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Characterization of Mass Transfer Properties Controlling Back Diffusion from Electrical Measurements During Tracer Injection

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25 YEARS OF ESTCP
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2019 | Enhancing DoD's Mission Effectiveness

Collaborators

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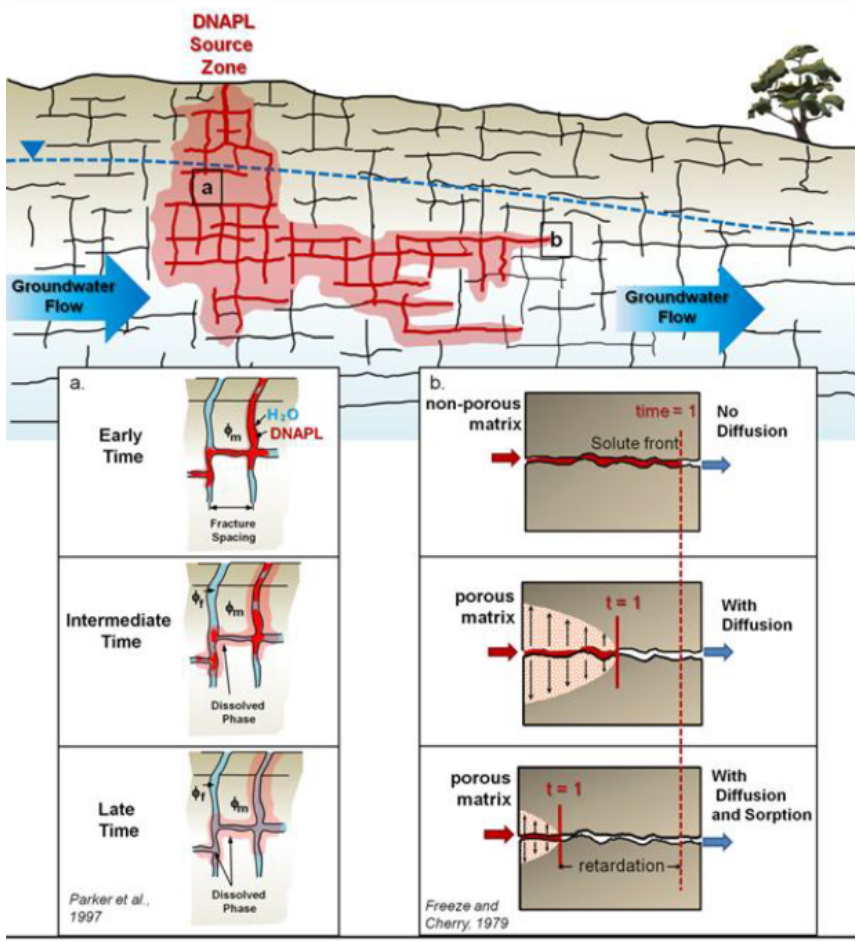
Background

- Development of novel borehole geophysical technologies to:

- [1] non-invasively estimate **pore geometric properties** controlling back diffusion
  [2] determine relevant **rate coefficients** controlling diffusion of contaminant mass



Parker et al., (2012)

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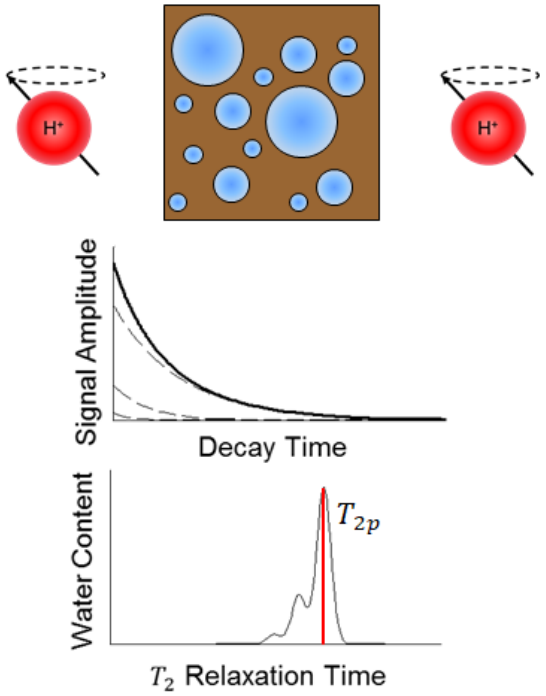
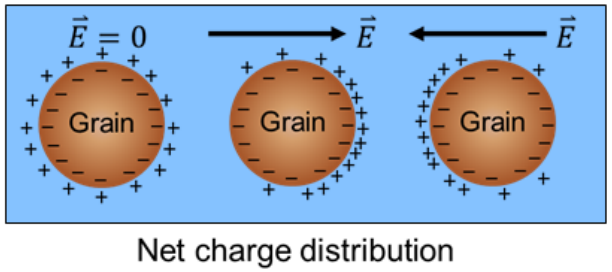
Emerging borehole geophysical technologies

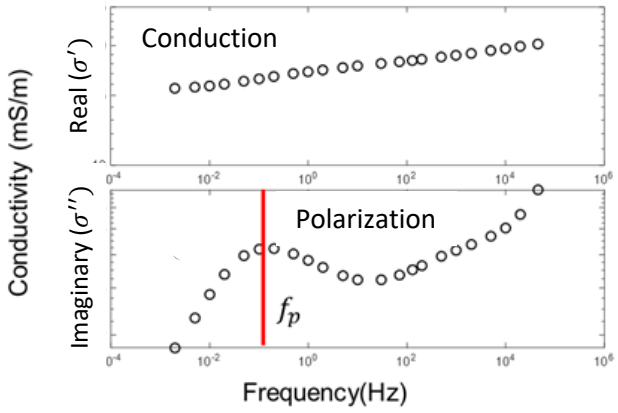
- Geophysical technologies that are sensitive to geometric properties controlling mass transfer: *pore size distribution*, *tortuosity*

Nuclear magnetic resonance (NMR)

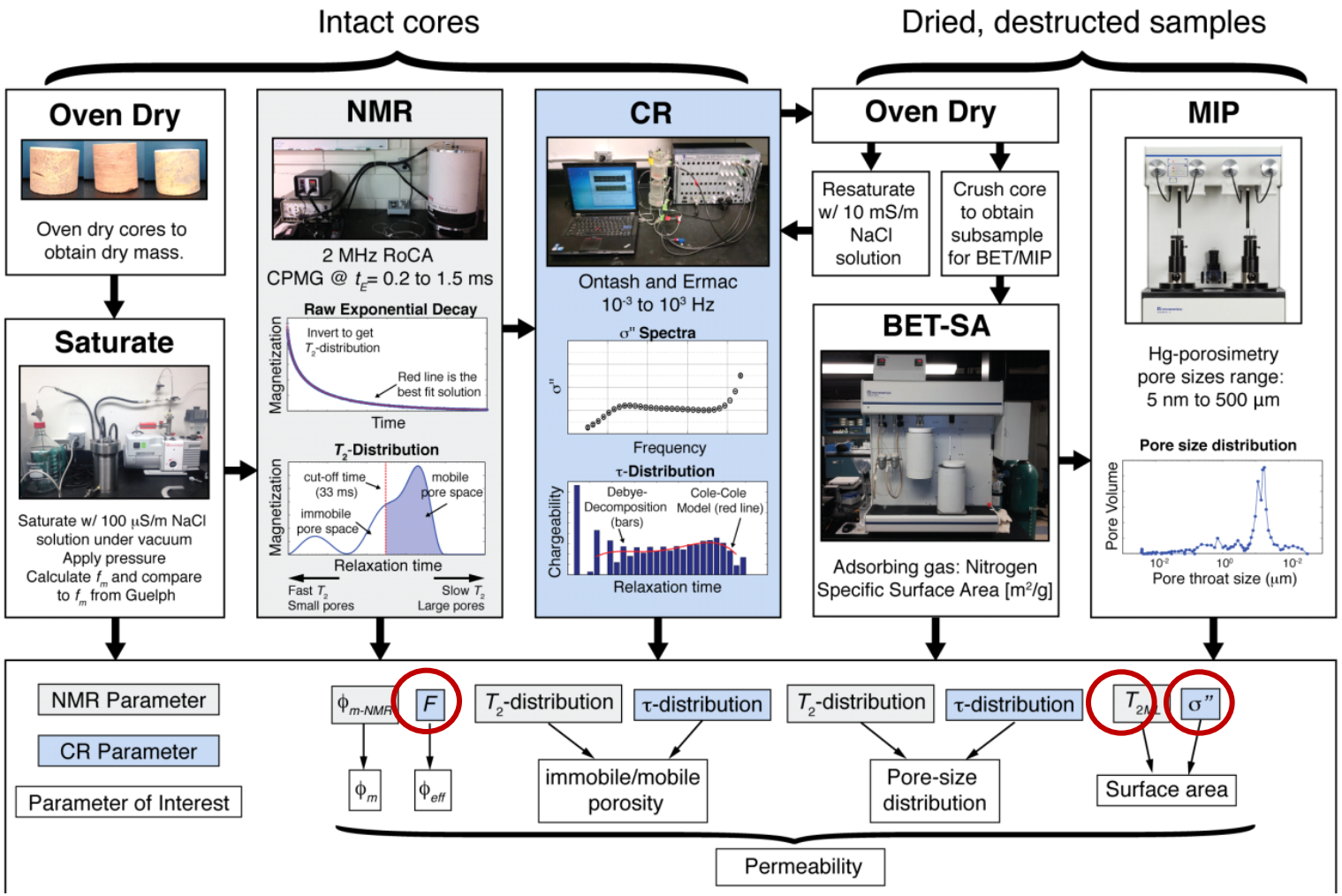


Complex resistivity (CR)





Integrated laboratory procedure



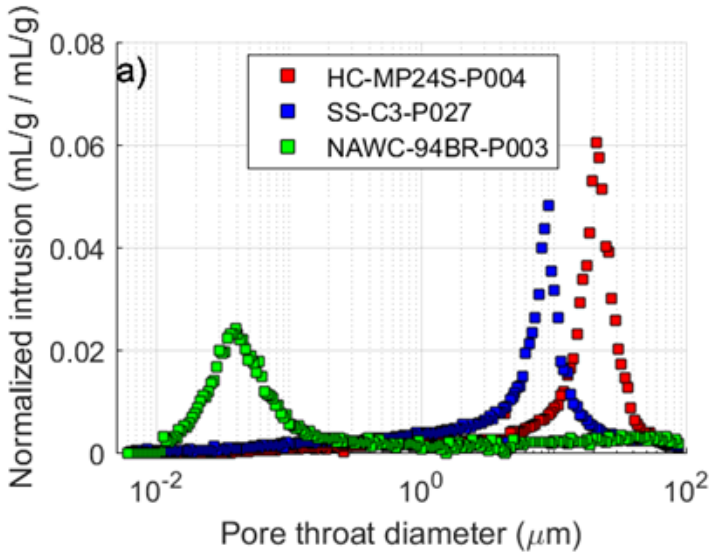
SANTA SUSANA: Deep-sea sandstone turbidite deposit

