the transient tensile side of passing ruptures. These pulverized damage zones represent long-lived inelastic off-fault deformation that affect fault dynamics throughout the seismic cycle. We explore the tensile origin of pulverized fault rocks associated with major strike slip faults through a modified Split-Hopkinson Pressure Bar (SHPB) experiment that induces 2D isotropic tension. In the experiments, a sandwich sample configuration is used in which a rock disk is bonded between two cylinders composed of more compliant material such as lead or polycarbonate. Axial shortening during experiments results in radial and circumferential tension in the rock disk due to radial expansion of the compliant end materials. Experiments on both porous granular (sandstone) and crystalline (granite) rocks enable us to evaluate variations in tensile stress based on the rock type. We validate strain and strain rate histories collected on SHPB strain gauges using high speed photography and digital image correlation. Our modified SHPB experiments on Westerly Granite show that at strain rates of $25 s^{-1}$ to $170 s^{-1}$, the rock fails by an isotropic pattern of polygonal fractures. Under similar conditions, deformation of Berea Sandstone is accommodated by distributed grain boundary failure and pore space expansion, therefore preventing fragmentation by fracture growth. These results explain asymmetric off-fault damage observed in the field where crystalline rocks 100-200 m from the core of the fault are pulverized, but adjacent porous sedimentary rocks appear to be relatively undeformed.

PROBLEM

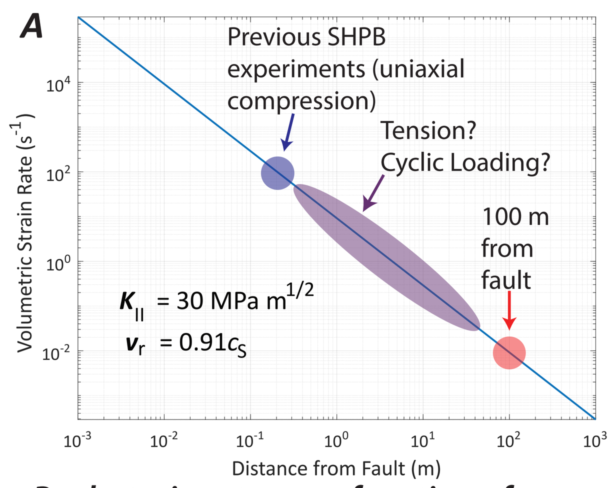
Brittle fragmentation is a fundamental process in the near-tip field of propagating earthquakes. This damage creation - leaving wide swaths of pulverized rocks around large strike slip faults - ***changes elastic moduli***, results in ***rapid slip rate fluctuations*** and ***high frequency content*** in seismic waves.



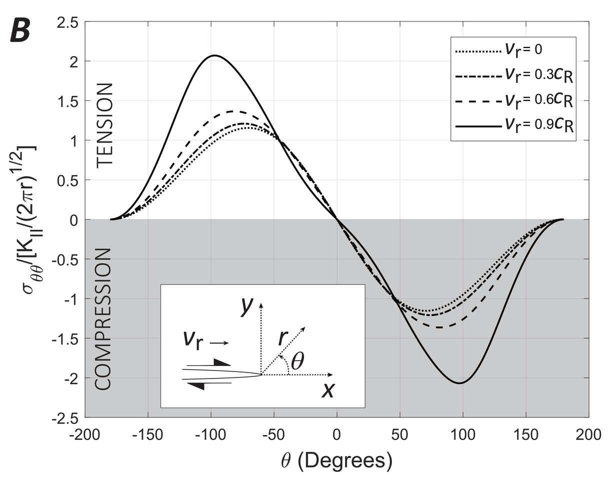
Rempe, Mitchell, *et al.* JGR (2013)

Pulverized damage zones can be 100m thick, but the mechanism for rock pulverization at distances this great from the principal slip zone is unclear:

- *Compressive rock strength increases dramatically with strain rate, and rocks pulverized under compressive loads in the lab require strain rates of ~$10^2 s^{-1}$.*
- *These conditions are only expected within cm's of faults, yet field evidence suggests that rock fragmentation occurs tens of meters from faults.*
- *Strong crystalline rocks seem to be preferentially pulverized compared to weaker sedimentary rocks*



Peak strain rates as a function of distance from fault (blue line).



