Subsurface Processes Lab

UCIrvine

Laboratory measurements of fracture permeability alteration

Implications for field-scale systems

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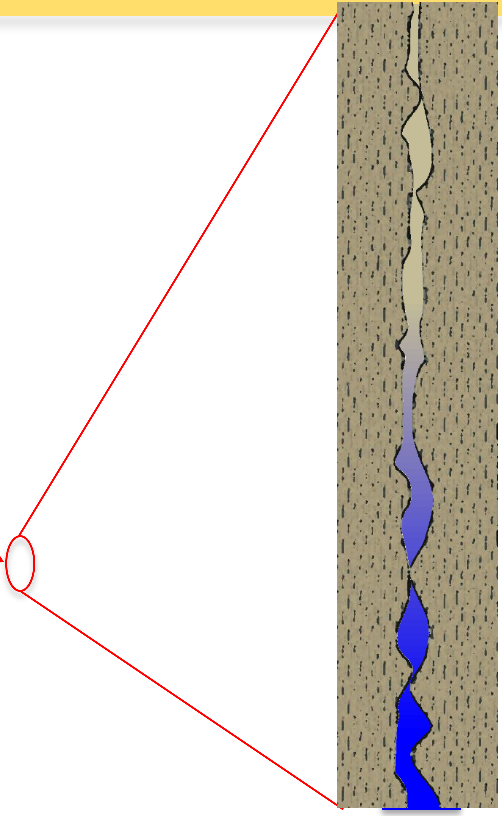
U.S. DEPARTMENT OF ENERGY

IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project

Schlumberger

Induced seismicity → potential for leakage

Induced seismicity
results from fracture
generation
and/or
fault reactivation

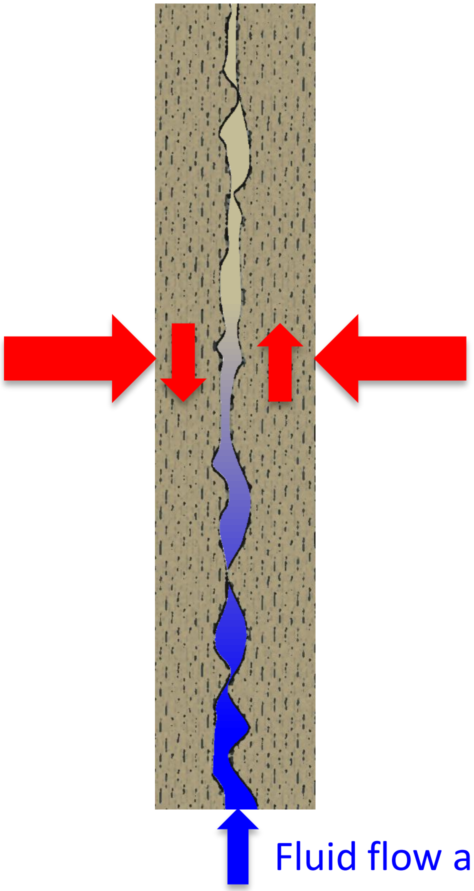


Can new and existing fractures provide a persistent path for leakage to near- surface aquifers?

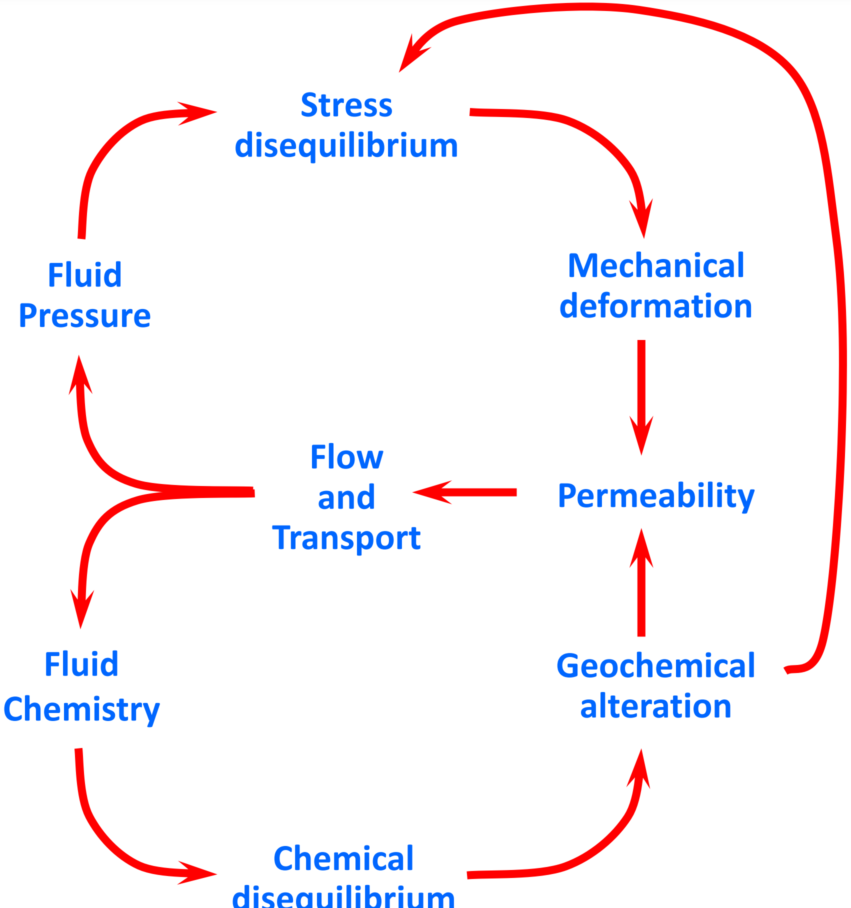
What effect do geochemical reactions have on leakage potential?

Coupled mechanisms control permeability alteration

Normal and shear stresses deform fractures

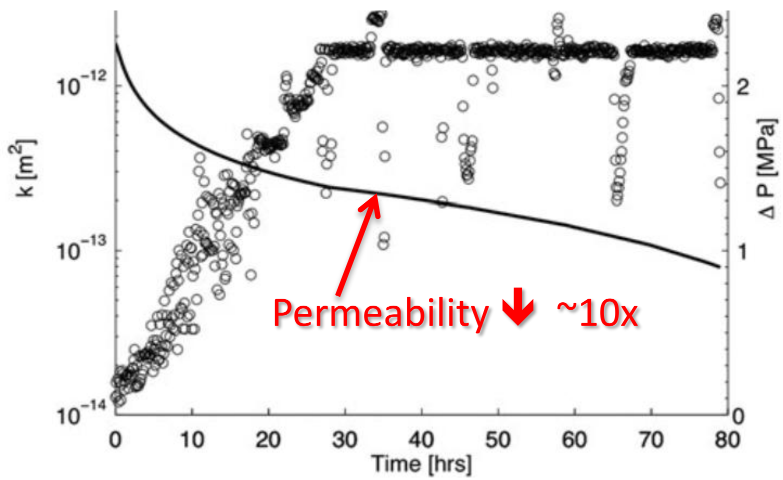


Fluid flow alters pore pressures and fluid chemistry

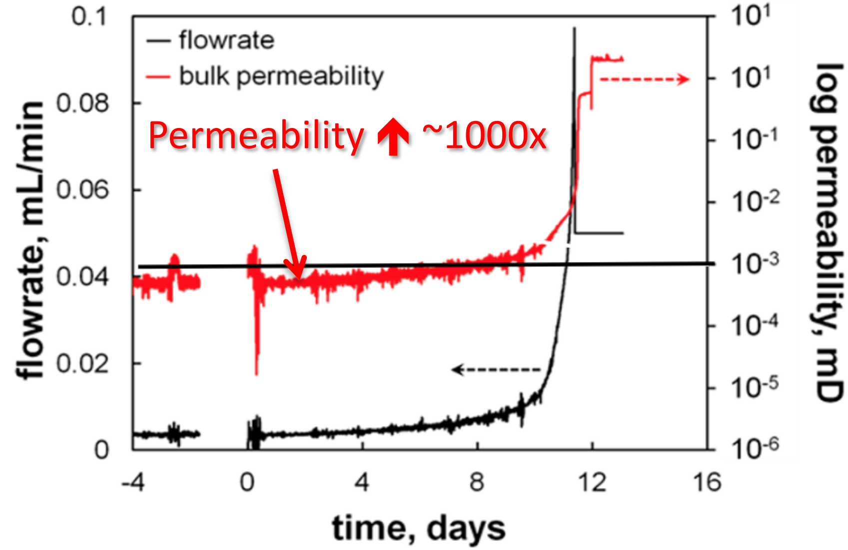


Recent lab-scale observations: Disparate permeability evolution in caprocks during reactive flow (mineral dissolution)

Ellis, et al., *Env. Eng. Sci.*, 2013



Smith, et al., *ES&T*, 2013

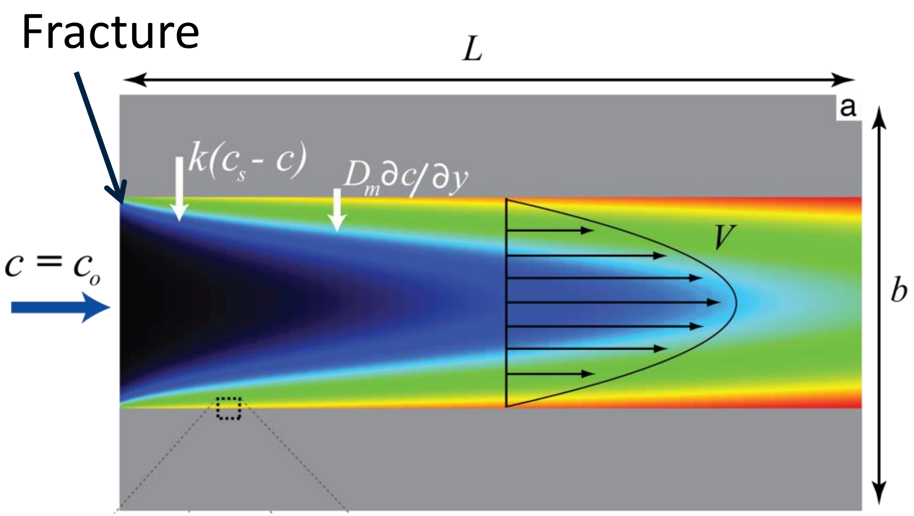


These studies each presented results from a single experiment.