HYDRITE: Fine grained quartzose sandstones and dolostones

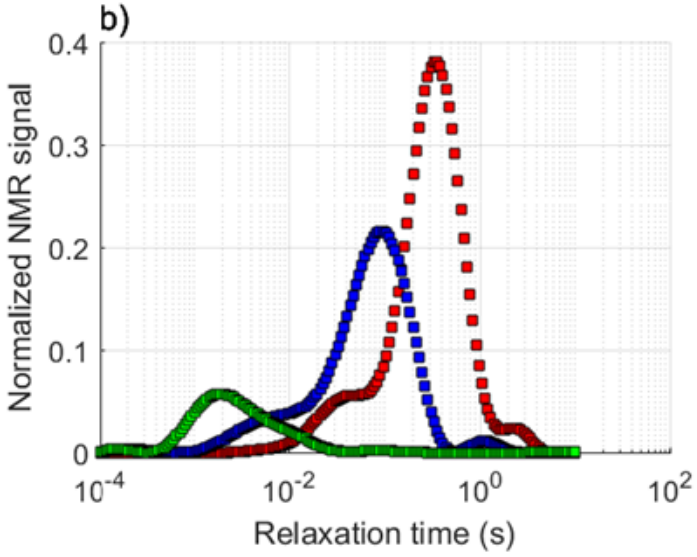
NAWC: Fine grained fractured mudstones

Quantifying pore geometric parameters: NMR example

Pore size distribution

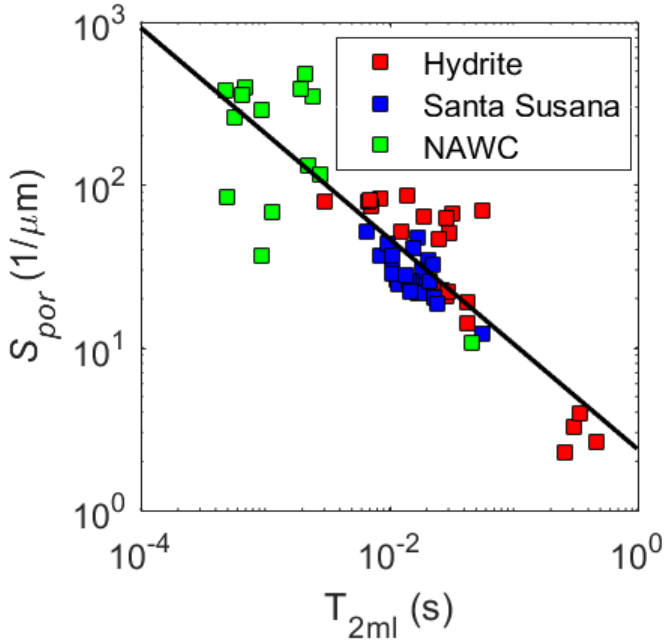


Mercury porosimetry (destructive, ~$400/sample)



Nuclear magnetic resonance (NMR) (non-destructive, ~$50/sample, borehole deployable)

Pore volume normalized surface area (S_{por})

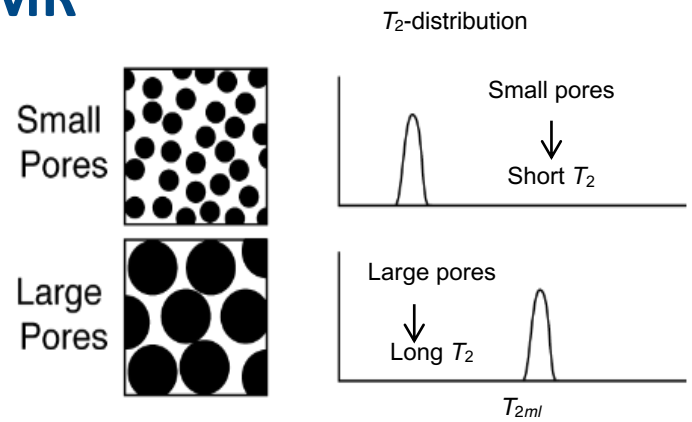


T_{2ml} = mean log relaxation time
BET-derived S_{por} (~$200/sample)

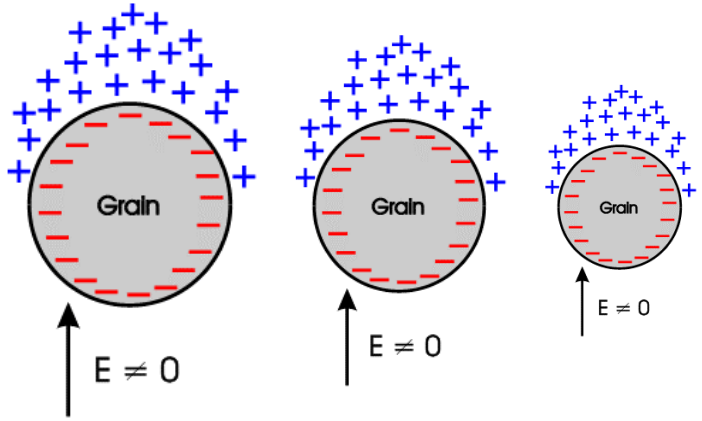
Permeability from geophysical length-scales

Exploit sensitivity to pore or grain size distributions

NMR



CR



Geometric length scales

Effective pore radius $r \approx \frac{1}{S_{por}}$ Surface normalized Pore volume

$r \approx \Lambda$ Mercury capillary Injection porosimetry

Equivalent geophysical length scales

NMR	CR	CR
T_2	$\frac{\sigma'' \text{ or } m_n}{c_p}$	τ
Transverse relaxation	Normalized Polarization	Relaxation time

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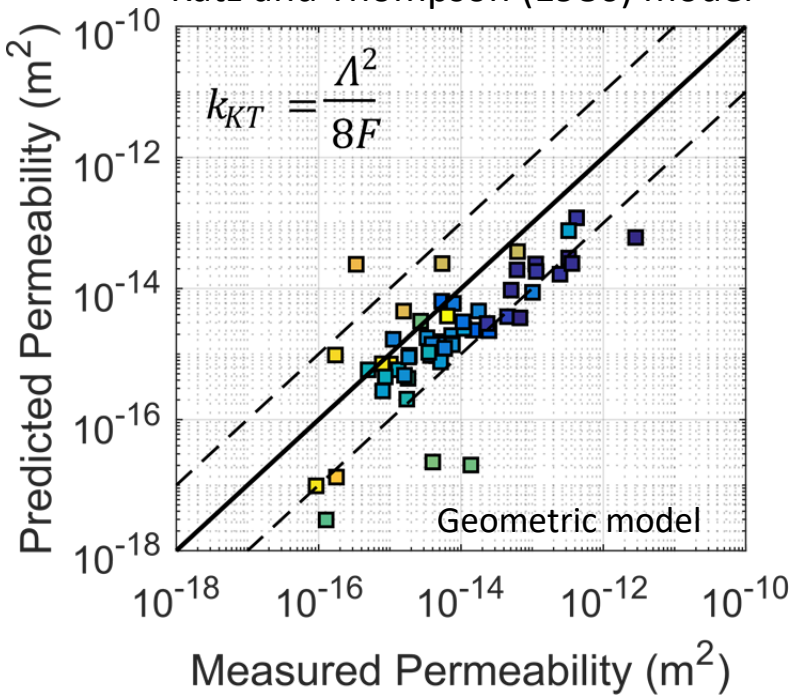
Permeability in sandstones: CR example

Permeability prediction from geophysical length scales (measurable *in situ*) comparable to that from geometric length scales

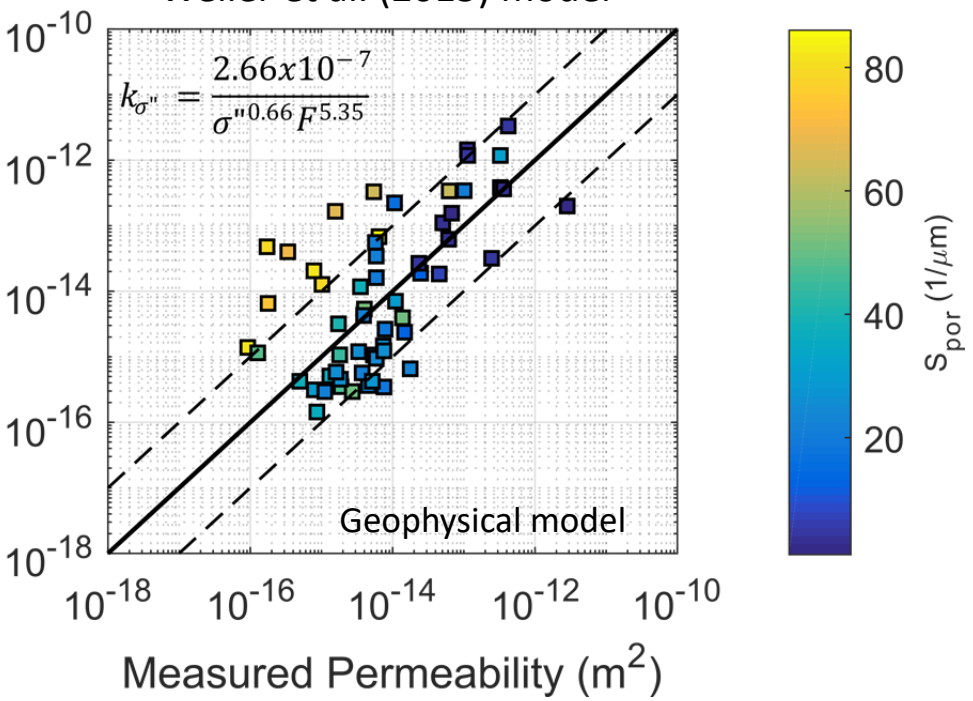
Λ from **mercury porosimetry**

Katz and Thompson (1986) model



σ'' from **complex resistivity (CR)**

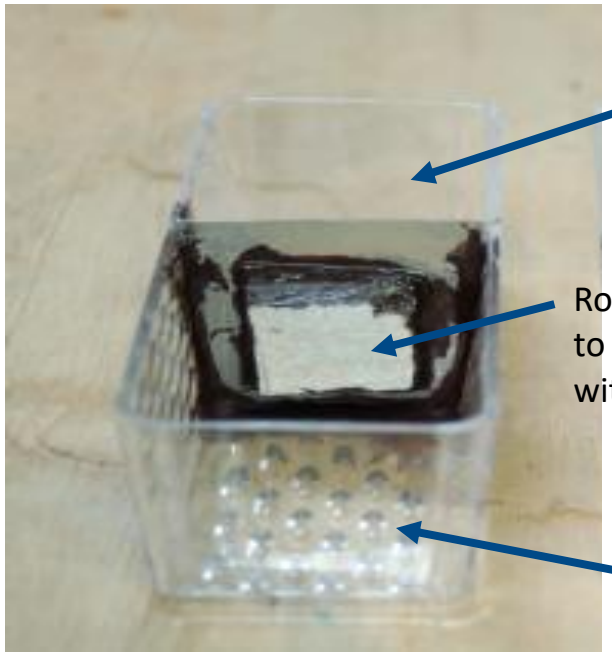
Weller et al. (2015) model



F = formation factor

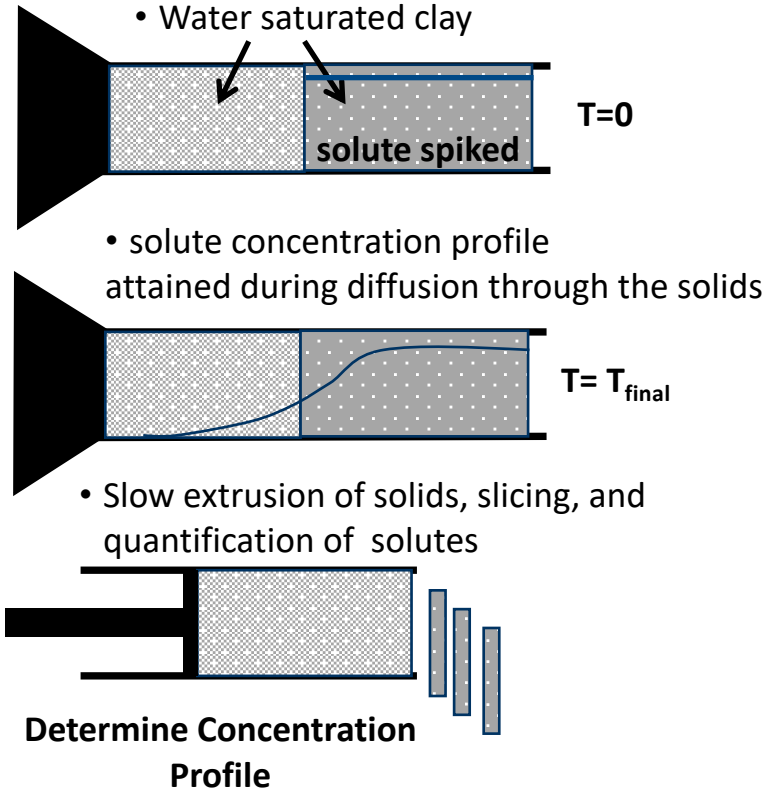
Robinson et al., 2018, ***Water Resources Research***

Geophysical estimation of effective diffusion coefficients?