Relationship between Mode II near-tip stress field and rupture velocity

OBJECTIVES

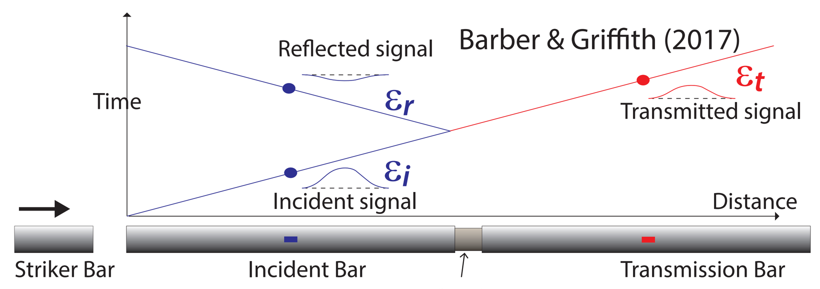
We hypothesize that far-field coseismic pulverization occurs via impulsive near-isotropic tensile stresses associated with passing earthquake ruptures, following evidence from numerical models (Xu & Ben Zion, GJI, 2017). We have designed an experimental technique to simulate 2D isotropic tensile stresses in the lab (see Griffith et al., JGR, 2018 for more details), and here we test the following questions:

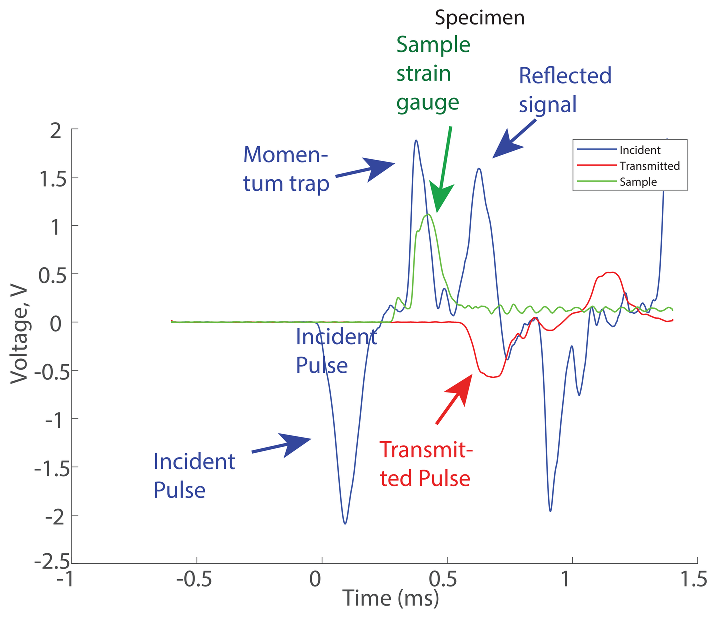
- ***What is the relationship between strain rate and rock strength under tensile loading?***
- ***How do crystalline granitoid rocks differ in their mechanical response to impulsive tensile loads compared to granular sedimentary rocks?***
- ***How are these mechanical behaviors reflected in rock structure?***
- ***How well do the experimental results scale to the natural prototype (pulverized damage zones)?***

EXPERIMENTS

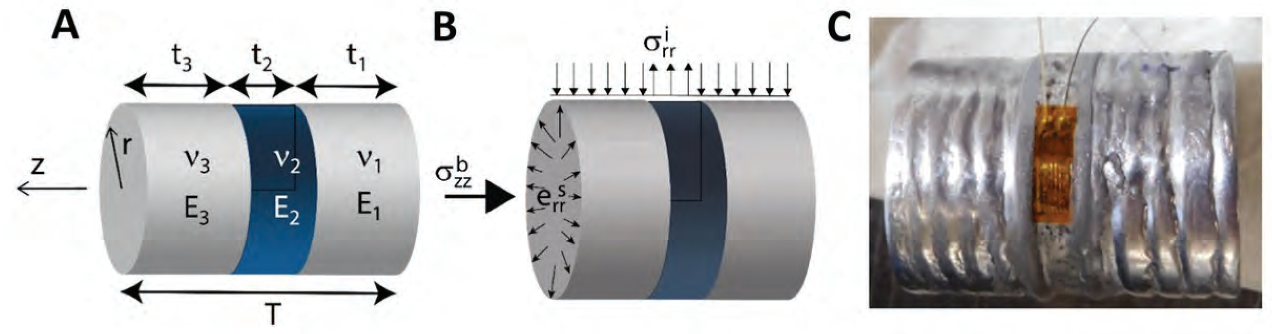
The ***Split Hopkinson Pressure Bar (SHPB)*** is a reliable high strain rate loading technique used to assess the dynamic strength and constitutive response of rock. A uniaxial compressive wave is generated by striker bar impact with the incident bar and is recorded by strain gauges on the incident and transmission bars. This results in a simple load history described by single compressive sinusoidal loading and unloading cycle.

