Schweizerischer Erdbebendienst
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EARTH & ENVIRONMENTAL SCIENCES

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Lessons learned from coupled hydro-mechanical modeling of induced seismicity

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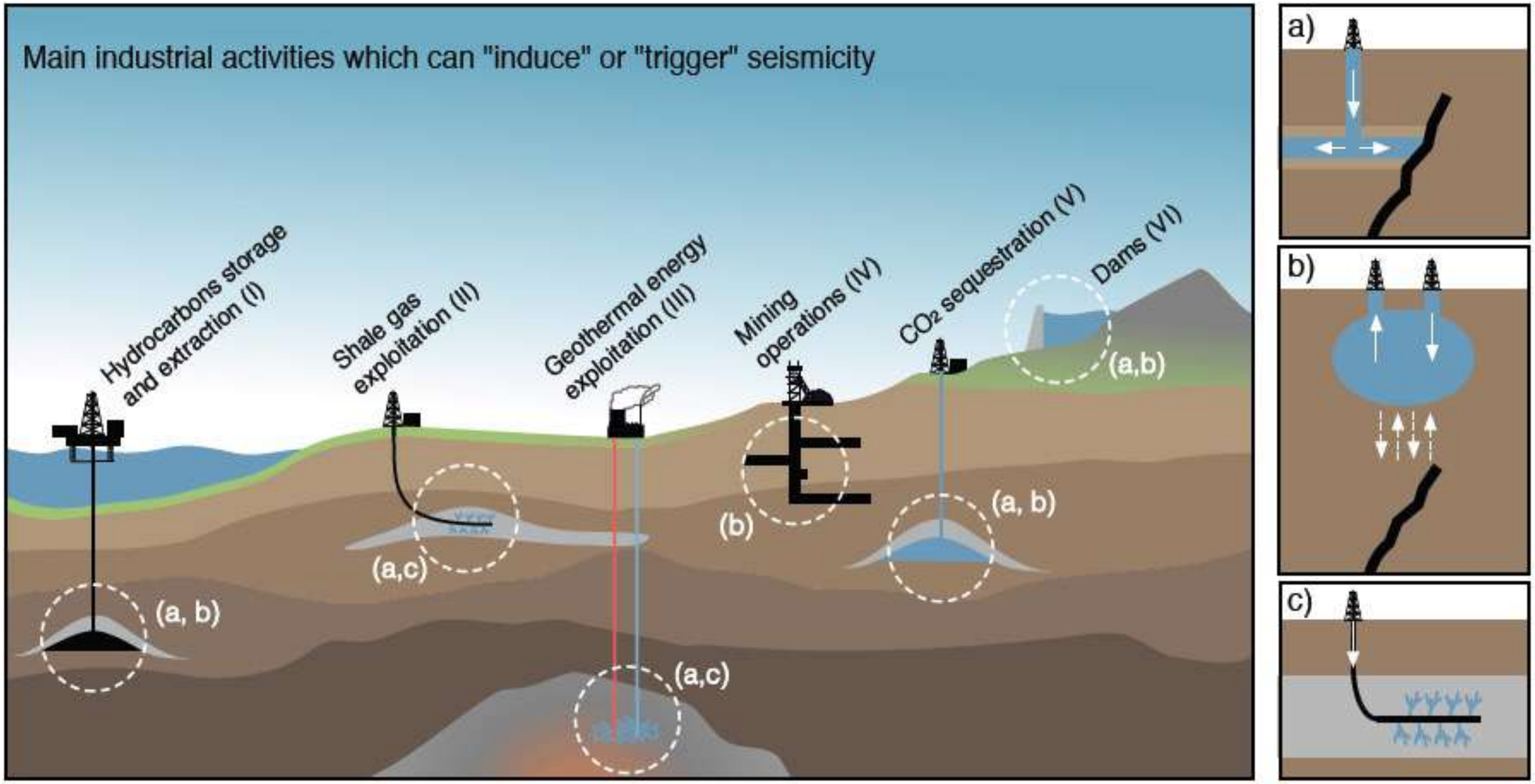
SOCIETÀ ITALIANA DI FISICA

107° CONGRESSO NAZIONALE
13-17 settembre 2021

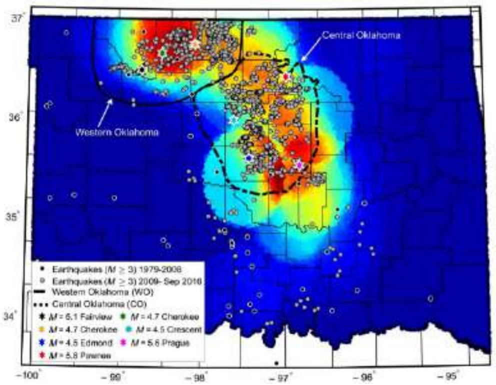
GeoEnergy applications and induced earthquakes belong together

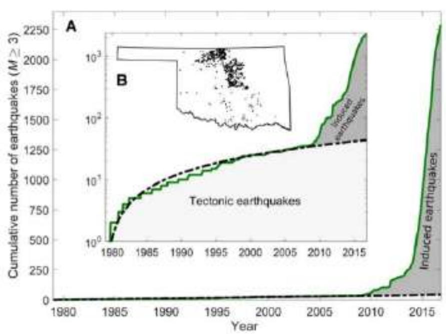


Grigoli et al., 2017

Examples of fault reactivation and related induced seismicity

Wastewater injection
(e.g., Oklahoma, US)



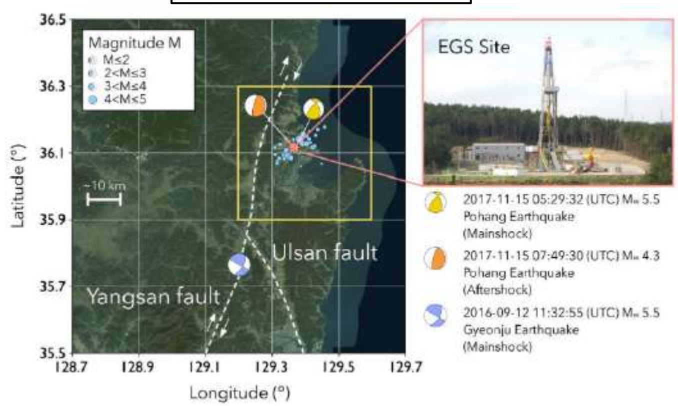


Langebruch and Zoback, 2016

Largest event: M=5.8

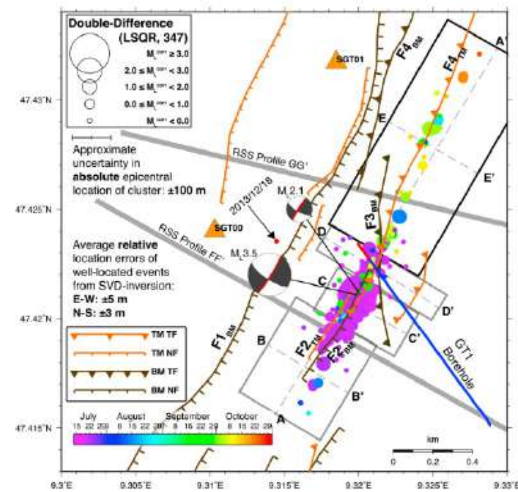
Enhanced geothermal system
(e.g., Pohang, South Korea)

Grigoli et al., 2018



Largest event: M_w=5.5

Deep geothermal energy
(e.g., St. Gallen,
Switzerland)



Diehl et al., 2017

Largest event: M_L=3.5

Modeling case studies for fault reactivation

- Deep underground injection/withdrawal of fluids:
  - Rinaldi et al. (2015), *Fault reactivation during CO_2 sequestration: effects of well orientation on seismicity and leakage*, Greenh. Gas. Sci. Tech., 5, 645-656, doi:10.1002/ghg.1511
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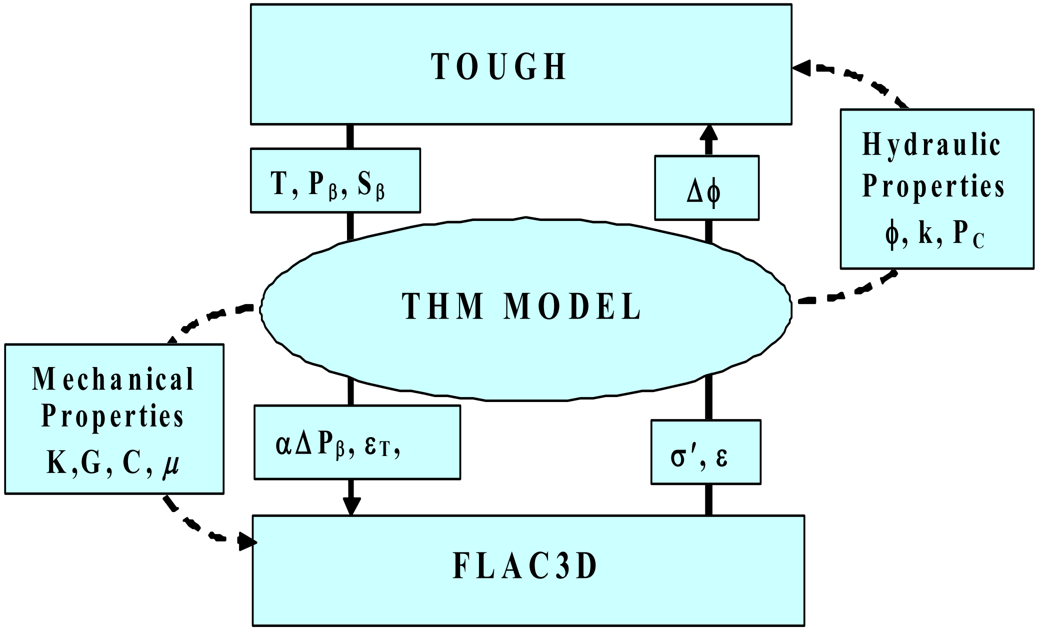
TOUGH-FLAC coupled simulator



C = Cohesion
G = Shear modulus
K = Bulk modulus
k = Intrinsic permeability
P = Pressure
Pc = Capillary pressure
SH = Hydrate saturation
T = Temperature
ε = Strain
ϕ = Porosity
μ = Coefficient of friction
σ' = Effective stress

Fixed-stress split sequential method to couple flow and geomechanics.

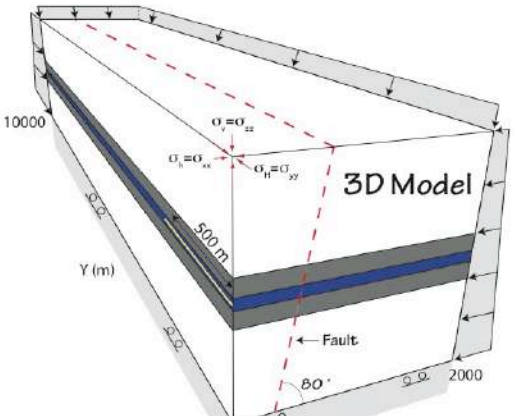
Direct couplings (solid arrow): Pore volume change, effective stress, thermal strain, and swelling

Indirect couplings (dashed arrow): Changes in mechanical and hydraulic properties

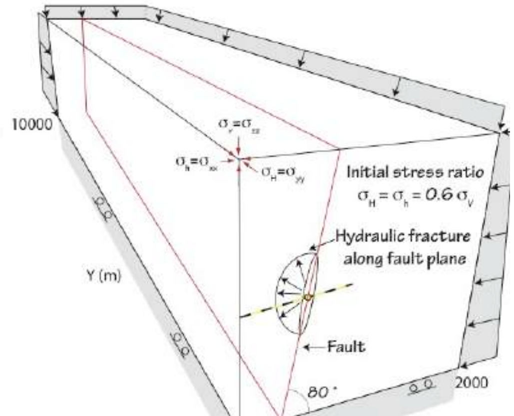
Rutqvist et al., 2002;
Rutqvist et al., 2011;
Blanco-Martin et al., 2016;
Rinaldi et al., 2021

Latest version accounting for parallel computing and python scripting for sequential coupling of the two codes (TOUGH3 and FLAC3Dv6/7)