Schaefer et al., 2012) *J. Environ. Engin.*

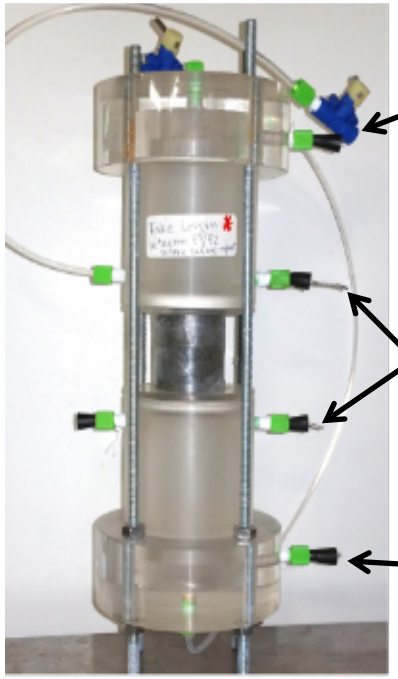
SOLUTE BREAKTHROUGH



Schaefer et al., 1995, *J. Contam. Hydrol.*

ELECTRICAL

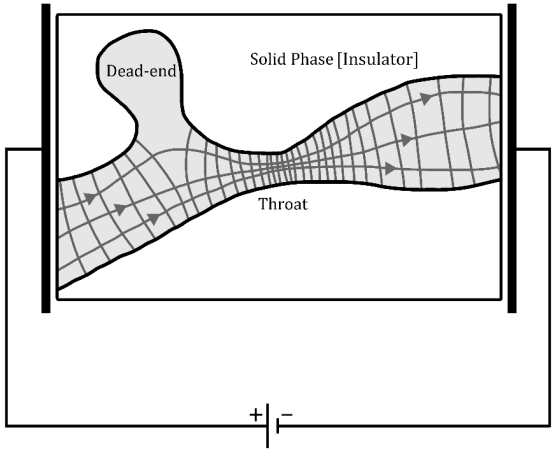
Solute **sink** reservoir



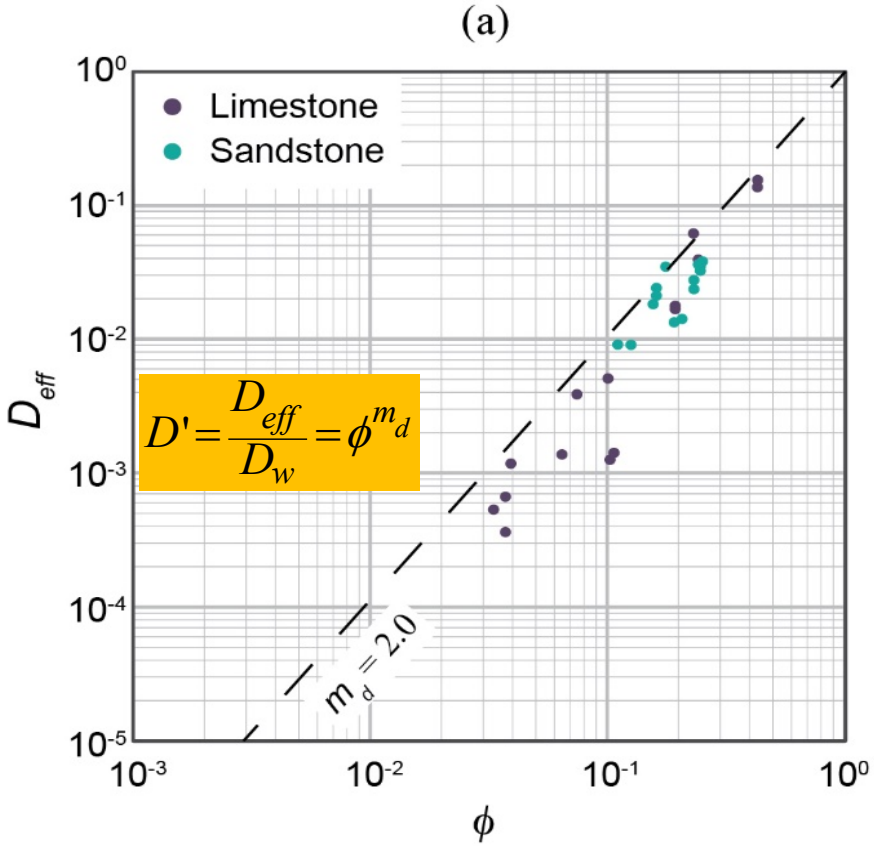
Solute **source** reservoir

Geophysical link to diffusion coefficients?

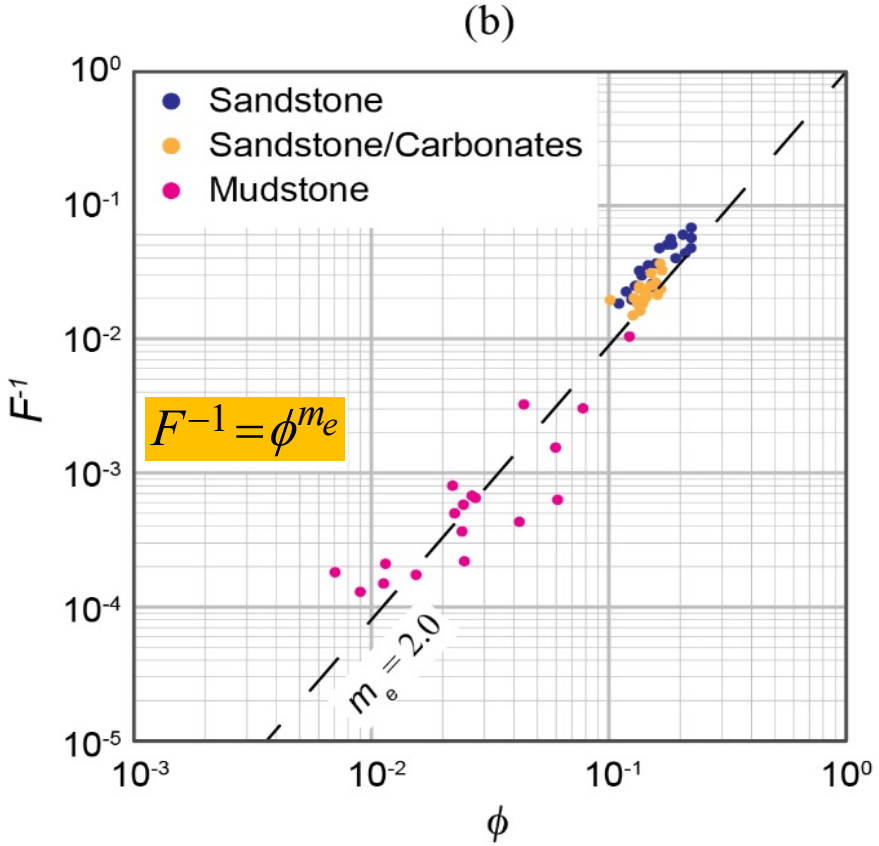
CR provides more accurate estimation of formation factor (*F*) relative to standard resistivity



Conventional diffusion experiment



Electrical measurement



Data from Boving and Grathwohl (2001)

Dual domain representation of a porous medium

Geologic medium broken up into a mobile and less mobile ("immobile") domain

Characterized by:

Mobile Domain Fraction (θ_m)
Less Mobile Domain Fraction (θ_{lm})
Porosity Ratio (β)
Mass Transfer Rate Coefficient (α) (s^{-1})

Diffusion coefficient (m^2/s)

$$\alpha = \frac{D}{L^2}$$

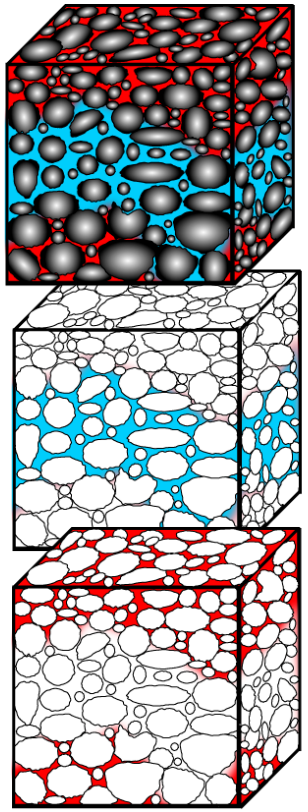
Length scale over which solutes diffuse into/out of immobile domain

Governing Equations

$$\theta_m \frac{\partial c_m}{\partial t} + \theta_{im} \frac{\partial c_{im}}{\partial t} = \nabla \cdot (\theta_m D \nabla c_m) - \theta_m v \cdot \nabla c_m$$

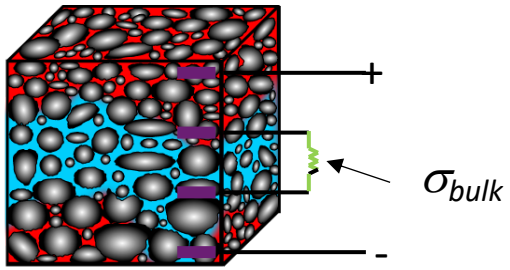
$$\theta_{im} \frac{\partial c_{im}}{\partial t} = \alpha (c_m - c_{im})$$

Dual Domain Porosity Model

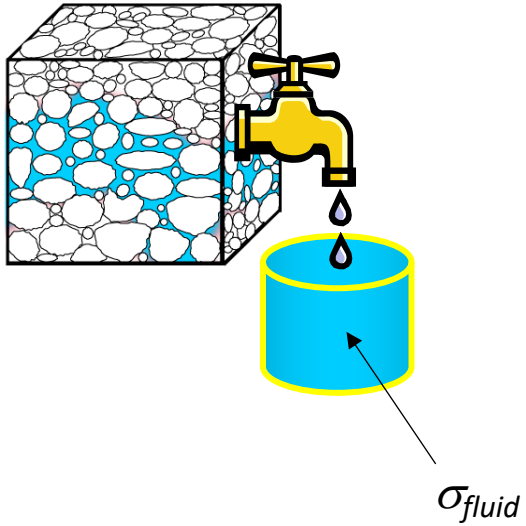


The electrical signature of a dual domain medium

Electrical geophysics senses both domains

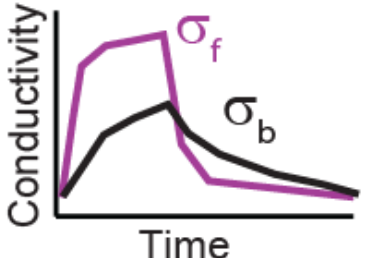


Groundwater samples/ probes sense mobile domain only

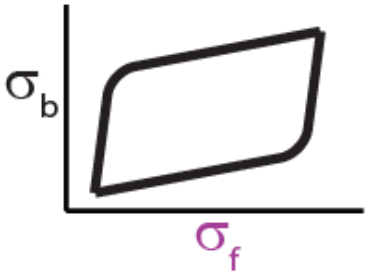


Diffusion between domains results in:

Delayed σ_{bulk} breakthrough



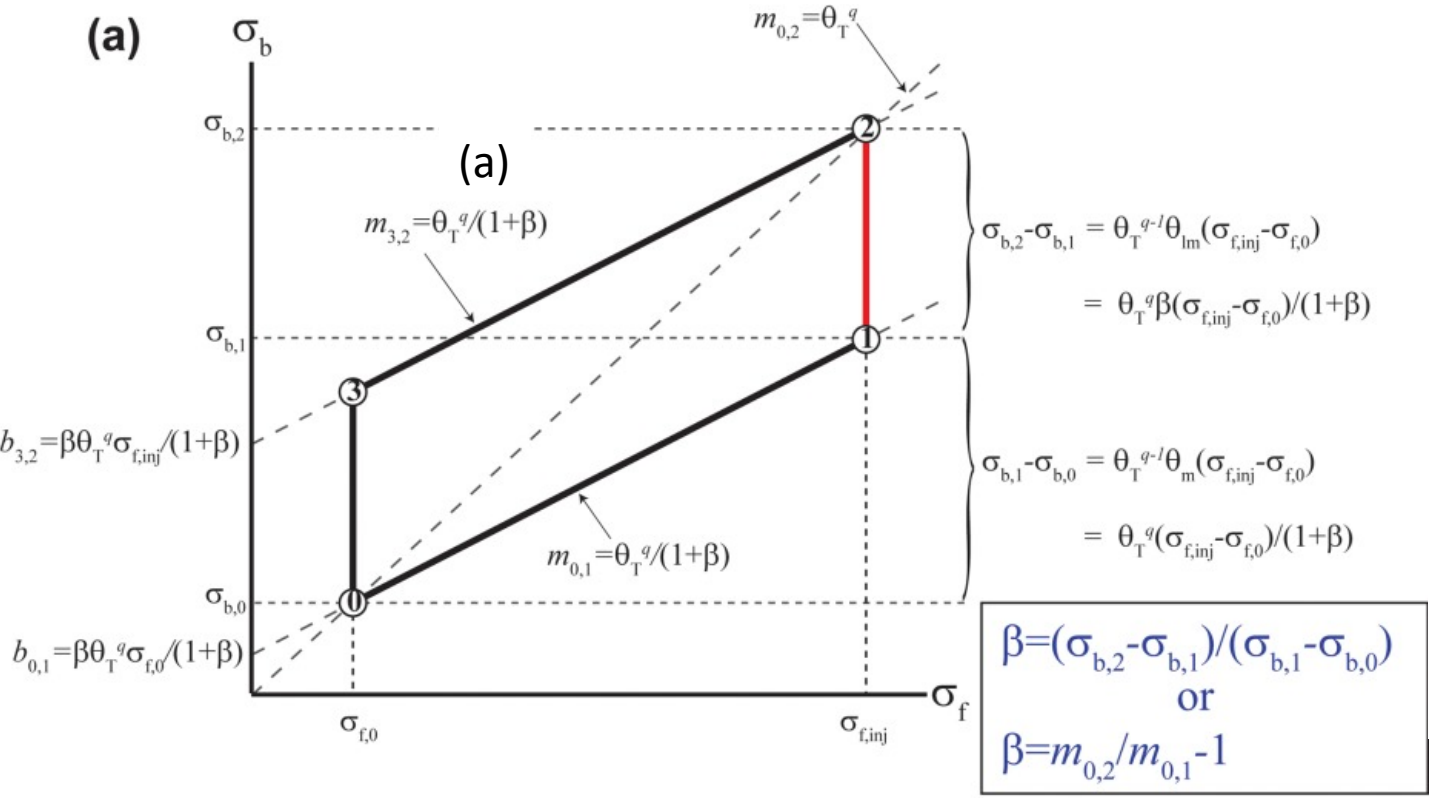
Characteristic hysteresis loop



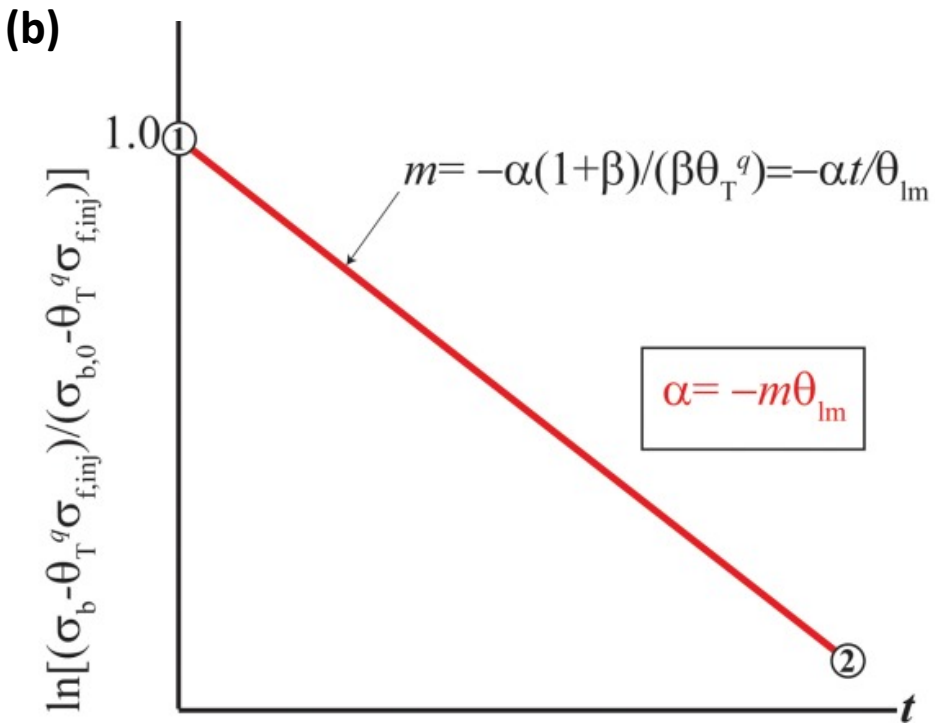
$$\sigma_{bulk} = el(\theta_m + \theta_{lm})^{m-1}(\theta_m\sigma_m + \theta_{lm}\sigma_{lm})$$

Singha et al. (2007) Bicontinuum Formulation

Analytical solution for mass transfer parameters



Ratio of immobile porosity to mobile porosity (β)

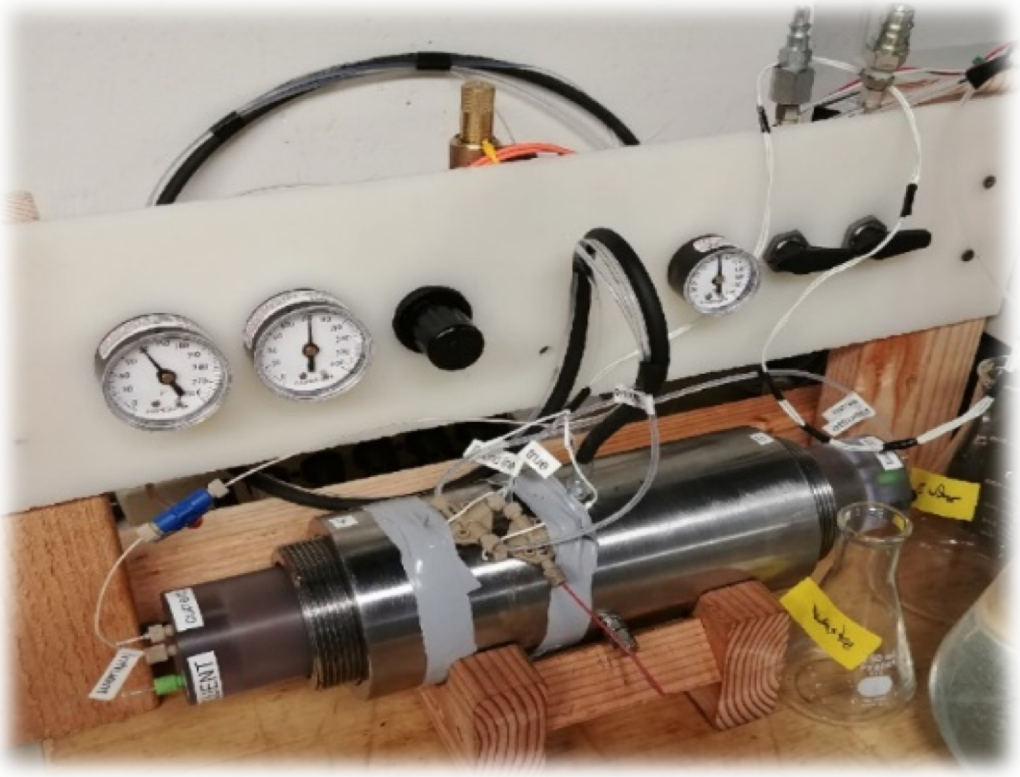


Dual domain exchange rate coefficient (α)

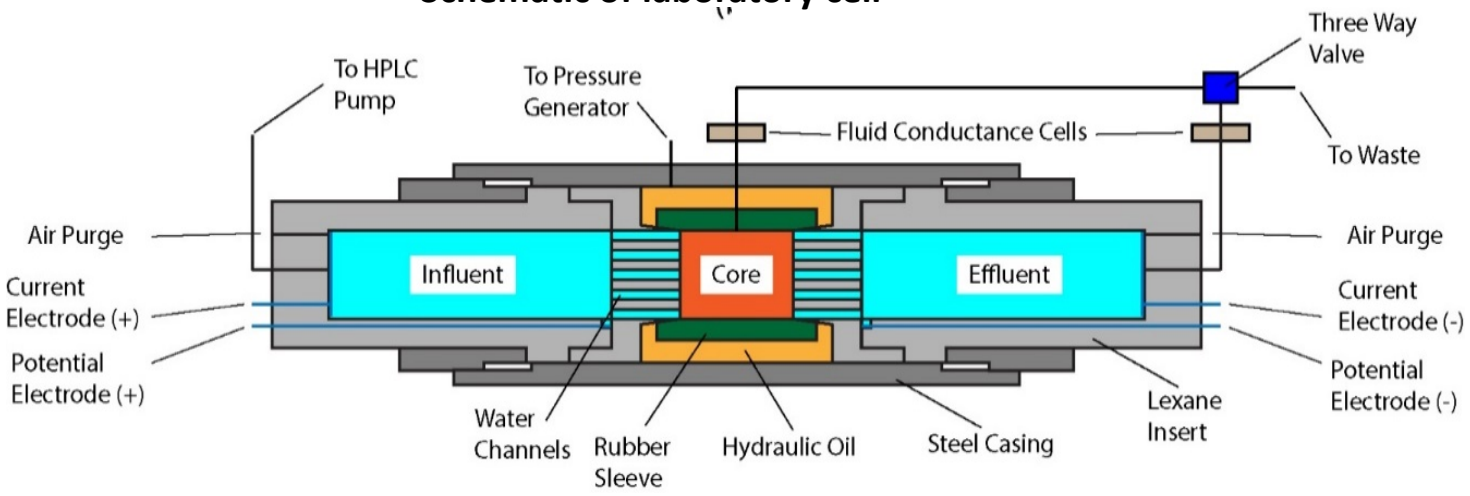
Briggs et al., 2014, Water Resources Research

Laboratory proof of concept for fractured rock aquifers

Developed laboratory instrumentation



Schematic of laboratory cell



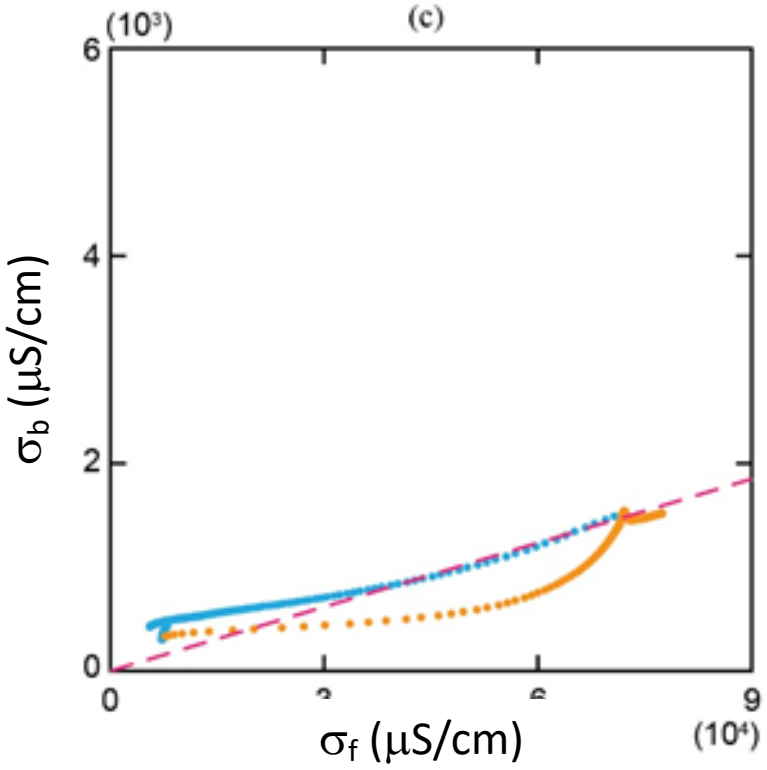
Santa Susanna

Hydrite

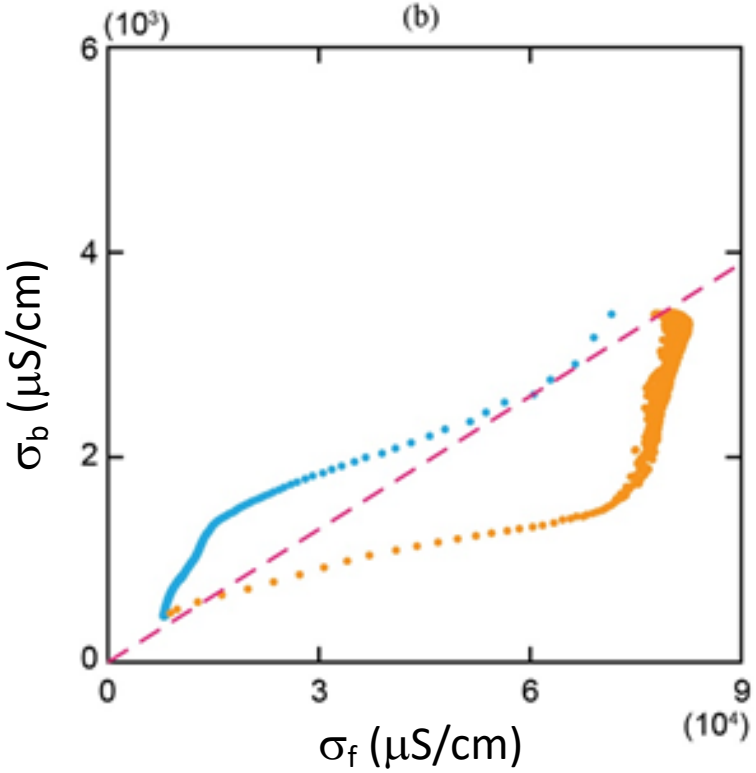
Laboratory observations

Compelling geo-electrical evidence of dual domain behavior in fractured rock **matrix**