Difficult to isolate cause of disparate behavior...

...however, residence time of fluids differed significantly

Relative time scales (advection / reaction) influence permeability evolution



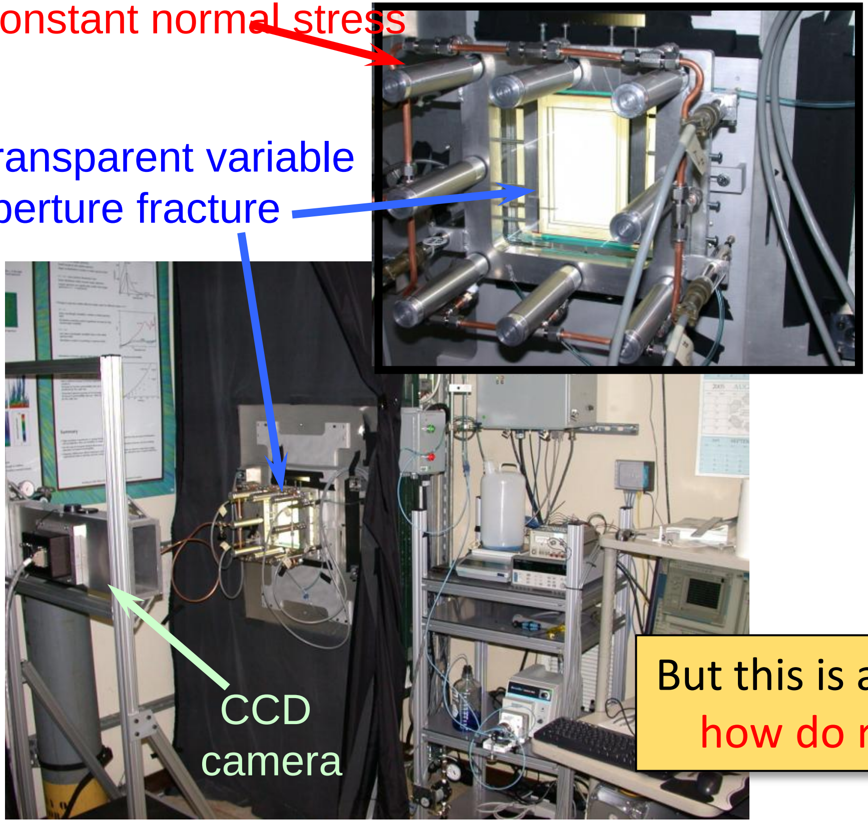
$$\tau_a = \frac{L}{V}$$ advective timescale

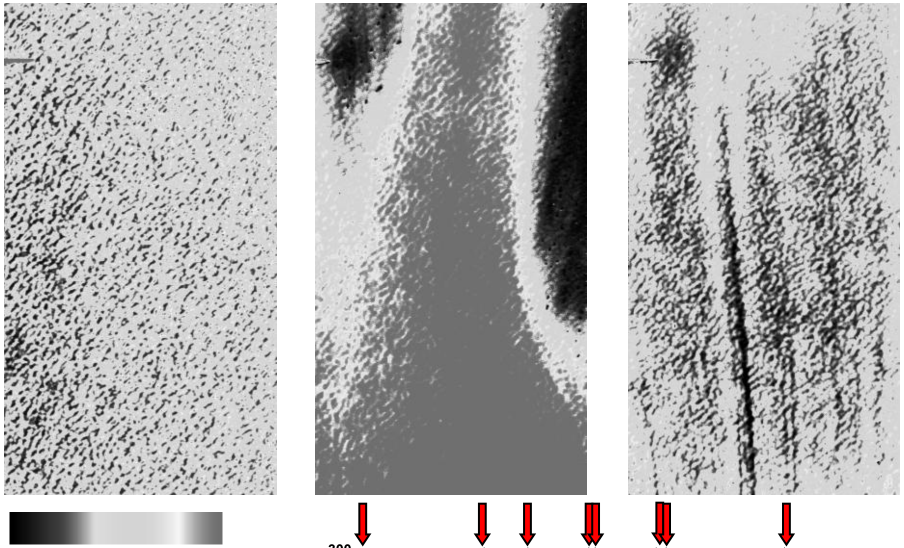
$$\tau_r = \frac{b}{k}$$ reactive timescale

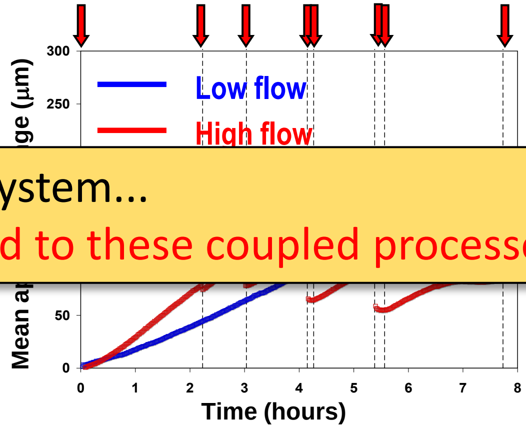
Damköhler Number

$$Da = \frac{\tau_a}{\tau_r} = \frac{kL}{Vb}$$

Experiments in transparent analogs quantify competing geochemical and geomechanical processes



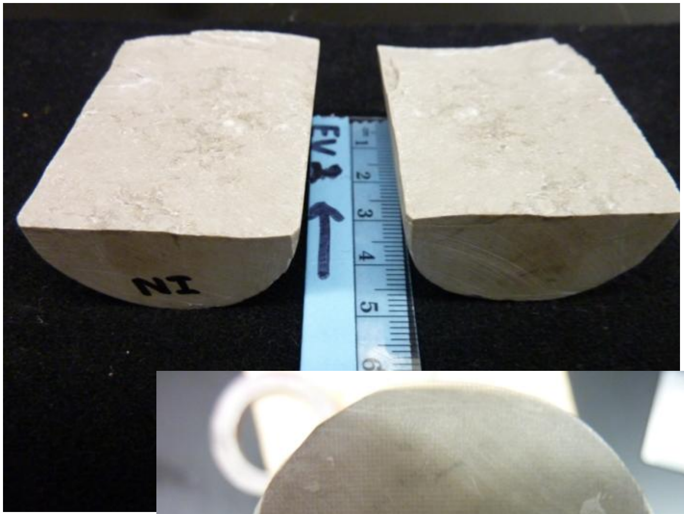




But this is a very idealized system...
how do real rocks respond to these coupled processes?

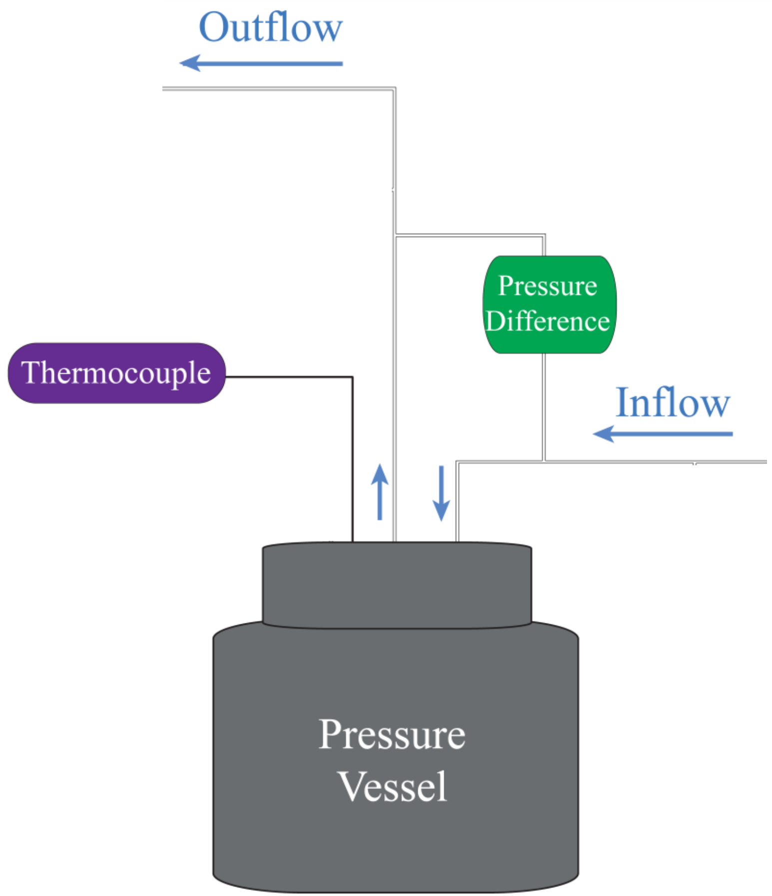
Detwiler, *JGR*, 2008, 2010

Permeability evolution of a dissolving and deforming fractured caprock




- 2 experiments
- Fractured dolomitic anhydrite
- Subcores from same 10-cm core (similar samples)
- Flow rate differed

Experimental setting mimics reservoir conditions



~1000 psi (~7MPa)

Subsurface
Processes
Lab

Dimensionless time provides means for directly comparing results

Sample	Flow Rate [ml/min]	Duration [day] (hours)	Dissolved Mass [%]
EV1	0.01	180 (4320)	2.5
EV2	0.60	7 (168)	2.5

Q = flow rate
c = concentration
R = dissolution rate
M_o = initial mass
$M(t)$ = dissolved mass at time, t