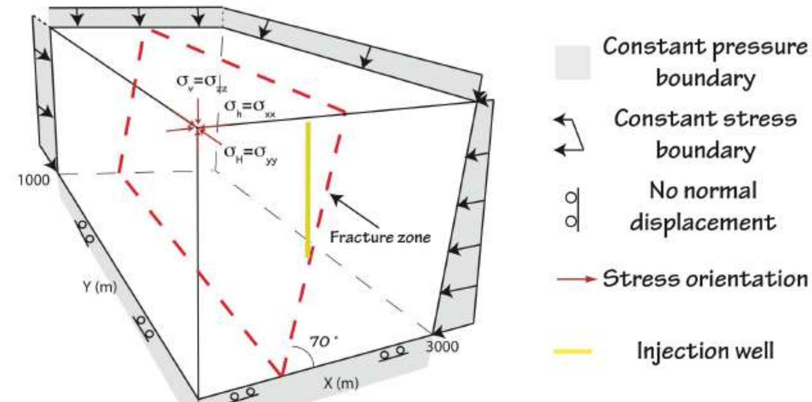
Fault model for understanding physical processes



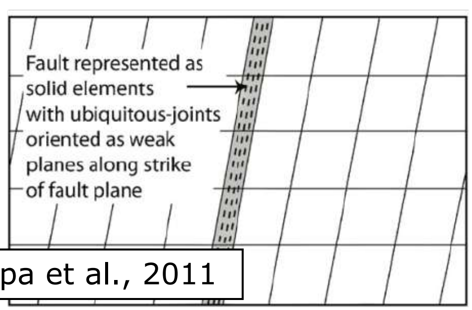
CO2/Deep injections
Rinaldi et al., 2015



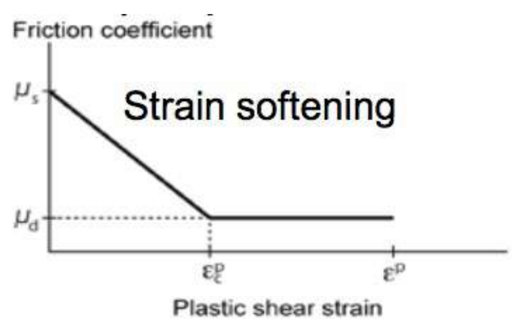
Hydraulic fracturing
Rutqvist et al., 2015



Geothermal
Rinaldi & Rutqvist, 2019



Cappa et al., 2011



$$M_0 = G \times A \times d$$

$$M_w = \frac{2}{3}\log_{10} M_0 - 6.1$$

Finite continuum fault, size and permeability depending on the case

Fault “seismic” reactivation trough frictional law

Magnitudes with seismological relationships

Case Studies for fault reactivation

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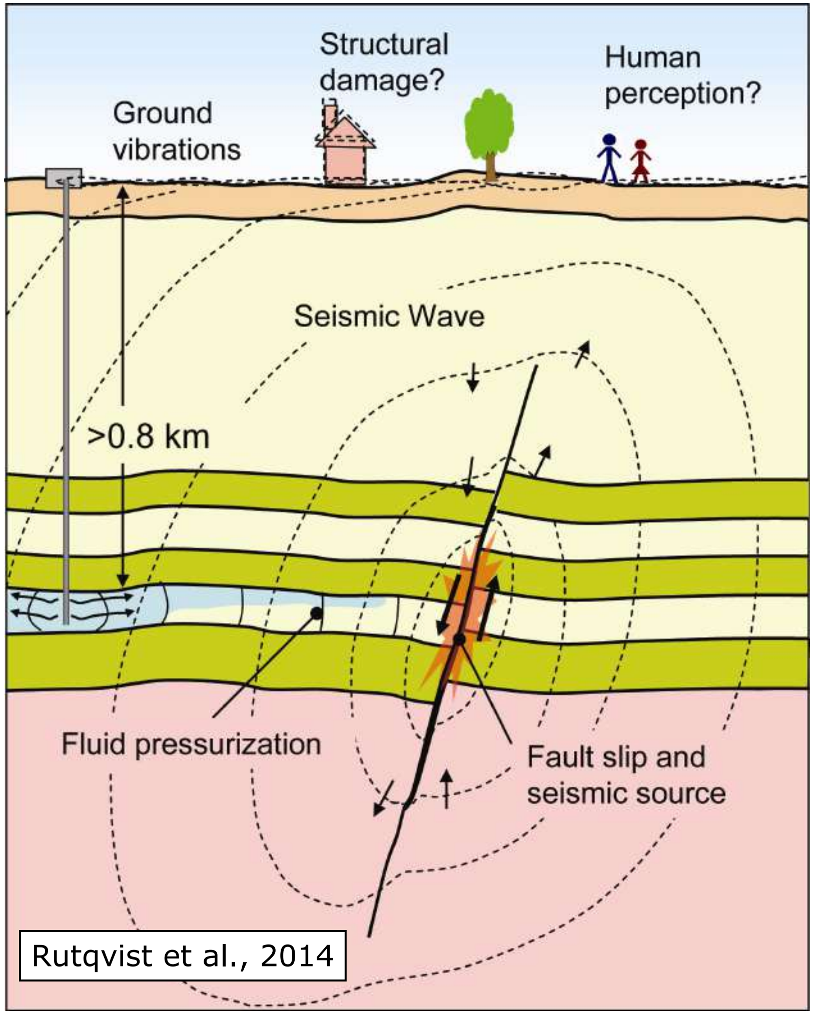
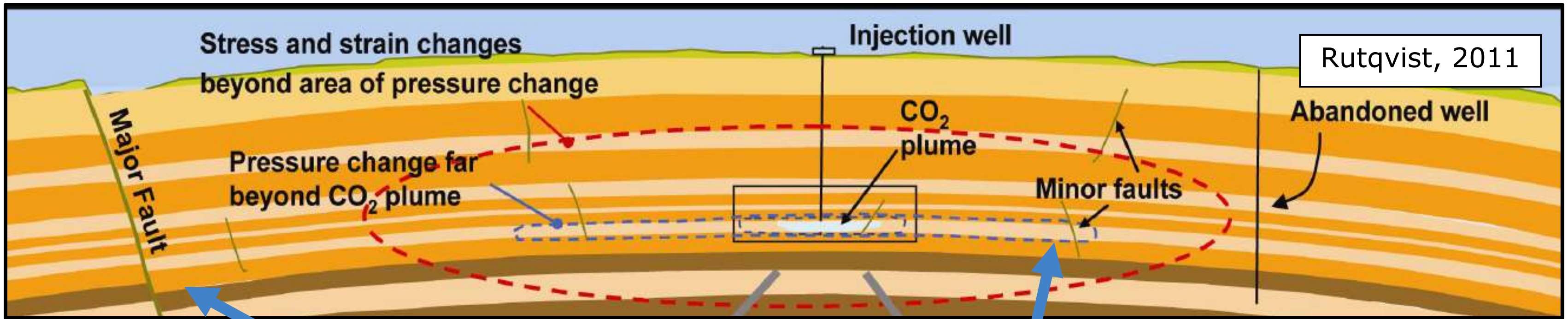
Fluid storage at depth



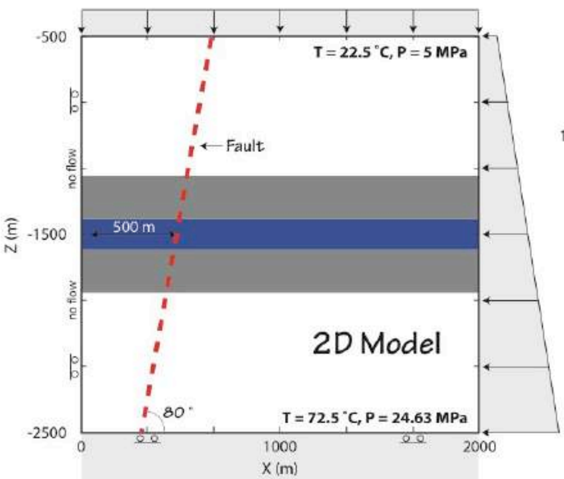
- Overpressures due to large-scale fluid injection may induce seismic events
- How much it takes to reactivate a fault?
- What is the role of the stress state and stress evolution?
- How is the magnitude varying?

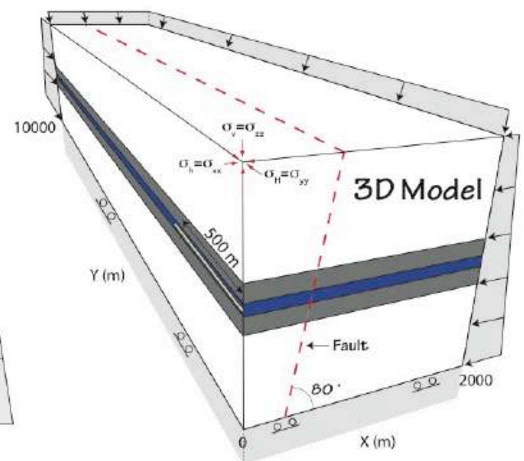
Minor versus Major Faults



- Large offset major faults can be detected at the ground surface and by seismic surveys. Sequestration site might be designed to stay away from such faults.

- The regional injection-induced (slow) crustal straining and minor (hidden) faults might be of greatest concern at future large scale injection sites (minor faults of unknown location and orientation)

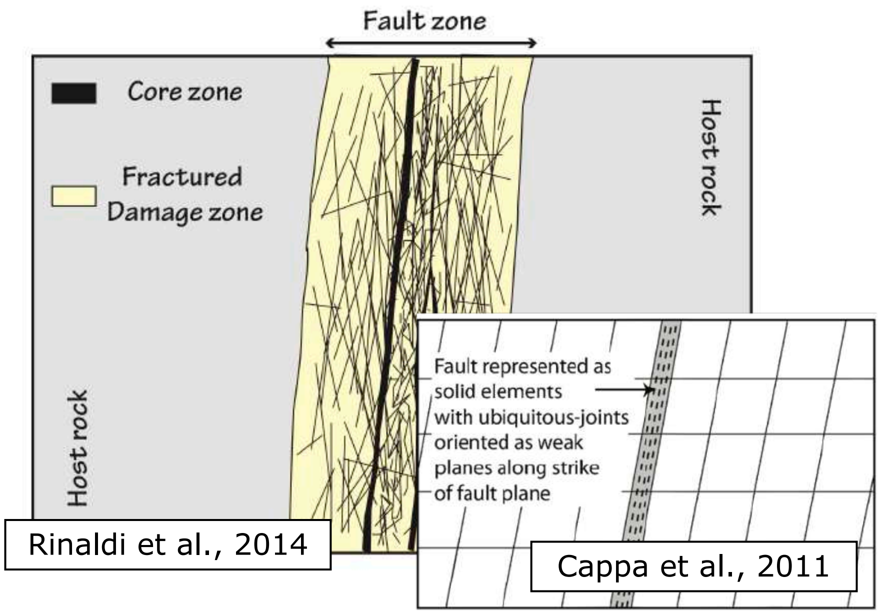




Central reservoir bounded by two low permeability caprock.