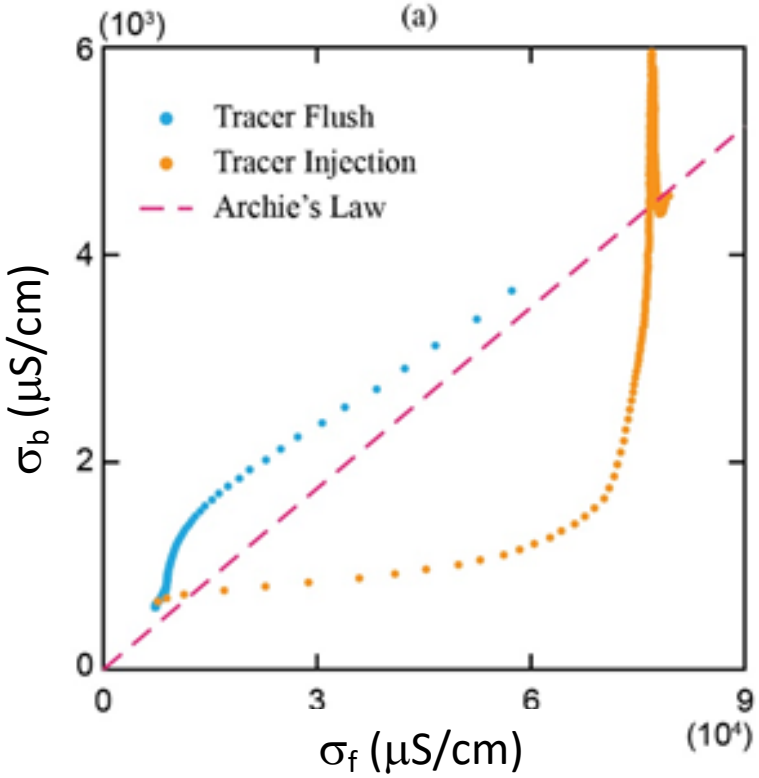
SS-C3-P-019



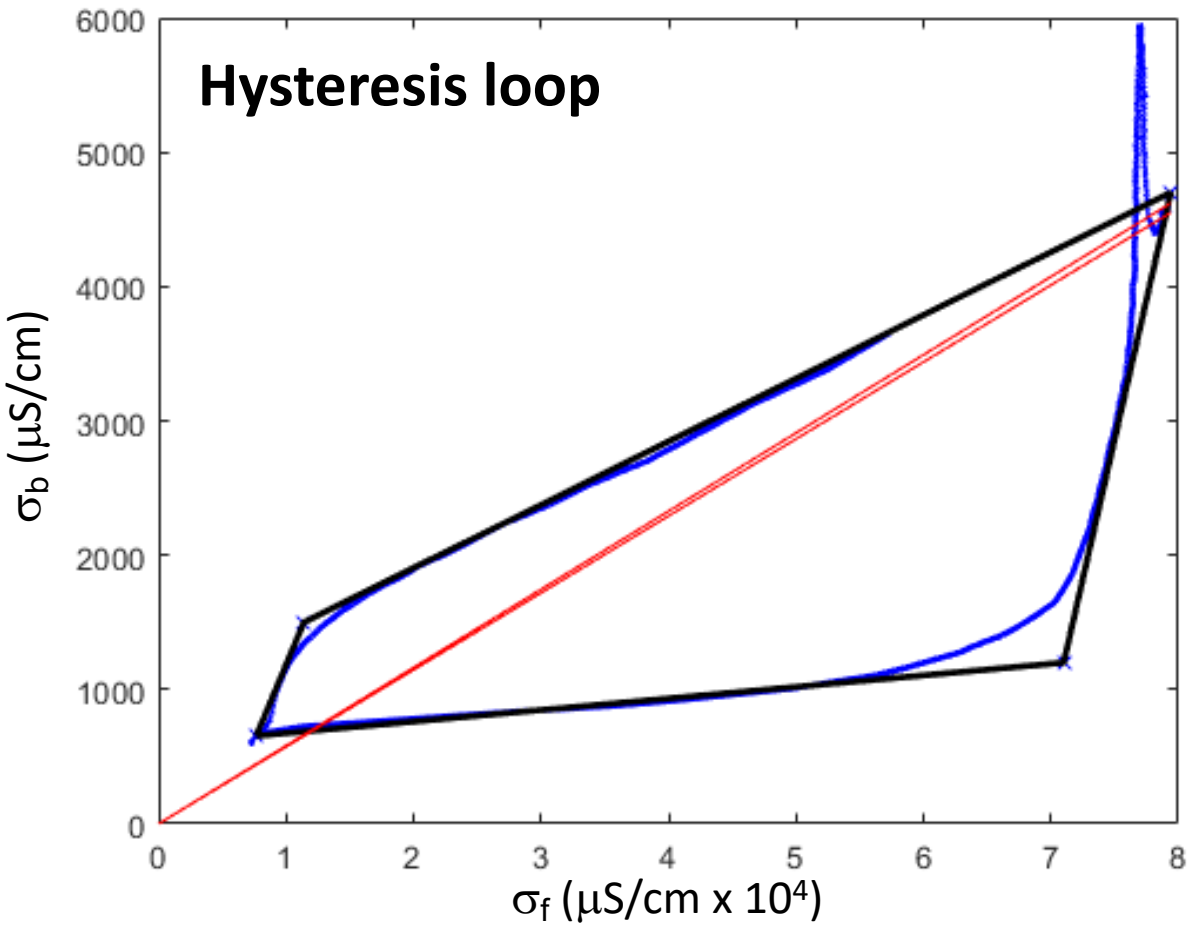
HC-MP24S-P-007-2H



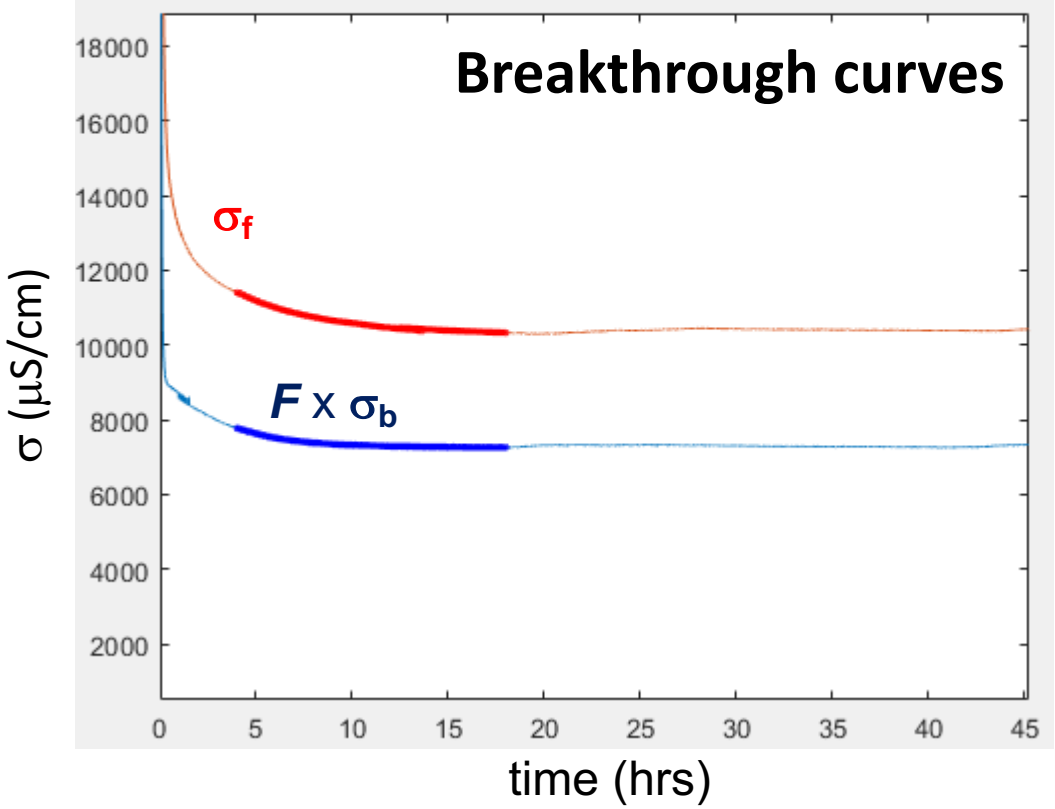
HC-MP24S-P-006-1V



Example dataset



Sample: HC-MP24S-P-006-1V



F = formation factor

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Forward modeling of decay curves

$$\frac{\partial \sigma_{\mathrm{b}}}{\partial t} = (\theta_{\mathrm{m}} + \theta_{\mathrm{lm}})^{q-1} \left\{ \theta_{\mathrm{m}} (ab\exp(bt) + cd\exp(dt)) + \alpha \left[a\exp(bt) + c\exp(dt) - \left(\frac{\sigma_{\mathrm{b}} / (\theta_{\mathrm{m}} + \theta_{\mathrm{lm}})^{q-1} - \theta_{\mathrm{m}} (a\exp(bt) + c\exp(dt))}{\theta_{\mathrm{lm}}} \right) \right] \right\}$$

