SAND2014-20248PE

Influence of Microstructural Variations in Strength and Stiffness on Continuum Failure and Elastic Moduli Degradation

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New Mexico Tech
3 December 2014

In Partial Completion of Ph.D. Requirements
E&ES Department

This material is based upon work supported as part of the Center for Frontiers of Subsurface Energy Security, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001114. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

Co-authors
Thomas Dewers, Scott Broome, Joe Bishop, and Sean McKenna

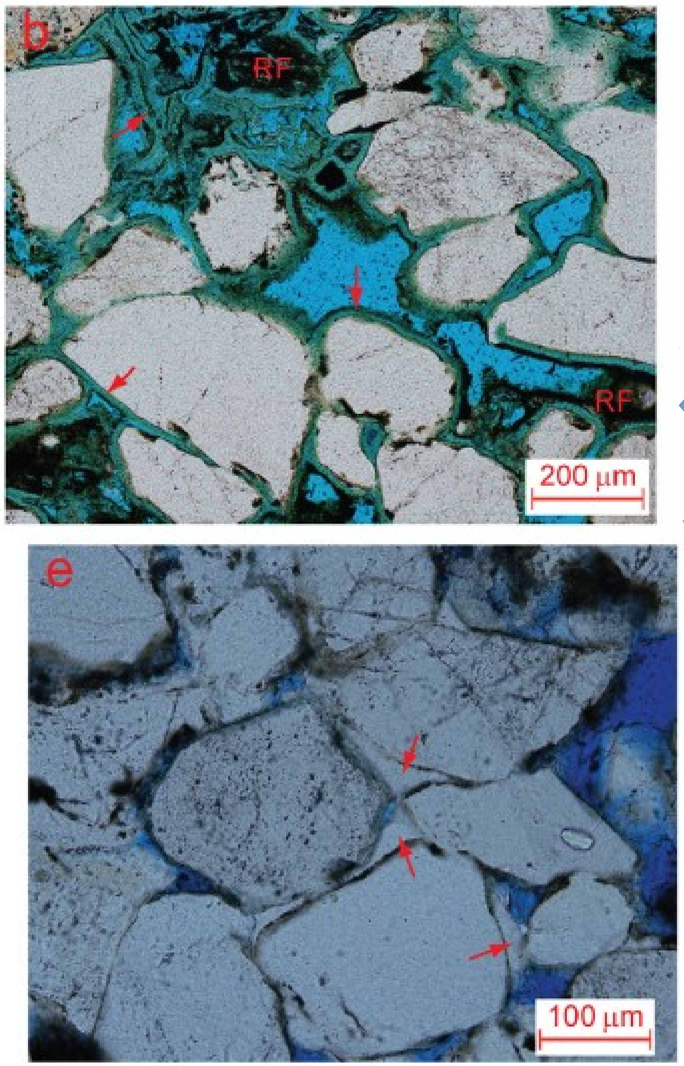
Laboratory Collaborators
Greg Flint, Perry Barrow, Steven Bauer and Mathew Ingraham.

BEG Collaborators
Susan Hovorka, James Donnelly, Seyyed Hosseini, and Seunghee Kim.

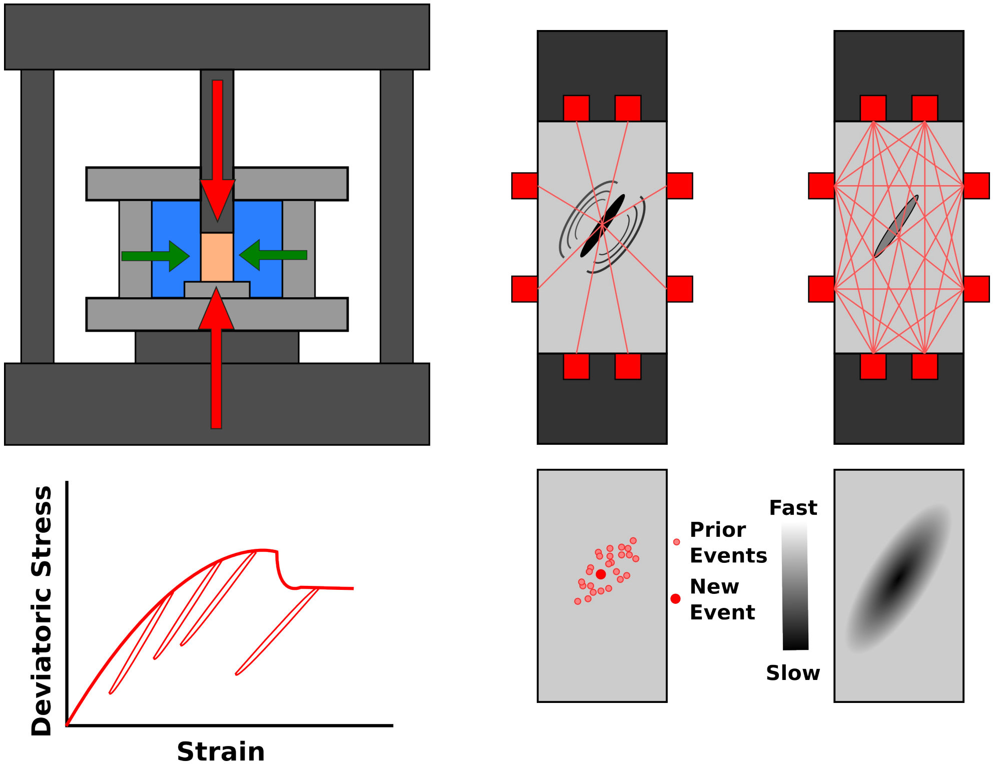
Project Manager and Ph.D. Committee
Susan Altman, Gary Axen, David Holcomb, Peter Mozley and **Glenn Spinelli**

Special Thanks
My parents, Michaella Gorospe, Bruce Harrison, Robert Wyckoff, Katrina Koski, Colin Cikoski, Dave Love, Pat Valentine, Karen Bowman, Soni Yatheendradas, Fred Phillips, Lisa M., Penny Boston, Dave Johnson, Karen Bowman, and everyone else who has touched my life during this long, long run.

Big Question—Small to Big and Back



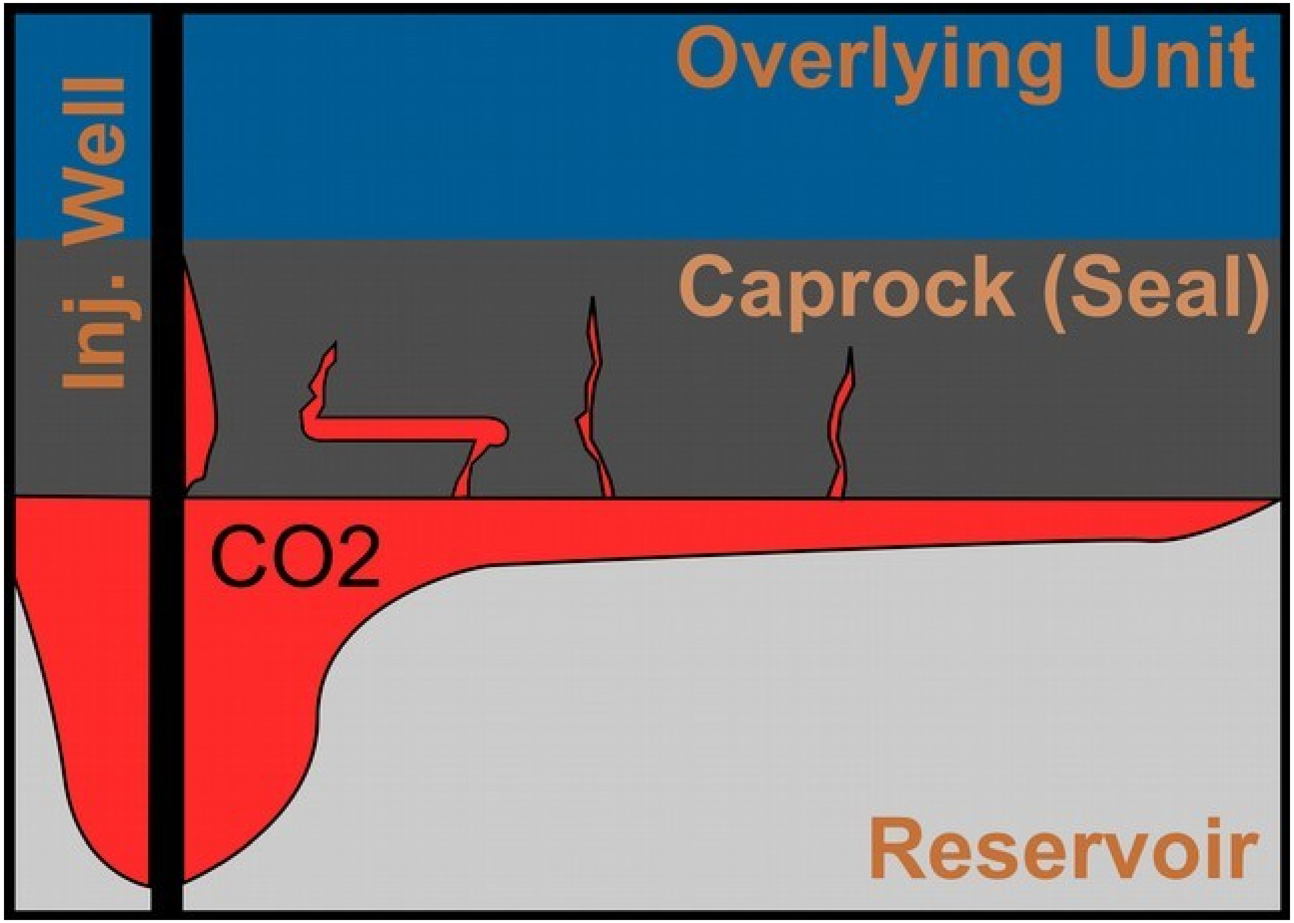
Lu et al. (2013)



How do petrographic and geologic observations to to how (and why and how much) they are damaged?

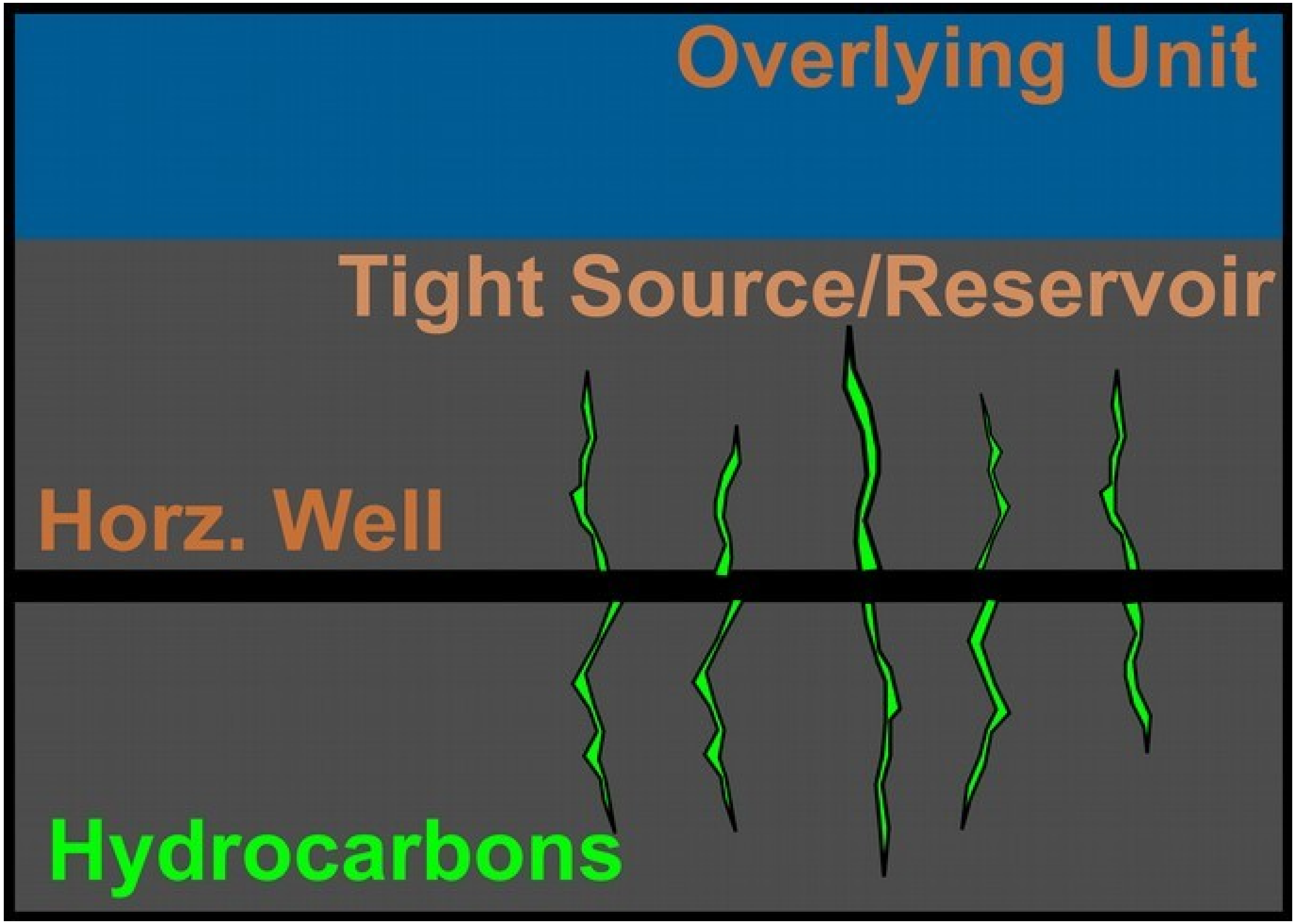
i.e., Use logic to interpret test results in terms of geologic observations.

Why Care?



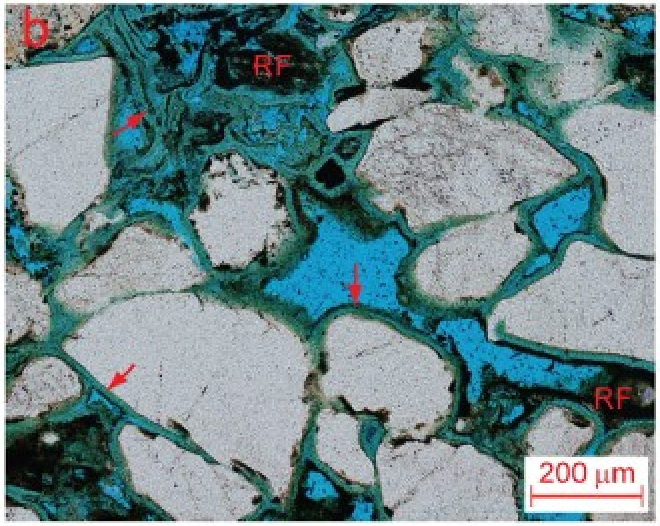
Subsurface CO2 storage leakage pathway.

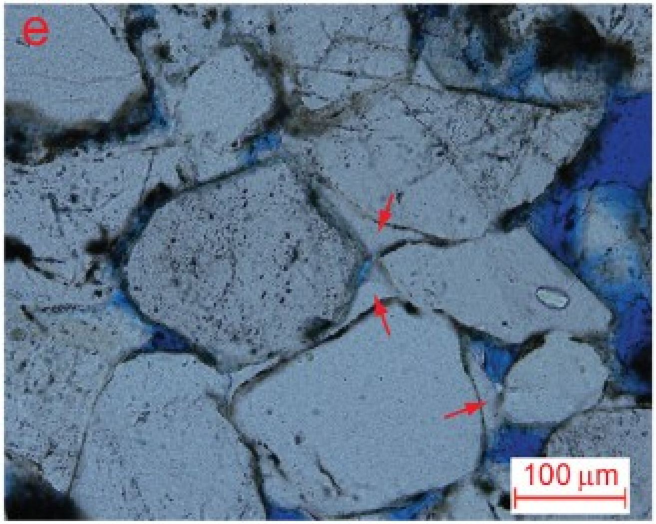
Why Care?



Natural Gas Release in Shales

Big Question—Small to Big and Back





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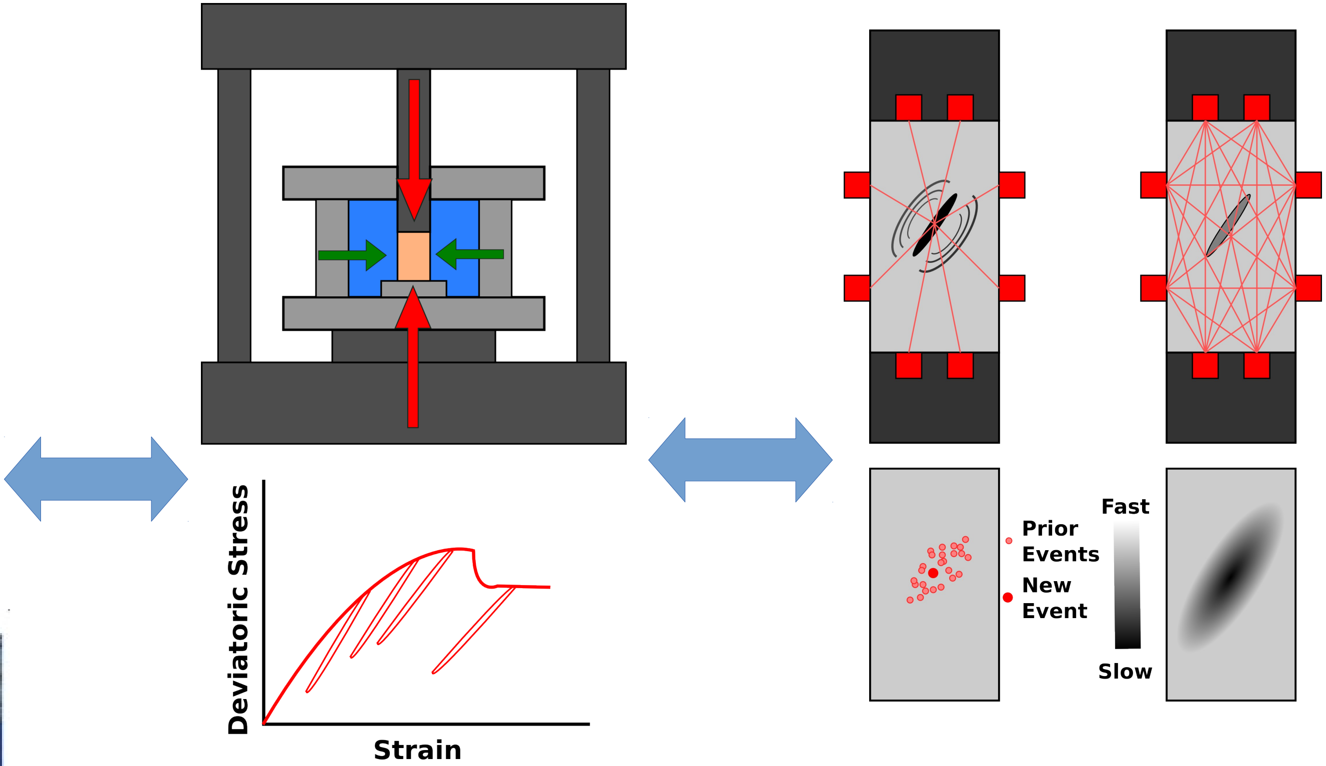

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Studies

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Method for automatic picking of P- and S-wave arrivals in acoustic emissions.

Mechanical heterogeneity of the Lower Tuscaloosa Formation, in support of SECARB CO2 injection pilot program, Cranfield DAS site.