Injection through vertical or horizontal well, with flow rate 120 kg/s (accounting for symmetry)

Geomechanics and fluid flow coupling



Damage zone: 10^{-15} m^2
porosity as function of mean effective stress (σ'_M), permeability depends on porosity changes (Davies and Davies, 2001)

$$\phi_{hm} = (\phi_0 - \phi_r)\exp\left(5 \cdot 10^{-8} \cdot \sigma_M^{'}\right) + \phi_r$$

$$\kappa_{hm} = \kappa_0 \exp[22.2(\phi_{hm}/\phi_0 - 1)]$$

Fault core: 10^{-17} m^2
Anisotropic coupling. Hydraulic parameters depend on anisotropic elasto-plastic properties. Porosity as function of plastic tensile (e_{ftp}) and shear strain (e_{fsp}), and dilation (ψ). Permeability as function of normal effective stress (σ'_n) and porosity changes (Hsiung et al., 2005). ***a*** and ***c*** empirical constants for normal-closure hyperbola (Bandis et al. ,1983)

$$\phi_{hm} = \phi_0 + \Delta\phi_{fp}$$

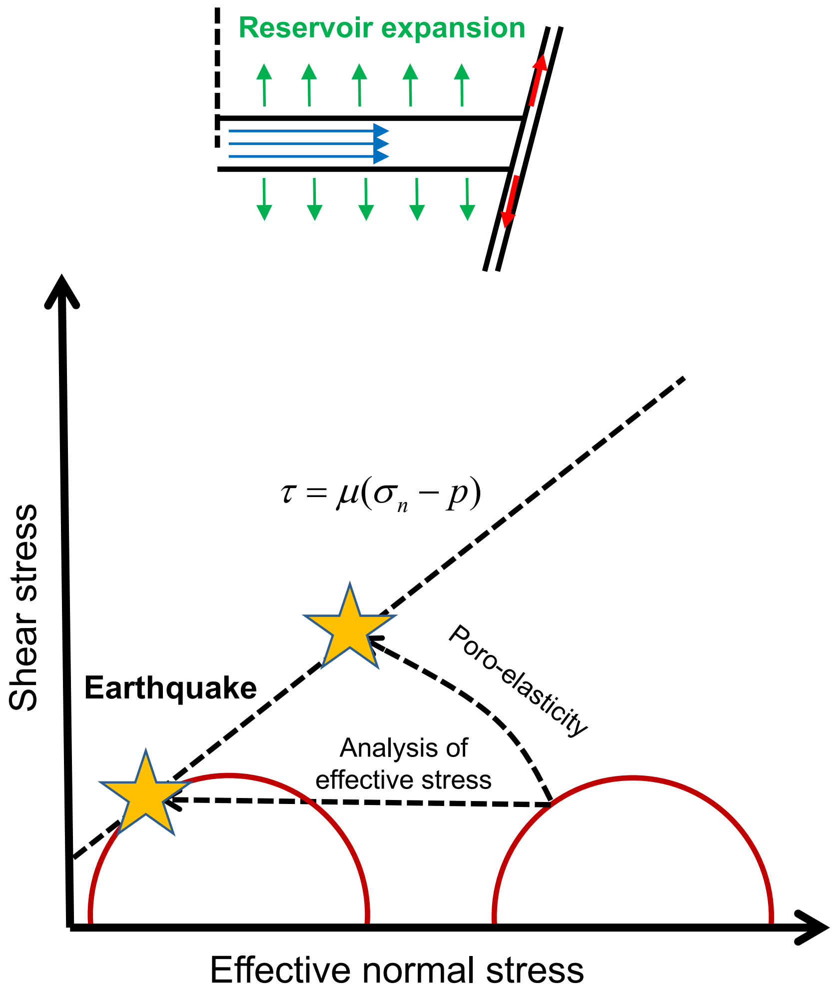
$$\Delta\phi_{fp} = e_{ftp} + e_{fsp}\tan\psi$$

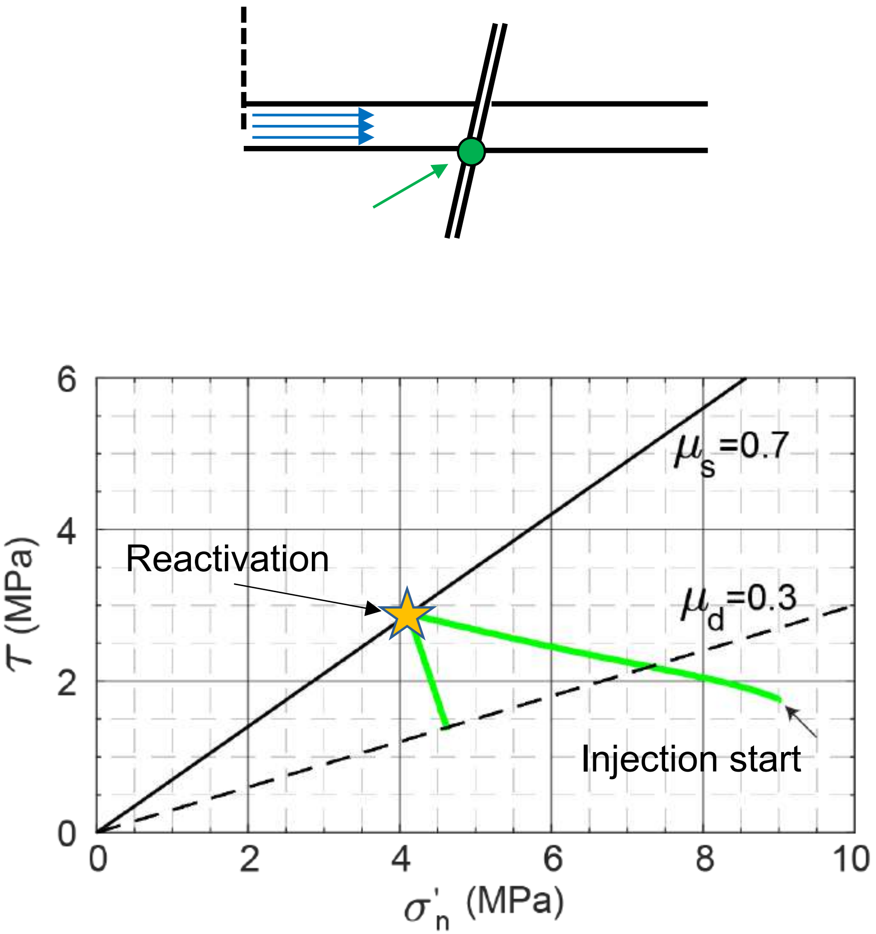
$$\kappa_{hm} = \kappa_0 \left[\frac{a}{c(c\sigma_n^{'} + 1)}\sqrt{\frac{\phi_0}{12\kappa_0}} + \frac{e_{ftp} + e_{fsp}\tan\psi}{\phi_0}\right]^3$$

$$a = K^{-1}$$

$$c = \frac{-1 \pm \sqrt{1 + 4\sigma_{n0}^{'}a\sqrt{\phi_0/12\kappa_0}}}{2\sigma_{n0}^{'}}$$

Poroelastic effects on fault reactivation

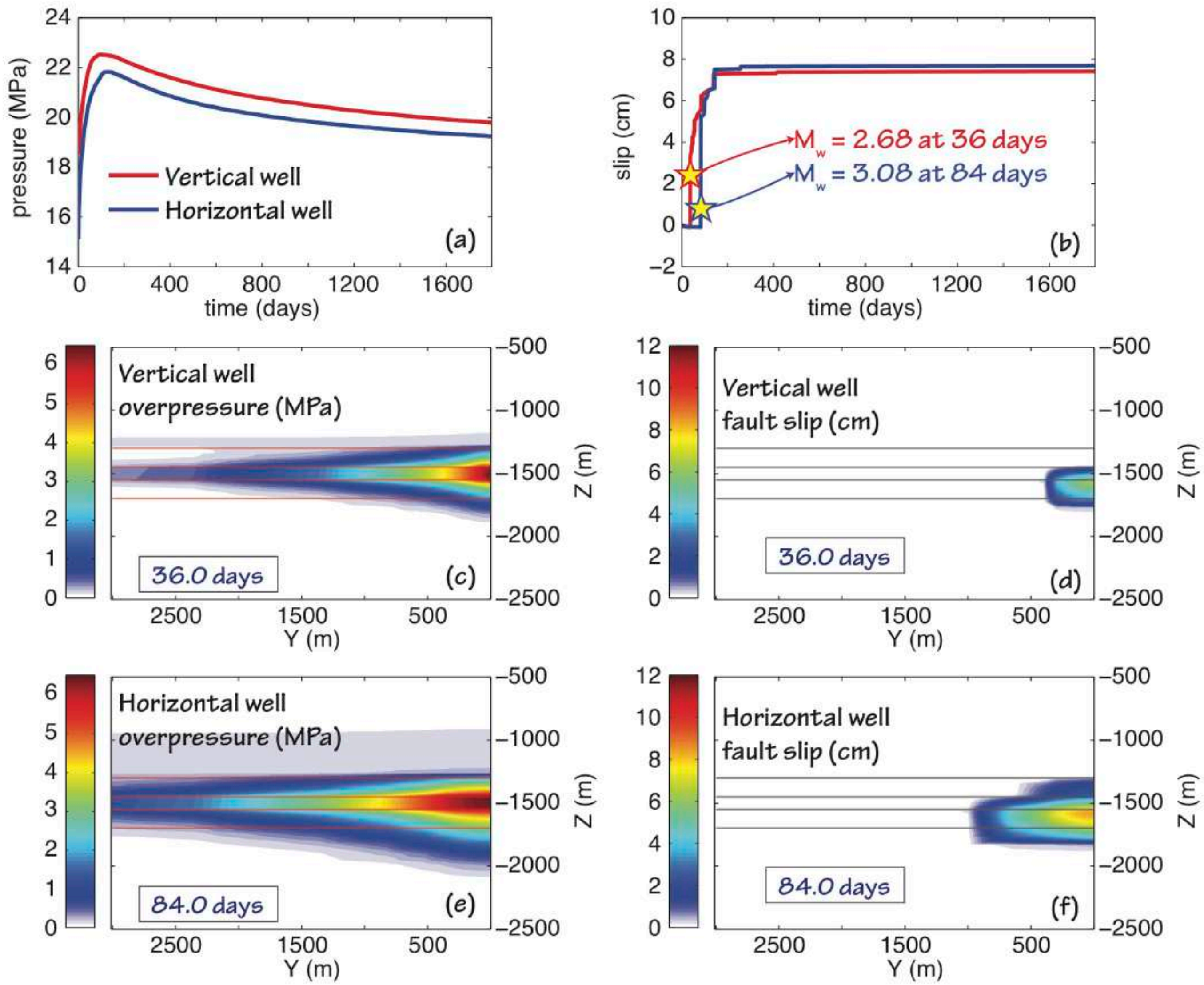




Horizontal vs Vertical injection well

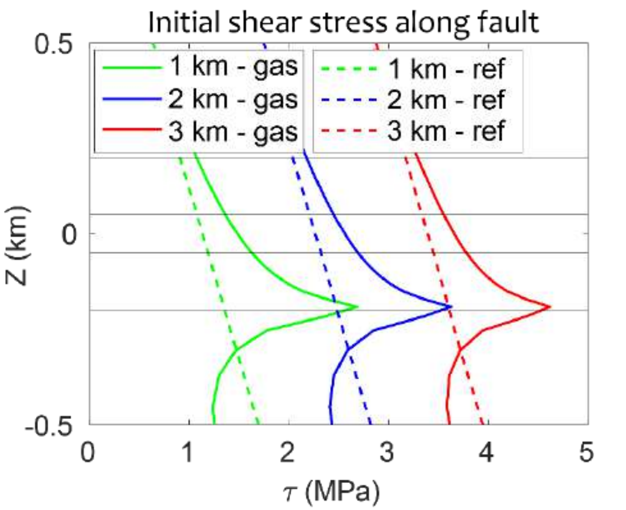
Rinaldi et al., 2015

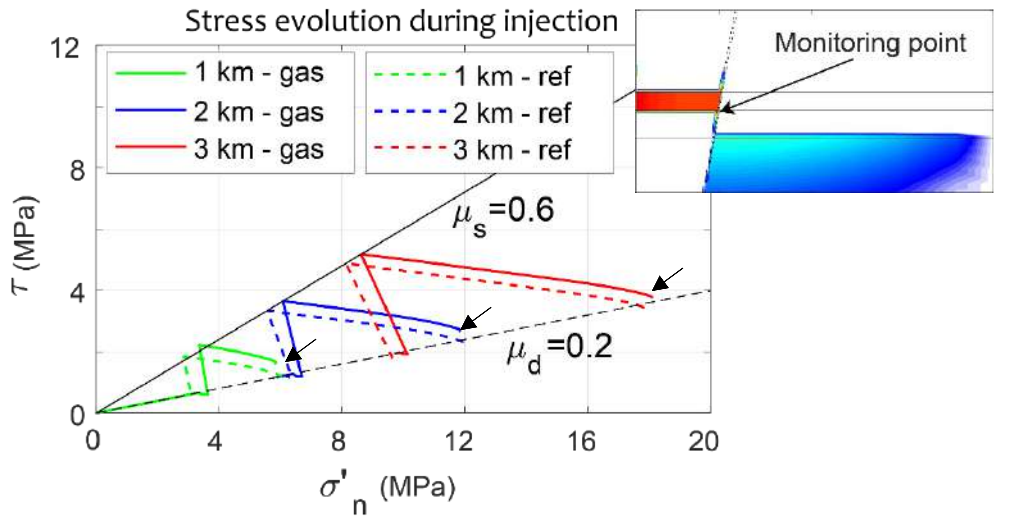
- 1 MPa difference at peak
- Different time of reactivation
- Critical pressure extent: 300 m for vertical and 700 m for horizontal
- Larger rupture area and slip for horizontal well injection
- 0.4 difference in earthquake magnitude (4 times more energy for horizontal well)