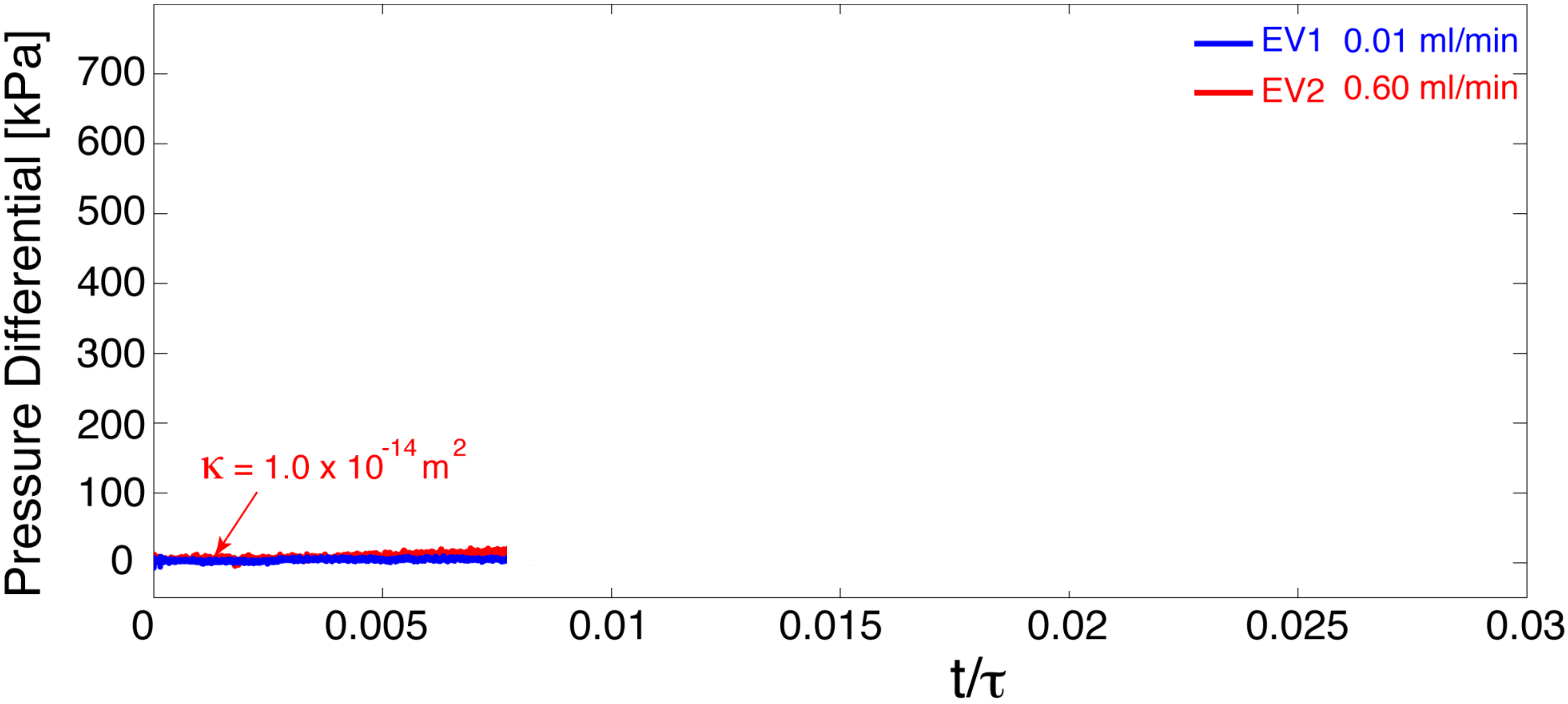
$$R(t) = Q \times c(t)$$

$$M(t) = \int_0^t R(\zeta) d\zeta$$

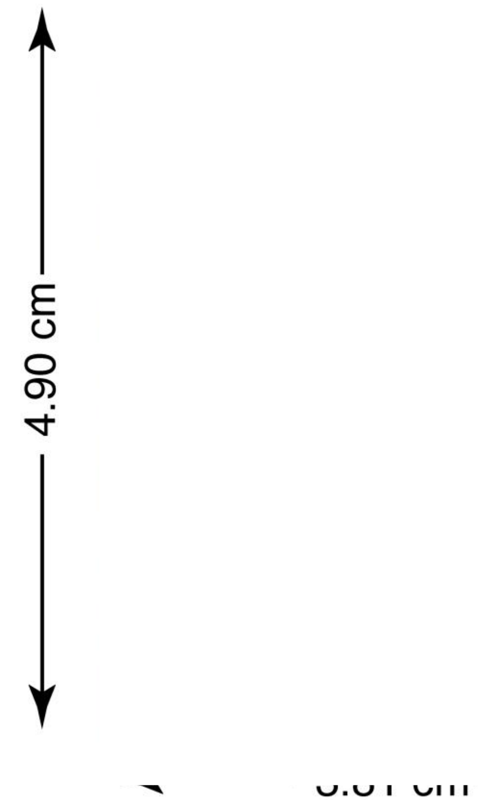
$$\boxed{\tau = \frac{M_o}{R(t \sim 0)}}$$