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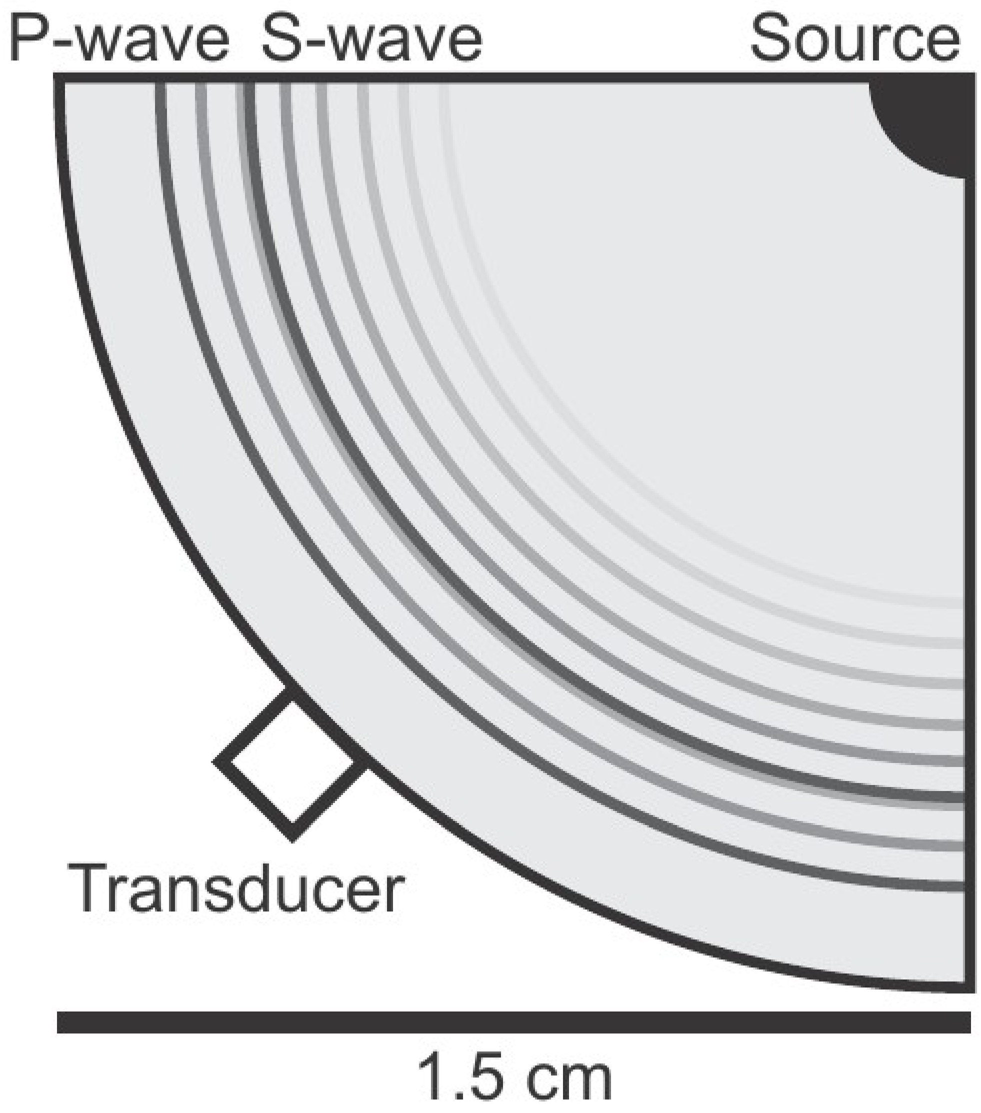
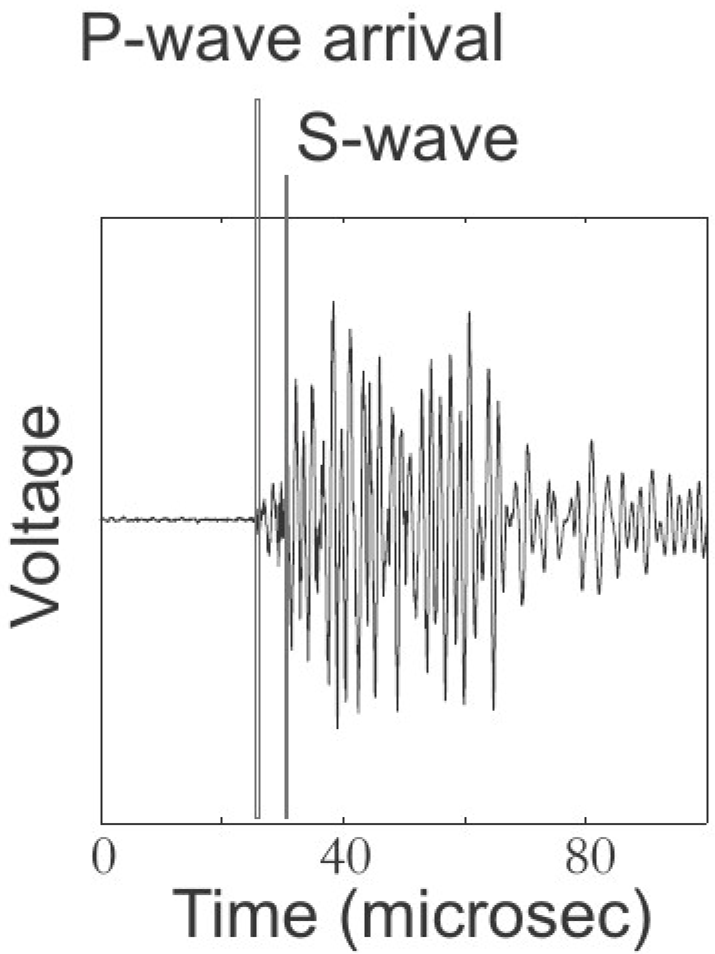
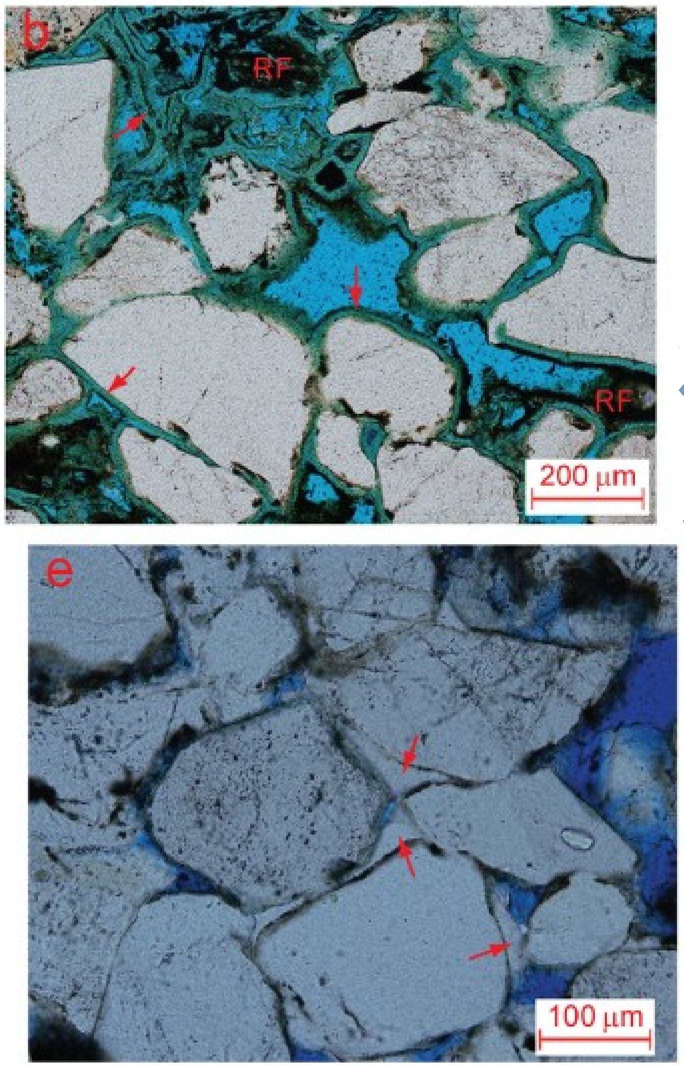
A Method for Automatic Picking of P- and S-wave Arrivals in Acoustic Emissions

The Problem


P-wave
S-wave
Source
Transducer
1.5 cm


P-wave arrival
S-wave
Voltage
0
40
80
Time (microsec)

A Tool to Help Link Grain-Scale and Continuum



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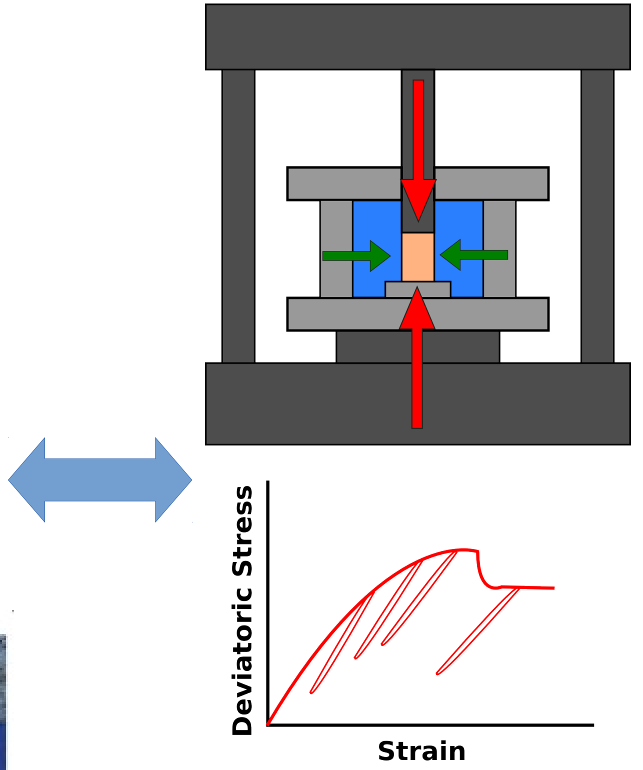
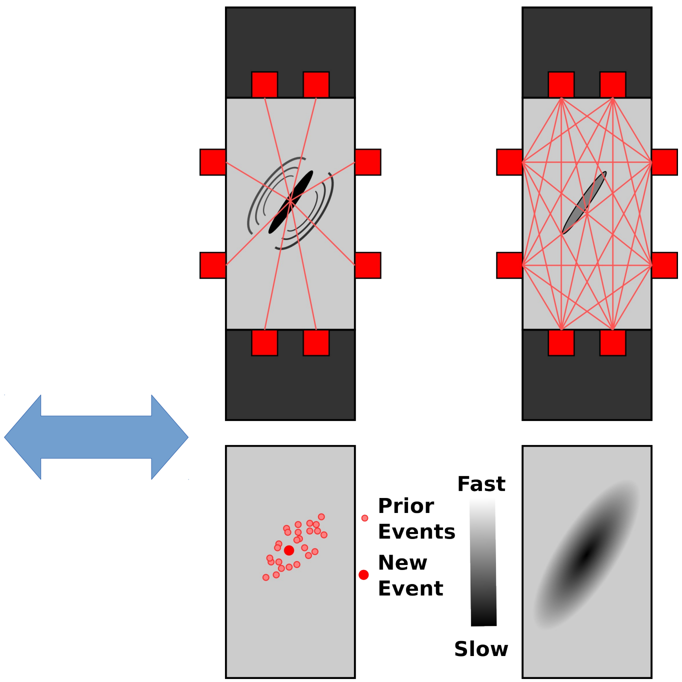
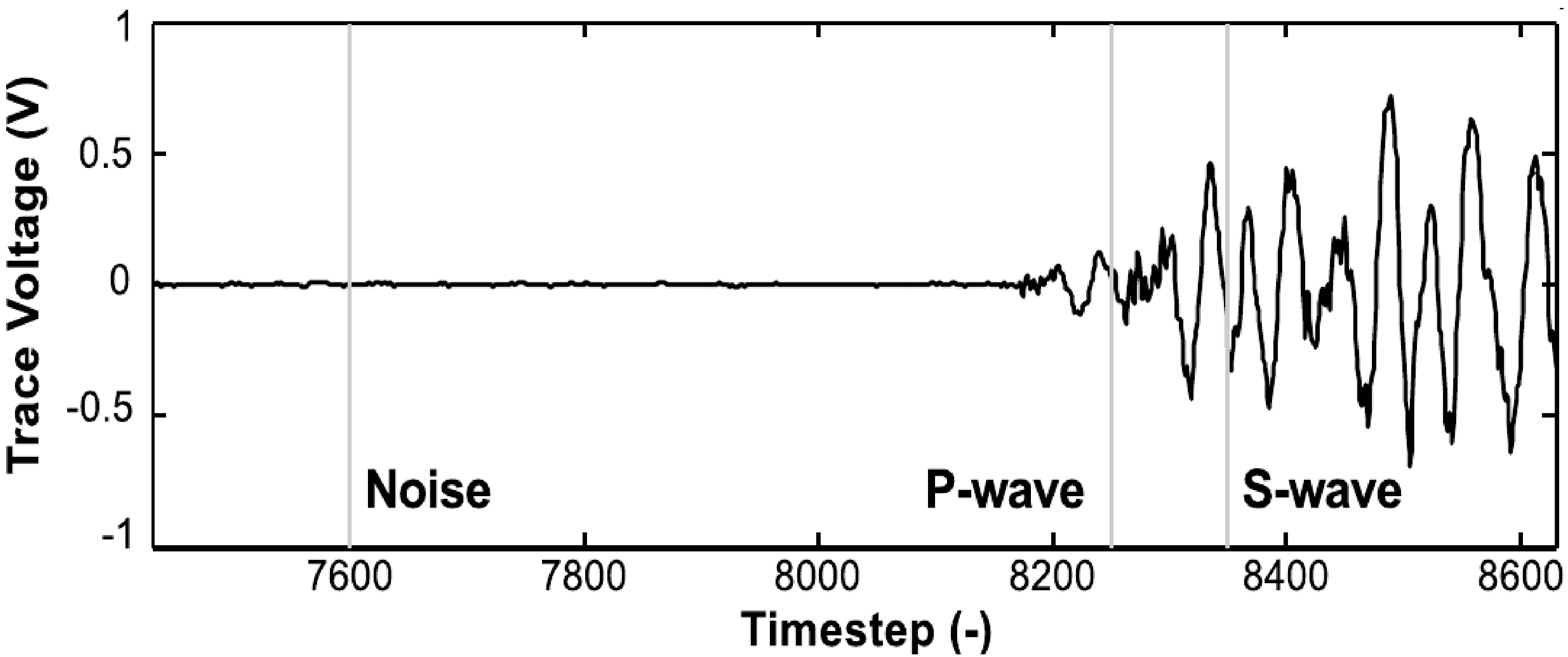




P-wave velocities include both bulk and shear elastic moduli.

Decoupling requires S-wave information, which only included shear moduli.

Justification and Method



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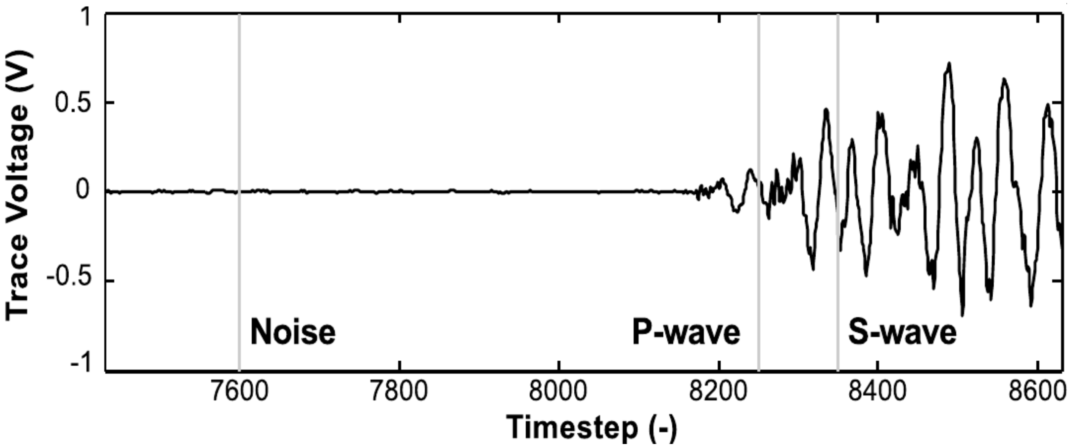
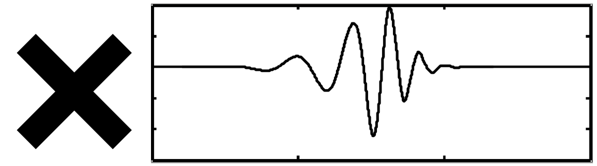
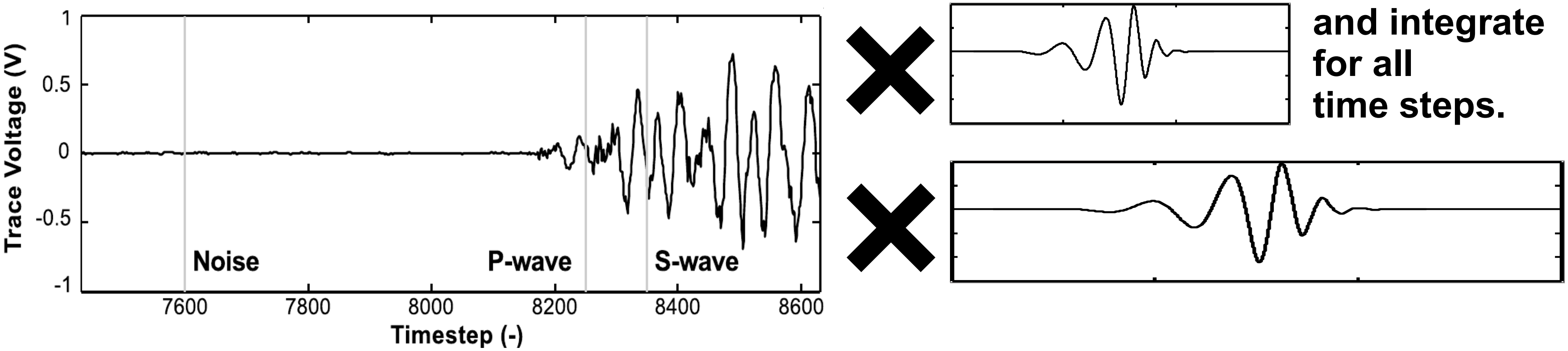




and integrate
for all
time steps.

Justification and Method



and integrate for all time steps.

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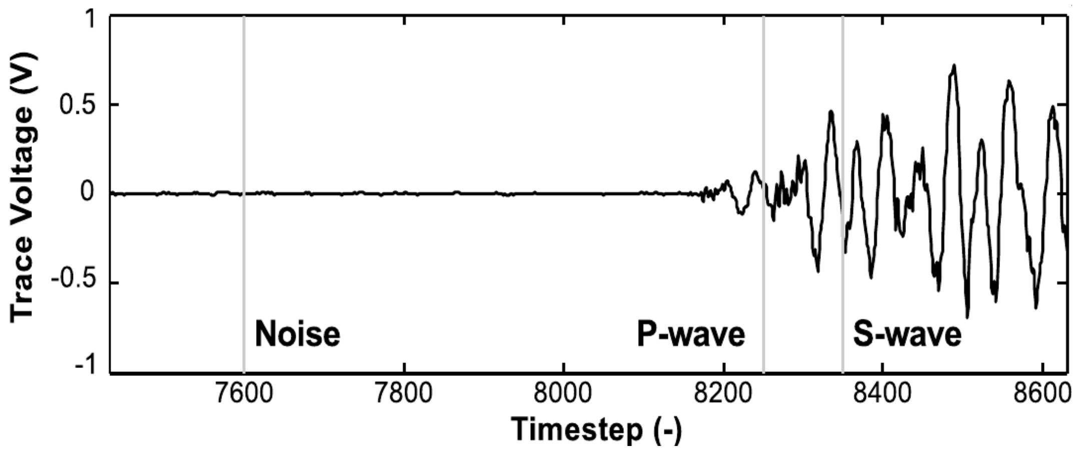

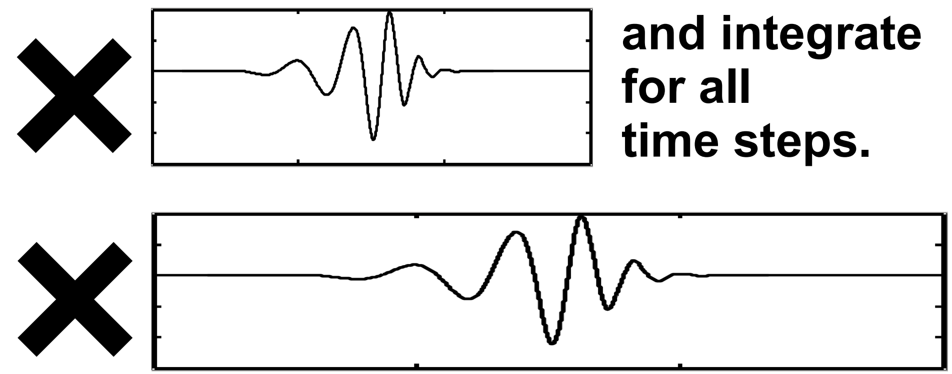

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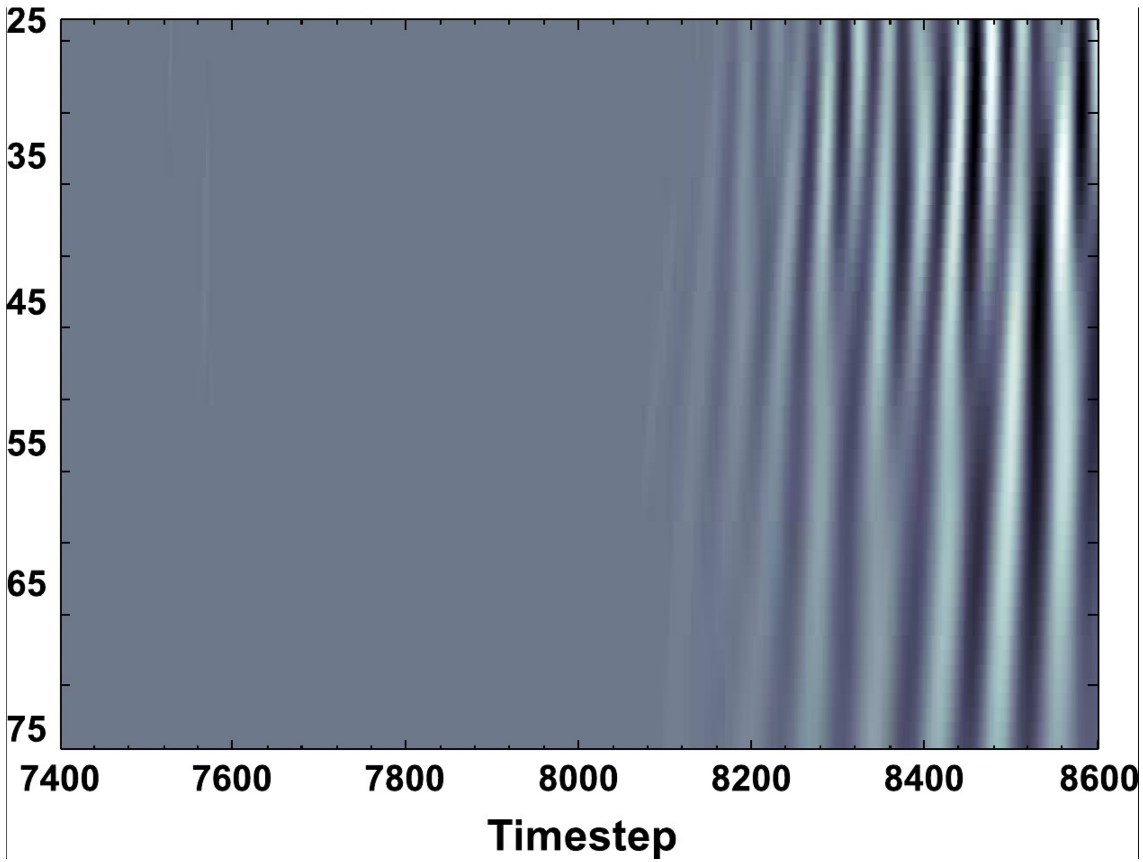

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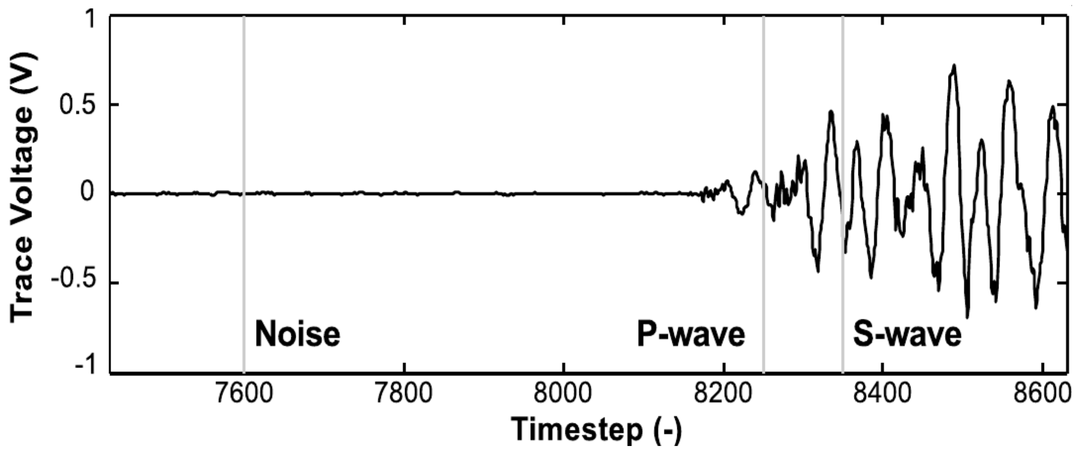