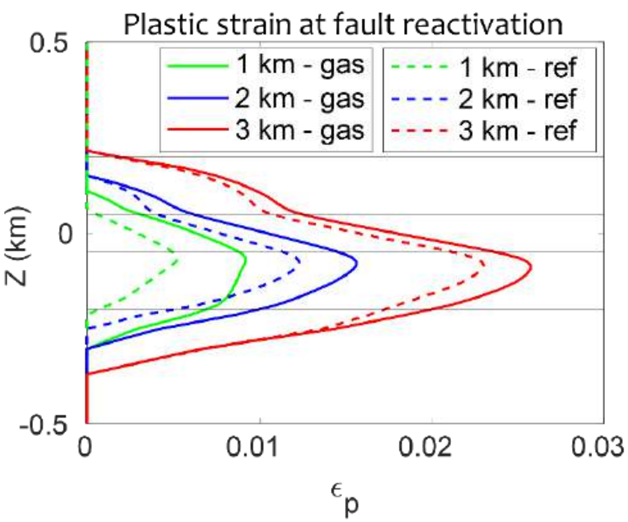


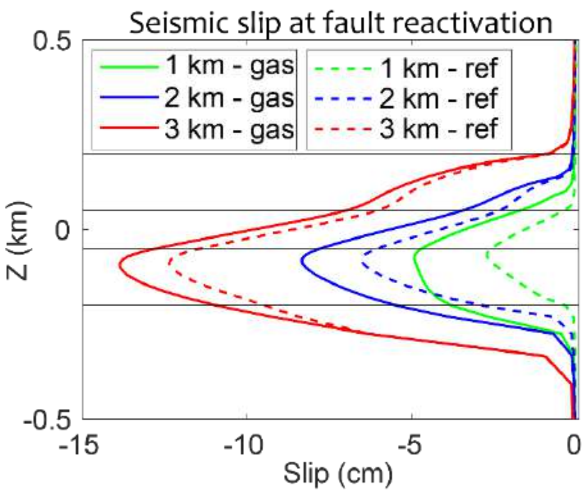
Effect of in-situ properties

Rinaldi et al., in prep









Time of reactivation:

1 km: 0.31 years (0.42 y)

2 km: 1.50 years (1.63 y)

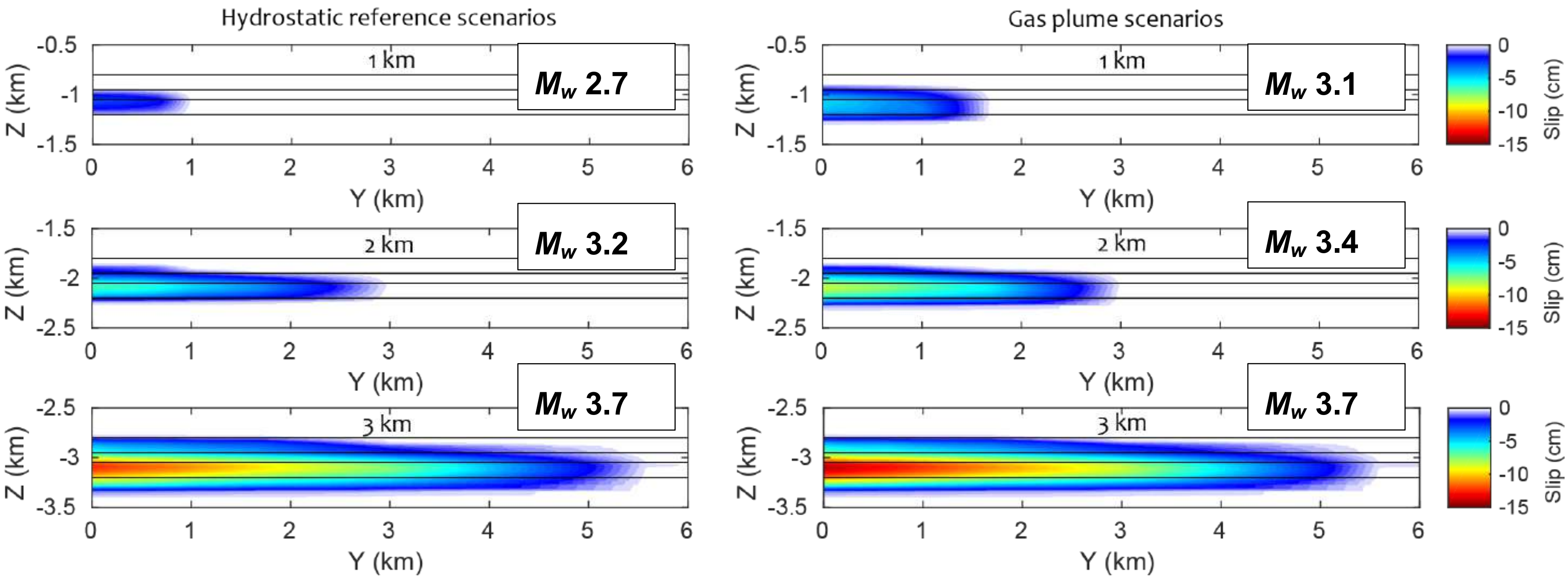
3 km: 3.54 years (3.60 y)

Gas (reference)

Fault slip and moment magnitude

Rinaldi et al., in prep

- Fault slip, rupture area and magnitude increase with depth
- Scenarios with gas lead to larger fault slip, larger rupture areas and larger M_w
- Influence of overpressurized gas decreases with increasing reservoir depth



Same model but multiple faults

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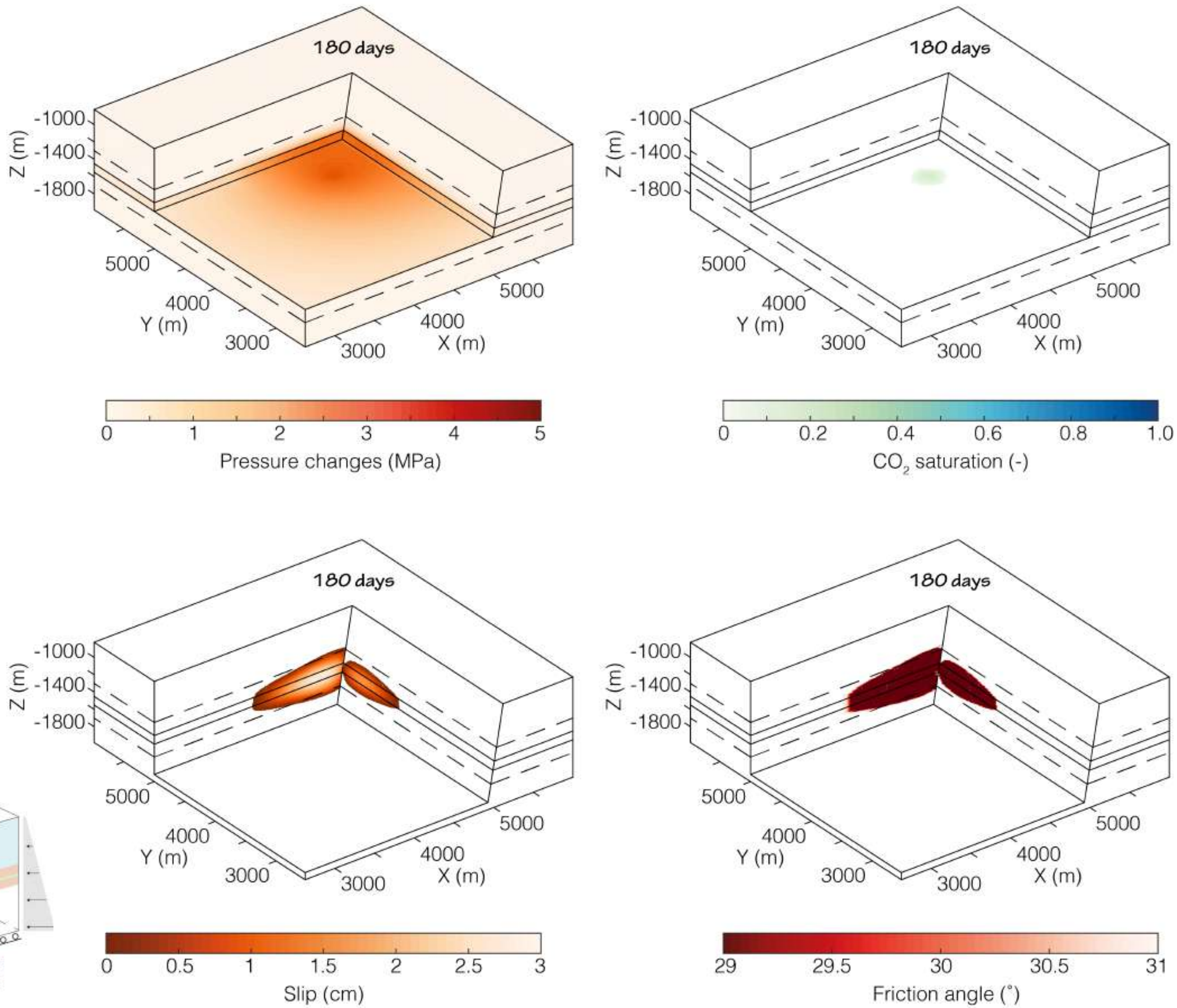
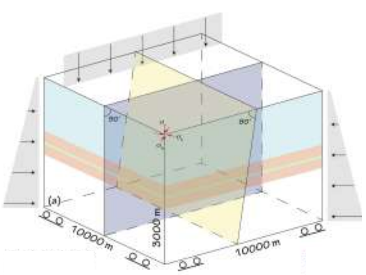
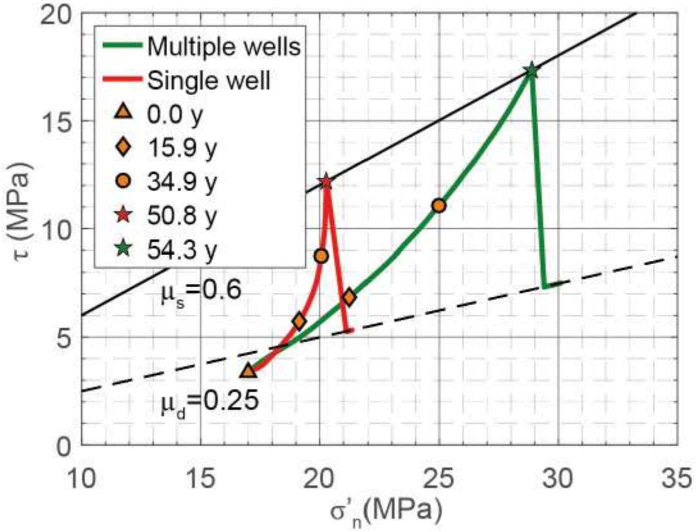
Rinaldi et al., 2021