$$t \longrightarrow t/\tau$$

Permeability evolution very different at high and low flow rates

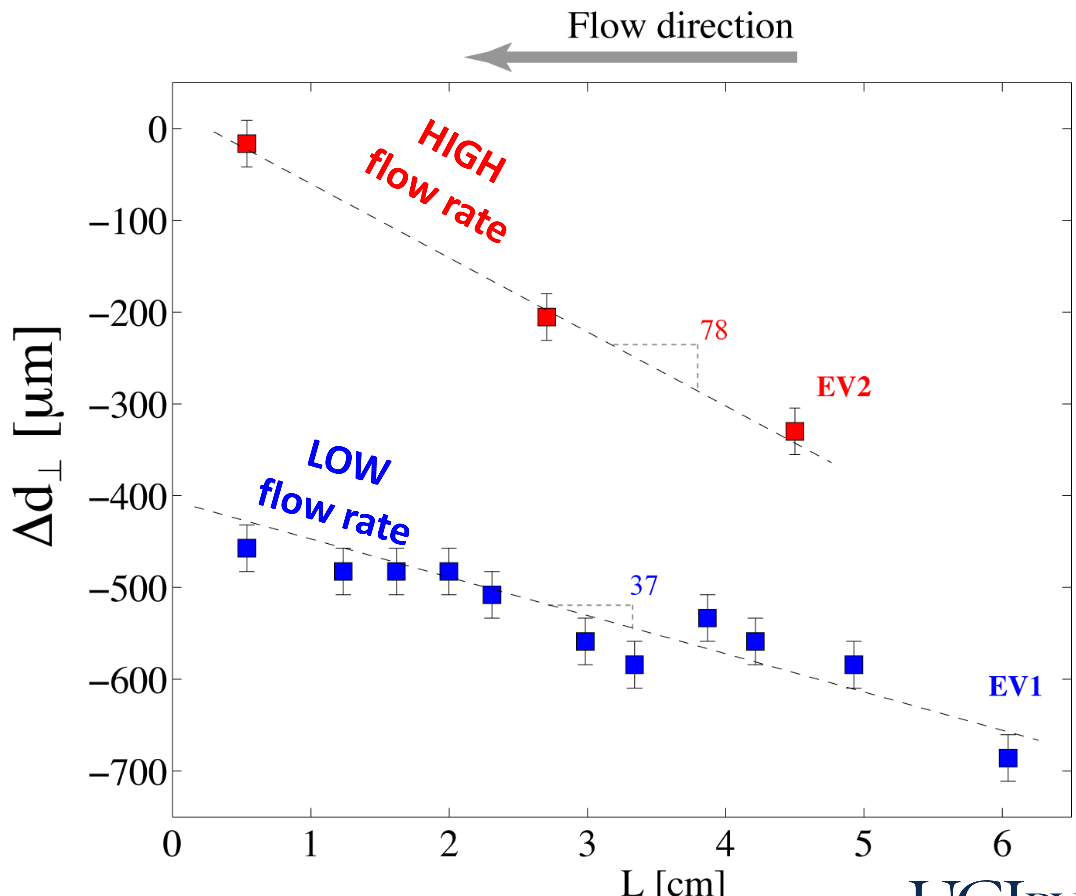


Fracture sealed during **HIGH** flow rate experiment

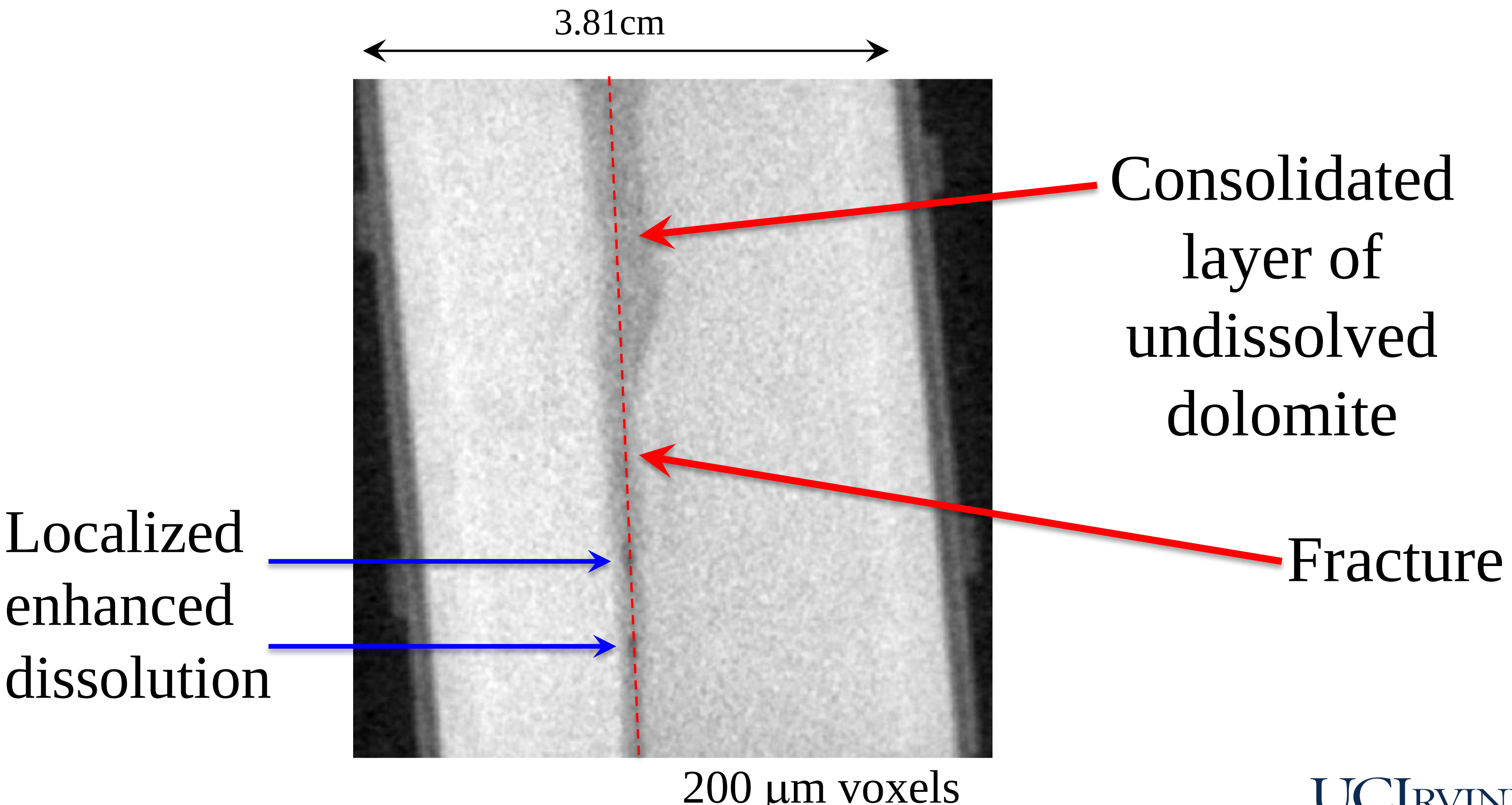


Reactive flow + mechanical stress dissolve *and* deform cores

The diameter of both cores decreased due to consolidation of rock adjacent to fracture.

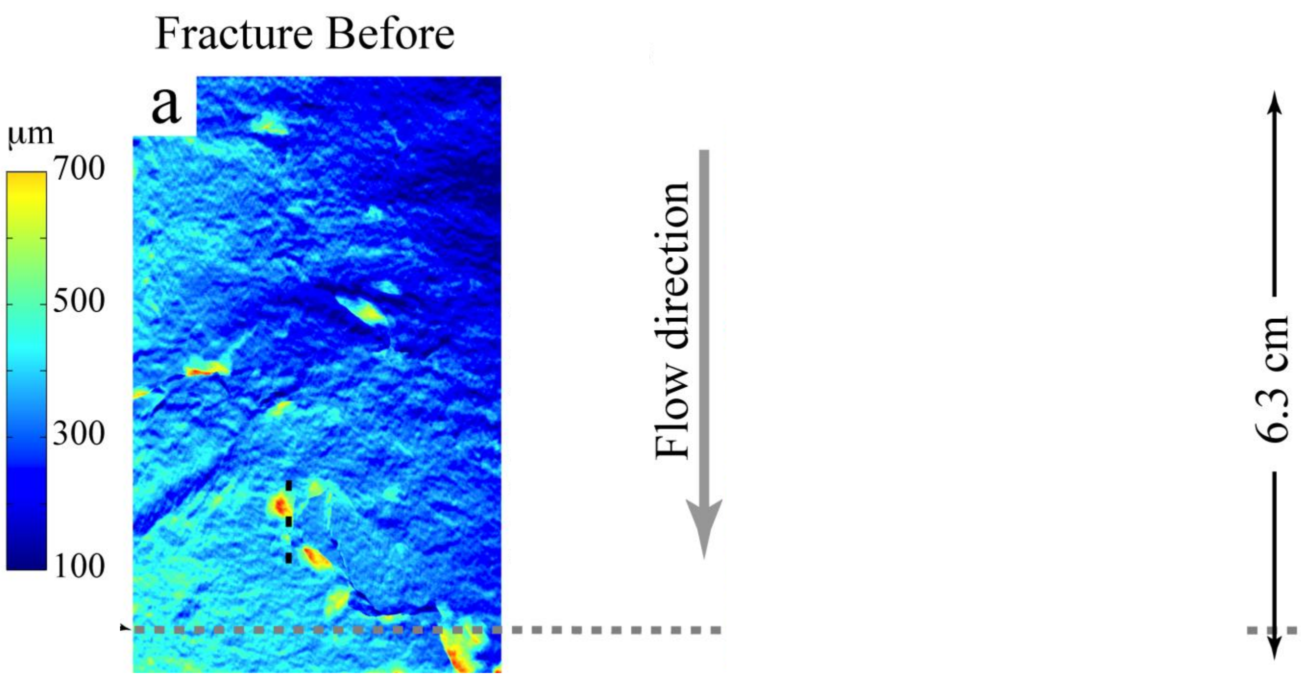


X-ray CT scan shows the localized aperture and the consolidated dolomite layer (**LOW** flow rate)

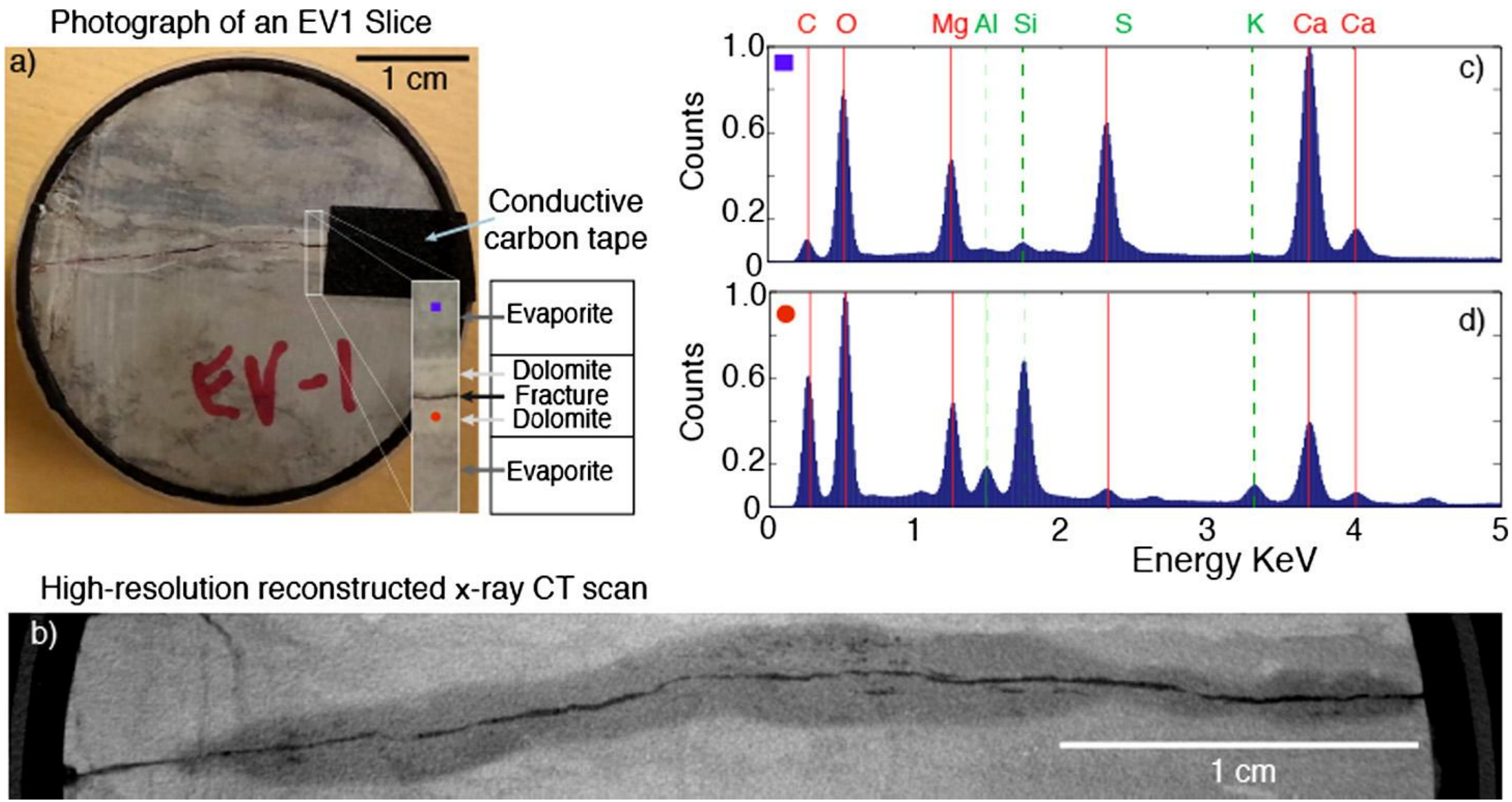


Persistence of preferential flow channel (**LOW** flow rate)