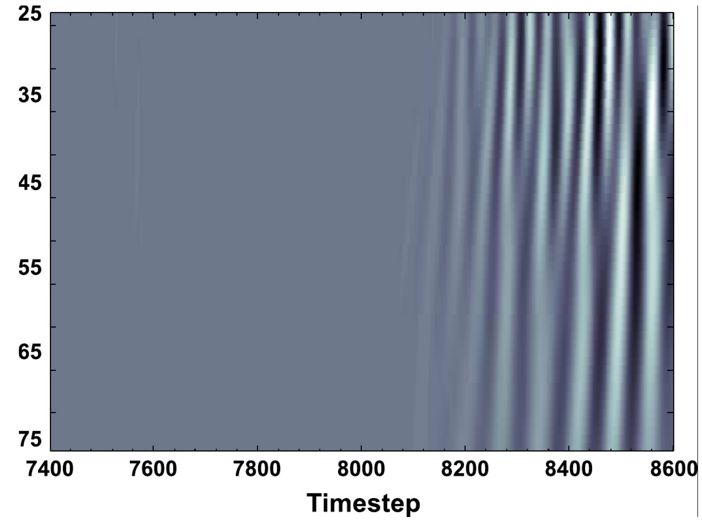

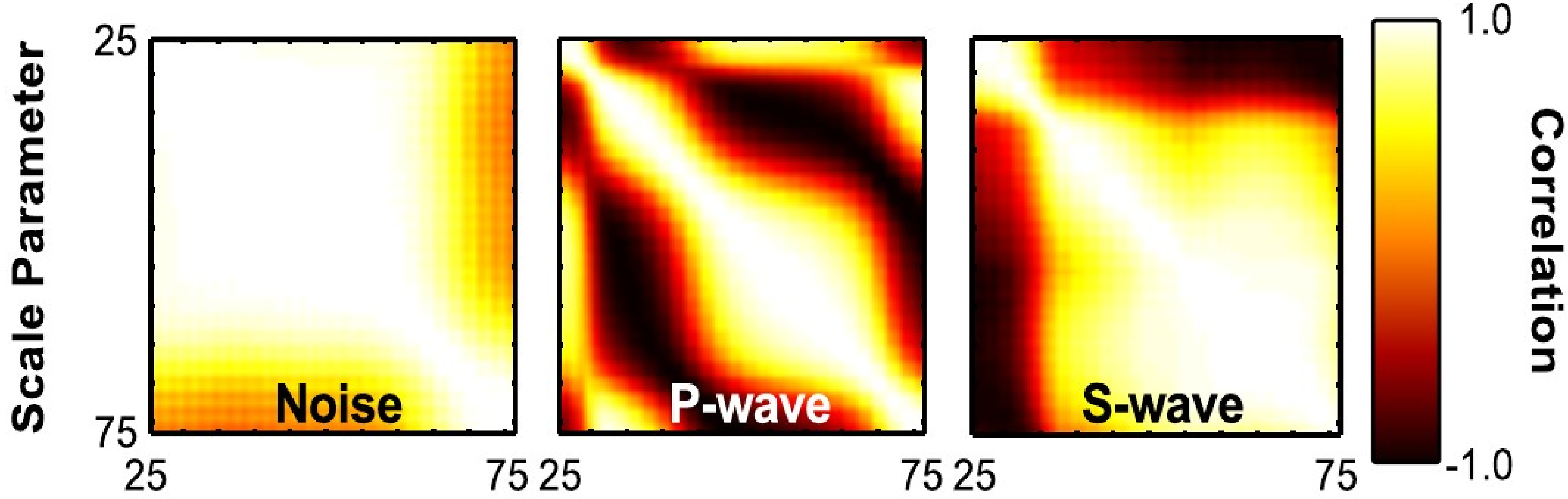

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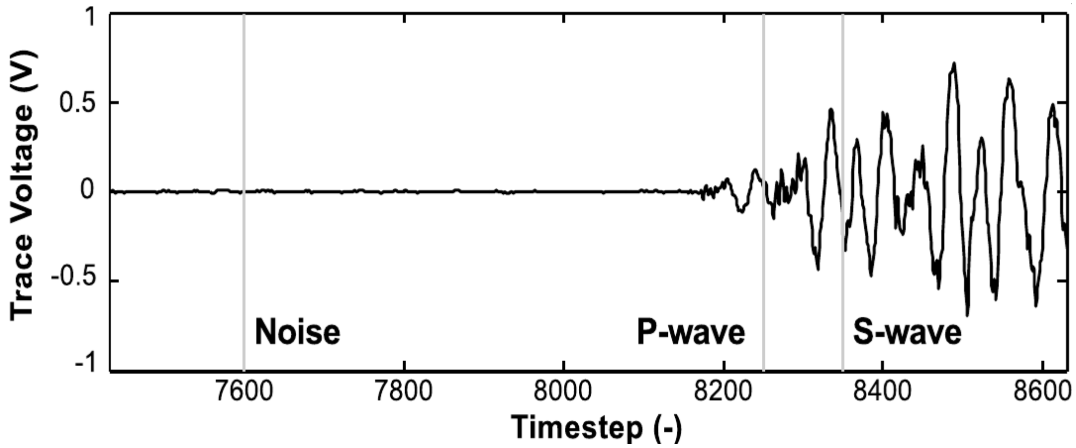

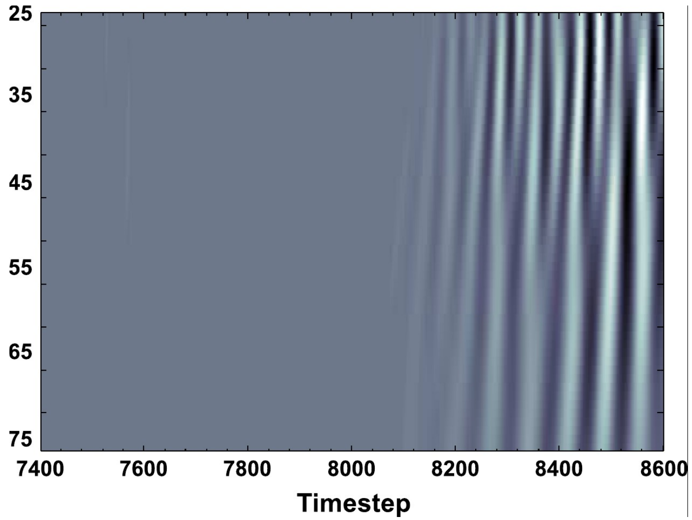

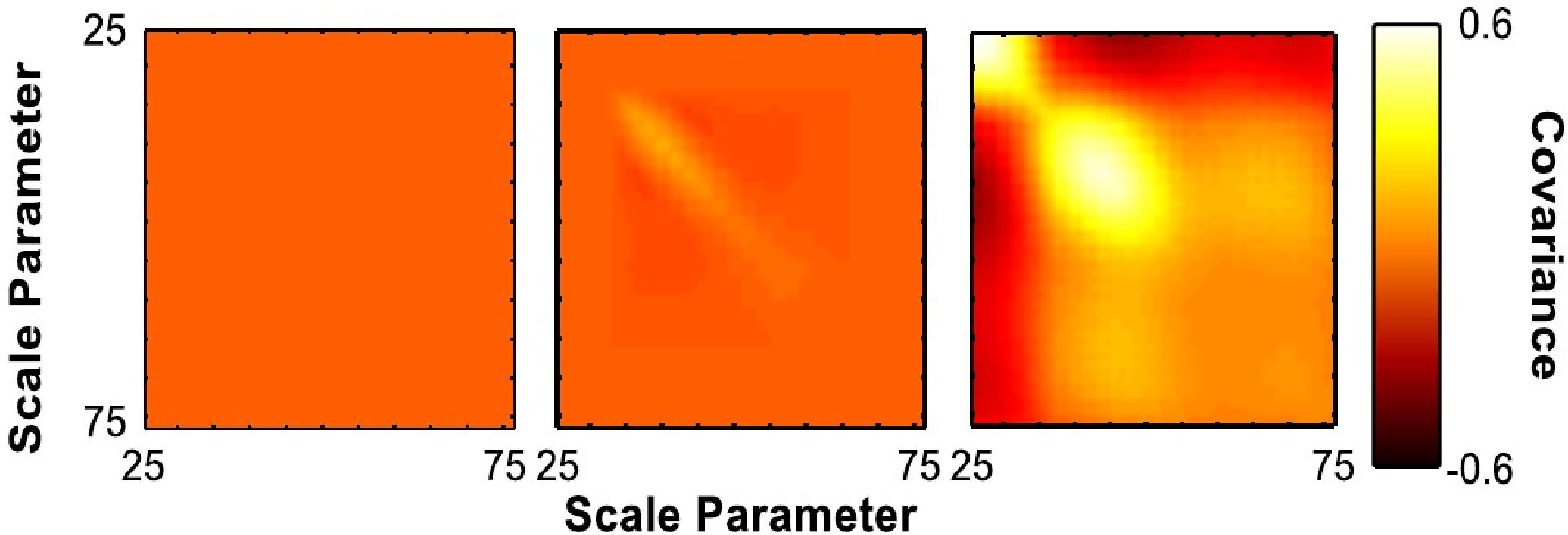

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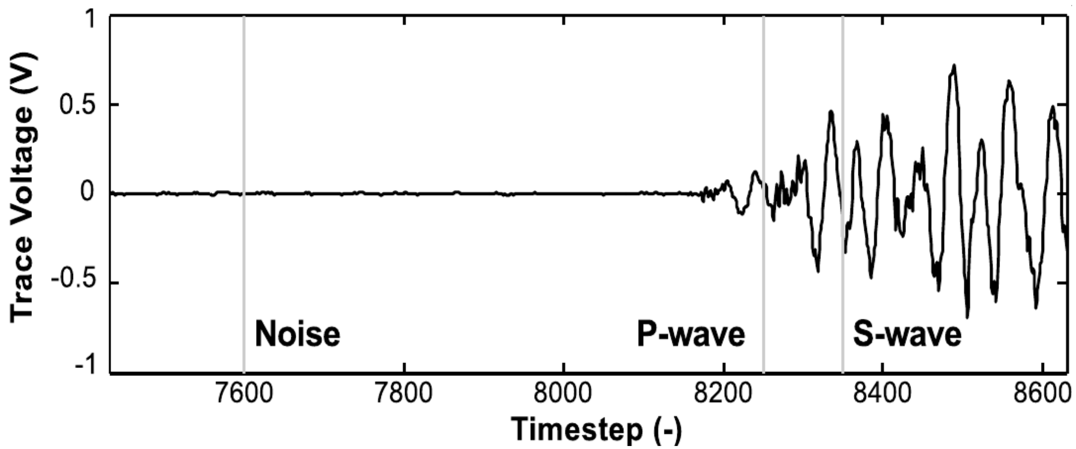

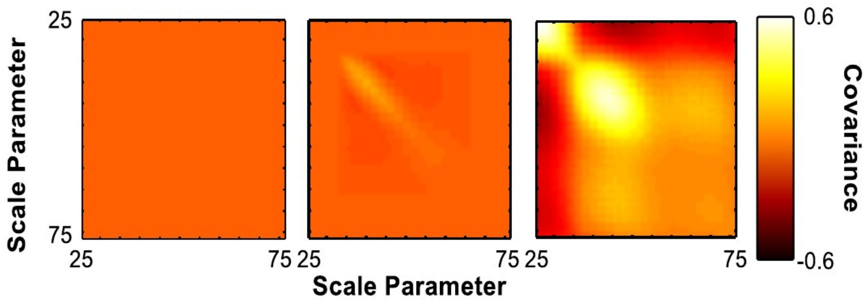

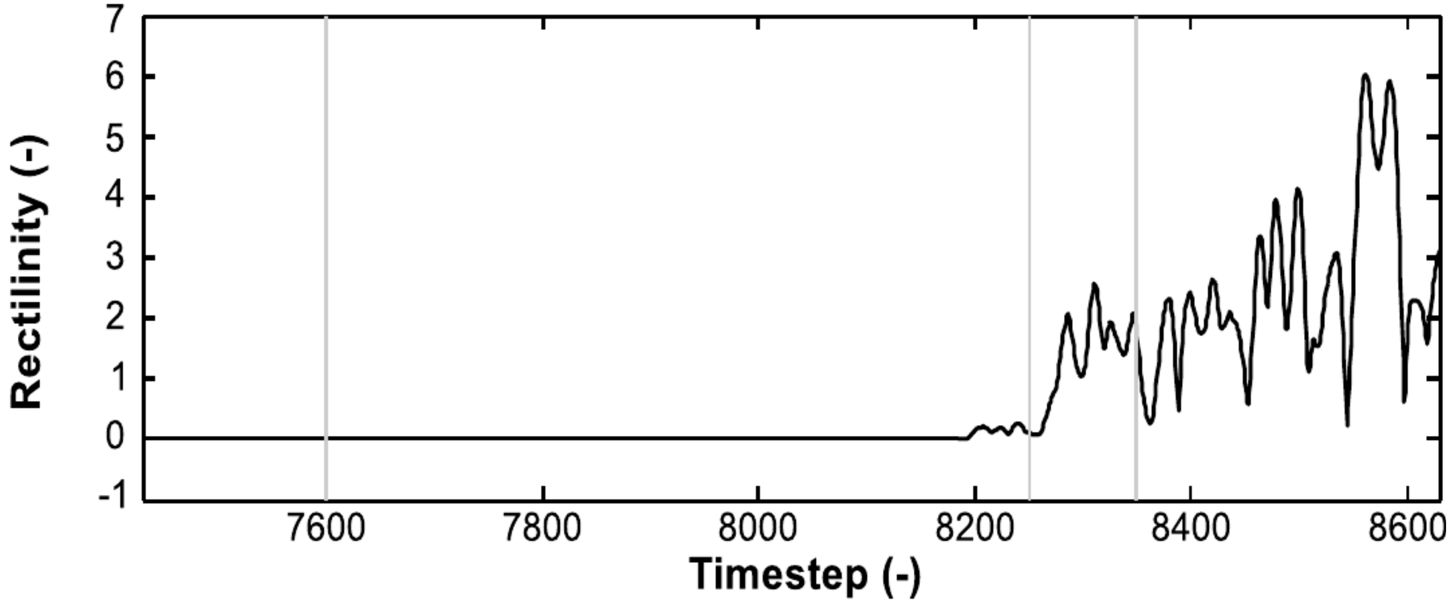

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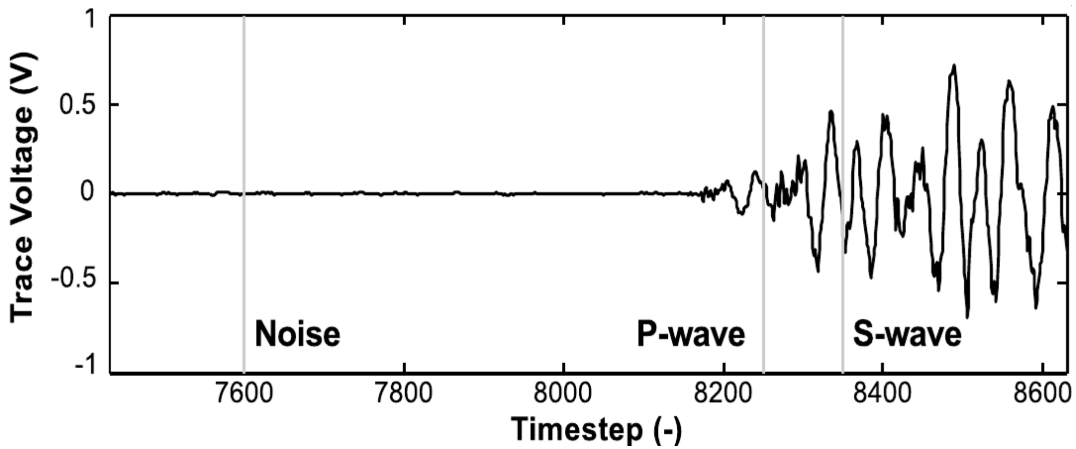
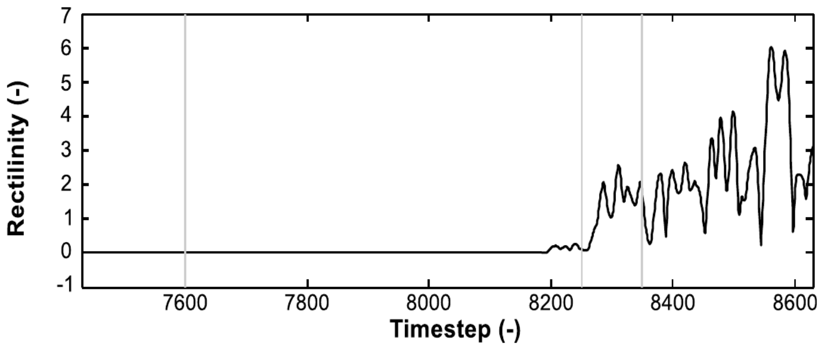
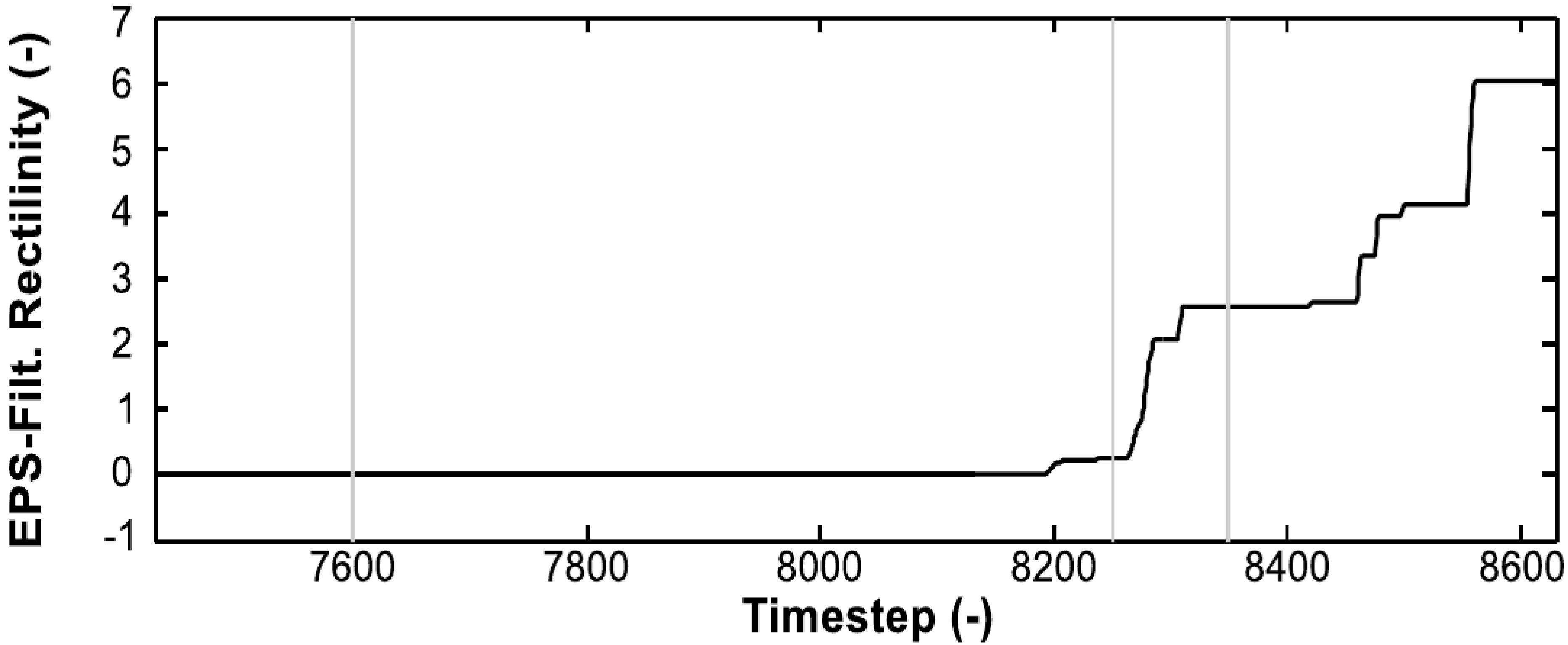
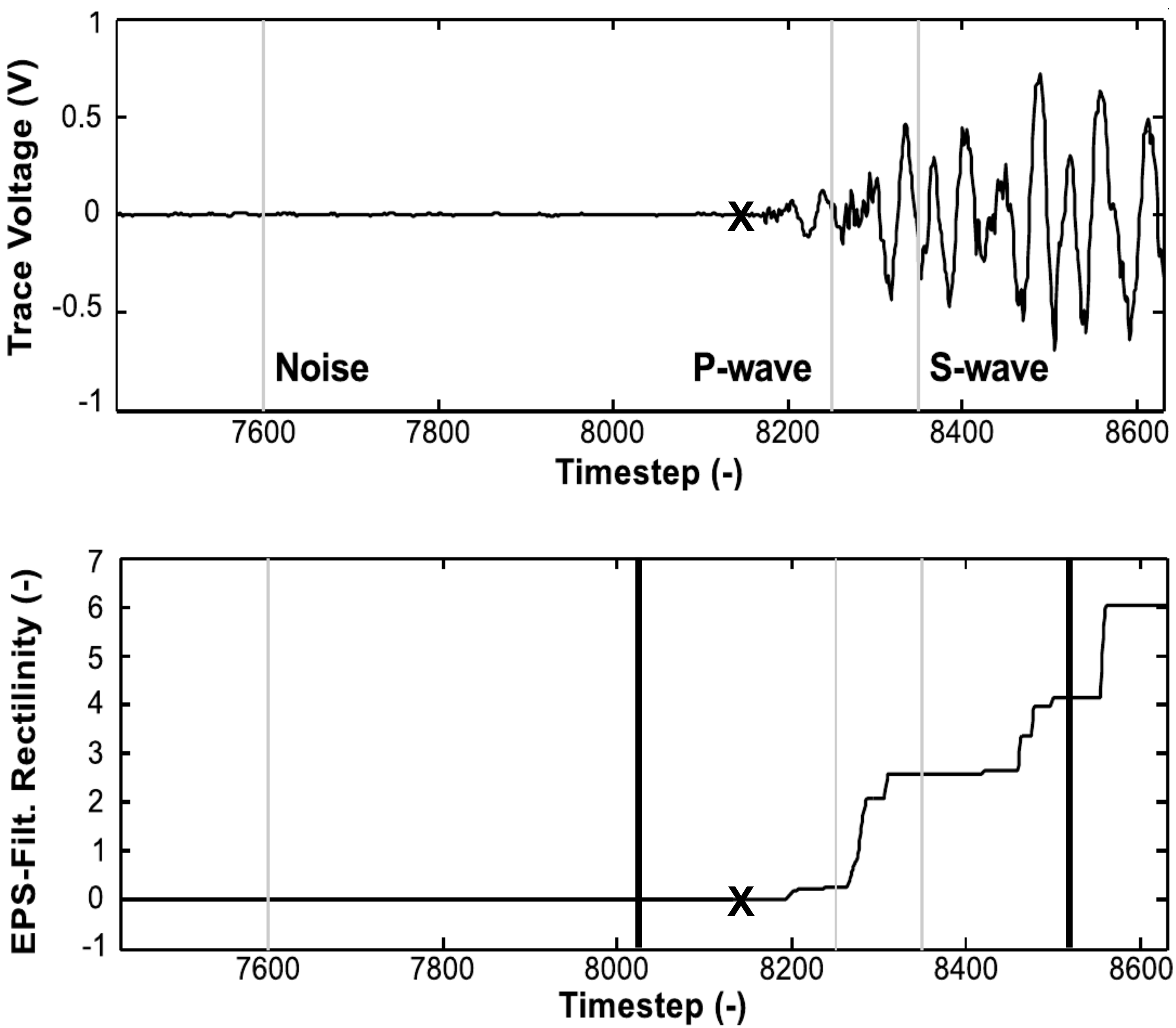