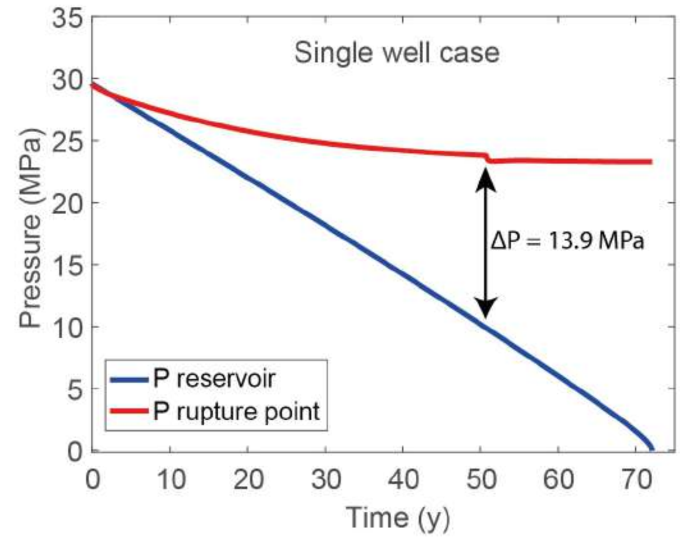


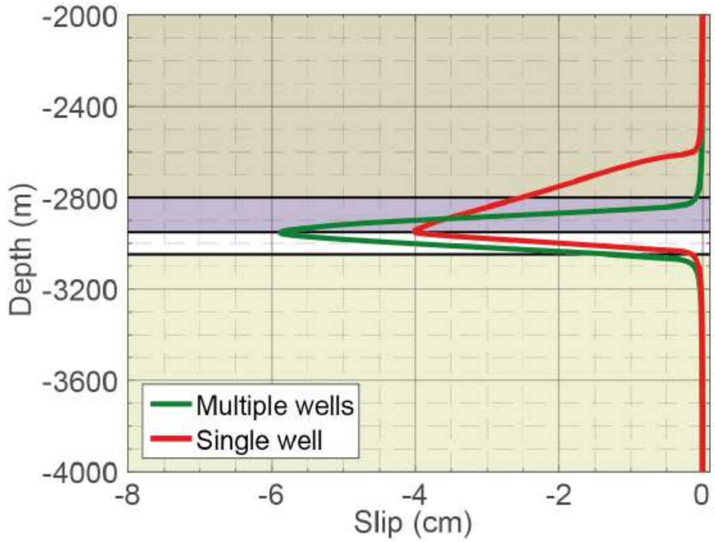


Fluid production even more affected by poroelasticity

Zbinden et al., 2017

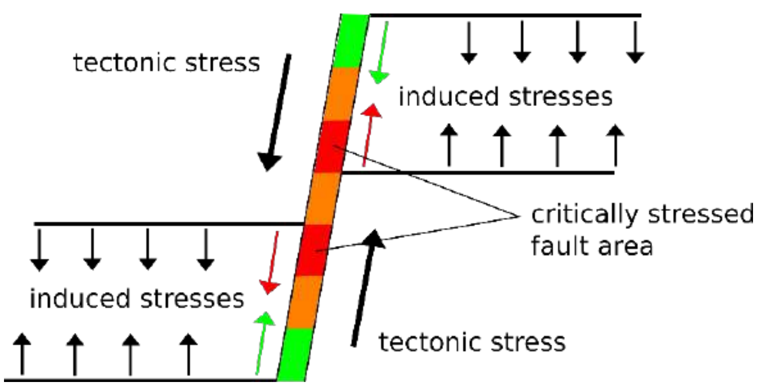






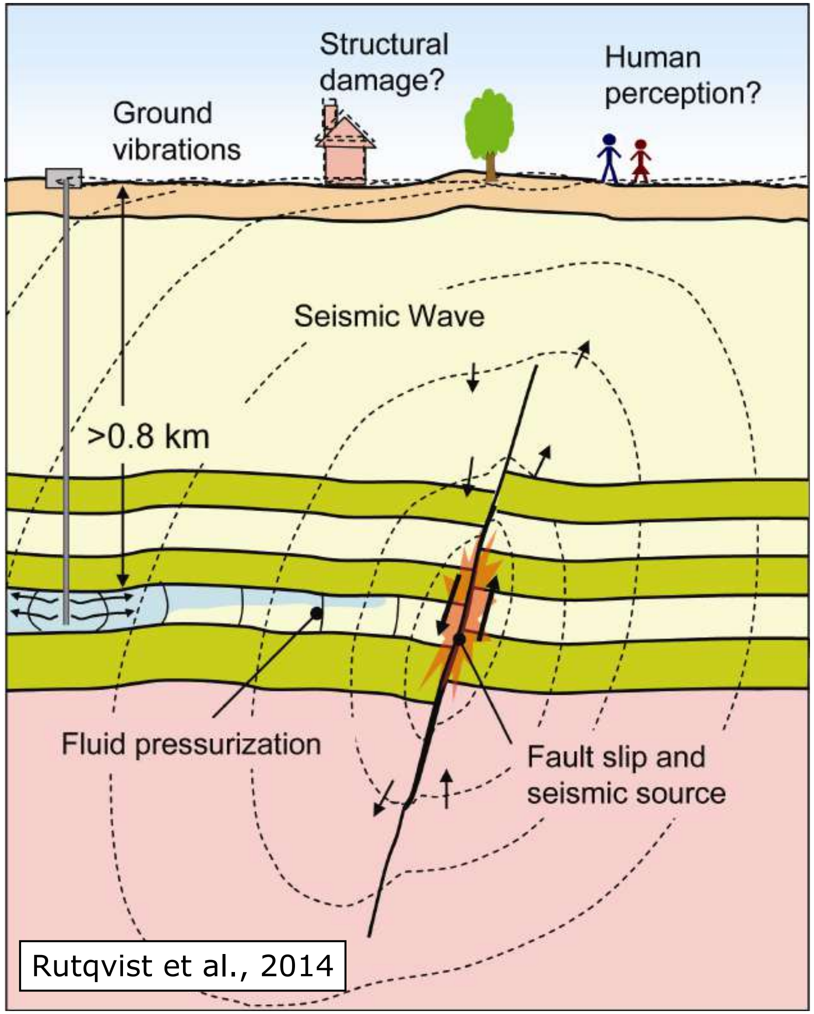
M_W 2.67

M_W 2.43



Conclusion – part 1

- Orientation of well do matter: **more localized** but faster and larger increase in pressure/stress for vertical wells, while pressure/stress distributes slower and over a **larger space** for horizontal wells
- **In-situ properties may have a large effect** on induced seismic event
- More complex with two interacting fault, but substantially same processes
- **Poroelastic stress changes** dominates the case of **production-induced** seismicity



Rutqvist et al., 2014

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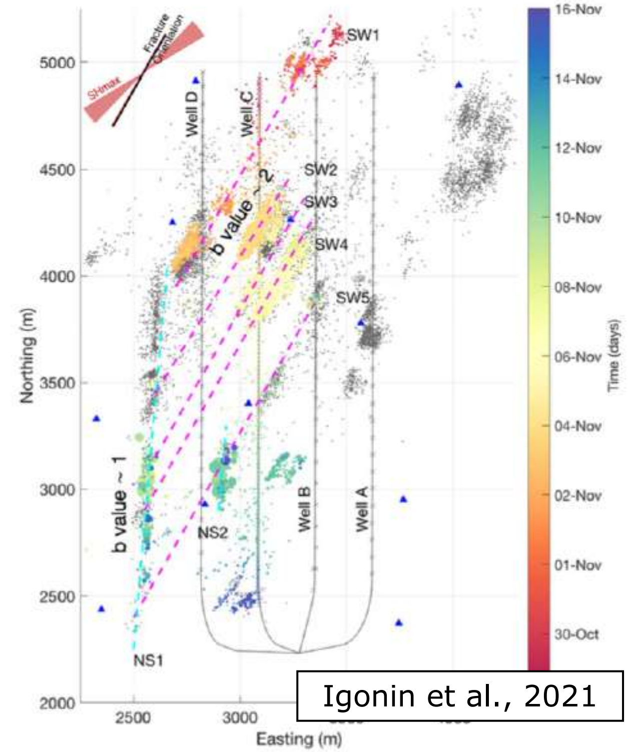
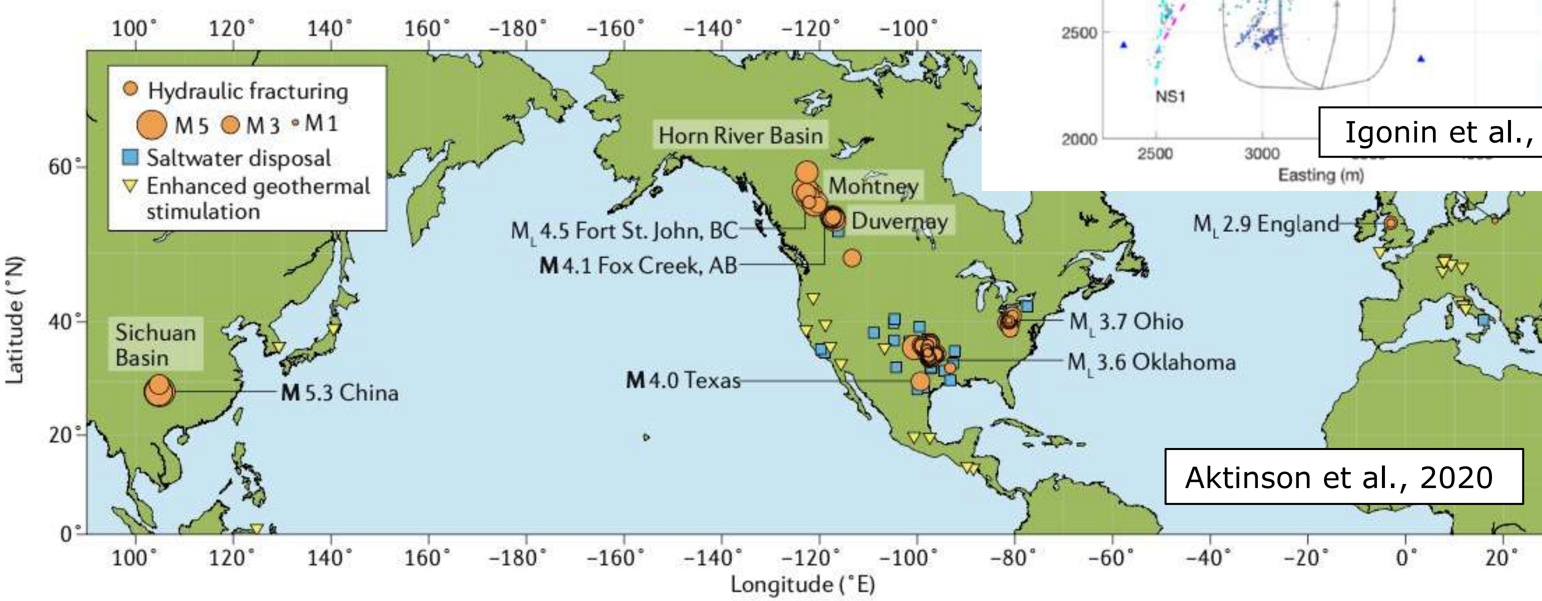
Fault reactivation linked directly to hydraulic fracturing

- Quite some seismicity associate with hydraulic fracturing (several tens of thousands of events for stimulation)
- Very often large events can be associated directly to hydraulic fracturing operations



Igonin et al., 2021



Aktinson et al., 2020

Fault model and permeability

Injection in low permeable fault.

Ubiquitous joint model with strain-softening:

- Shear can occur only on joints
- Fracturing occur on matrix

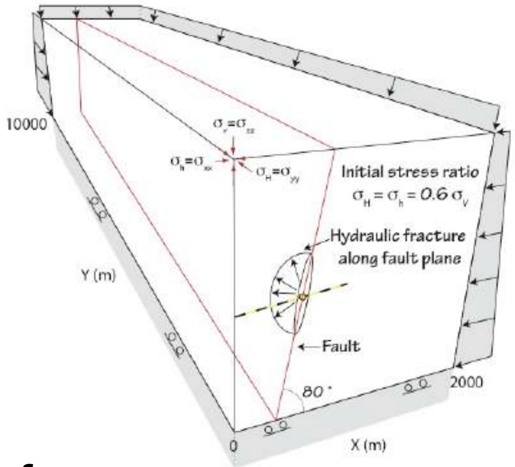
Permeability with threshold model as function of the plastic strain, allowing for simulating fracture propagation

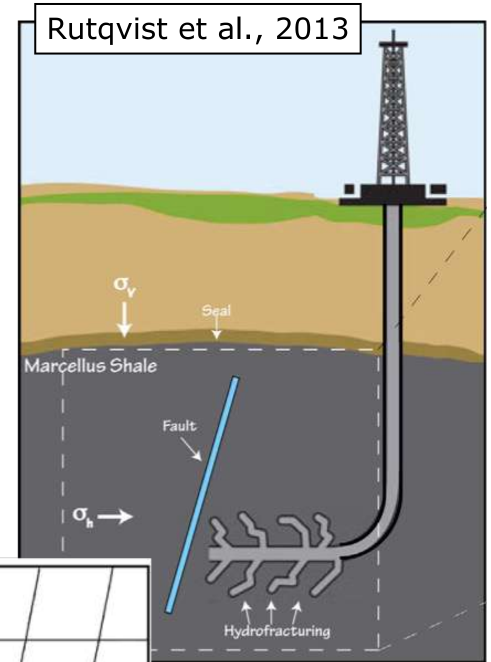
$$\kappa = \kappa_0 + \kappa_f = \kappa_0 + A\left(\varepsilon_n - \varepsilon_n^t\right)^3$$