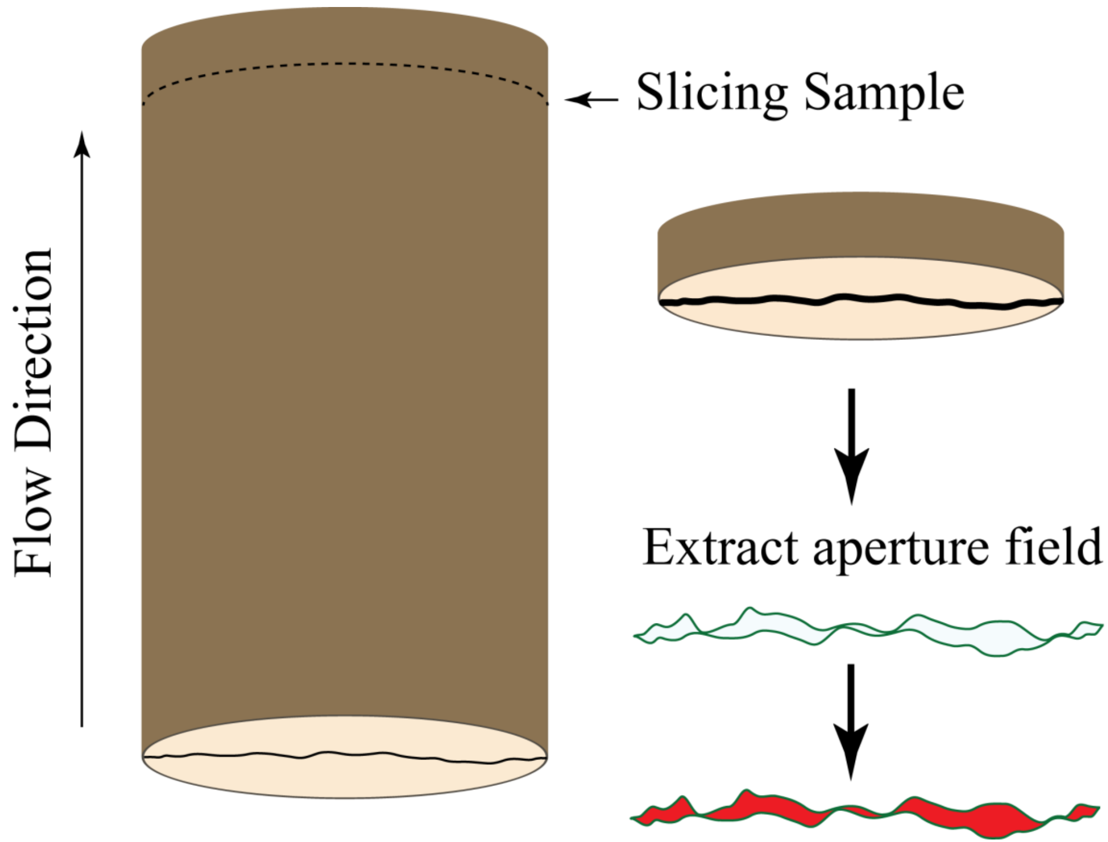
Optical Profilometer



SEM imaging confirmed dolomite-rich layer



Slicing fractured core samples, after impregnating with epoxy, allowed direct measure of fracture aperture profiles



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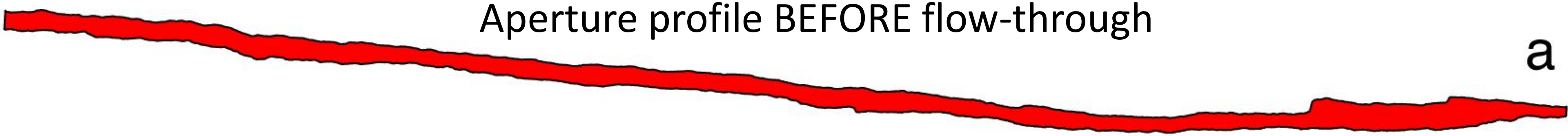
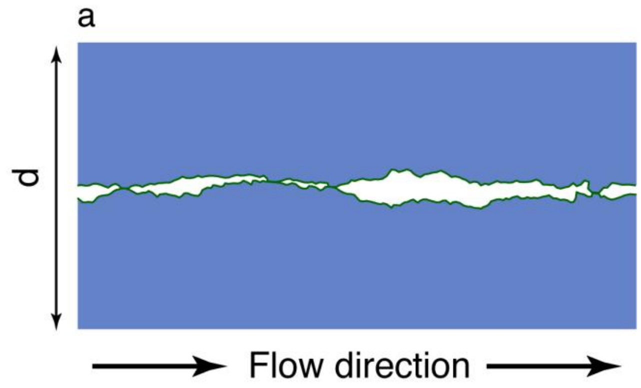
Ameli, Elkhoury & Detwiler, *WRR*, in review

Enlarged preferential flow paths maintained permeability (**LOW** flow rate)

Aperture profile BEFORE flow-through



Reactive flow and mechanical stress alters sample geometry and strongly affects the evolution of permeability



Damköhler number

$$Da = \frac{kL}{Vb}$$

← Large *Da*

← Small *Da*

L = fracture length
b = aperture
k = reaction rate
V = fluid velocity

Implications for field-scale behavior

Our results demonstrate the **strong influence of Da** on permeability changes caused by coupled chemical alteration and mechanical deformation in a poly-mineralic caprock

$$Da = \frac{kL}{Vb}$$

Large Da, flow paths persist, Permeability unchanges $\longrightarrow$ Leak

Small Da, fracture seals, Permeability decreased 100x $\longrightarrow$ Red... (... eak

However

Implications for field-scale behavior

Da is inversely proportional to V and directly proportional to L

Increasing L (field-scale) will have a similar effect to decreasing V at the lab scale → development of **preferential flow paths** is more likely **at field scale**.

and

Under pressure controlled conditions, sealing will decrease permeability and reduce flow (increase Da) → **increase** the potential for **preferential flow-path formation**.

Conclusions

- Our experiments **argue against** the likelihood of a fractured dolomitic-anhydrite caprock **sealing** by the combined influence of geochemical alteration and mechanical deformation (increased Da is favorable under reservoir conditions).

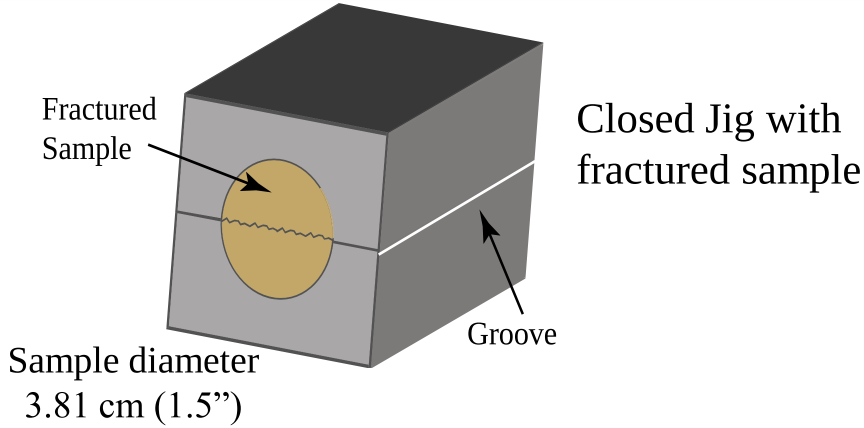
- Laboratory experiments **coupled with appropriate scaling analyses** can provide insights into field-scale behavior.

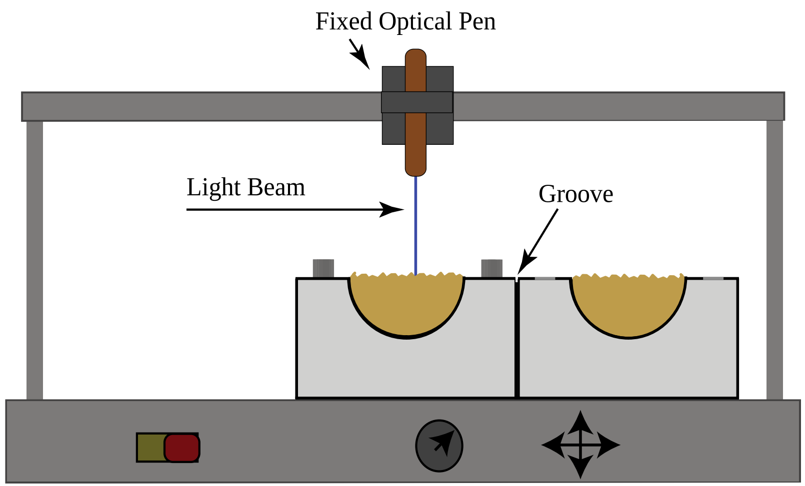
- Our results are qualitatively consistent with previous studies, but mechanisms differ → experiments with specific mineral / fluid combinations needed to understand / predict behavior.

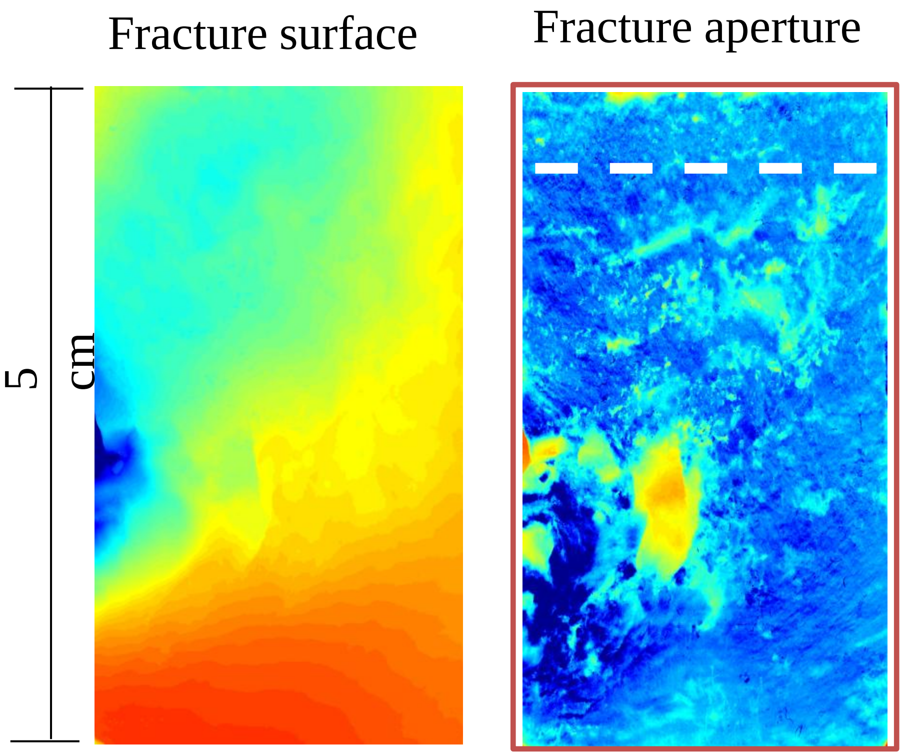
Elkhoury, et al., *Earth and Planetary Science Letters*, 2015