Using voltage time series from strain gauges, we can recontruct macroscopic axial ***strain, strain rate***, and ***stress*** histories and quantify the ***energy dissipated during sample failure (W_d)***.





Modified sample configuration to induce radial/circumferential isotrpic tension



$$e_{\theta\theta}^{elastic} = -\frac{\nu\sigma_{zz}^{b}}{E} \qquad \sigma_{\theta\theta} = E\left(e_{\theta\theta}^{data} - e_{\theta\theta}^{elastic}\right)$$

We modified the traditional uniaxial compression SHPB experiment to induce radial/circumferential tension in a disk-shaped rock specimen. By sandwiching rock disk between two compliant, low compressibility materials (lead cylinders), axial compression causes lead to flow and expand radially outward, pulling the rock specimen apart. This is intended to mimic quasi-isotropic tensile pulses carried by the propagating rupture tip. Tensile failure results in **polygonal fractures in granite** and **disaggregation in sandstone** that are markedly different than fracture patterns produced in traditional unaixial compression experiments. During the experiments, we can monitor circuferential stress using strain gauge mounted directly on the rock. In all experiments, lead disks are 10-15 mm thick and rock disks are 5-10mm thick.

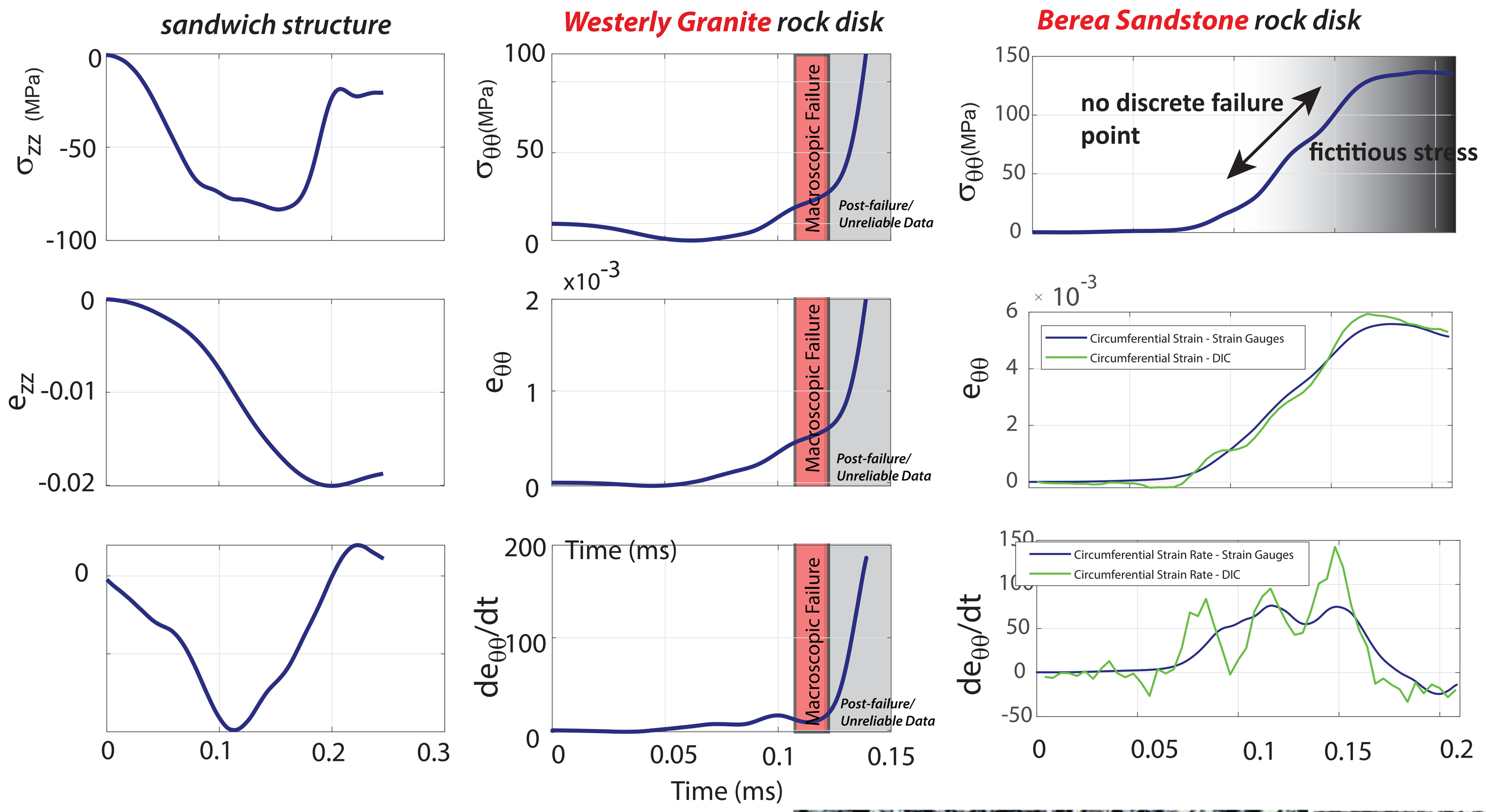
RESULTS

Stress, Strain, Strain-Rate Timeseries

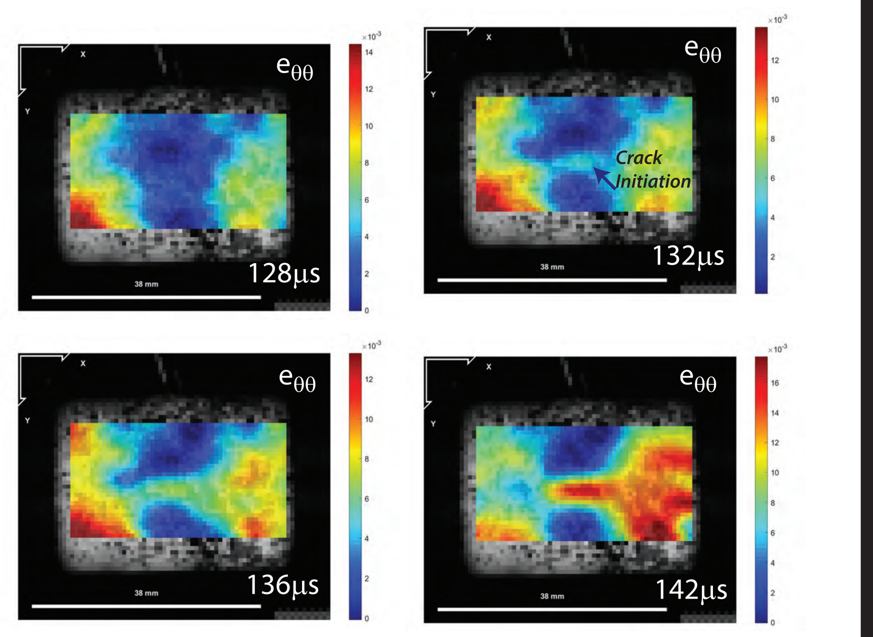
Example of axial and circumferential strain rate, strain, and stress-timeseries:

- *Compressive stress and shortening strain are negative.*
- *Axial time series represent overall axial values forsandwhich sample; Circumferential time series represent values for rock disk*
- *Overall plastic deformation in axial stress plot controlled by yielding of lead*
- *Brittle failure of rock disk shown by rapid slope increase in circumferential strain rate*

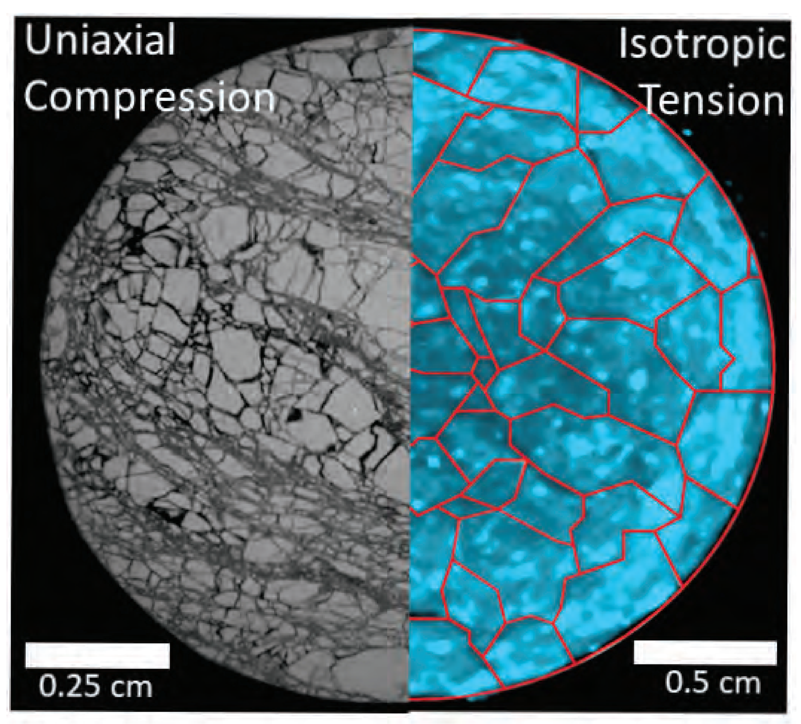
Axial time series for sandwich structure / *Circumferential time series for Westerly Granite rock disk* / *Circumferential time series for Berea Sandstone rock disk*