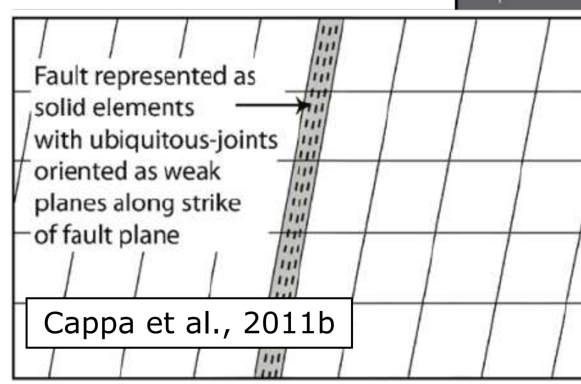
Seismicity counting the elements reactivated (with Coulomb failure and strain-softening) in a single time step

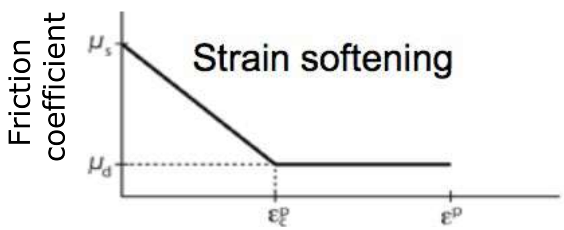
$$M_0 = \sum_{p=1}^{p=N} m_0^p \qquad m_0^p = GAd$$

$$cumM_w = \frac{2}{3}\log_{10} M_0 - 6.1$$









Base case results

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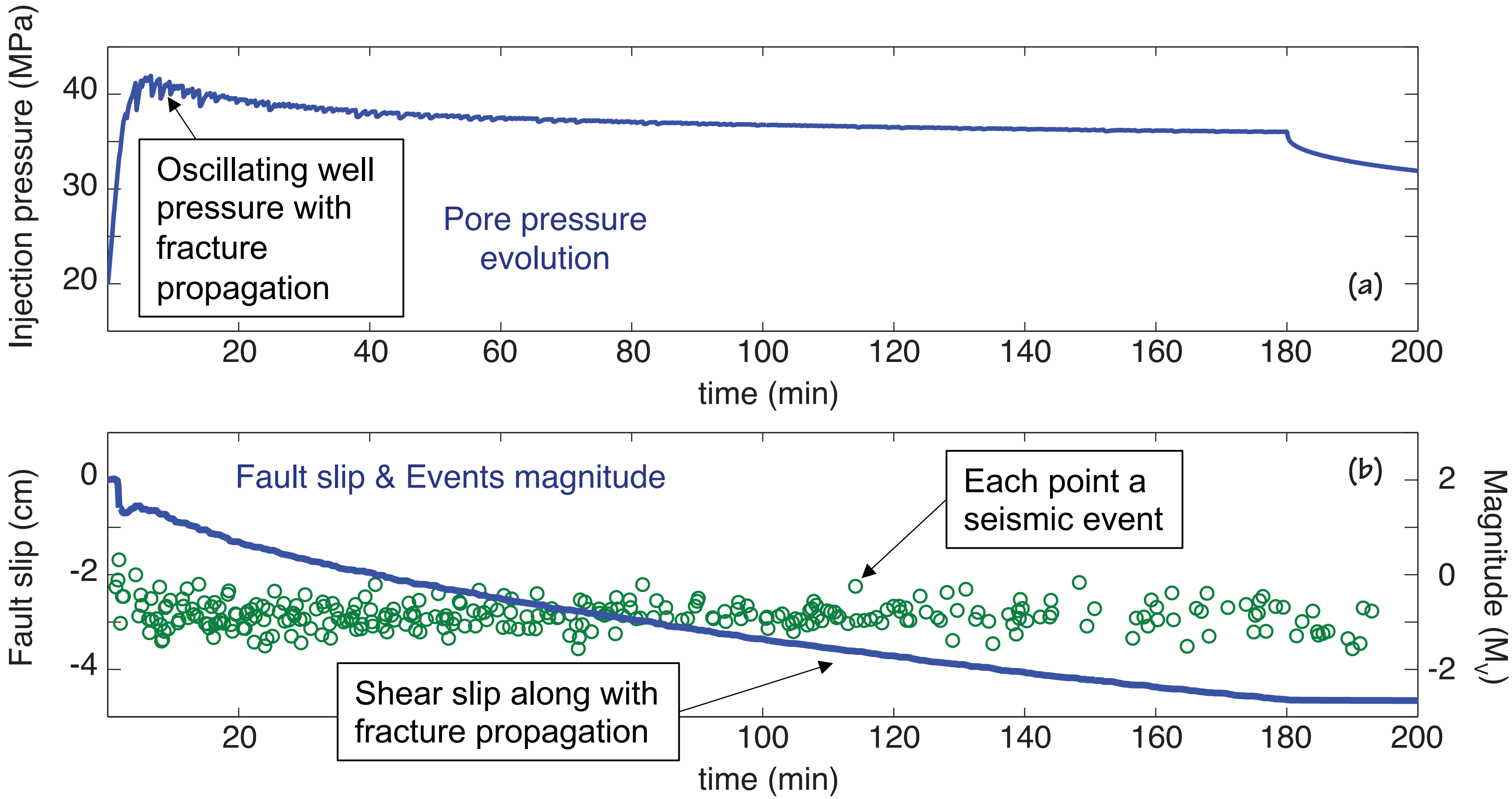
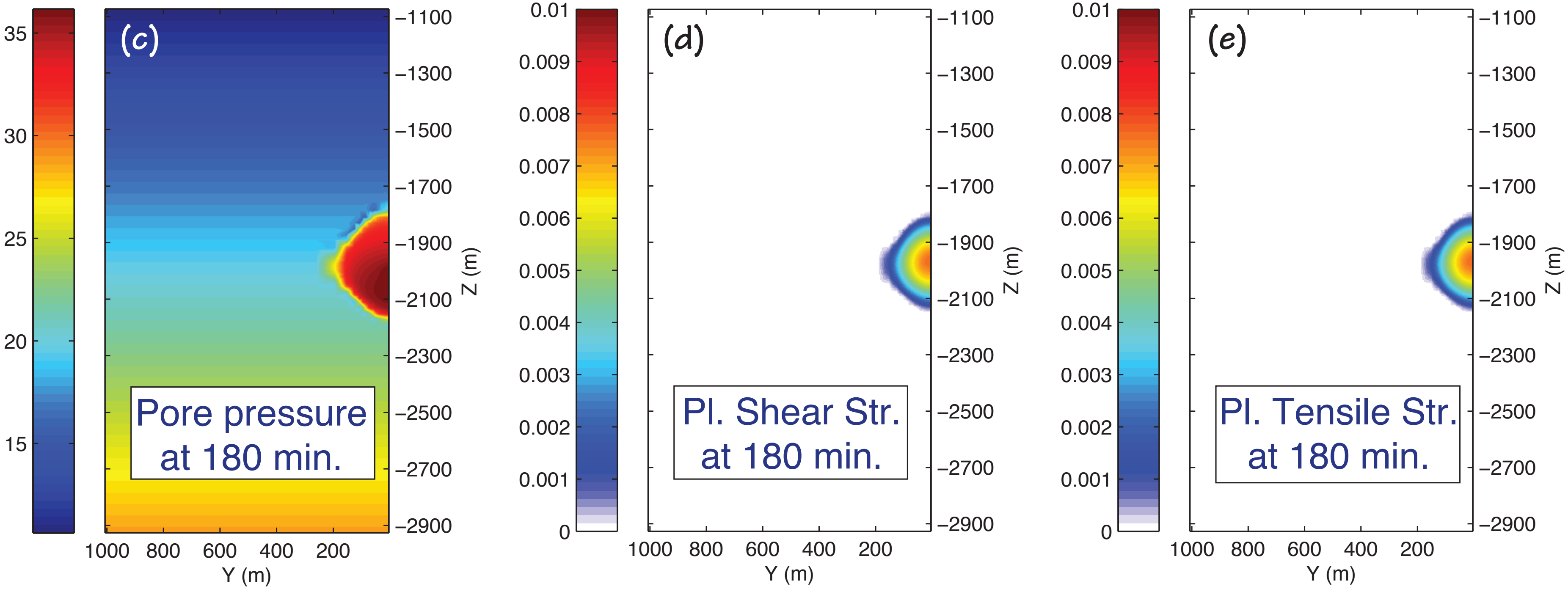


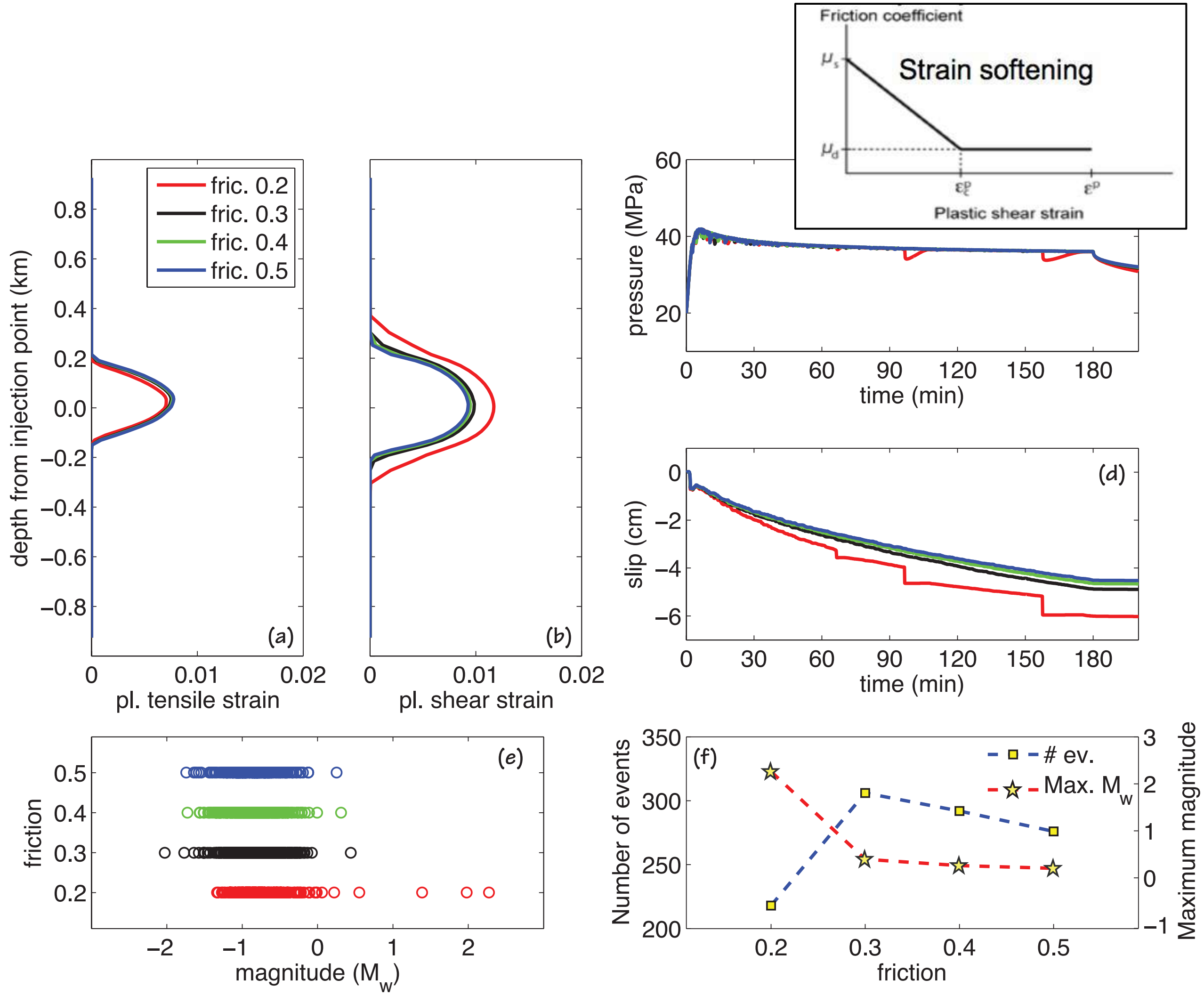
Spatial distribution



Sensitivity analysis

Several parameters:

- Peak (static) and residual friction angle (dynamic)
- Injection depth
- Fault dip
- Initial fault permeability
- Injection rate
- Threshold strain for slip-weakening



Sensitivity analysis

Several parameters:

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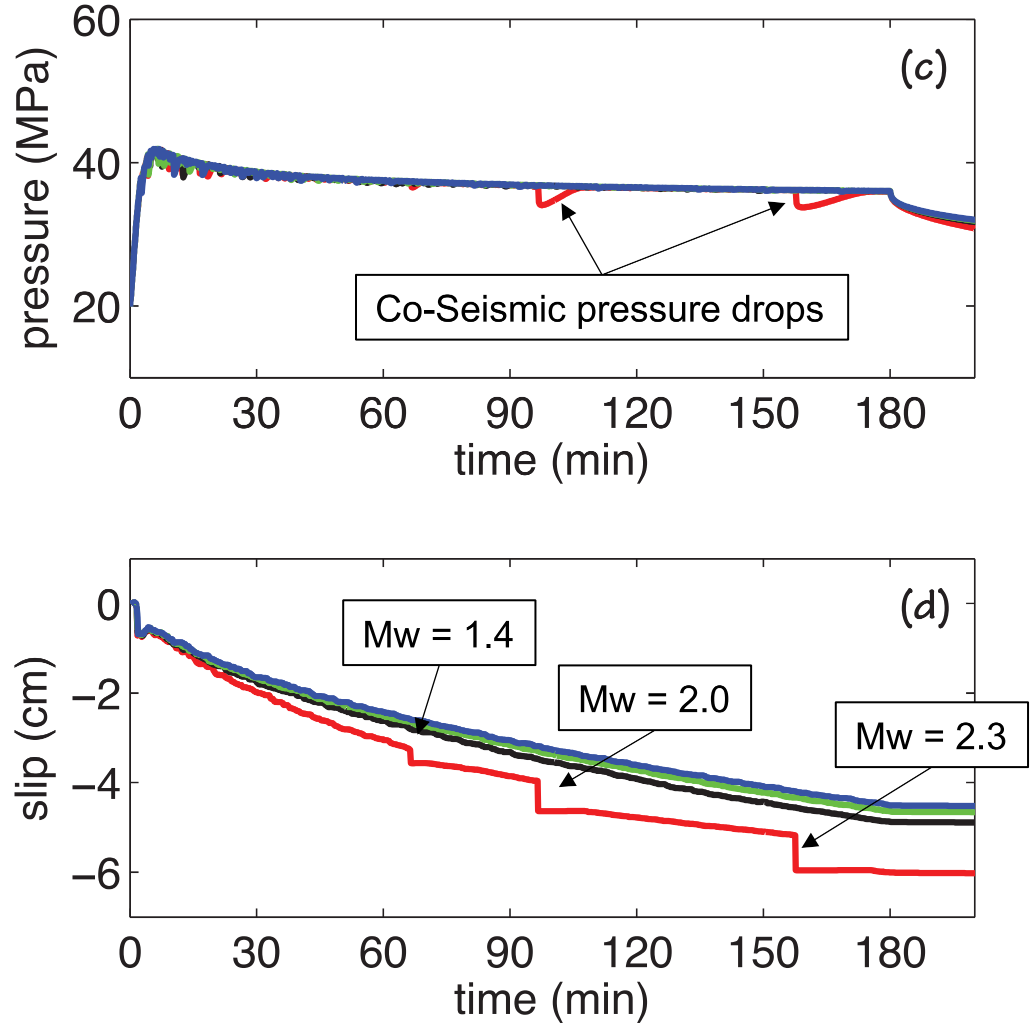
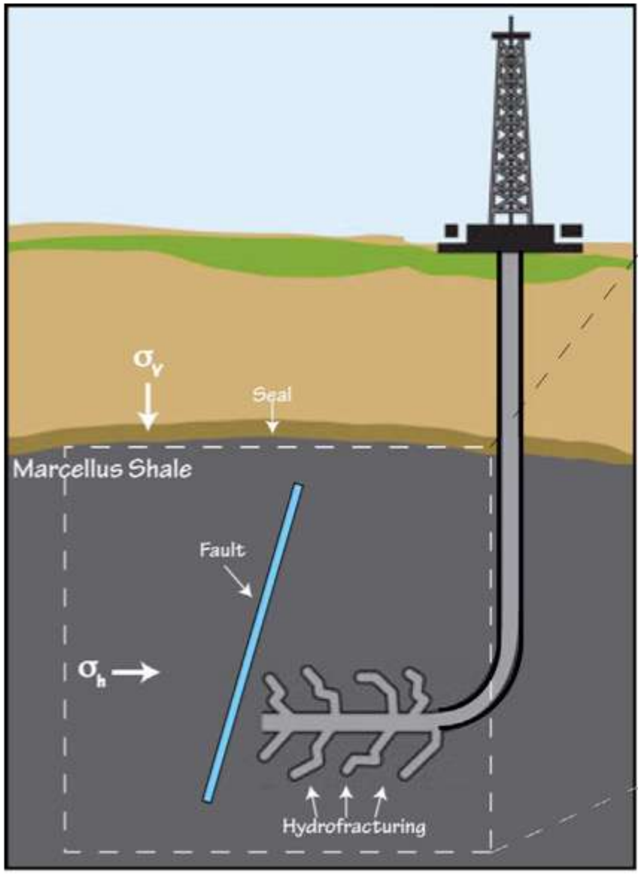
Variation of residual friction may explain the occurrence of large events, while on average very low magnitude events



Conclusion – part 2

- Shear activation (shear failure) is concurrent with the hydraulic fracturing (tensile failure), starting near the well and **propagating with repeated microseismic events**.
- Over the course of the 3-h injection, repeated events and aseismic **slip amounted to up to 0.06 m**, with the total radius of the shear **rupture extending up to 200 m.**
- The moment magnitudes in the range Mw -2.5 to 0.5.
- The microseismic magnitude increased depends on several factors, e.g. in general with increases with depth and for more optimally oriented for higher shear stress,
- The largest event (Mw 2.3) was calculated for a **very brittle fault with low residual**.



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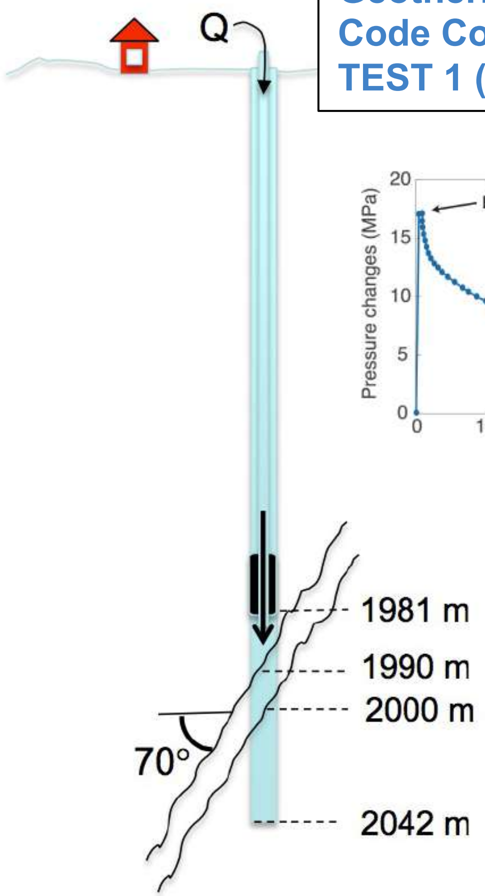
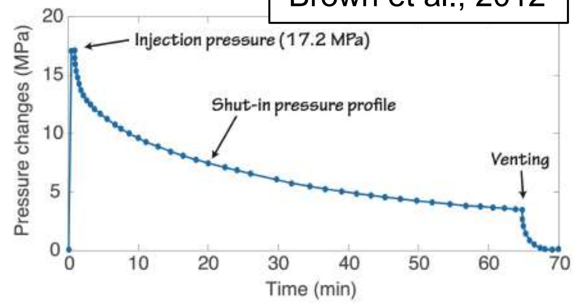
  - Zbinden et al. (2017), On the physics-based processes behind production-induced seismicity in natural gas fields, J. Geophys. Res. – Solid Earth, 122, 3792-3812, doi: 10.1002/2017JB014003
  - Rinaldi et al. (2021), TOUGH3-FLAC3D: a modeling approach for parallel computing of fluid flow and geomechanics, Comput. Geosci., submitted.
  - Rinaldi et al. (in prep.), Modelling the effects on in-situ conditions and two-phase fluid flow on induced seismicity
- Hydraulic fracturing:
  - Rutqvist, et al. (2015), *Modeling of Fault Activation and Seismicity by Injection Directly into a Fault Zone associated with Hydraulic Fracturing of Shale-gas Reservoirs*, J. Petrol. Sci. Eng., 127, 377-386, doi:10.1016/j.petrol.2015.01.019
- Fracture stimulation for geothermal:
  - Rinaldi, A. P., J. Rutqvist, (2019), *Joint opening or hydroshearing? Analyzing a fracture zone stimulation at Fenton Hill*, Geothermics, 77, 83-98. doi:10.1016/j.geothermics.2018.08.006

Fenton Hill Experiment: fracture inflation

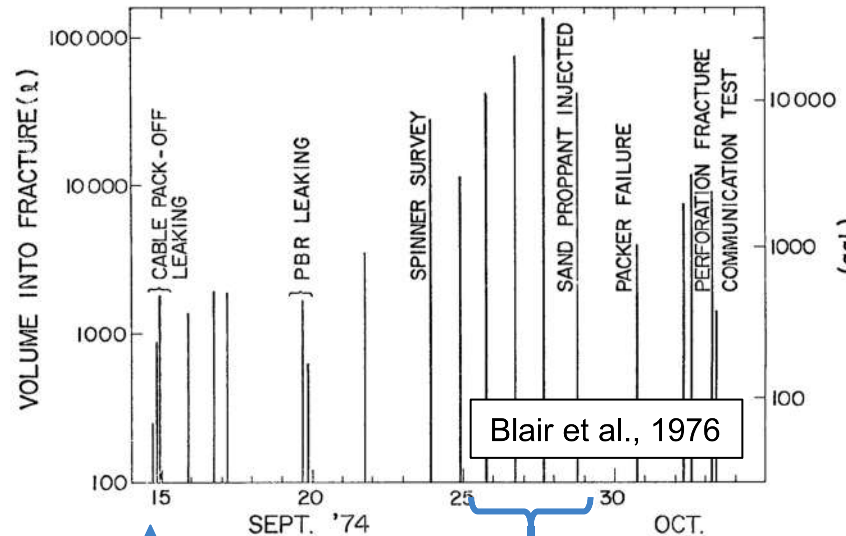
Geothermal Technology Office Code Comparison Study TEST 1 (White et al. 2016)



Brown et al., 2012

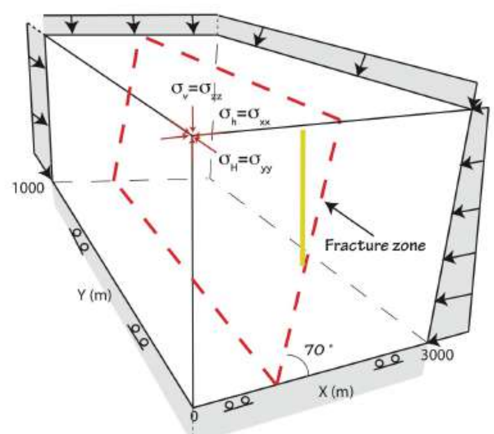


Summary of GT-2 fracture inflation experiments



Blair et al., 1976

TEST 2 TO TEST 4, much less 50 % flow back



Injection directly in fracture

TEST 1 – 4 at constant flow rate of 7.9 l/s. (Total volumes 0.4, 42, 76, 98 m^3) then flow back to recover fluid.