Thank You

High resolution optical profiler measures fracture surfaces from which we produce fracture aperture

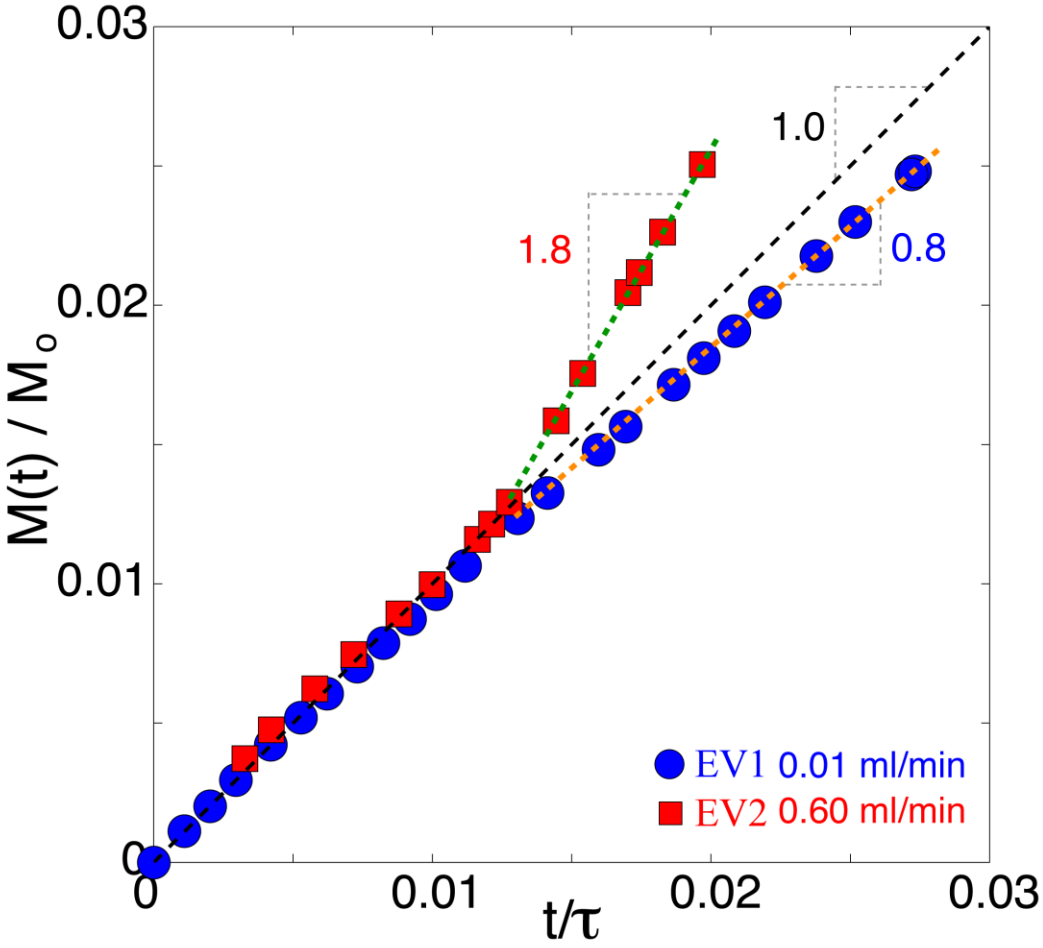






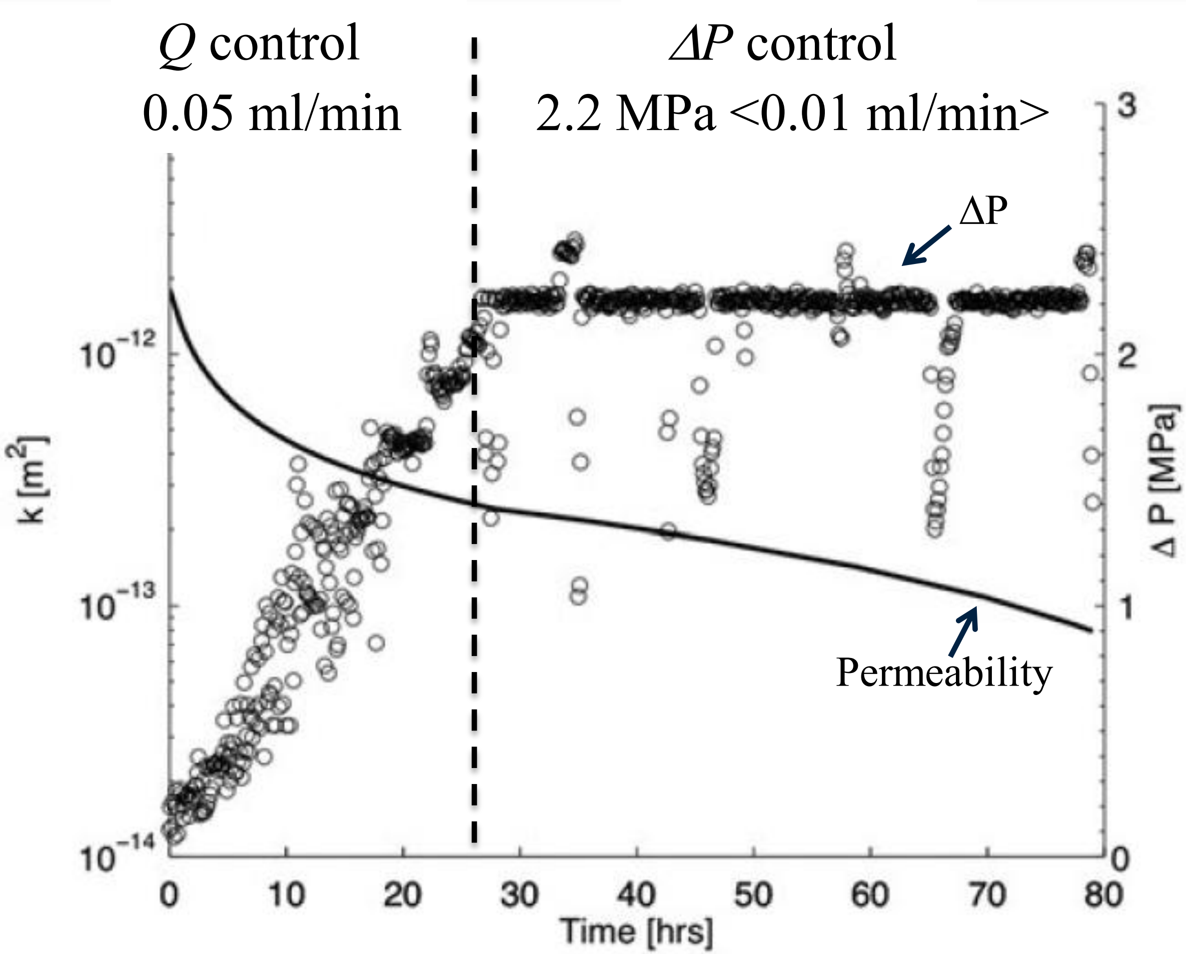
Ameli, Elkhoury & Detwiler, *WRR*, in review

Dissolved mass rate increases under high flow rate and decreases under low flow rate



Change of reactive surface area

Particle mobilization could clog flow path and decrease Permeability



Calcite + Dolomite (>90%)
(quartz, K-feldspar, clay minerals)
Temperature = 30°C

calcite dissolution along the fracture pathway

⬇

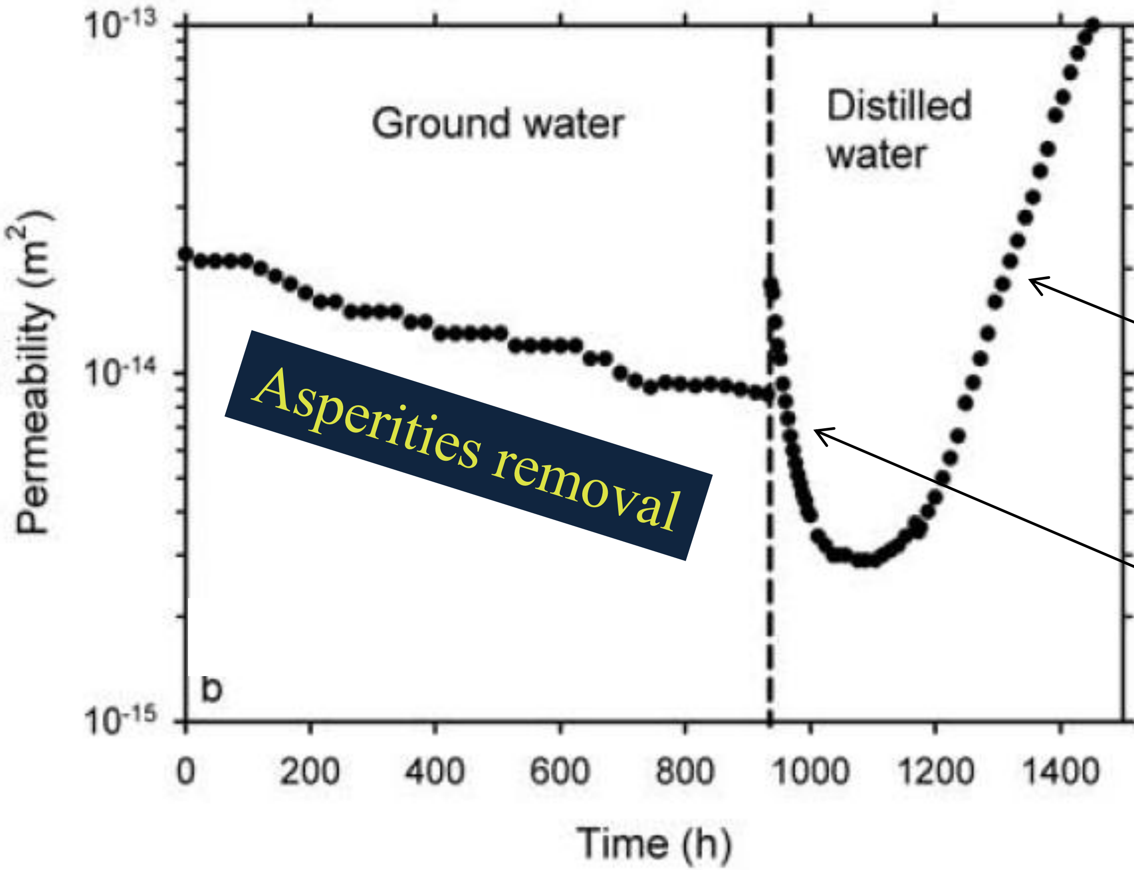
mobilization of less soluble mineral particles