The Final Picks



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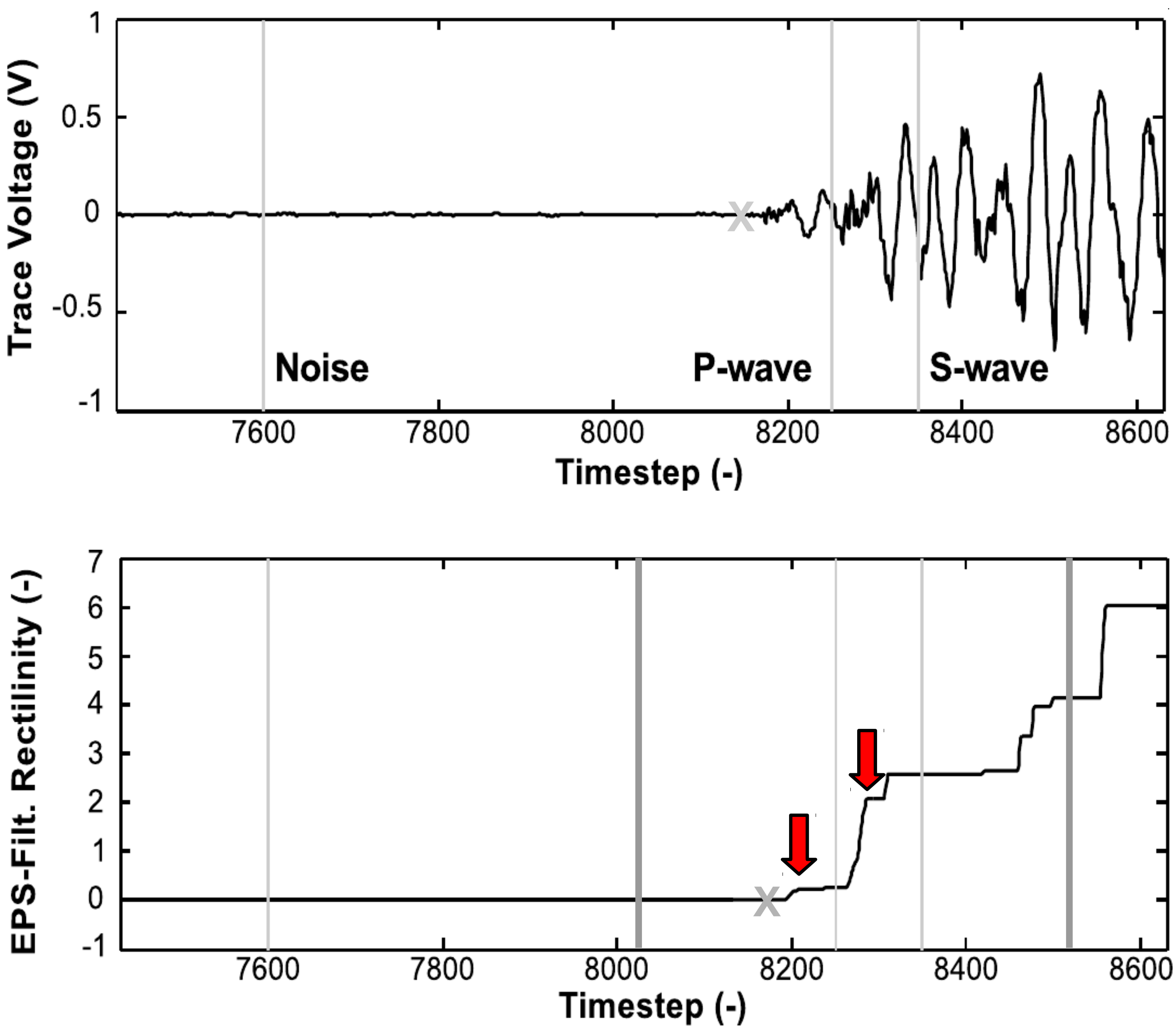
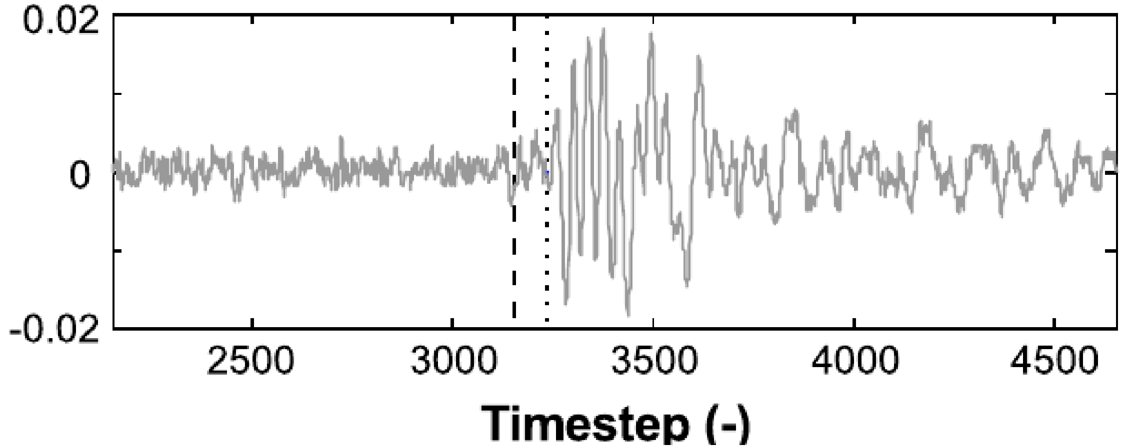
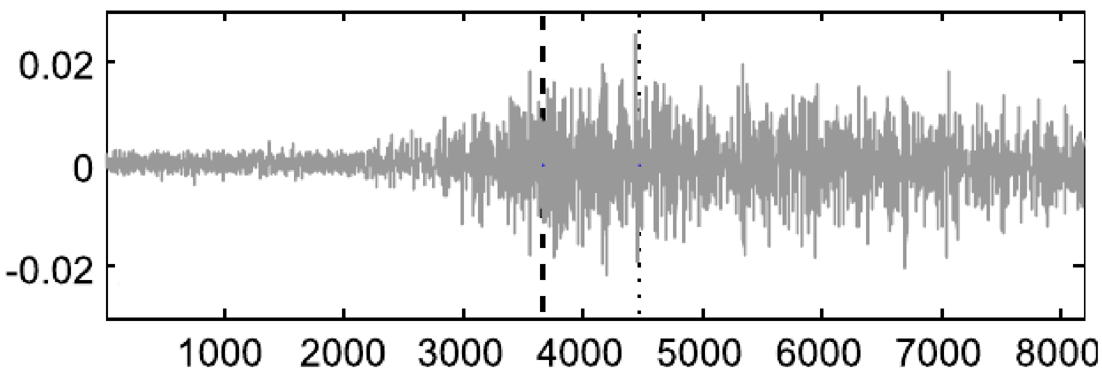


Example in Siltstone

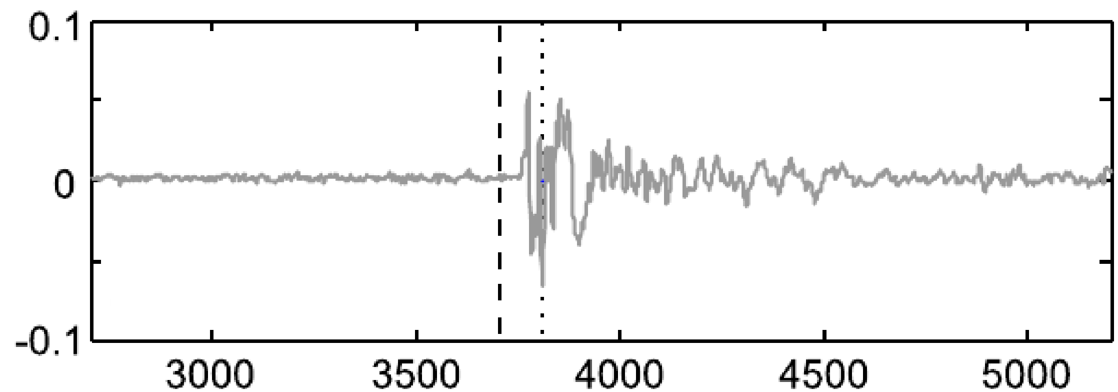
Clean Event



Rumbles



Complicated Noise



Summary

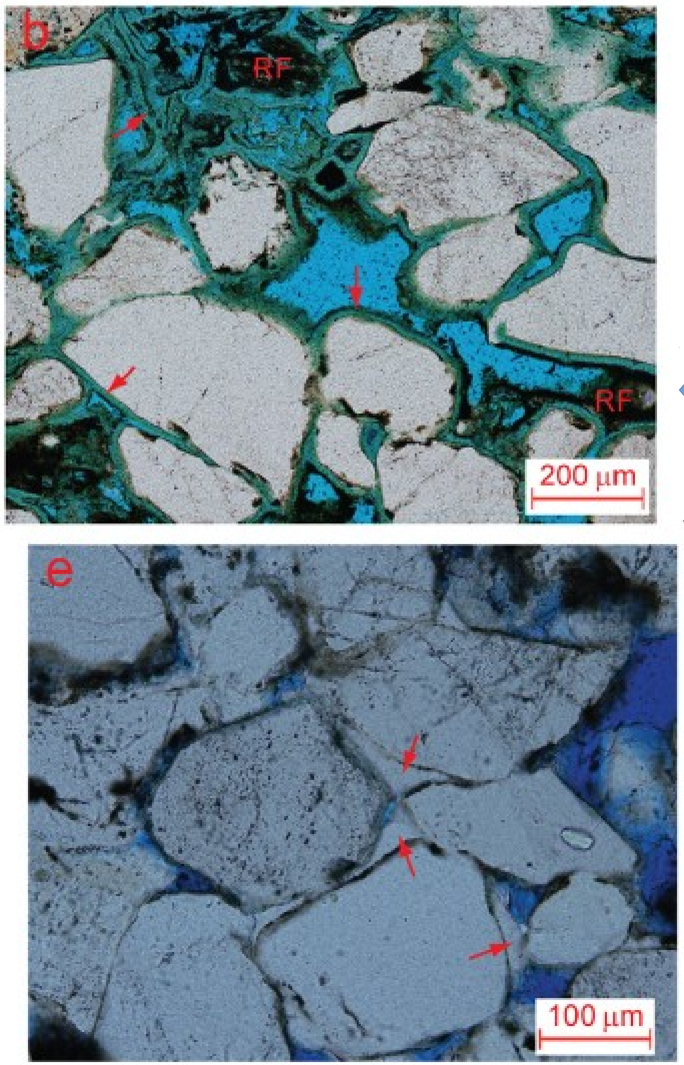
- Changes in covariance structure across wavelet scales allow consistent arrival time estimates in P- and S-wave in acoustic emissions.

- Requires multiple filtering and data assurance steps.
  - Initial identification of onset.
  - CWT transform and filtering.
  - Covariance and f-metric calculation.
  - Filtering of f-metric.
  - Identifying plateaus with multiple thresholds.

- Difficulty with
  - Long 'rumbly' events.
  - Complicated eletrical noise.

- Will allow passive source estimates of both elastic moduli changes during testing.

Big Question—Small to Big and Back



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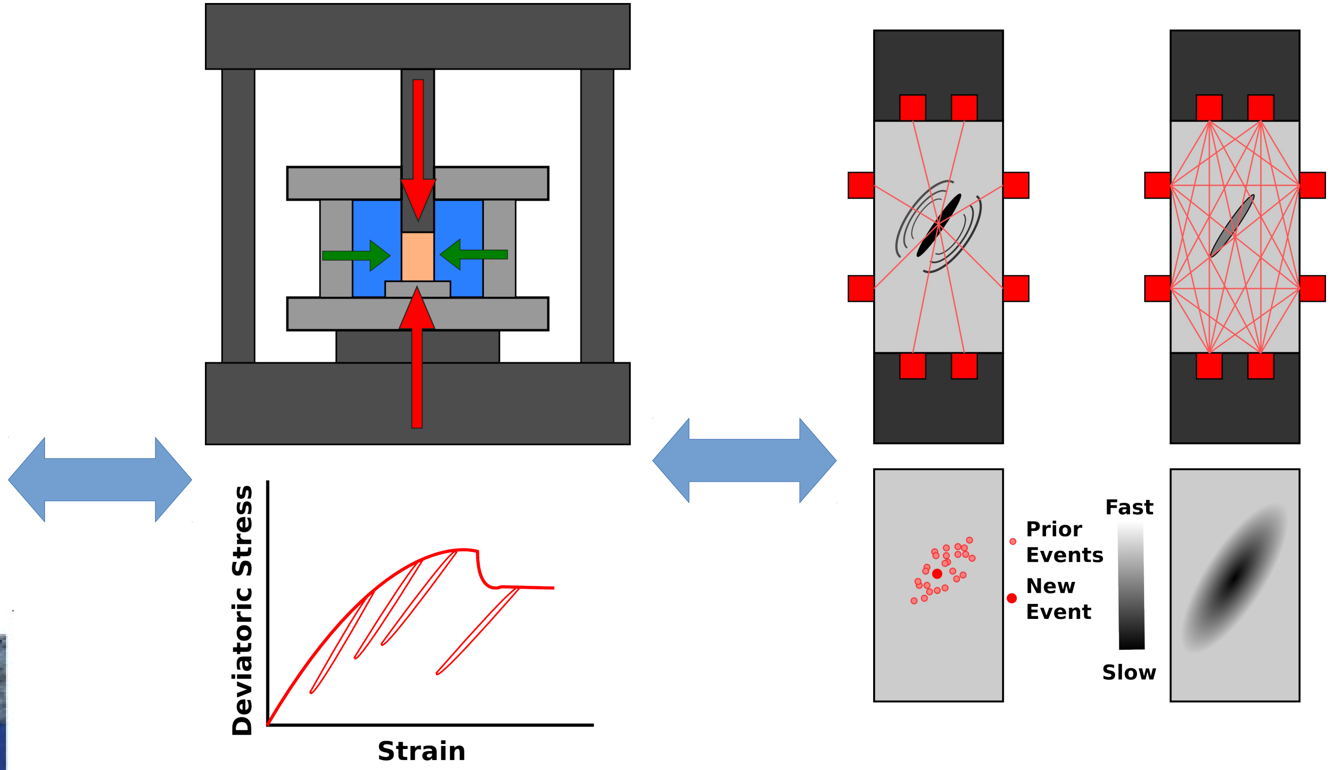

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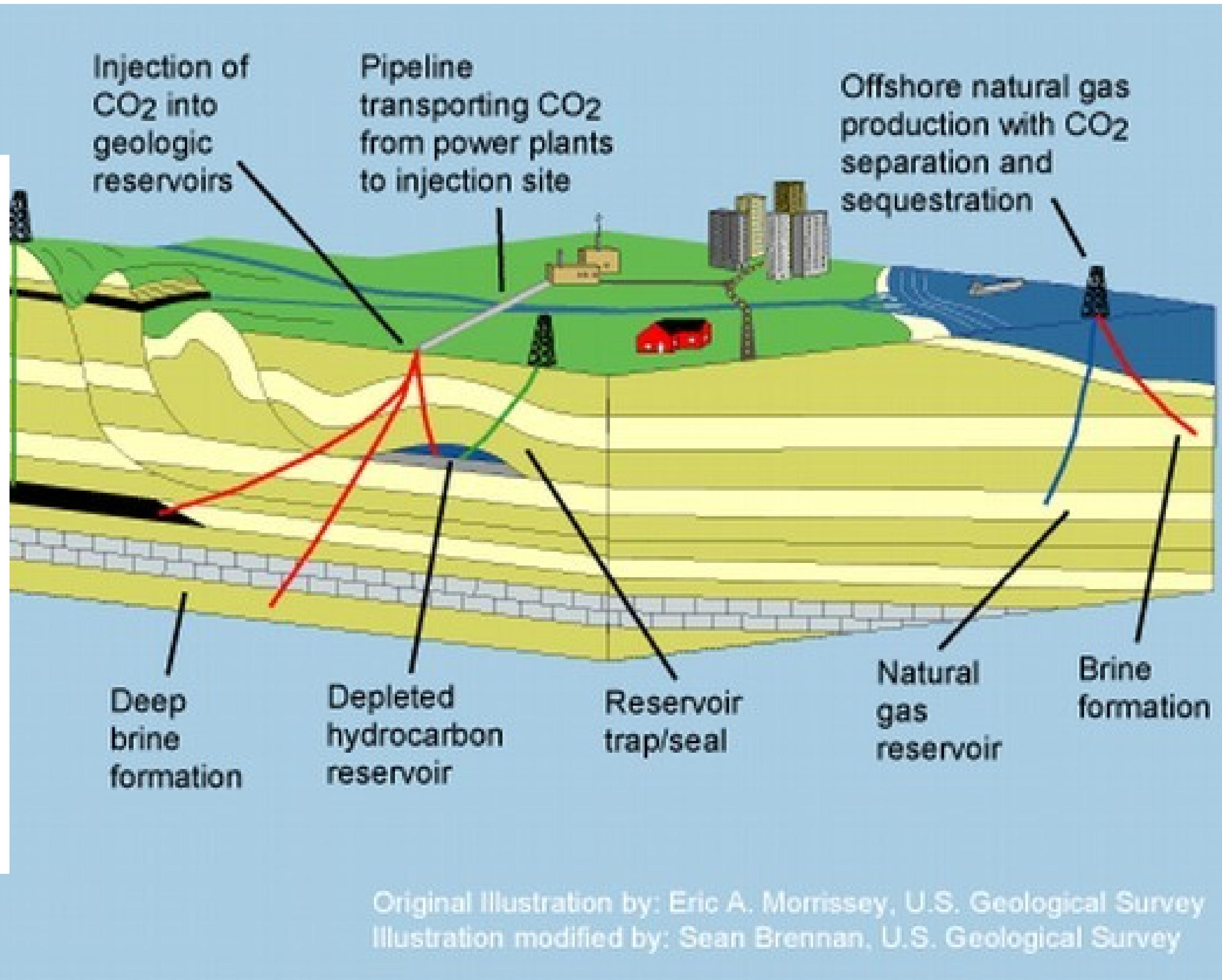
Mechanical Variability at Reservoir Conditions of Lower Tuscaloosa Formation in Support of SECARB Injection Pilot Program at DAS, Cranfield Site

CO2 sequestration

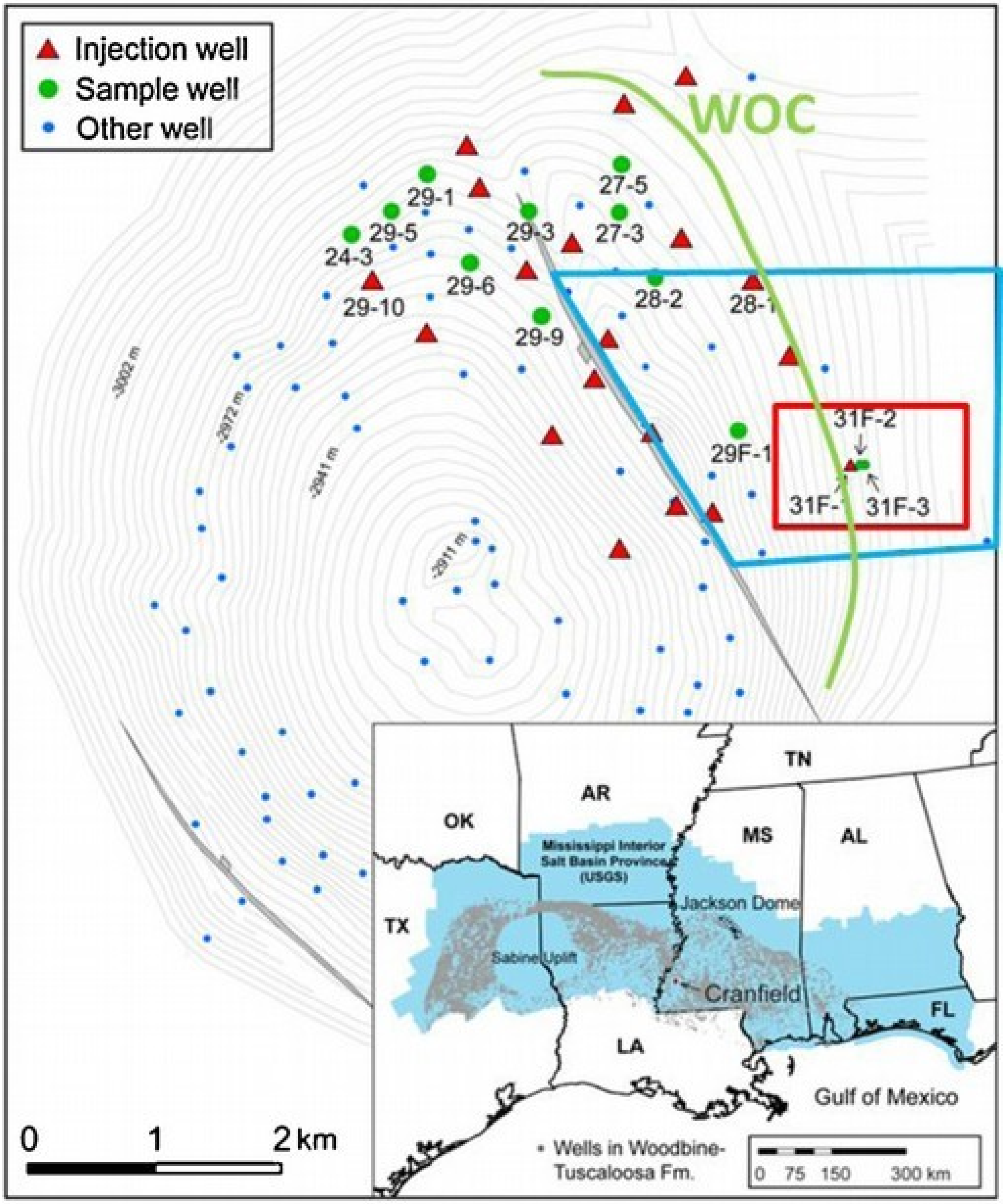
What information is needed for site selection and operations?

Are there hydromechanical complications from CO2 injection?



Cranfield 'Early Test' Pilot Injection Program

- Leverage EOR operations of Cranfield oilfield for CO2 injection and storage.
- Injection horizon is D-E member of Lower Tuscaloosa Formation.
- Trap is shallow anticline above salt dome with Middle Tuscaloosa sealing.
- Injected 3.54 million tons of CO2 between 2009 and Feb 2012.
- Performed geophysical, geochemical, surface and tracer monitoring.