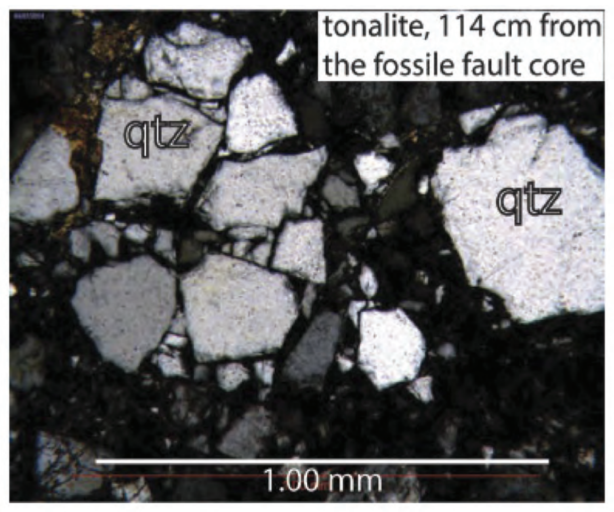
Strain Fields from Digital Image Correlation for Westerly Granite

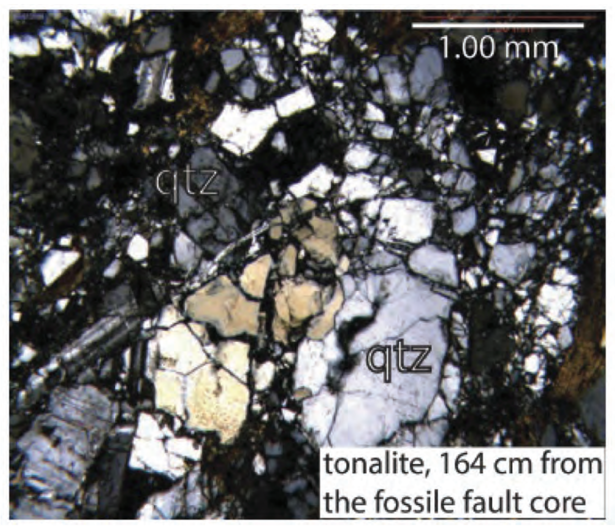


Post-Mortem Rock Structures

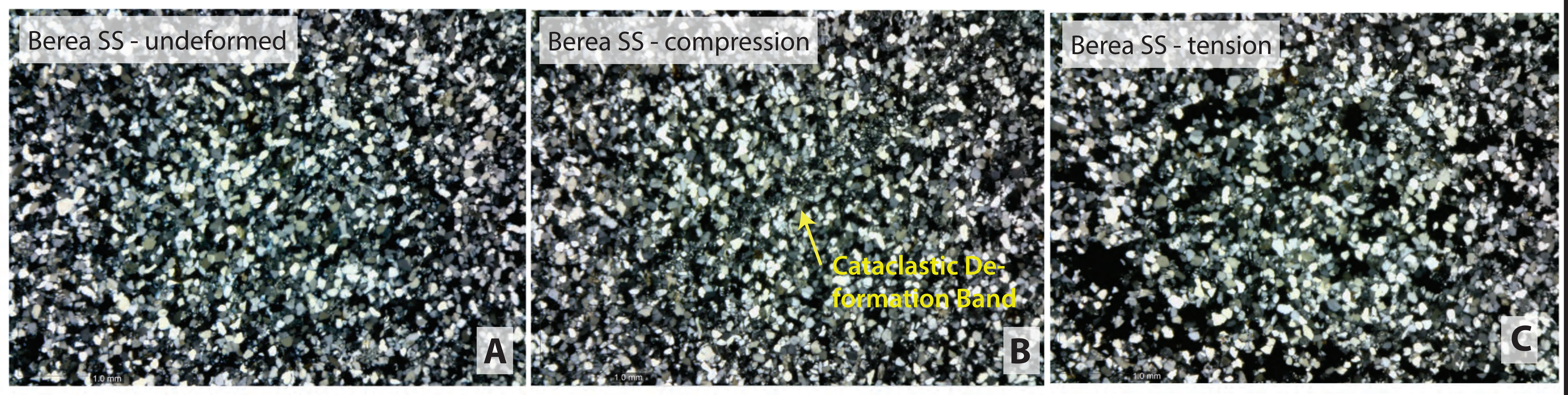


Comparison of experimentally-produced fracture patterns under axial compressive (left) fragmentation of Arkansas Novaculite vs. isotropic tensile fragmentation (right) of Westerly Granite



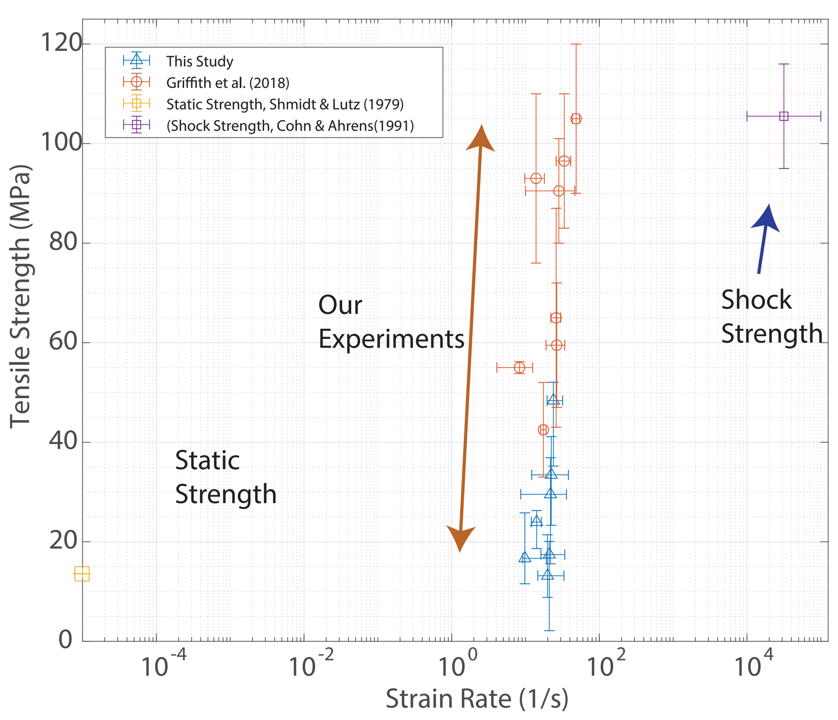


Fragmented Tonalites from the Clark strand of the San Jacinto Fault in Rock House Canyon, western Salton Trough (Whearty, Rockwell & Geary, 2017)



Under **compression**, Berea Sandstone exhibits similar mechanical behavior to granite in terms of strain-rate sensitivity to strength, but failure under light confinement occurs by formation of cataclastic deformation bands ***(B)***. Under **isotropic tension**, failure occurs by grain boundary failure and disaggregation ***(C)*** with no distinct brittle failure strength. This latter deformation mechanism may be impossible to identify in outcrop.

Dynamic Tensile Rock Strength



Range from static (Schmidt & Lutz, 1979) to shock (Cohn & Ahrens, 1992) tensile strength of Westerly Granite occurs in the range 10^0 to $10^2 s^{-1}$ in our experiments. Berea Sandstone does not exhibit an abrubt tensile strength in our experiments.

CONCLUSIONS

New technique tests dynamic tensile strength with easy sample prep

Technique simulates rapid expansion under shallow confinement, scalable to natural pulverized fault zones

Transition between static and dynamic tensile rock strength btwn 10^0 & $10^2 s^{-1}$ for Westerly Granite

No descrete failure occurs in similar experiments for Berea Sandstone

Tensile and Compressive fragmentation produces distinctly different microstructures in both crystalline and granular rocks

IMPLICATIONS

Tensile fragmentation can explain heavily fragmented rocks at large distances from faults

Granular sedimentary rocks appear to simply dissagregate during impulsive tensile loading, which may explain why stronger crystalline rocks are preferentially fragmented in pulverized zone

Asymmetric damage patterns with microstructures diagnostic of coseismic stress state may imply long term preferred rupture directivity

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