⬇

clogging of flow path

Ellis et al., *Env. Eng, Sci.*, 2013

Changes in fluid chemistry alter the sign and the rate with which fracture permeability evolves



Limestone

T = room °C

Q = 2 ml/min

Localized dissolution

Enhanced dissolution

~ 63 days

Elsworth & Yasuhara, *PAGEOPH*, 2006

Perturbations from equilibrium and the coupling/feedback between mechanisms alter fracture properties

Most transport studies, particularly of large scale systems, assume constant properties [permeability and porosity (aperture)]

However, large perturbations $\underbrace{\text{(mechanical/chemical/hydrological/thermal)}}^{\text{Coupling/Feedback}}$ from equilibrium can alter fracture aperture and permeability

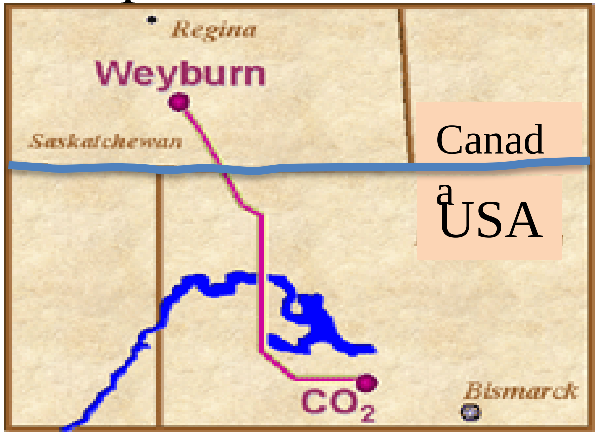
Polak et al., *GRL*, 2003
Elkhoury et al., *Nature*, 2006
Elsworth et al., *PAGEOPH*, 2006
Manga et al., *Rev. Geophys*., 2012
Elkhoury et al., *IJGGC*, 2013
Ellis et al., *Env. Eng. Sci*,.2013

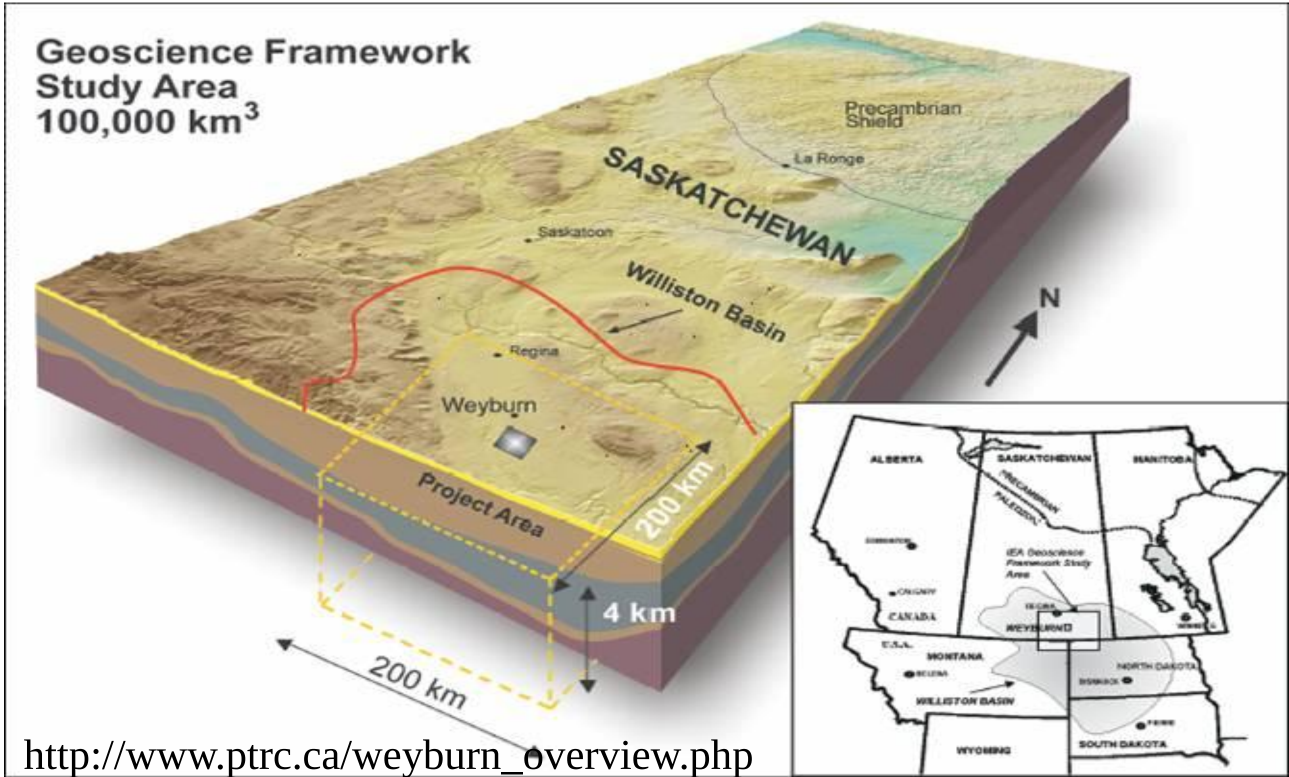
1) Earthquake Triggering,
2) Reservoir permeability enhancements,
3) Waste isolation,
4) Enhanced oil recovery,
5) Geothermal energy production and
6) CO_2 sequestration

The CO_2 Weyburn project

CO_2 measuring, monitoring and verification initiative

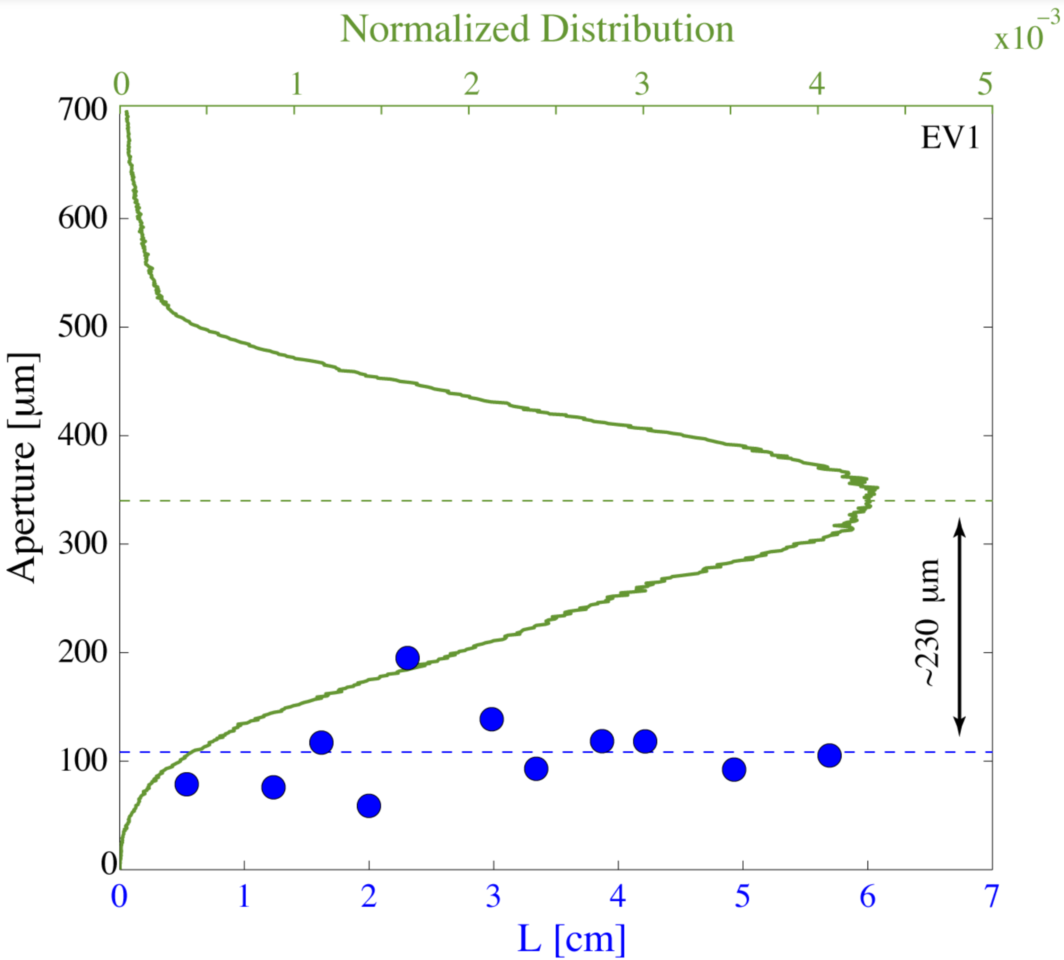
CO_2 is captured from an industrial source and injected to revive oil production.