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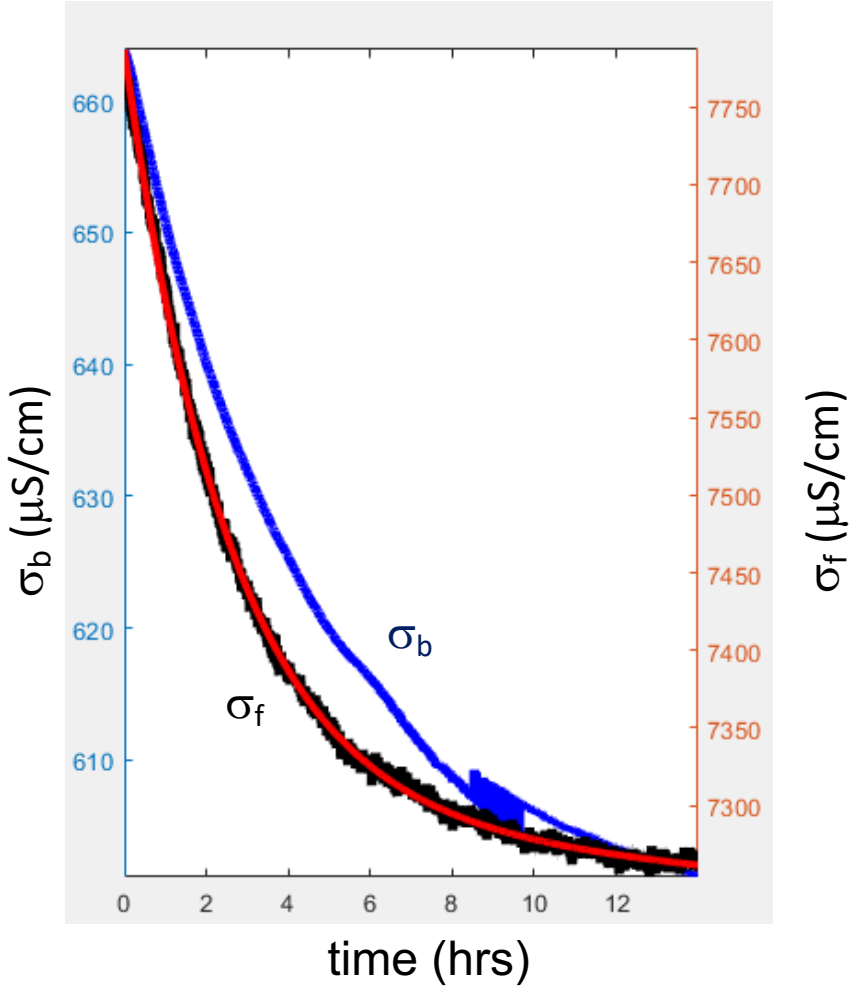
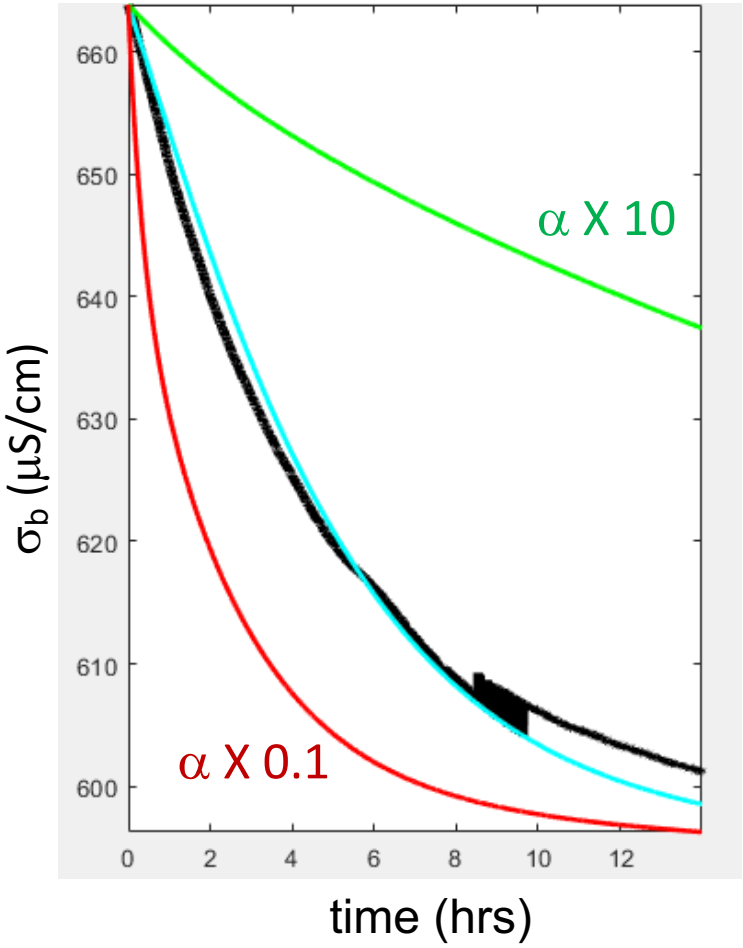
Model Result: HC-MP24S-P-006-1V





Best estimate:

α = 1.3/day

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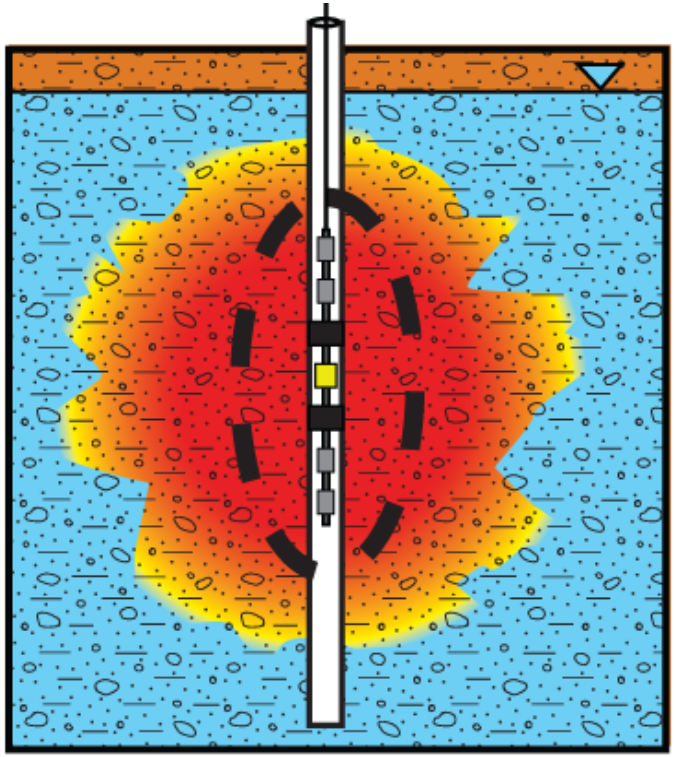
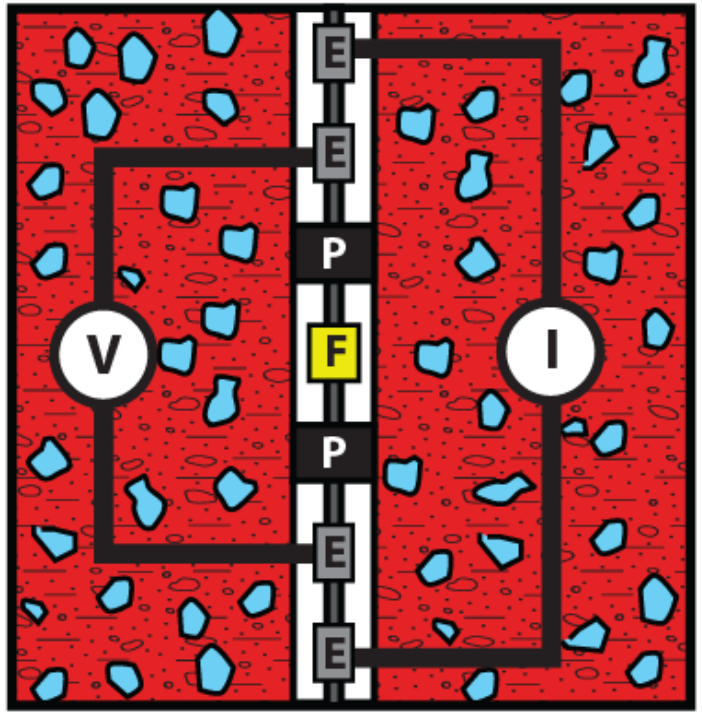
Estimated mass transfer coefficients

	β	θ_m	θ_{im}	α (day^{-1})
HC-MP24S-P-007-2H	1.74,2.18	0.08, 0.07	0.14, 0.15	1.41
HC-MP24S-P-006-1V	3.79, 6.43	0.03, 0.05	0.19, 0.17	1.31
SS-C3-P-019	2.76, 6.40	0.04, 0.02	0.11, 0.13	21.1

Field Demonstration of Geoelectrical Inference of Mass Transfer

- ESTCP ER-201732 (R. Iery, NAVFAC-EXWC, PI)

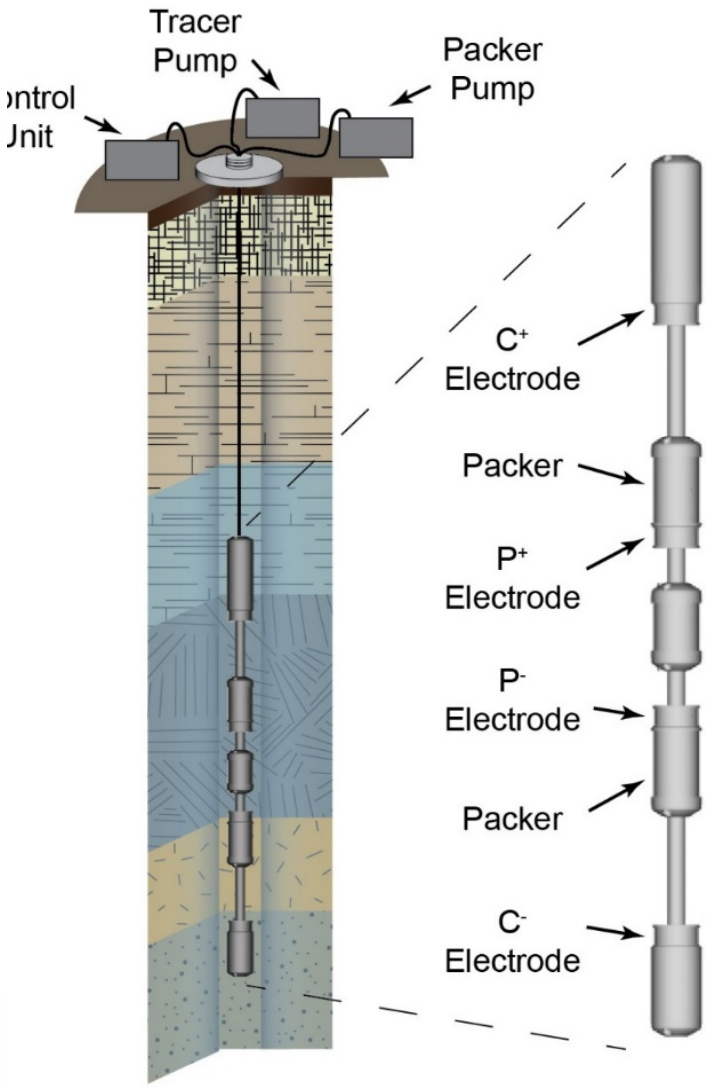




Field deployment in a packed off borehole

Electrodes (**E**)
Packers (**P**)
Fluid sampling port (**F**)

Mobile-immobile porosity exchange tool (MI-PET)

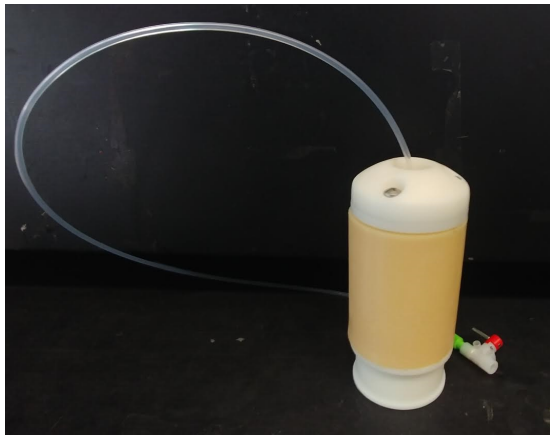


MI-PET concept

MI-PET components

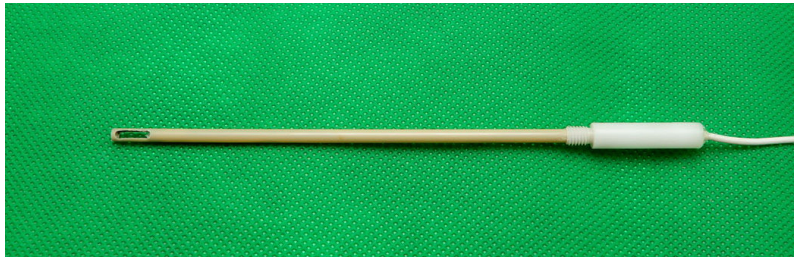
3D printed packer/electrode modules

Internal view of Packer Module



External view of Packer Module, liner installed

Specific conductance (I2C interface)