From Hossieni et al., 2013. International Journal of Greenhouse Gas Control.

Prelim. Results of Injection

- Some fine tight sandstones act as seal, while flow directed in preserved conglomeratic channels.
- CO_2 did not change brine chemistry significantly, due to high concentrations in brine.
- Permeability changed inconsistently in pathways to closely spaced monitoring wells. (Between Dec. 2009 and March 2010)
- Hypothesized to be from changes in wettability.

We hypothesize that CO_2 may have altered mechanical properties of injection horizon, leading to compaction and decreases in permeability.

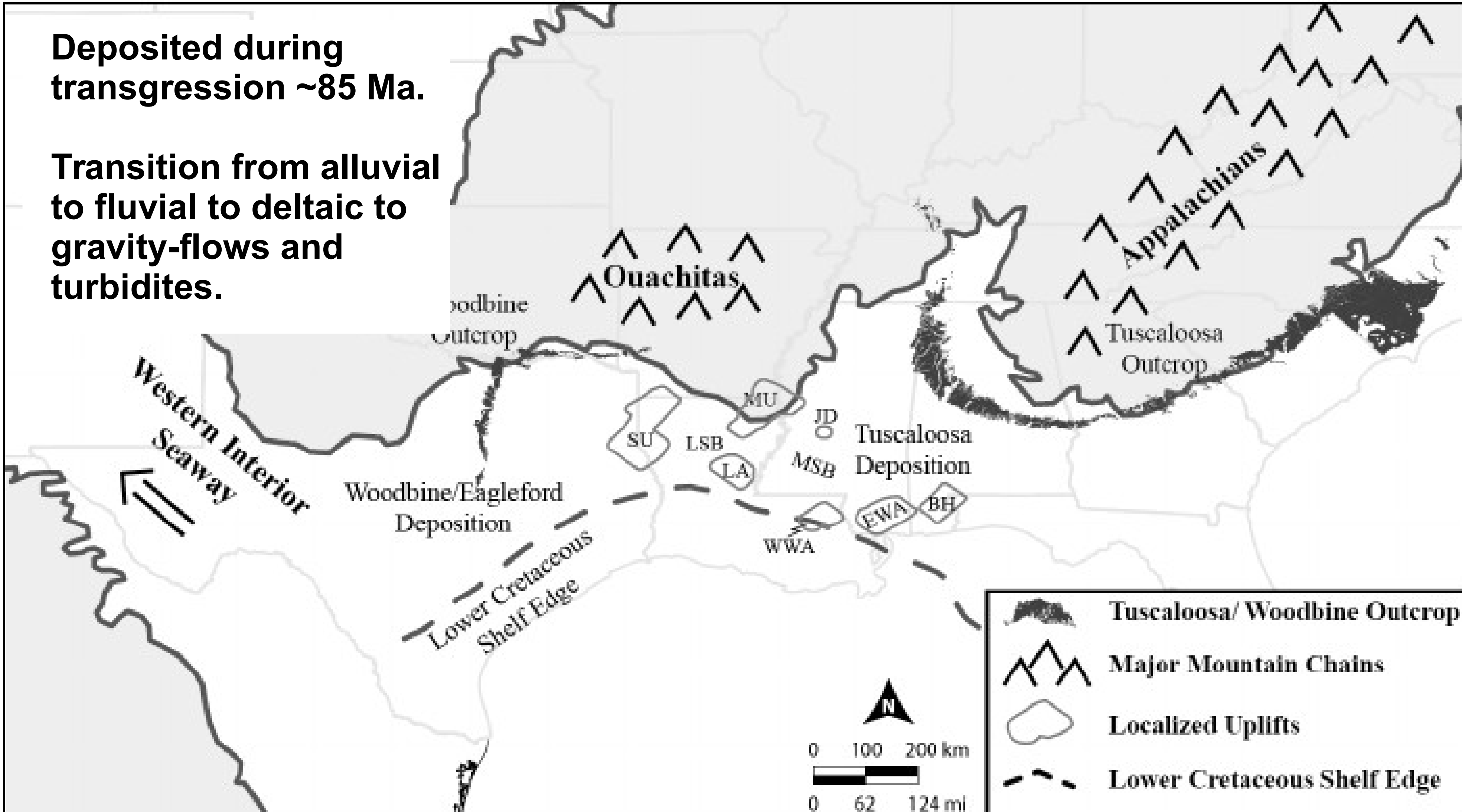
Driving Questions

- What is the heterogeneity of the injection horizon?
- Does CO2 weaken some parts of the rock?
- What are the geologic controls on chemically activated deformation?
- How may flow be affected by the chemical-mechanical coupling?

Lower Tuscaloosa Fm. (Regional)

Deposited during transgression ~85 Ma.

Transition from alluvial to fluvial to deltaic to gravity-flows and turbidites.



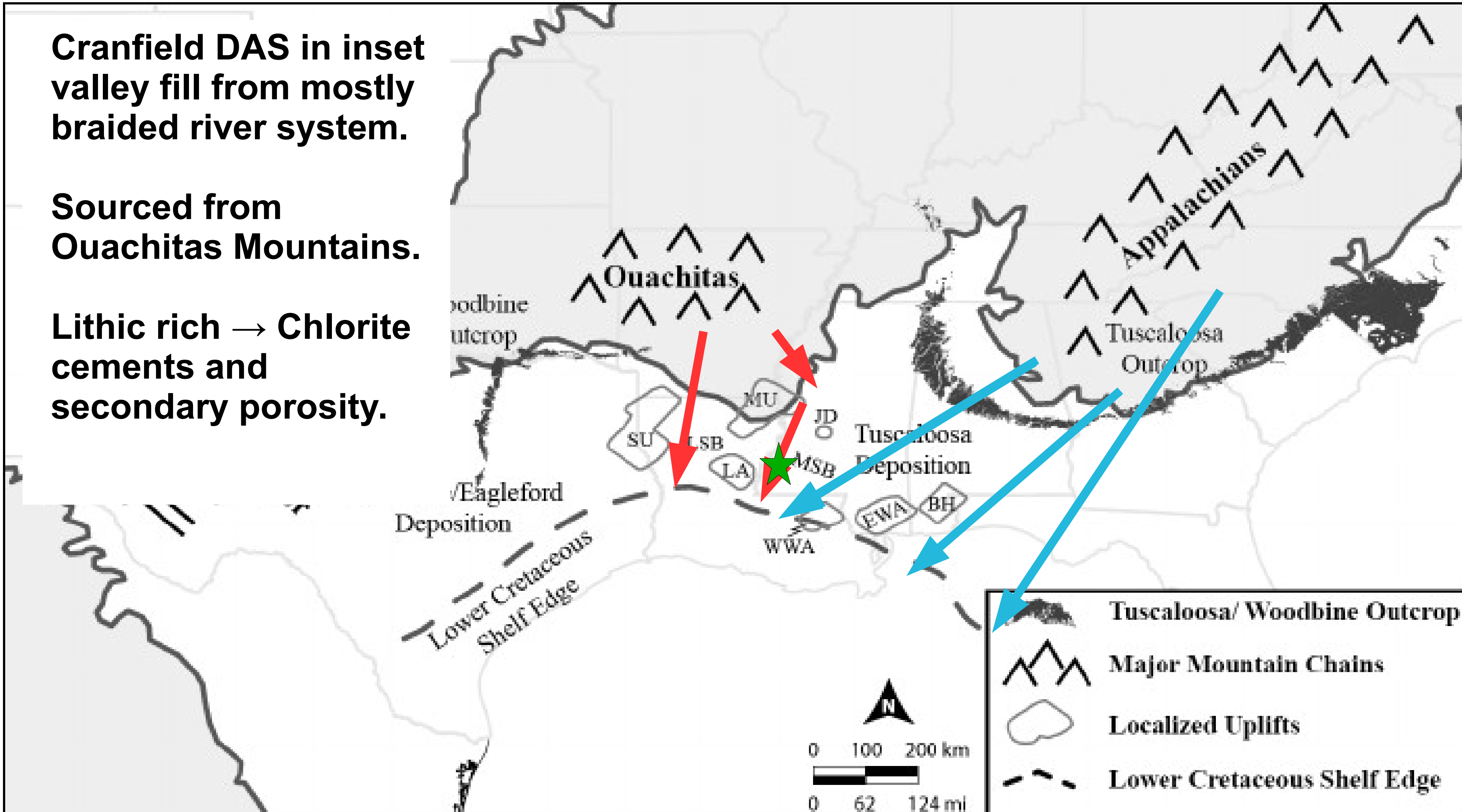
Woolf dissertation (2012)

Lower Tuscaloosa Fm. (Regional)

Cranfield DAS in inset valley fill from mostly braided river system.

Sourced from Ouachitas Mountains.

Lithic rich → Chlorite cements and secondary porosity.



Woolf dissertation (2012)

Core Description from Cranfield

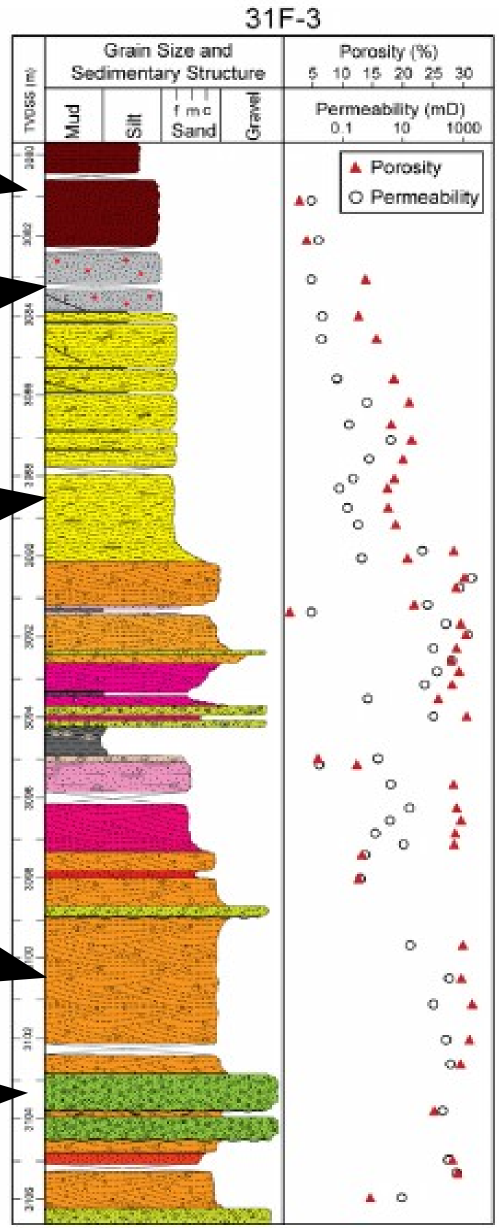
Red terrestrial siltstone

Tabular, very fine grained qtz cemented sandstone

X-bedded, coarse fine grained qtz/chlorite cemented sandstone

Coarsely x-bedded coarse pebbly chlorite-cemented sandstone

Conglomerate



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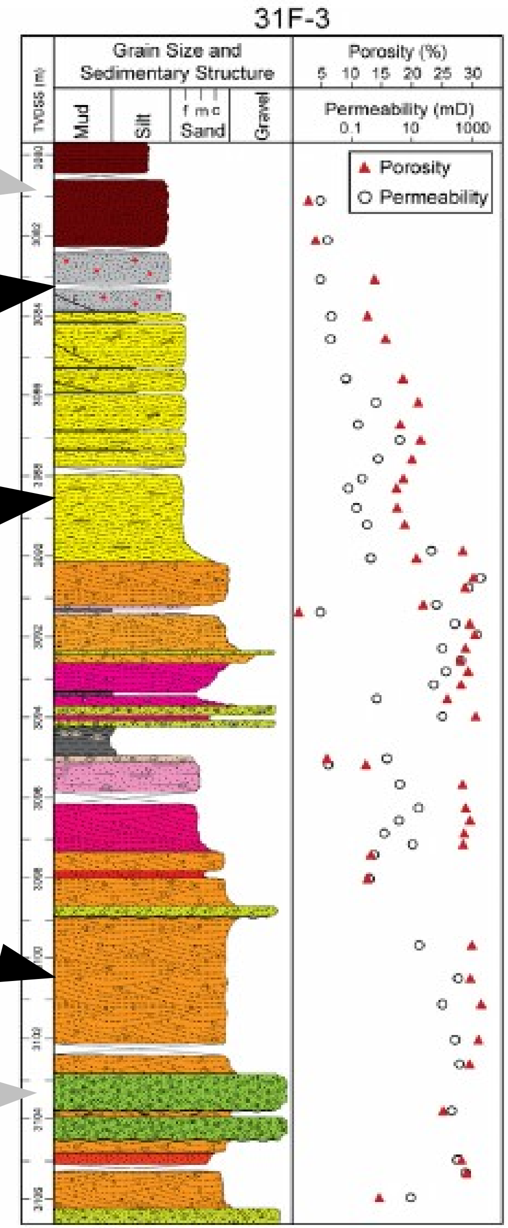


Red terrestrial Siltstone

C Tabular, very fine grained qtz cemented sandstone

B X-bedded, coarse fine grained qtz/chlorite cemented sandstone

A Coarsely x-bedded coarse pebbly chlorite-cemented sandstone

Conglomerate

From Lu et al., 2013. International Journal of Greenhouse Gas Control.

Core Images

C

Siltstone **Tabular Sandstone**

B

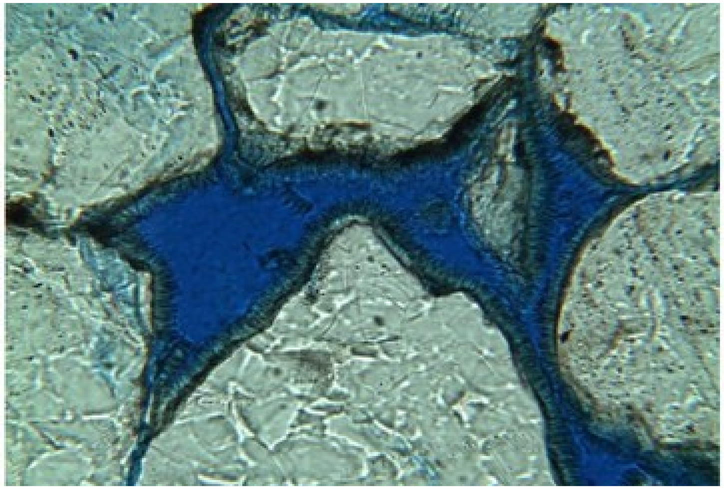
X-Bedded Sandstone

A

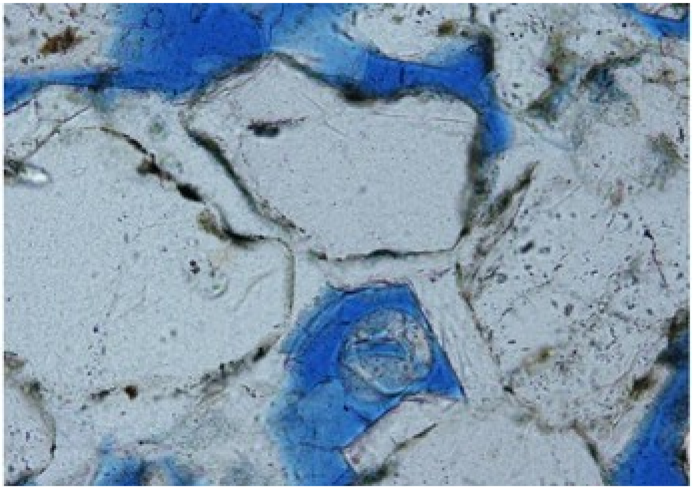
Congl. Sandstone

Slabbed core from Well CFU 31-F3 at Texas BEG Core Repository, Austin, TX.

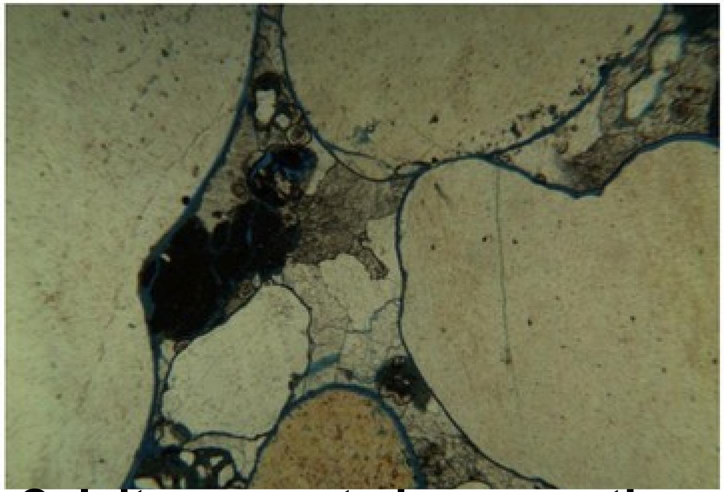
Petrography and Cements



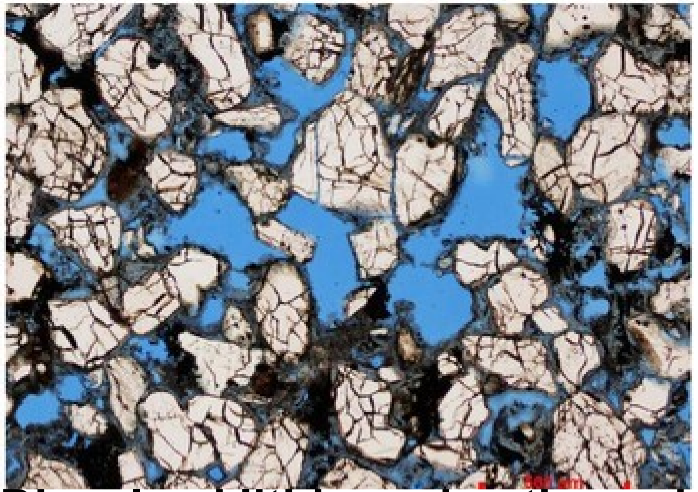
Chlorite cements in cong. sandstone.



Quartz cements in fine sandstones.



Calcite cements in concretion.



Dissolved lithic grains throughout.

From Hossieni et al., 2013. International Journal of Greenhouse Gas Control.

Driving Questions

- What is the heterogeneity of the injection horizon?
- Does CO2 weaken some parts of the rock?
- What are the geologic controls on chemically activated deformation?
- How may flow be affected by the chemical-mechanical coupling?

Driving Questions

- **What is the hydrologic, chemical and mechanical heterogeneity of the injection horizon?** *Grainsize and type of cement?*

- **Does CO2 weaken some parts of the rock?** *Prevelance of chlorite vs. quartz cements?*

- **What are the geologic controls on chemically activated deformation?** *Source terrain, depo. env.?*

- **How may flow be affected by the chemical-mechanical coupling?** *Differential compaction leading to changing permeability, but only in some facies?*

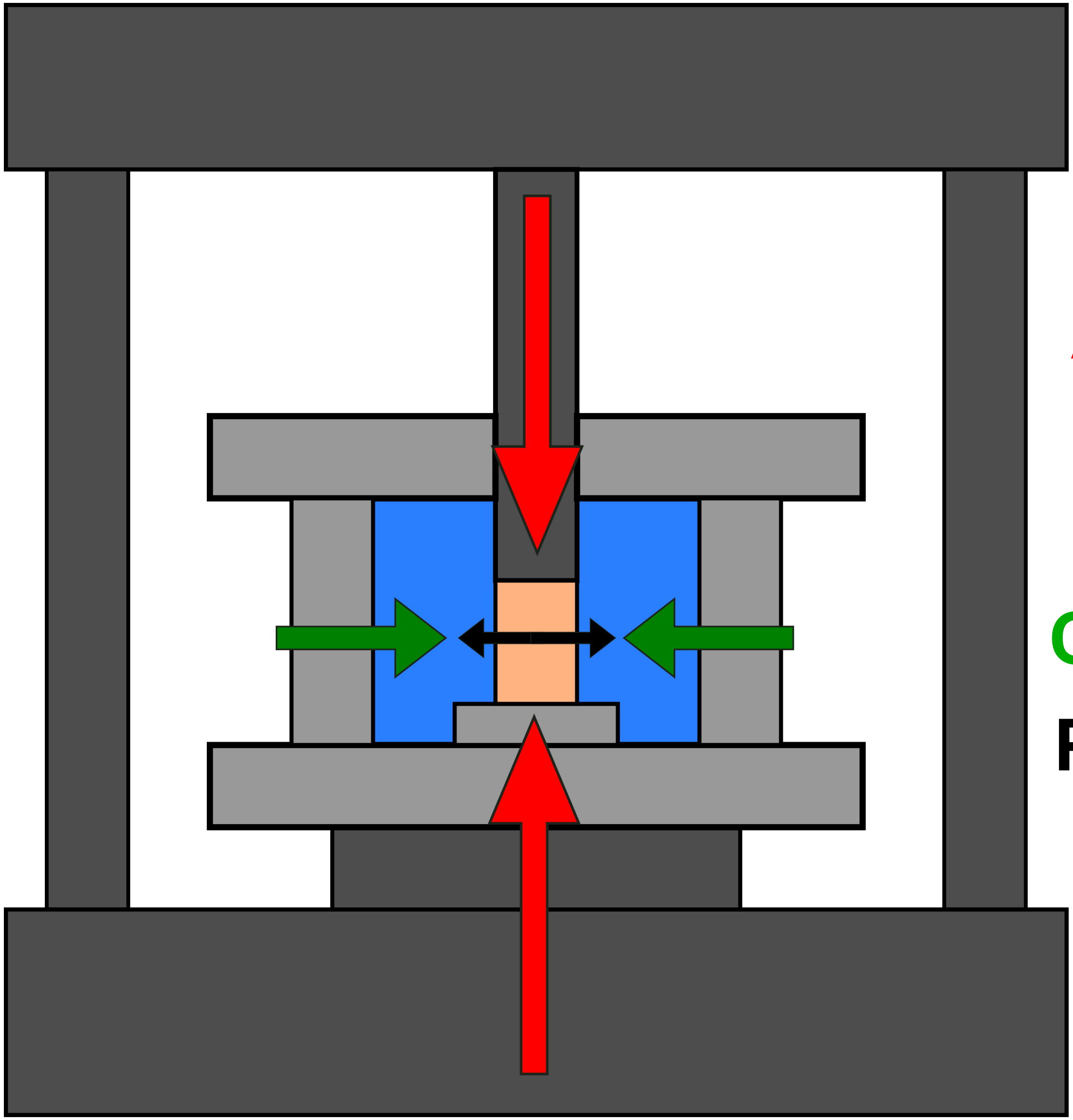
Testing Requirements

Simulate reservoir conditions.

- Temperature at 100°C temperature.
- Pore fluid is reservoir brine simulant.
    - 130 ppt TDS, used Na-Ca-NO3 brine.
    - Equilibrated with supercritical CO2.
- Pore pressure is 30 MPa.
- Depth of 3,000 m (lithostatic pressure is ~70 MPa).