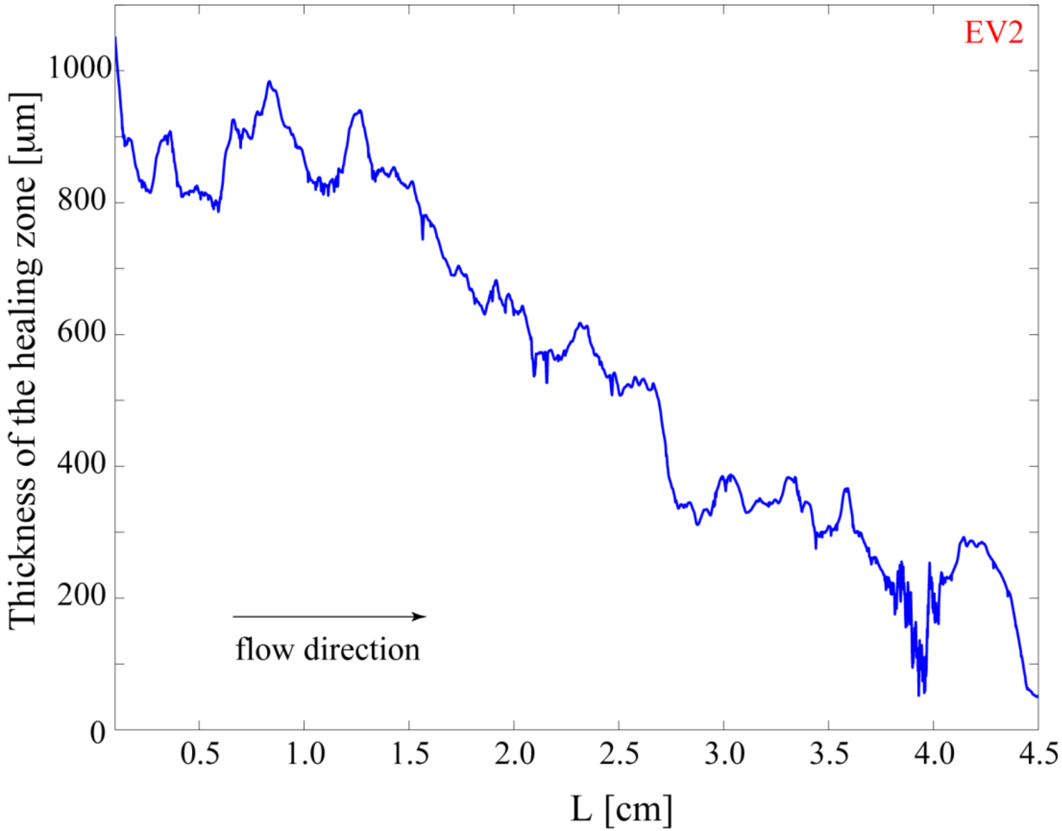


http://www.ptrc.ca/weyburn_overview.php

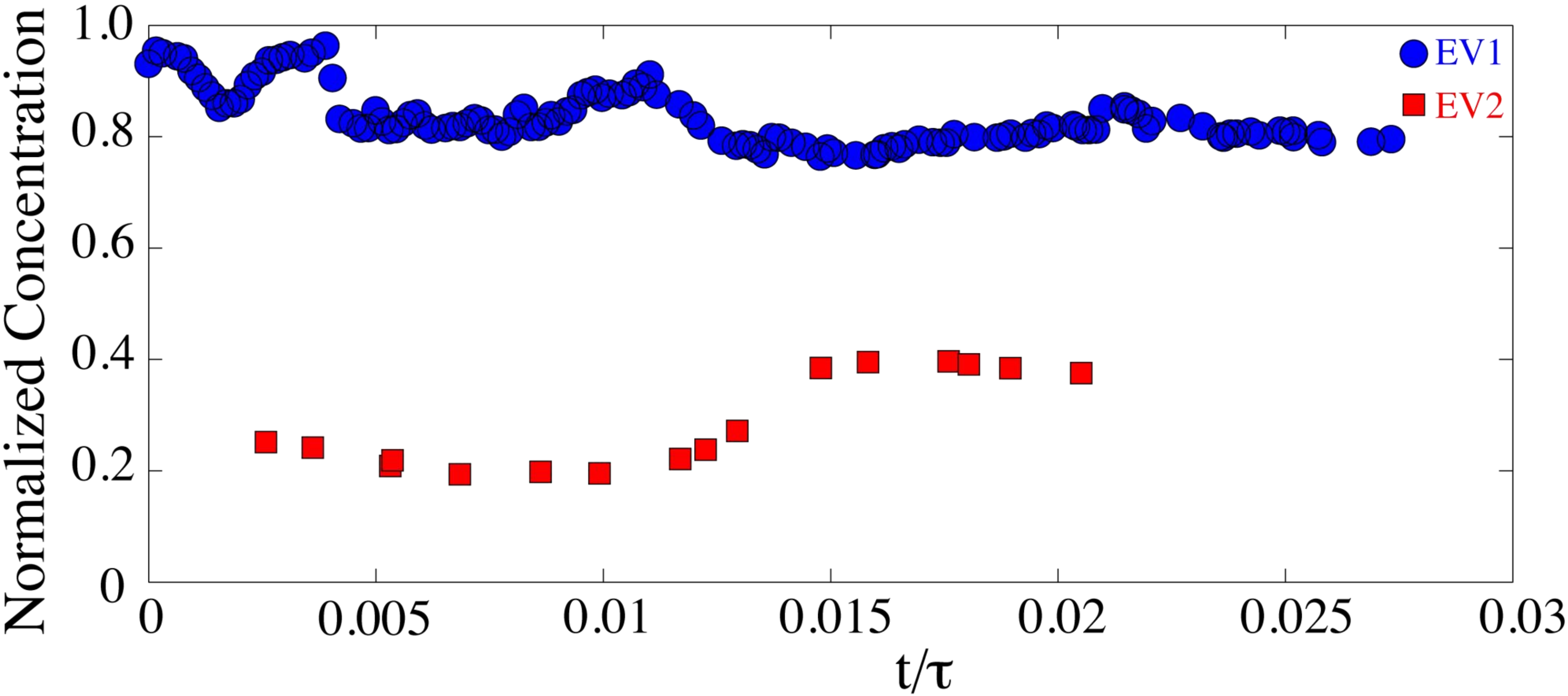
Aperture field evolution



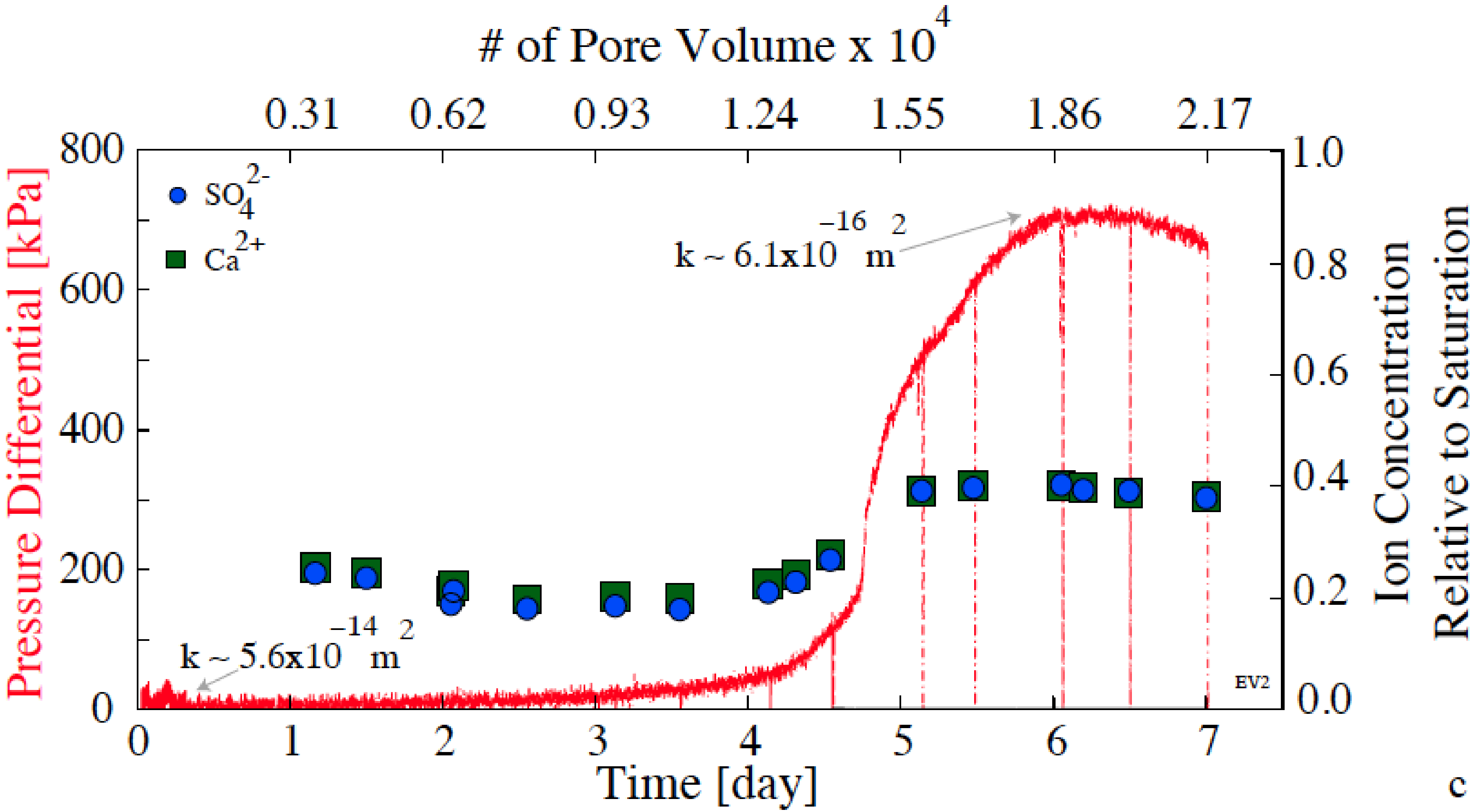
Thickness of healing zone (compacted gypsum)



Temporal evolution of effluent ion concentration



Chemistry and Pressure



Dissolution increase fracture permeability

Mineral heterogeneity

- We need to quantify it
- Is it the dominant mechanism?
- How about hydro-chemical mechanism?

Schematic diagram of Sample holder