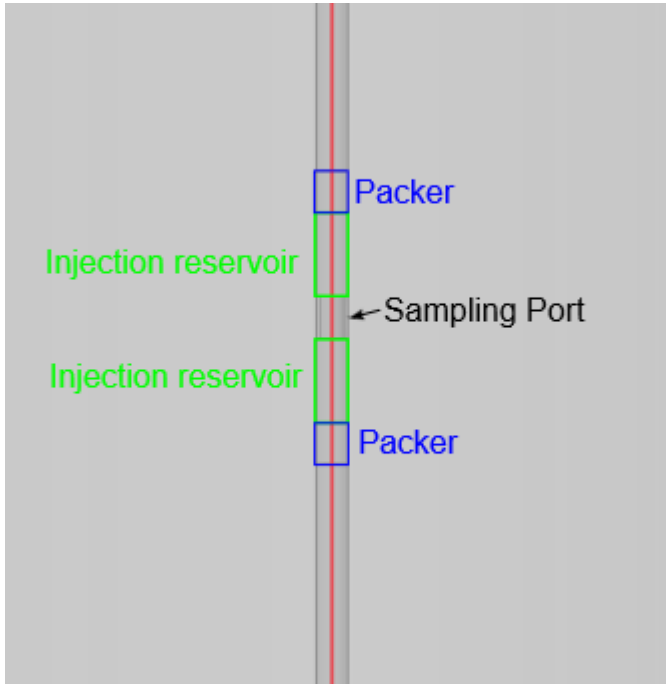
Data acquisition/recording

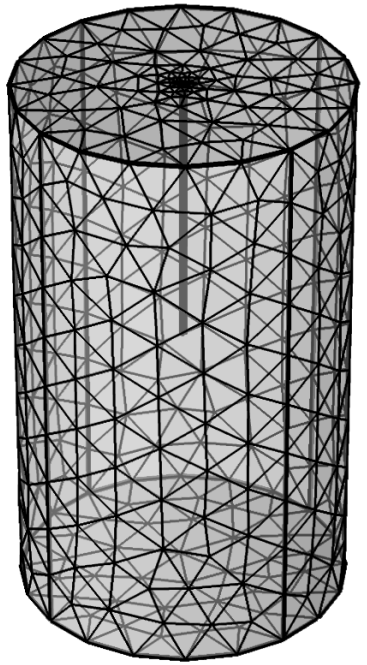
Raspberry - Pi

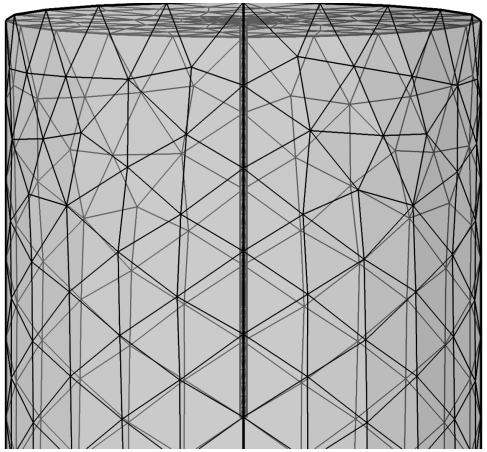
Complete design of instrument prototype

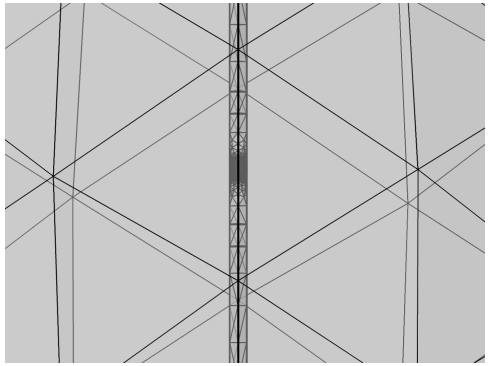
Numerical modeling of MI-PET performance

- Model fluid flow and electrical current flow in COMSOL







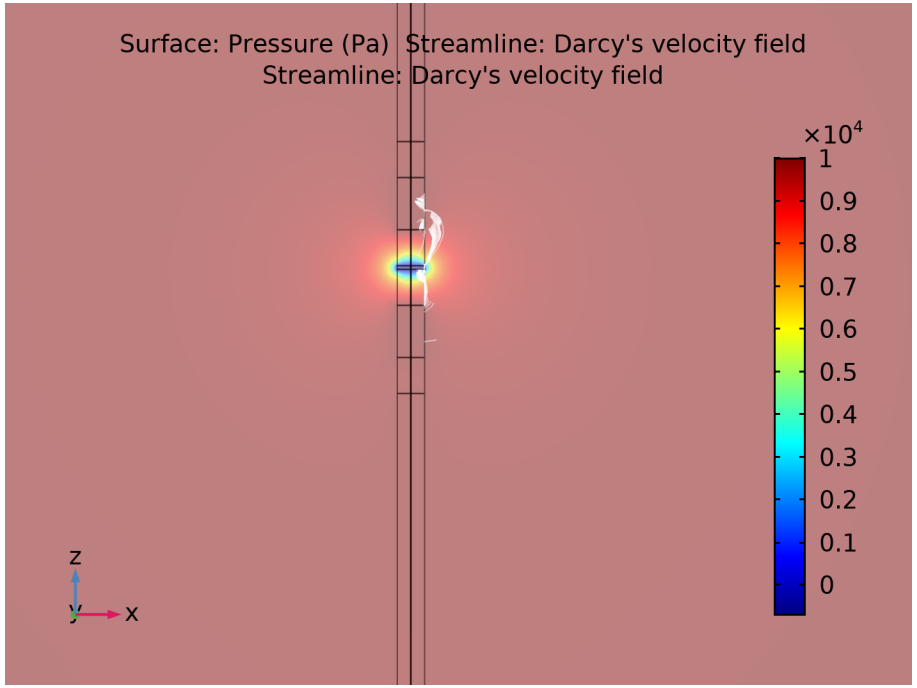


MI-PET Modeling in COMSOL: Hydraulic

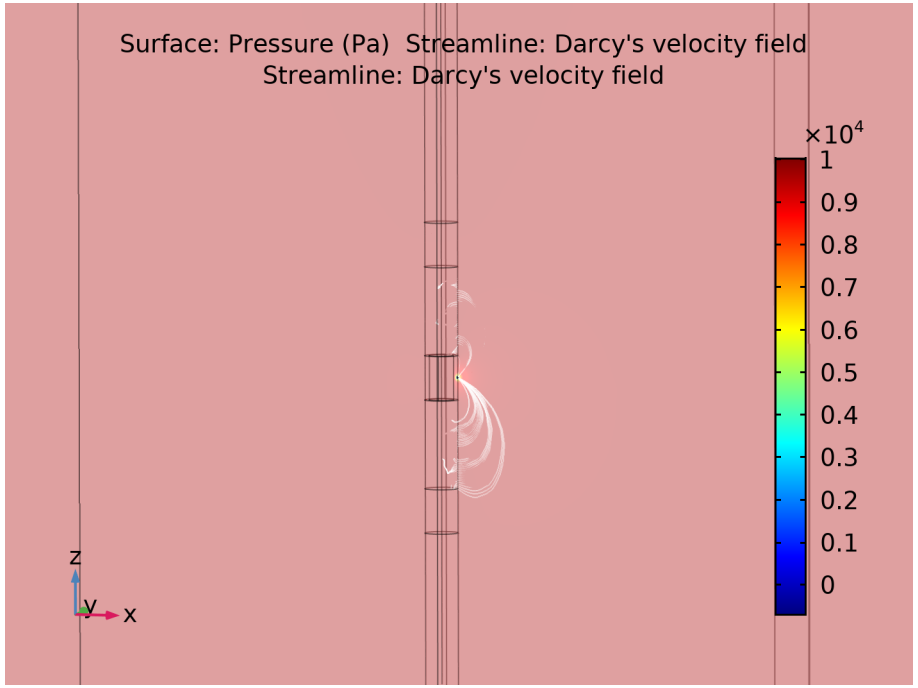
Investigate:

- Flow patterns around packers and ports
- Support volume beyond boreholes
- Effects of packers on fluid flow

Initial configuration



Modification

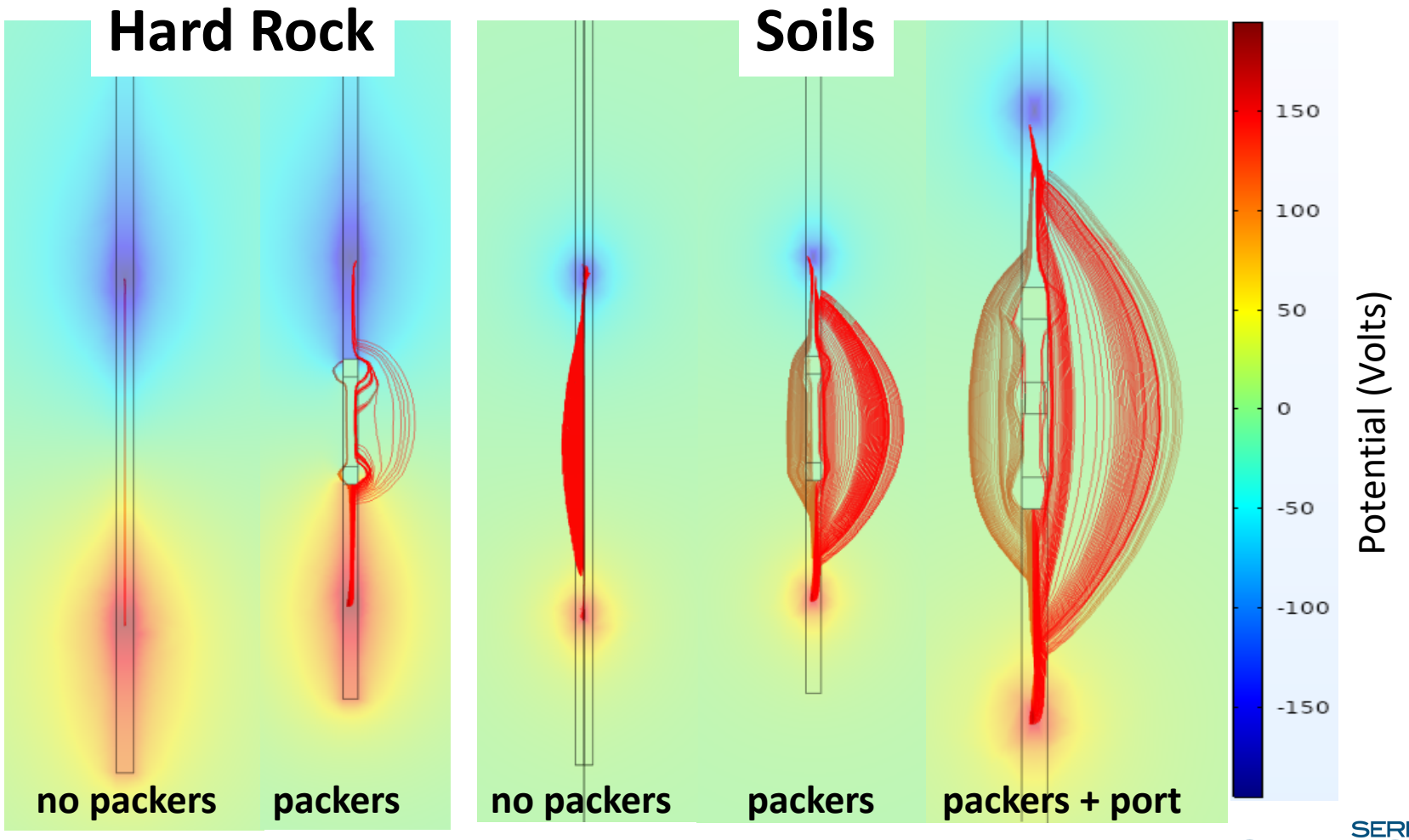


Color bar: Pressure (kPa); White lines: flow lines into porous matrix

MI-PET Modeling in COMSOL: Electrical

Investigate:

- Optimal electrode locations
- Support volume beyond boreholes
- Effects of packers on electrical current flow