Generate enough stress paths to estimate elastic properties, and yield and failure envelopes. When possible, include acoustic emission monitoring.

Definitions



Axial Stress

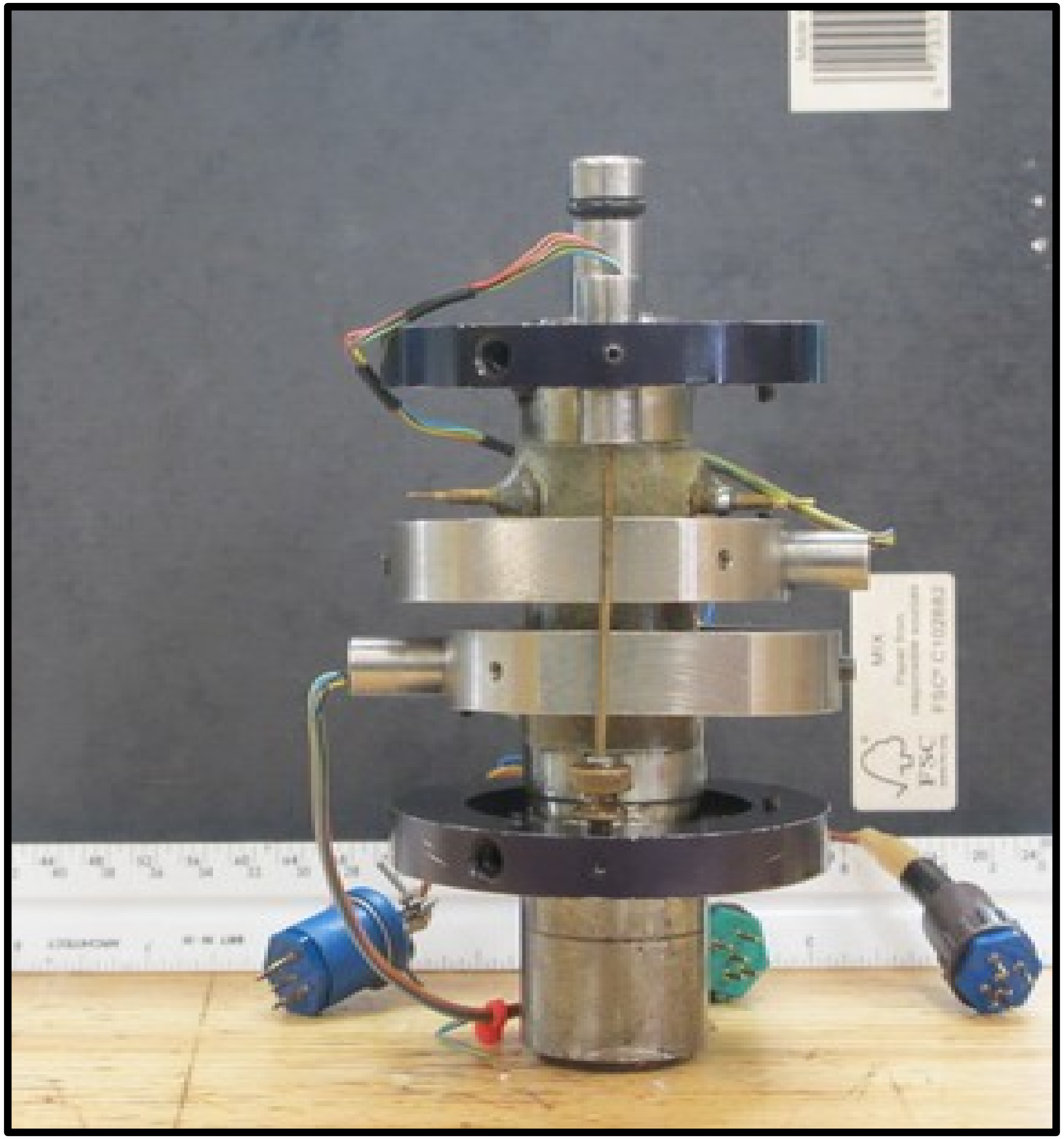
Confining Pressure

Pore Pressure

Test Plan – Mechanical

- Test suite for each of the 3 lithofacies.
  - Hydrostatic crush-out.
  - Effective unconfined compressive strength.
  - 1-2 constant confining pressure triaxial strength tests.
- Monitor stress, strain and acoustic emissions.
- All tests in quasistatic strain rates.
- Monitor for deformation during chemical and thermal equilibration periods, and during pauses in quasistatic loading.

Experimental Setup



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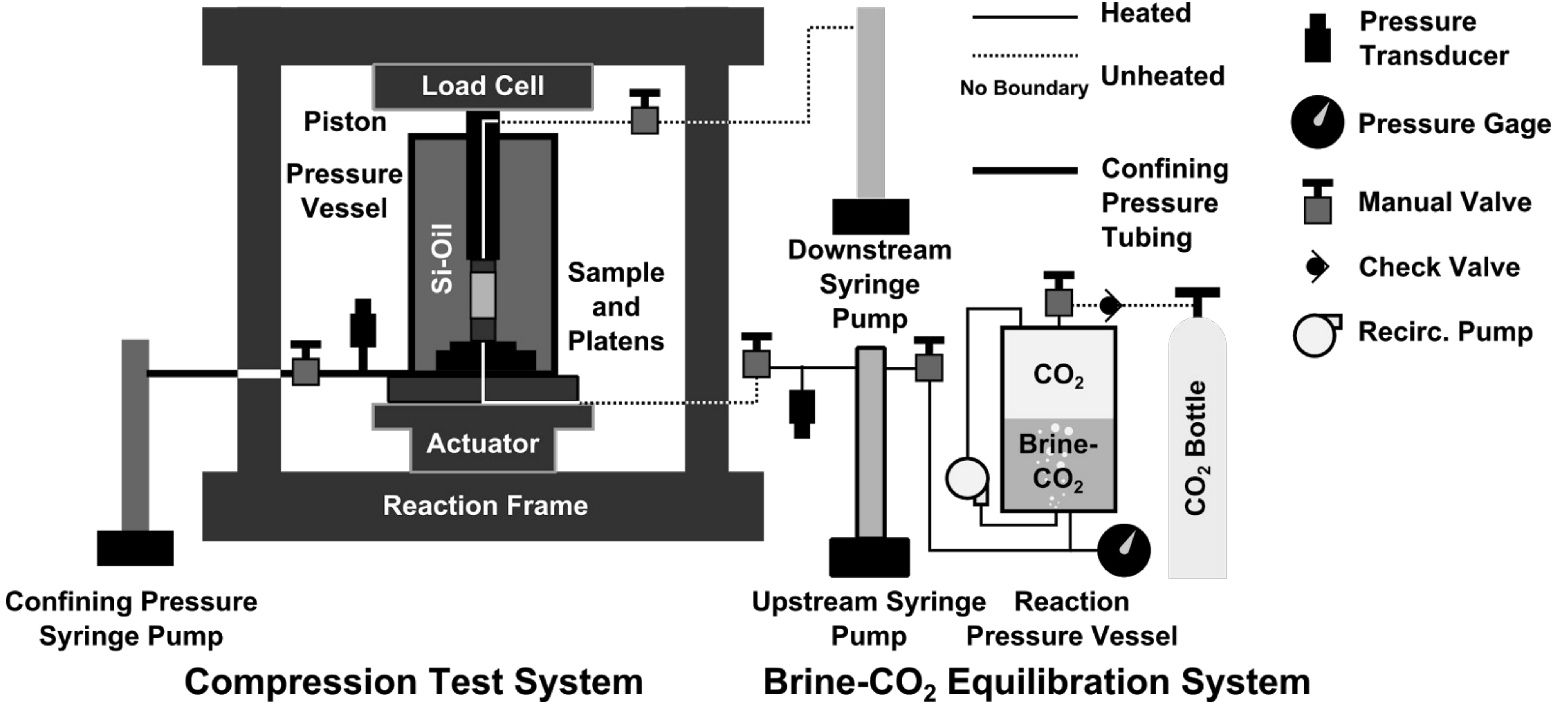
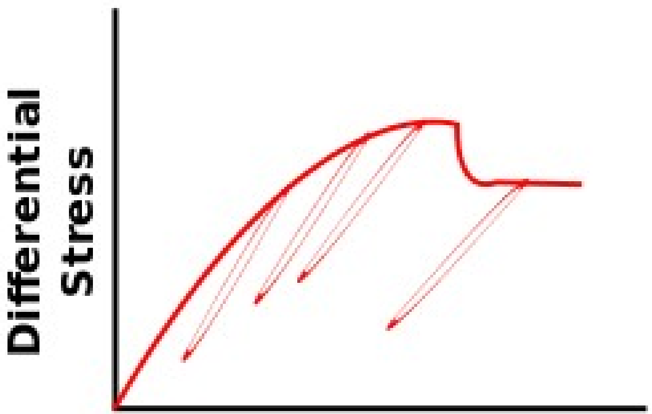
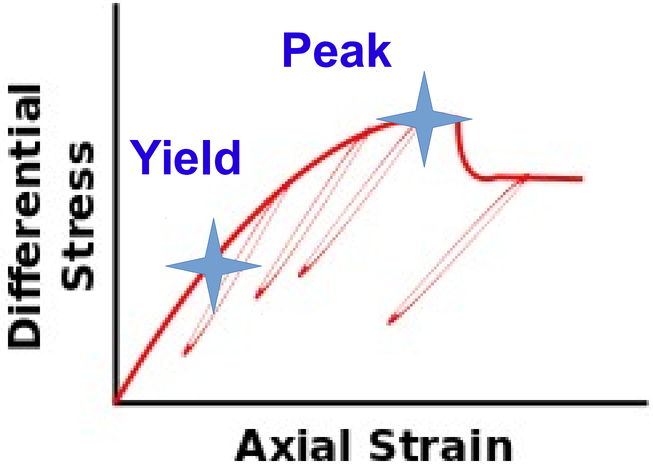


How to Interpret Results





Yield

Beginning of inelastic deformation (damage).

Peak Stress

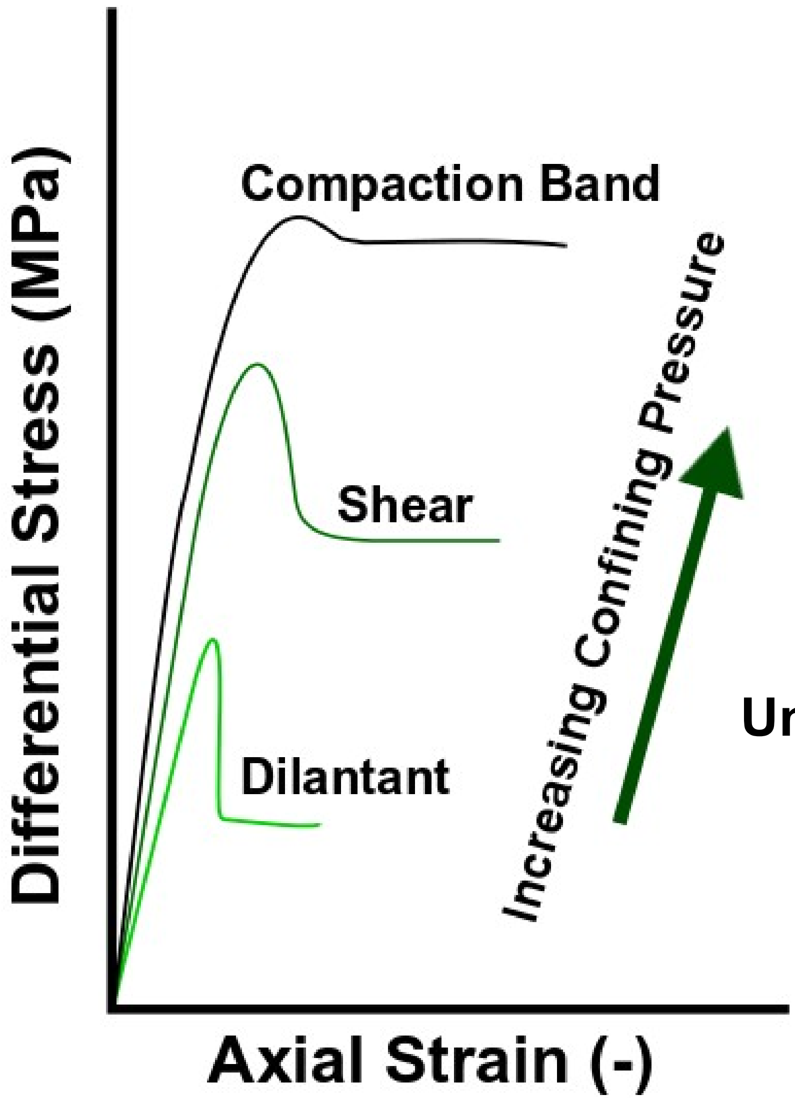
Highest differential stress material can withstand.

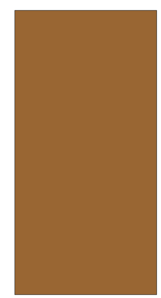
Elastic moduli degradation

Elastic 'stiffness' becomes smaller with increasing Damage.

Time independent (assumes no creep/subsidence)

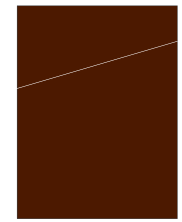
How to Interpret Results





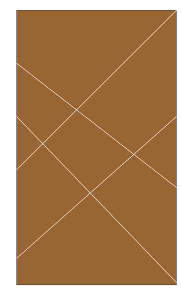
Undeformed Sample

Perm.



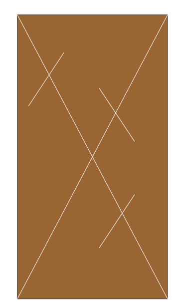
Compaction Band

Initial plane of weakness, then grain crushing and porosity loss.



Shear failure

Some dilatancy common, med. angle fractures.



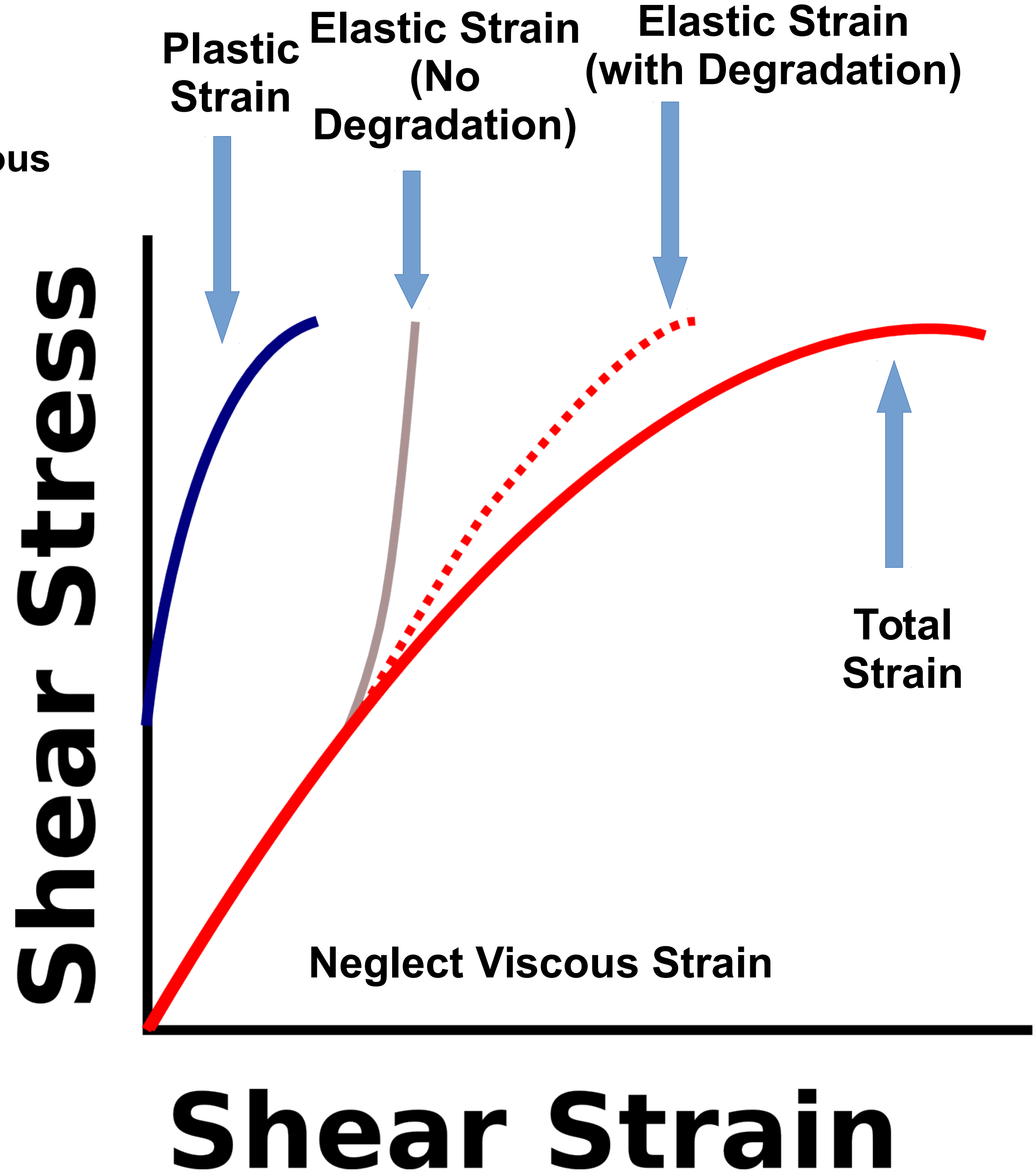
Dilantant failure

Volume increase from lateral crack opening, high angle fractures from crack coalescence.

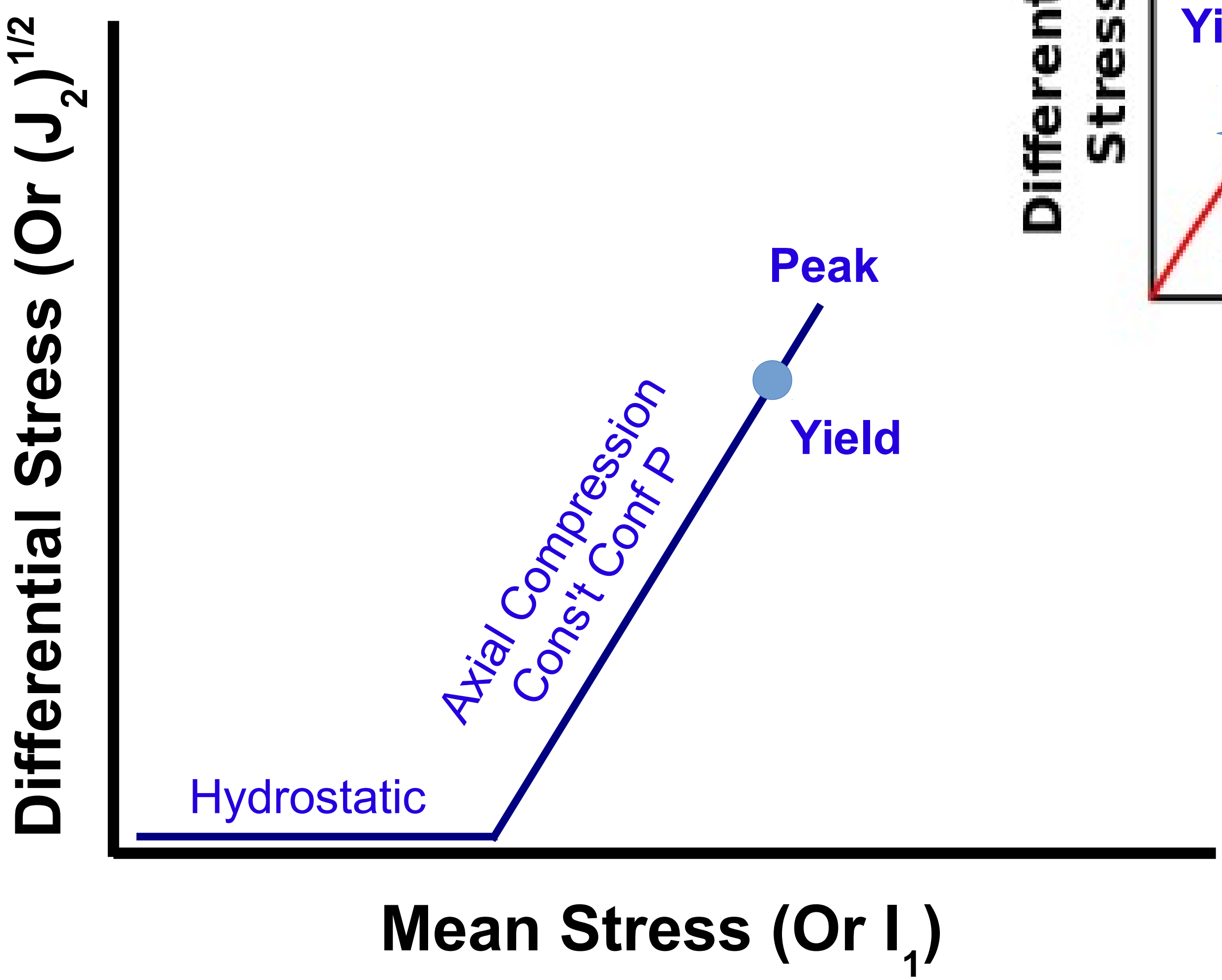
Strain Partitioning

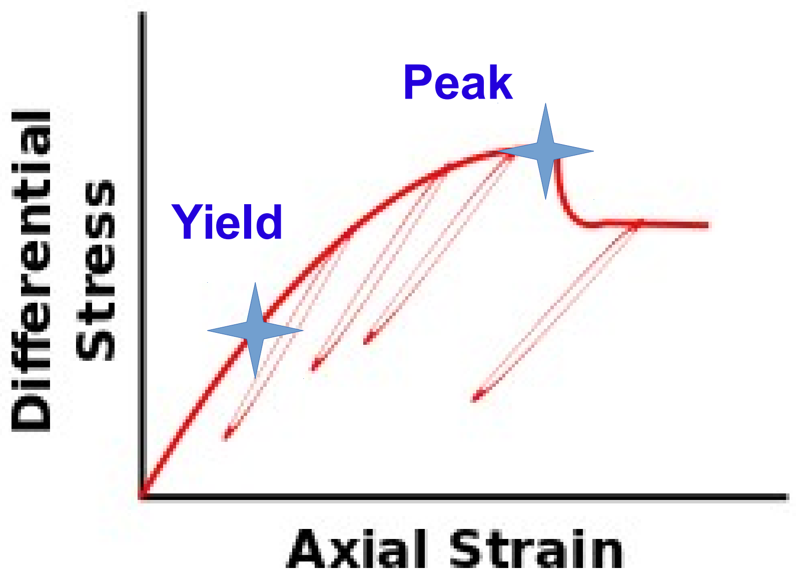
$$\varepsilon_{tot} = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{viscous}$$

$$\varepsilon_{tot} = \varepsilon_{elast,degr}(\varepsilon_{plastic}) + \varepsilon_{plastic} + \varepsilon_{viscous}$$

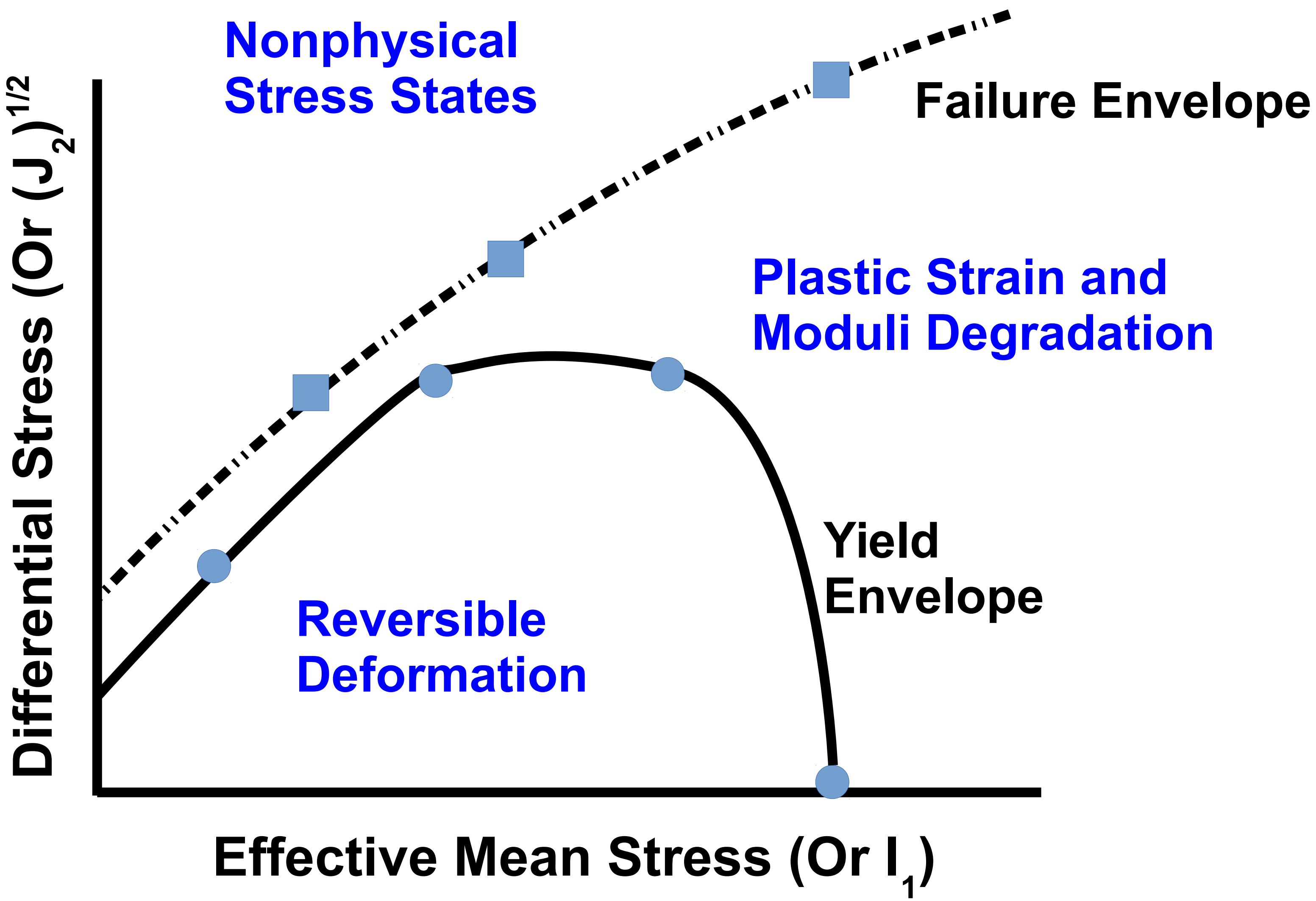


Failure Envelopes

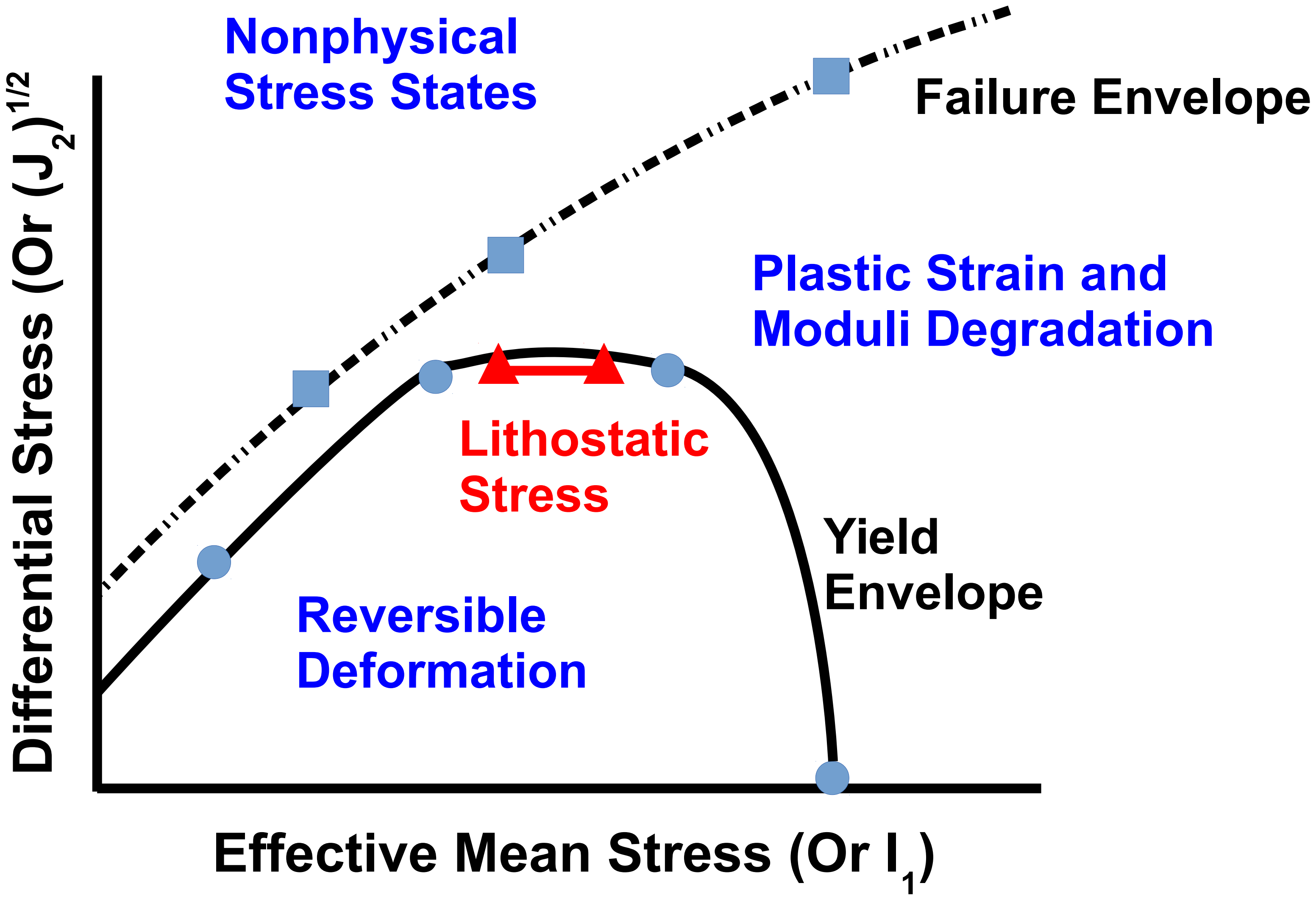




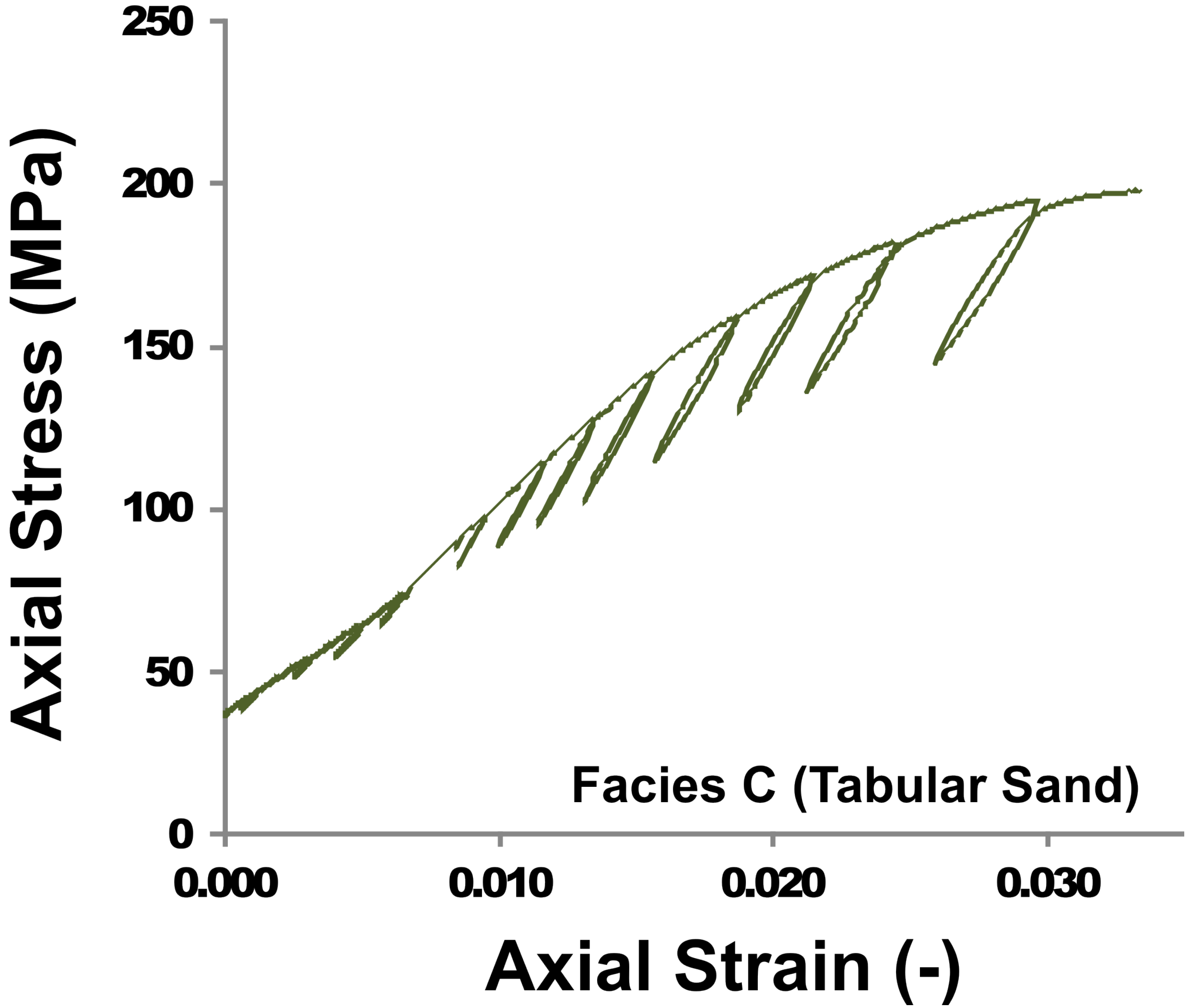
Failure Envelopes



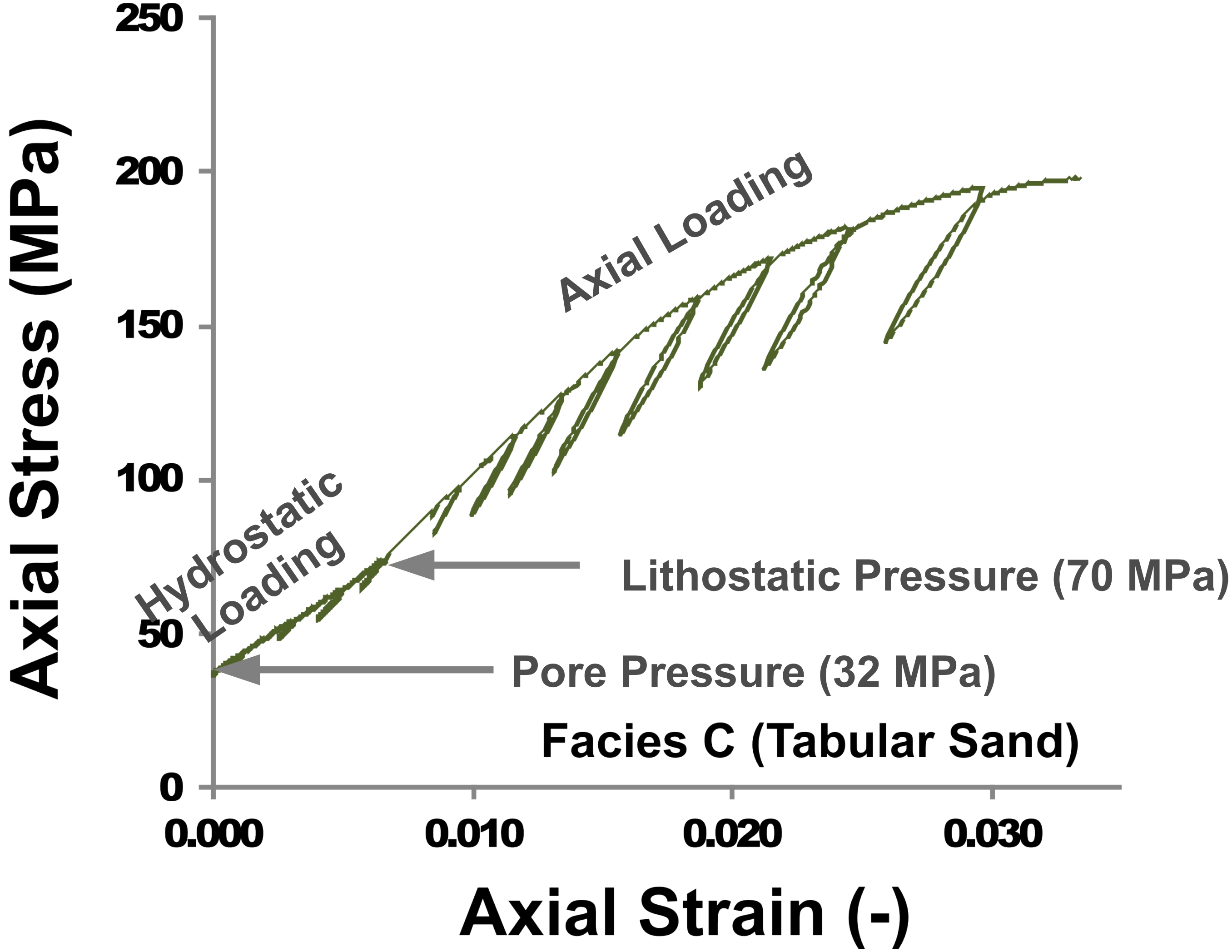
Failure Envelopes



70-MPa Triax Stress Strain Data



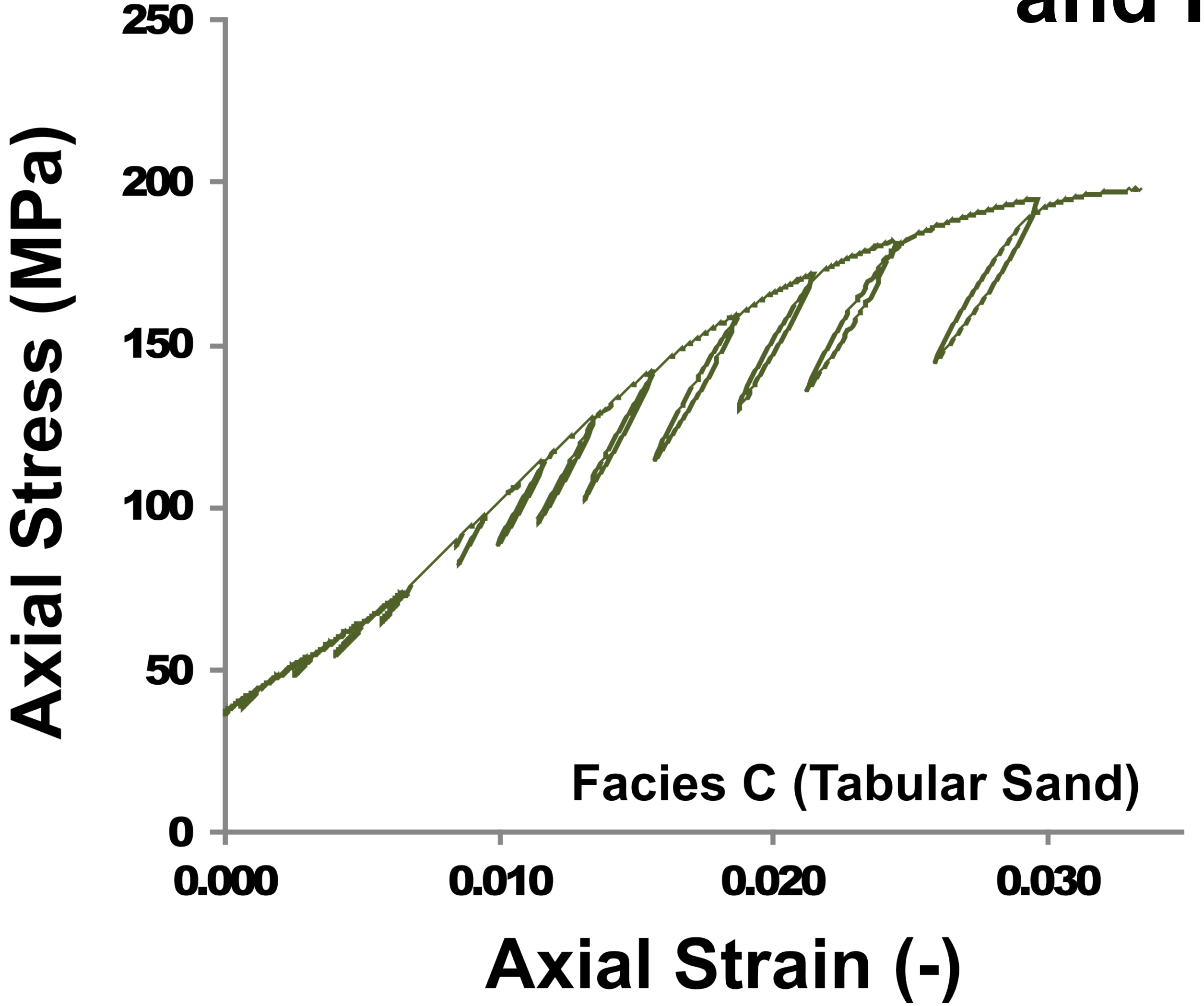
70-MPa Triax Stress Strain Data



70-MPa Triax Stress Strain Data

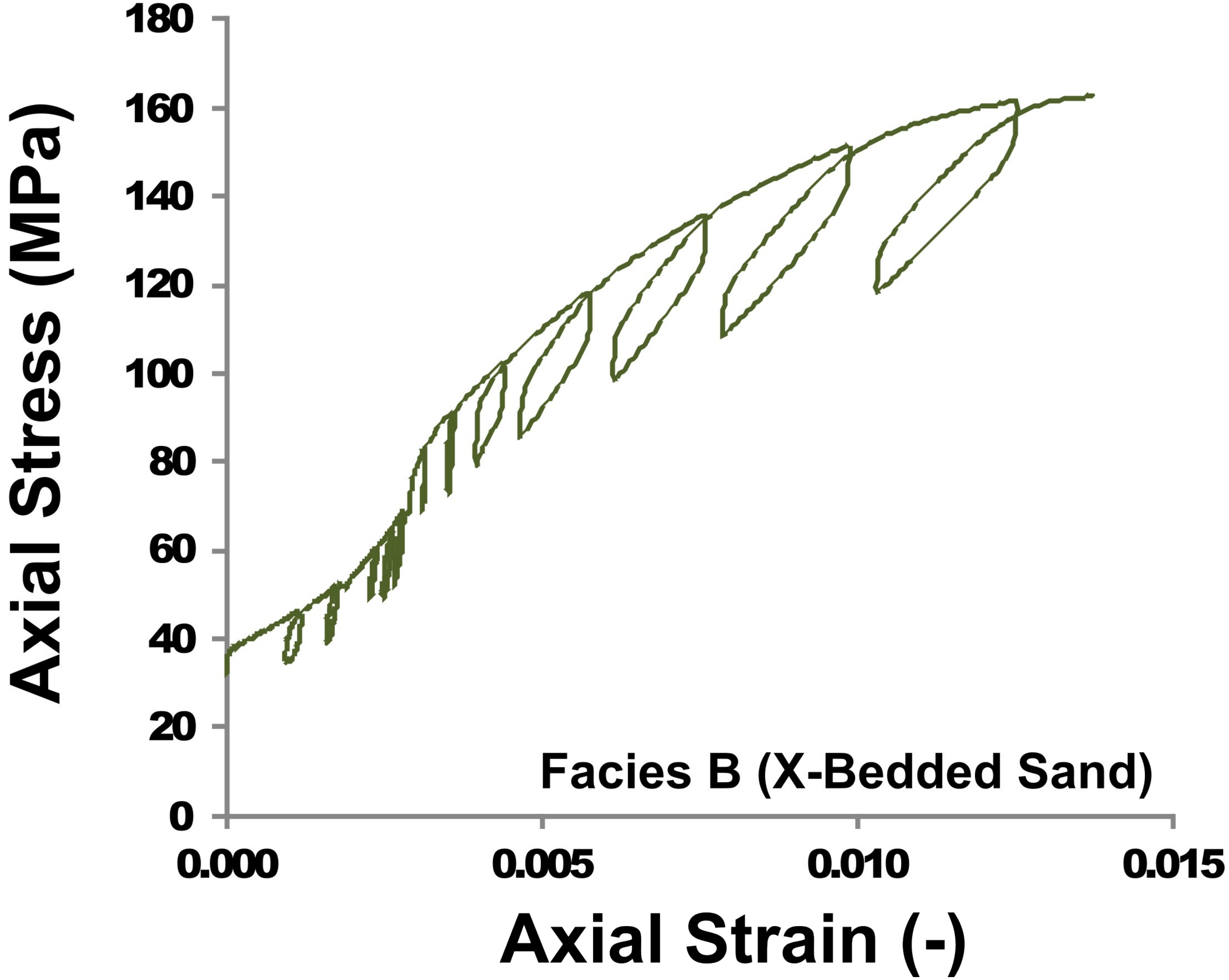
Peak Axial Stress and Failure Style

C: 210 Mpa
Shear Band



70-MPa Triax Stress Strain Data

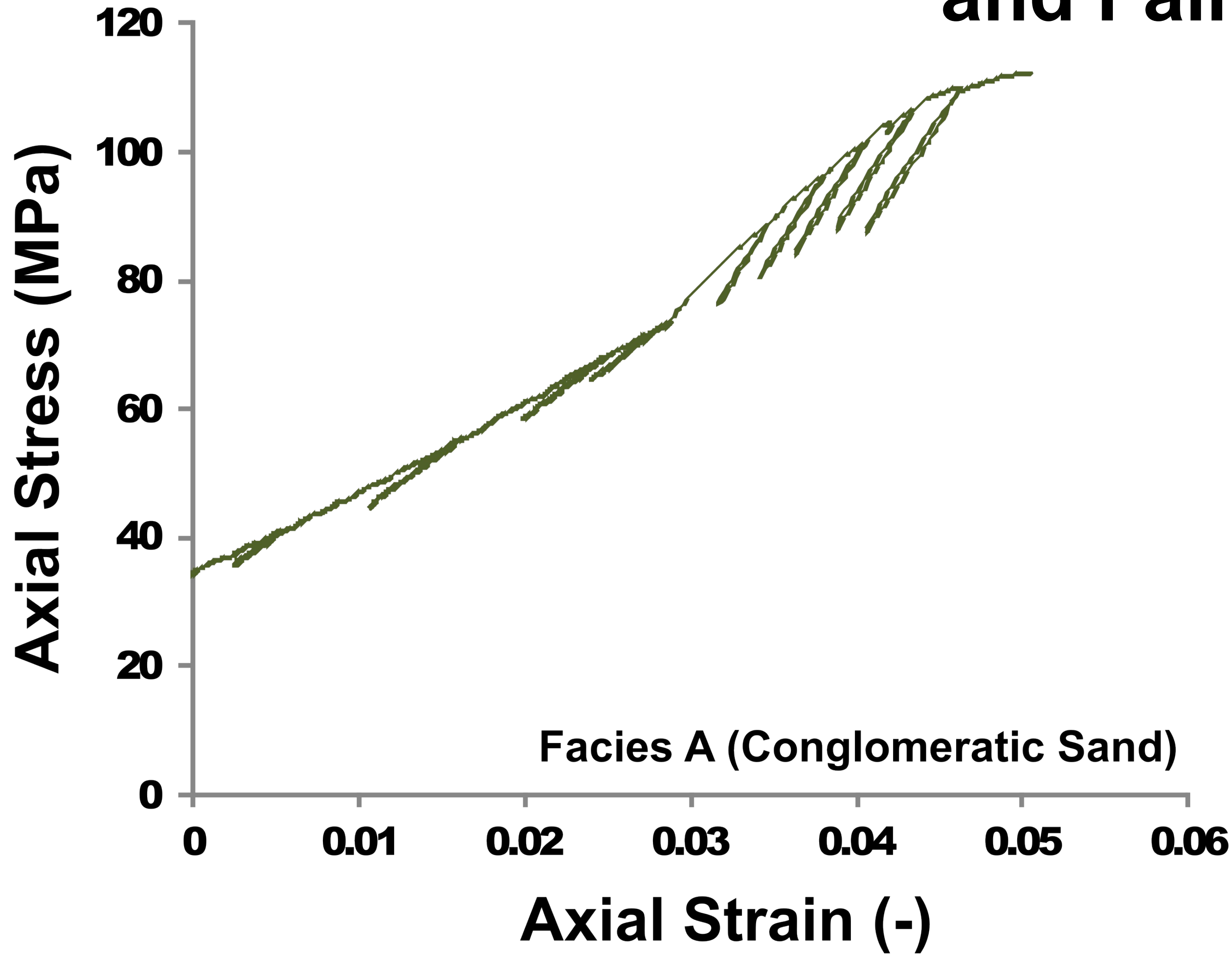
Peak Axial Stress and Failure Style



C: 210 MPa
Shear Band

B: 163 MPa
Shear Band

70-MPa Triax Stress Strain Data



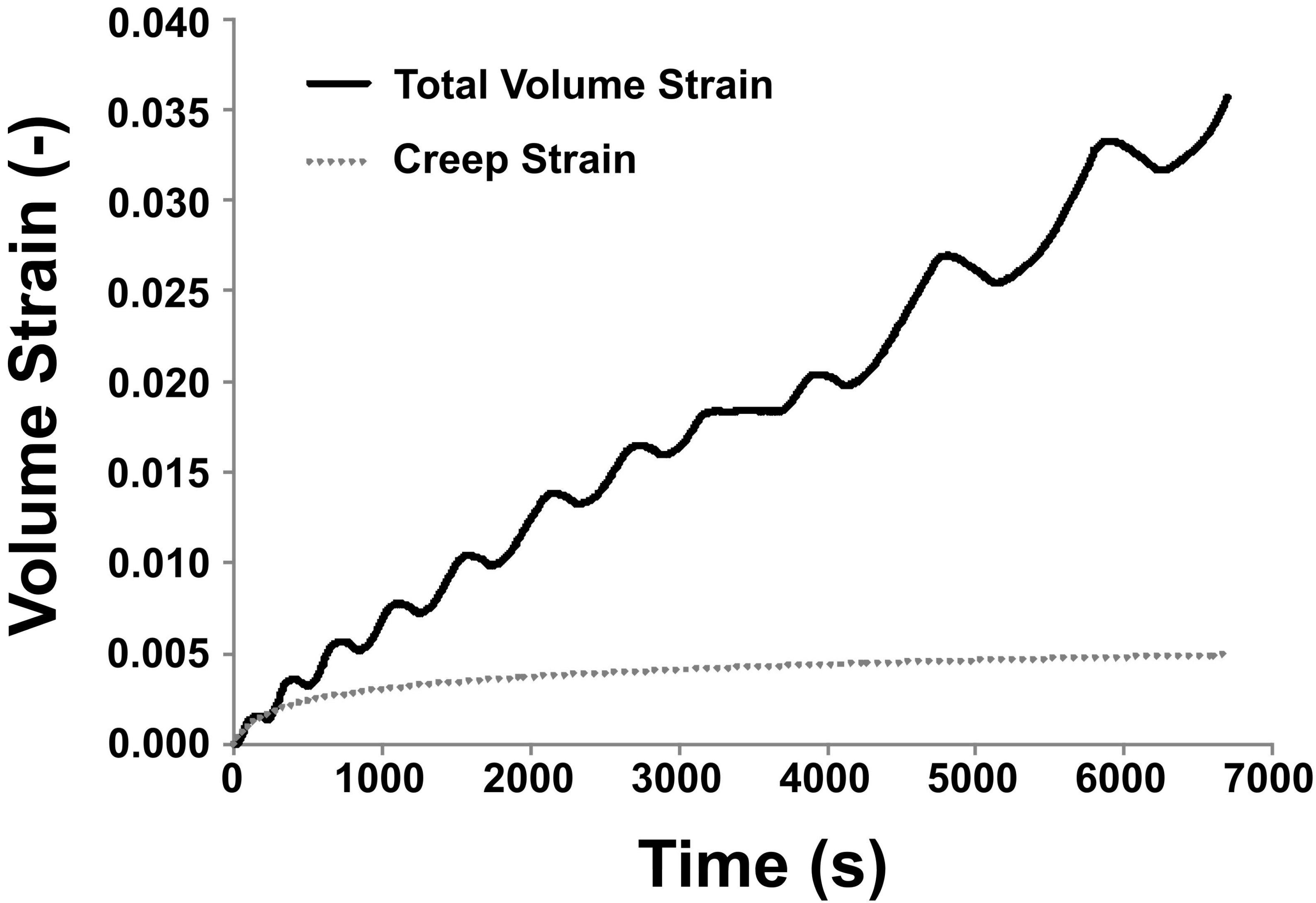
Peak Axial Stress and Failure Style

C: 210 MPa Shear Band

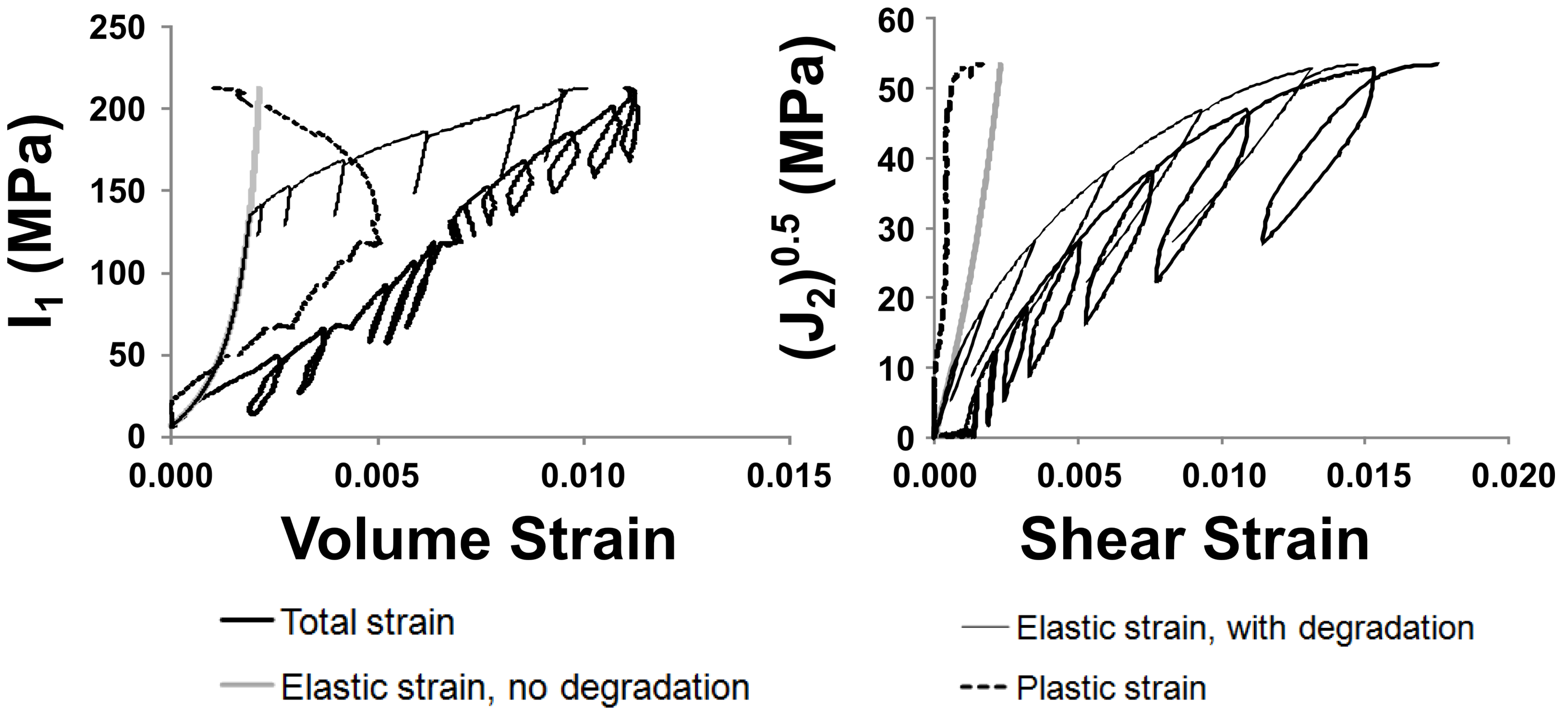
B: 163 MPa Shear Band

A: 97 MPa Compaction

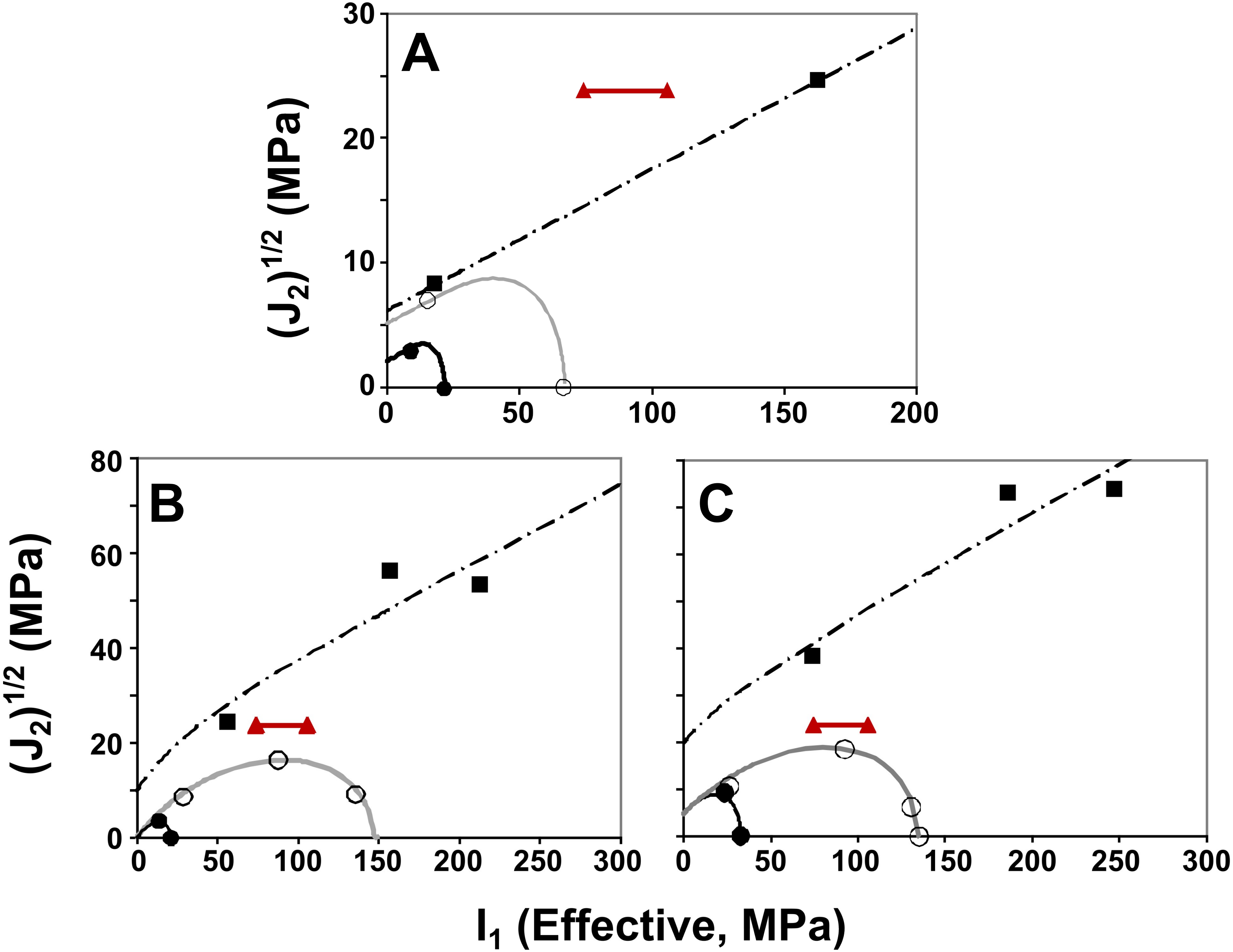
70-MPa Triax Facies A Creep



70-MPa Facies A Strain Partition



Failure Envelopes



In-situ stress estimate from Kim and Hosseini, personal communication, 2014.

Results (Stress-Strain)

- The three different sandy lithofacies of the D-E member of the Lower Tuscaloosa have dramatically mechanical strengths at near-wellbore conditions in the presence of CO2.

- Elastic degradation greatest in Facies A, then Facies B, then weak in Facies C.

- Rapid (hours) creep accumulation in Facies A, negligible creep strain in B and C.

- For 70 MPa-tests, Facies B and C fail in shear, Facies A fails as compaction band.
    - Facies A decreases in permeability from both quasistatic failure and creep deformation.

Results (Envelopes)

- Facies C/Tabular (strongest) → Facies B/X-bedded → Facies A/Conglomerate (weakest).

- Plastic strain (yield) very early relative to in-situ stress.
    - Rocks "remember" maximum depth of burial/stress state.

- Elastic moduli degradation separate from onset of plastic strain. Argues for different mechanisms.