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MI-PET System

Borehole with Installed Probe

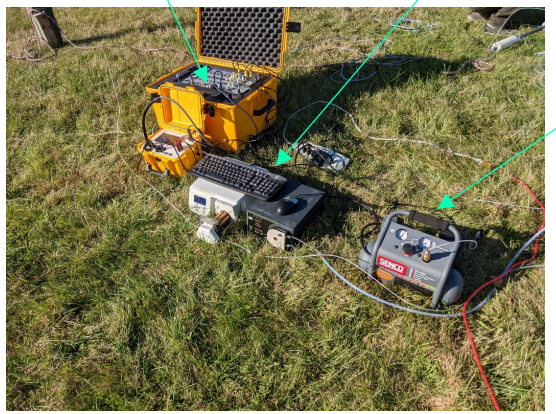
System Setup during tracer experiment

Probe

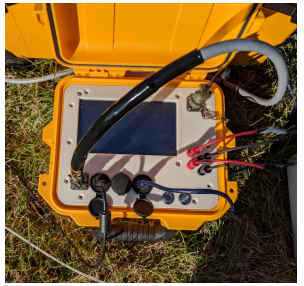
Complex Resistivity System

Sampling and Injection Pumps

Air Compressor



Supporting Equipment



Control Module

Field Site

- Barge Park, Carlstadt, NJ
- Meadowlands (estuary system)
- Fine grain sediments/anthropomorphic deposits (i.e. construction waste)
- 3” borehole drilled to depth of 15’

Measurement Protocol

- Probe installed at depth of ~6’ (center)
- Pump lines evacuated (i.e. filled with water)
- Packers inflated/sampling flow established for 20 minutes
- Initial ambient measurements collected
- Tracer injection phase, followed by tracer flush phase

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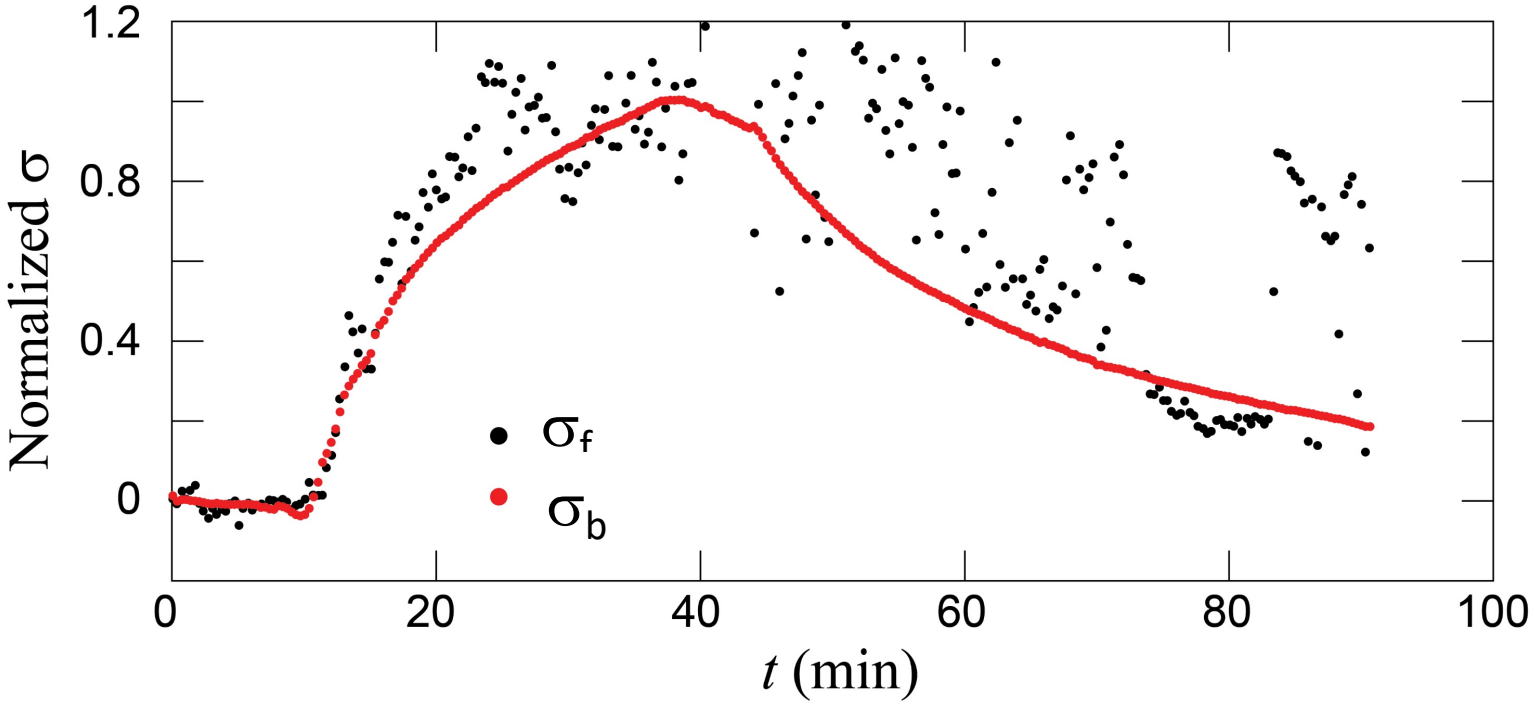
Tracer Injection/Flush Results

- Breakthrough curves observed for both tracer injection and flush
- Specific conductance probe noisier than geophysical measurement due to measurement volume difference
- Tidal variation and brackish conditions may have complicated study



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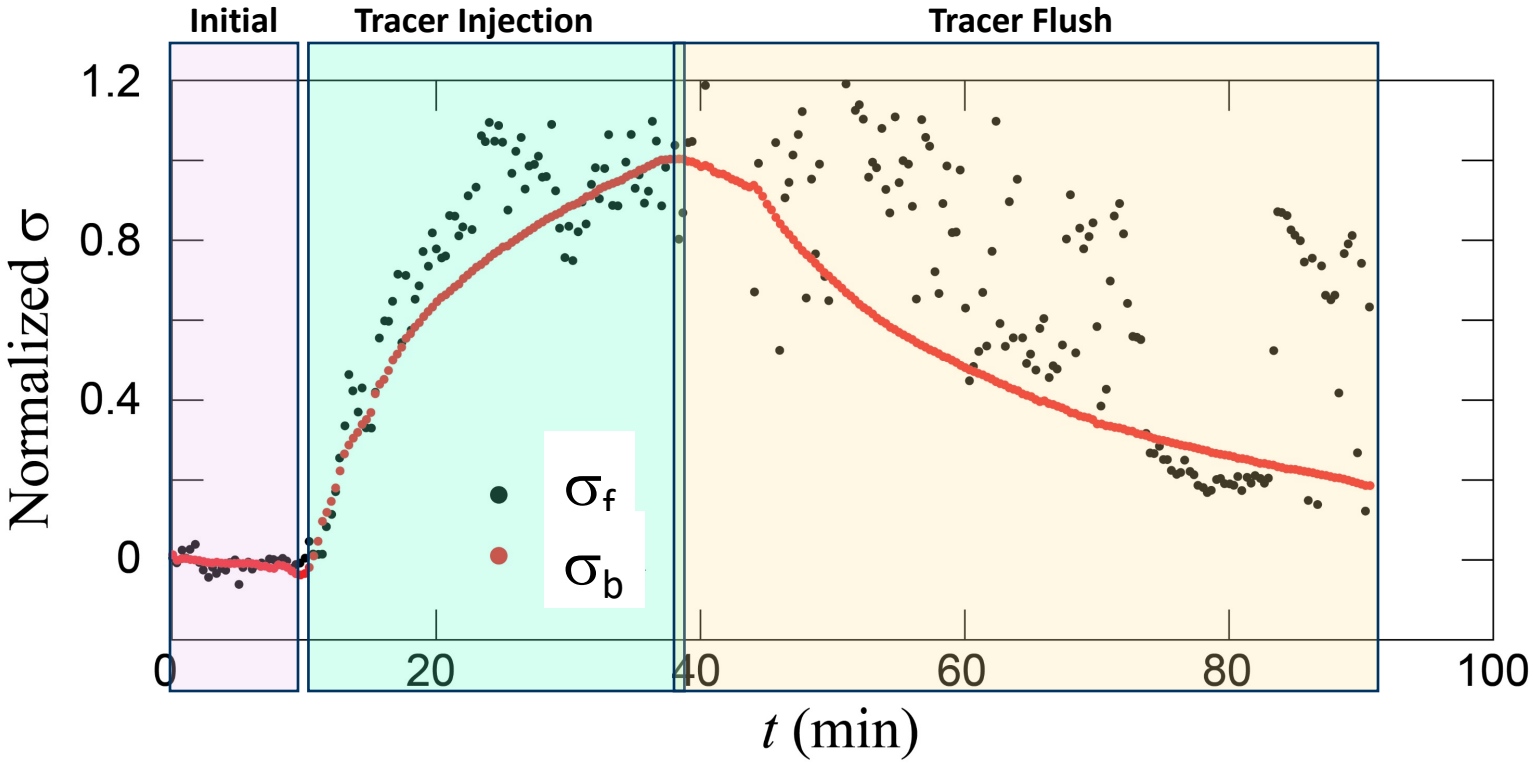

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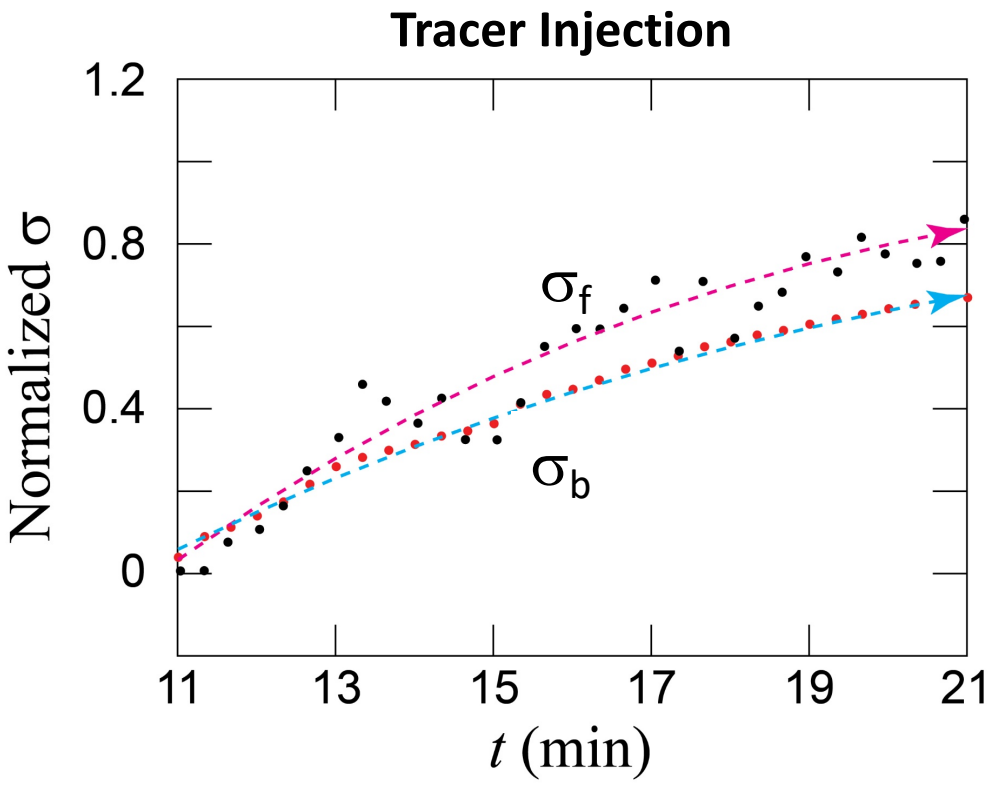
Tracer Injection/Flush Results

Analysis of initial response

- σ_{bulk} lags behind σ_{EC} as expected.
- Most evident in the tracer injection breakthrough curve
- Presence of this lag indicates significant mass transfer associated with dual domain porosity



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Summary

- Estimation of pore geometric parameters and diffusion/mass transfer coefficients possible with emerging geophysical technologies
- Rock matrix from three sedimentary rock sites exhibits electrical signature of mobile-immobile porosity exchange
- Borehole technology (under development) to quantify mobile-immobile porosity ratios and mass transfer coefficients developed and field tested
- Initial field measurements confirm functionality of the system, and present evidence of field-characterized dual domain porosity mass transfer