- Facies B and C have in-situ stress away from initial yield, near onset of moduli degradation.

- Facies A failure envelope lower than in-situ stress.
    - Compaction from failure during injection.
    - Possibly decreasing permeability.

Conclusions and Implications

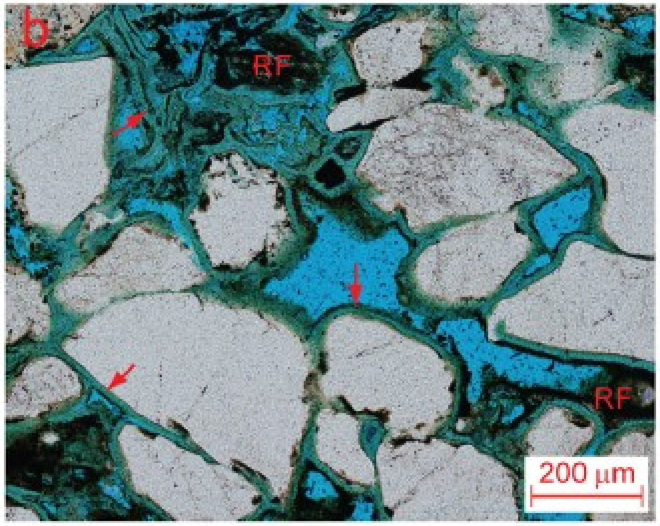
- CO_2 impacts strength and 'creep' of siliceous rocks through interaction with cements.

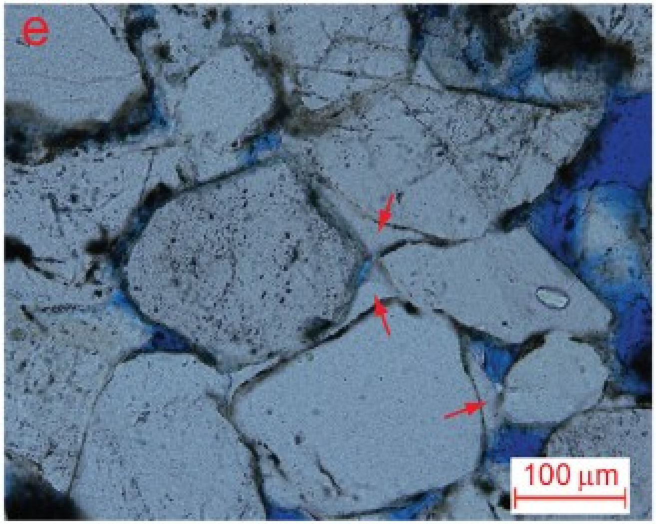
- Evolution of permeability (and how to manage well field) can be controlled by CO_2-enhanced compaction through chlorite cementation.
    - Facies A (main injection horizon) hydraulically sensitive to CO_2 injection b/c of CO_2-chlorite interactions.

- Different mechanisms for plastic strain (deformation in chlorite cements) and elastic moduli degradation (grain fracture).

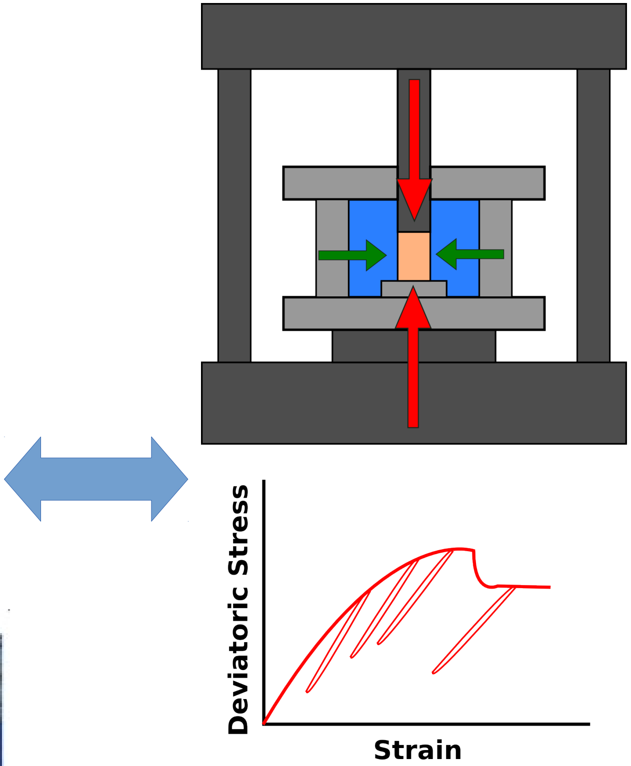
- Coupling of regional geology, mechanics, hydrogeology and fluid-solid chemistry need all to be accounted for with reservoir rocks, not analogs.

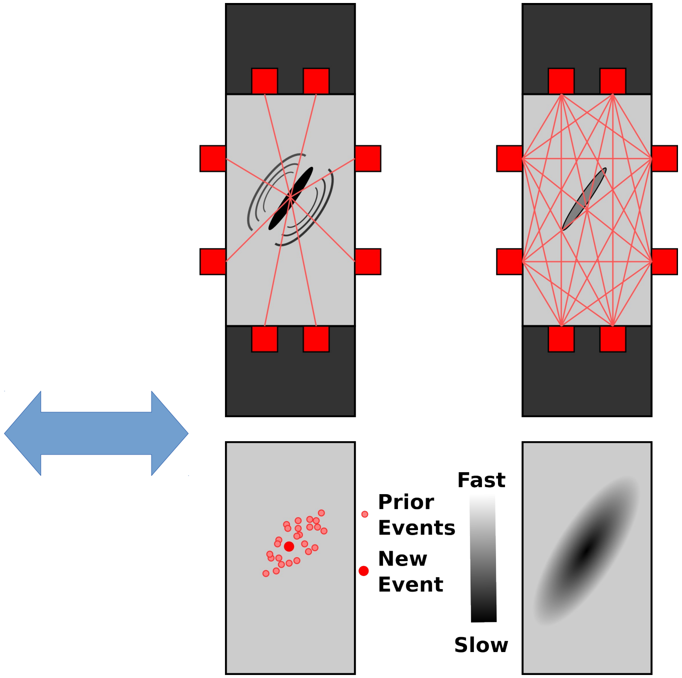
Big Question—Small to Big and Back





Lu et al. (2013)





How do petrographic and geologic observations to to how (and why and how much) they are damaged?

i.e., Use logic to interpret test results in terms of geologic observations.

Ancillary Slides

Test Plan – Chemical

X-bedded Sandstone, Lam. Sandstone, and Congl.

- Initial pore fluid is a high ionic strength brine with close to reservoir cation chemistry equilibrated with super-critical CO2.
  - [NaNO3] = 2.1 M, [CaNO3] = 0.4 M, and [MgCO3] = 0.06 M.

- Equilibrate sample with brine-CO2 fluid at 32 MPa confining pressure and ~32 MPa pore pressure overnight.

- Heat sample to 100 C and equilibrate at this temperature for a least 3 hours.

Siltstone

- Perm too low to saturate with brine in time needed.

- Use constant relative humidity (77%) in sample to make consistent measurements between siltstones.

- RH controlled by equilibrating sample with 2.4 [NaNO3] brine at ~100 C overnight.