Fracture radius
Estimated to 270 m

Hydroshearing model for fracture zone

$$\boldsymbol{b = b_{el} + b_{shear} + b_{op}}$$

Elastic opening:

$$b_{el} = b_r + b_{max}\exp(\alpha\sigma'_n)$$

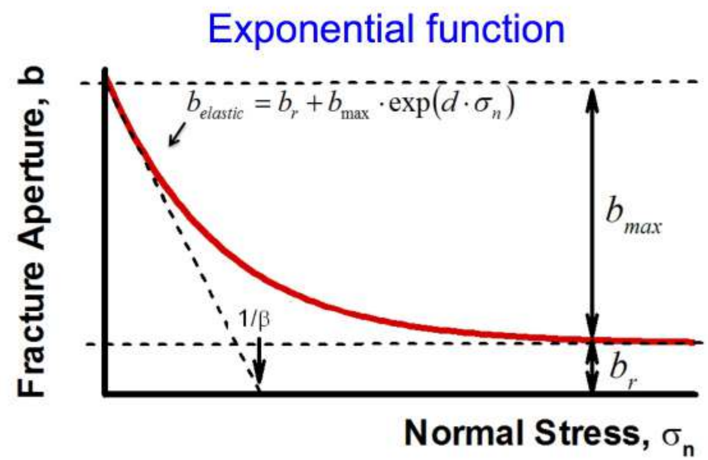
Shearing and tensile opening:

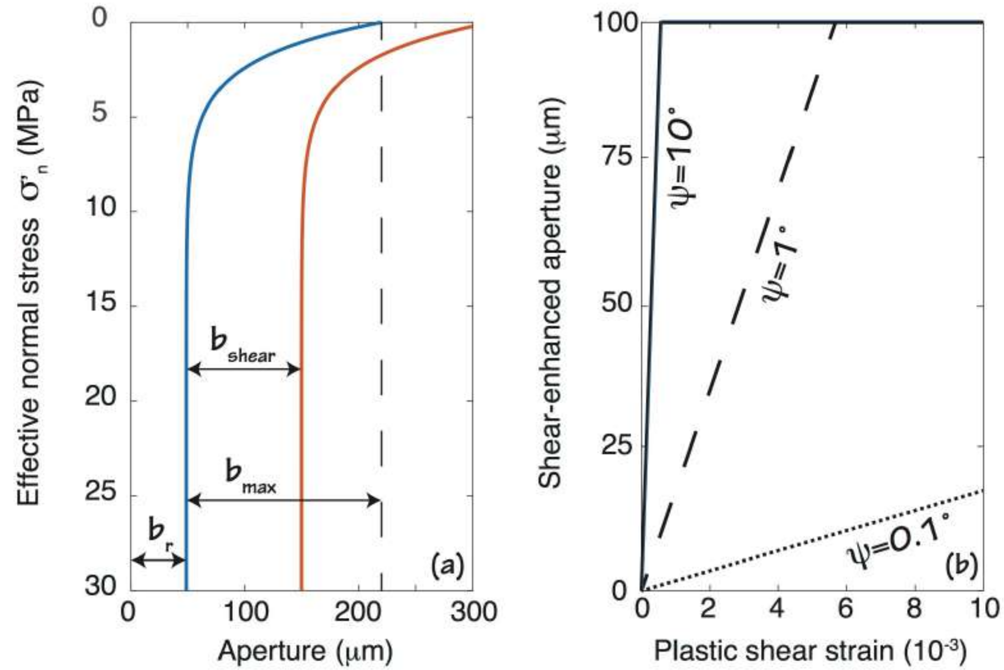
$$b_{shear} = \varepsilon_{ps}\tan(\psi)/f_d$$

$$b_{op} = \varepsilon_{pt} w$$

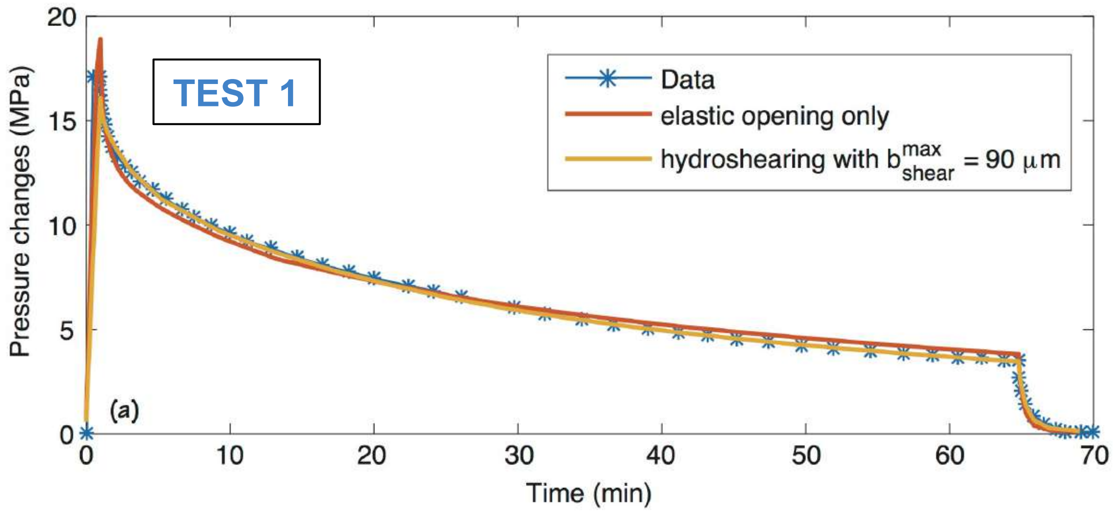
Fracture permeability governed by “cubic law”:

$$\kappa_f = f_d \frac{b^3}{12}$$





Hydroshearing or elastic opening?



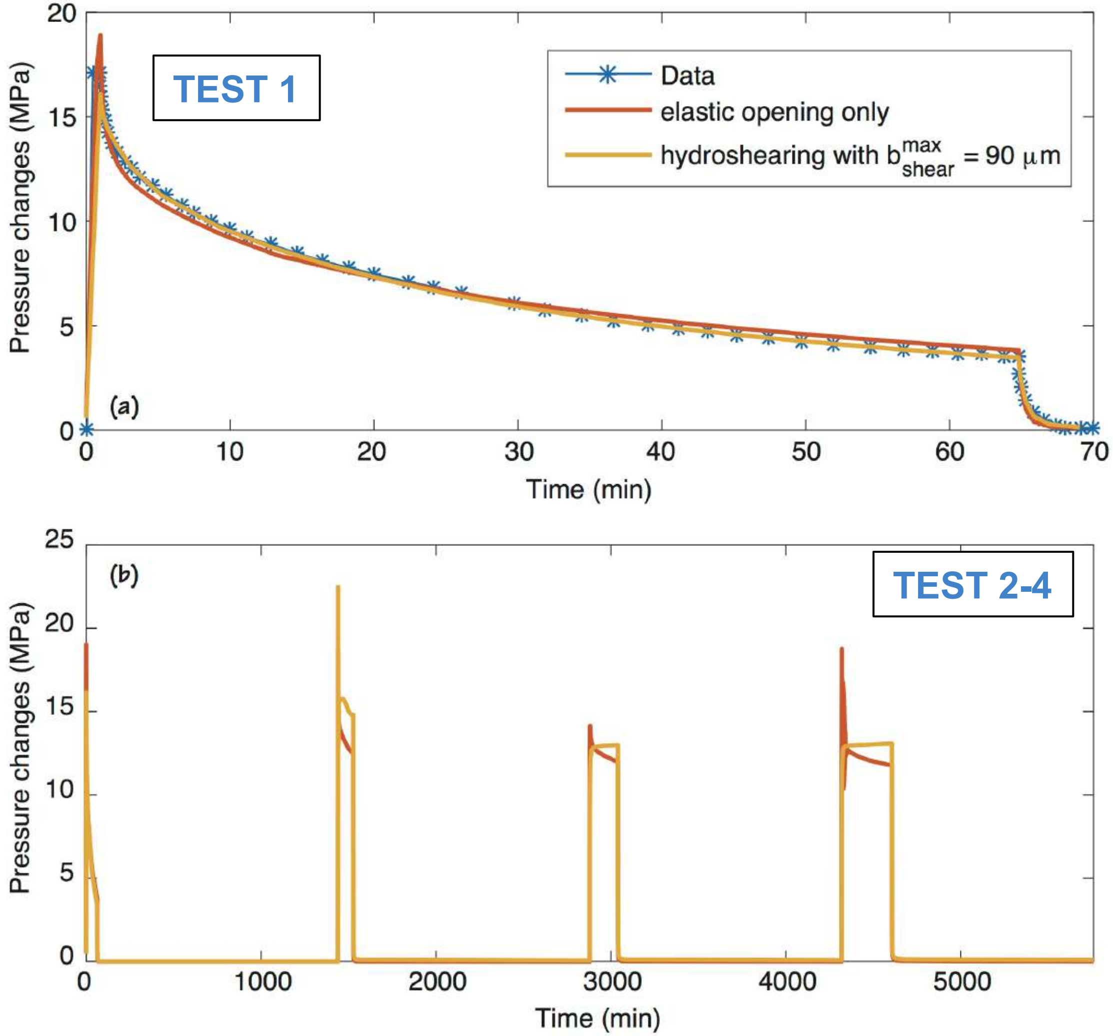
	EL	HS
residual aperture b_r (μm)	18.2	21.1
maximum aperture b_{max} (μm)	1300	569
stress dependency α (MPa⁻¹)	0.37	0.45
maximum shear aperture b_{shear}^{max} (μm)	-	90
dilation angle ψ (°)	-	10

Calibrated parameters

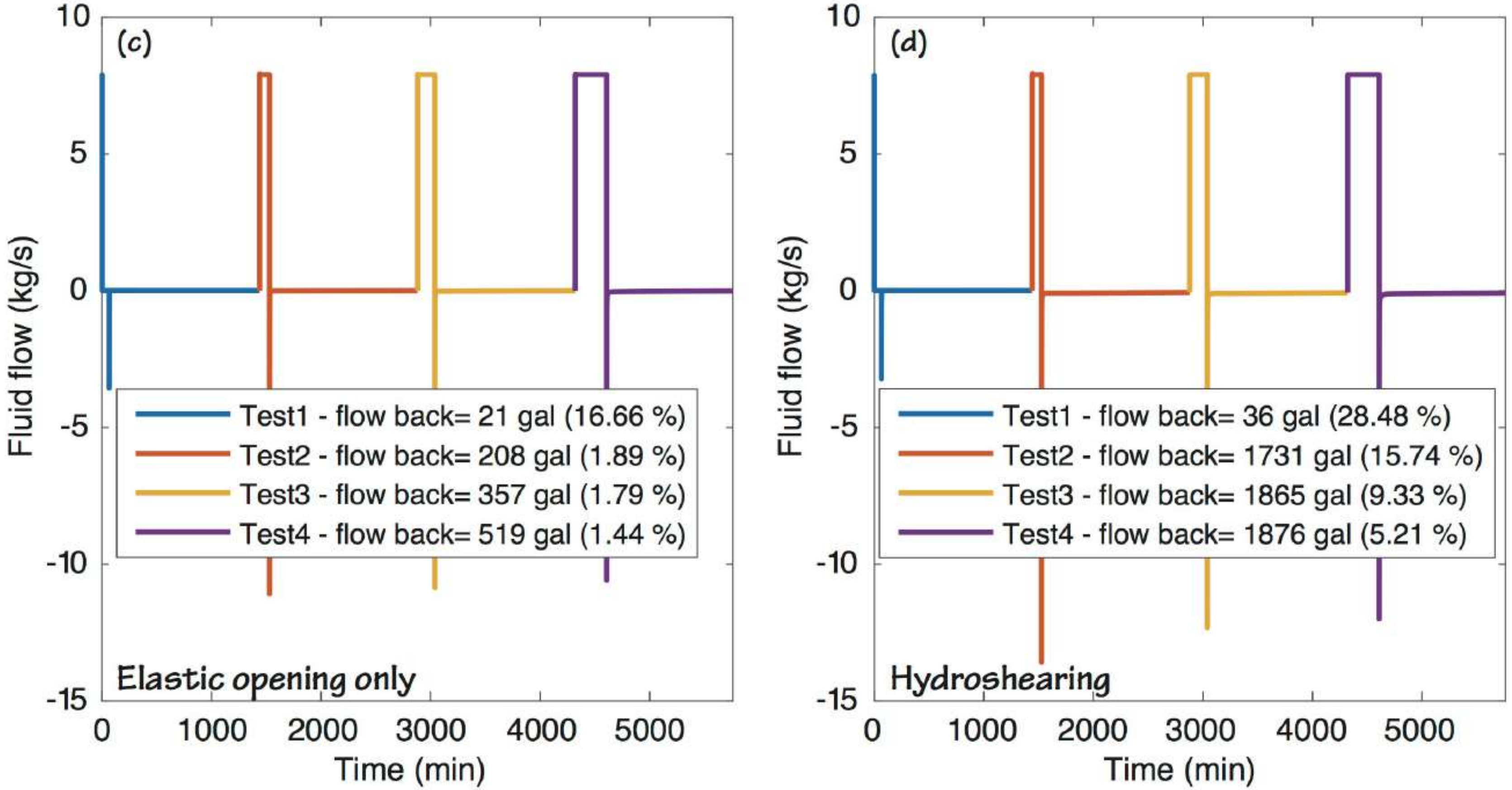
Calibration with iTOUGH2-PEST + TOUGH-FLAC

(Rinaldi et al., 2017)

Hydroshearing or opening?
Pressure evolution

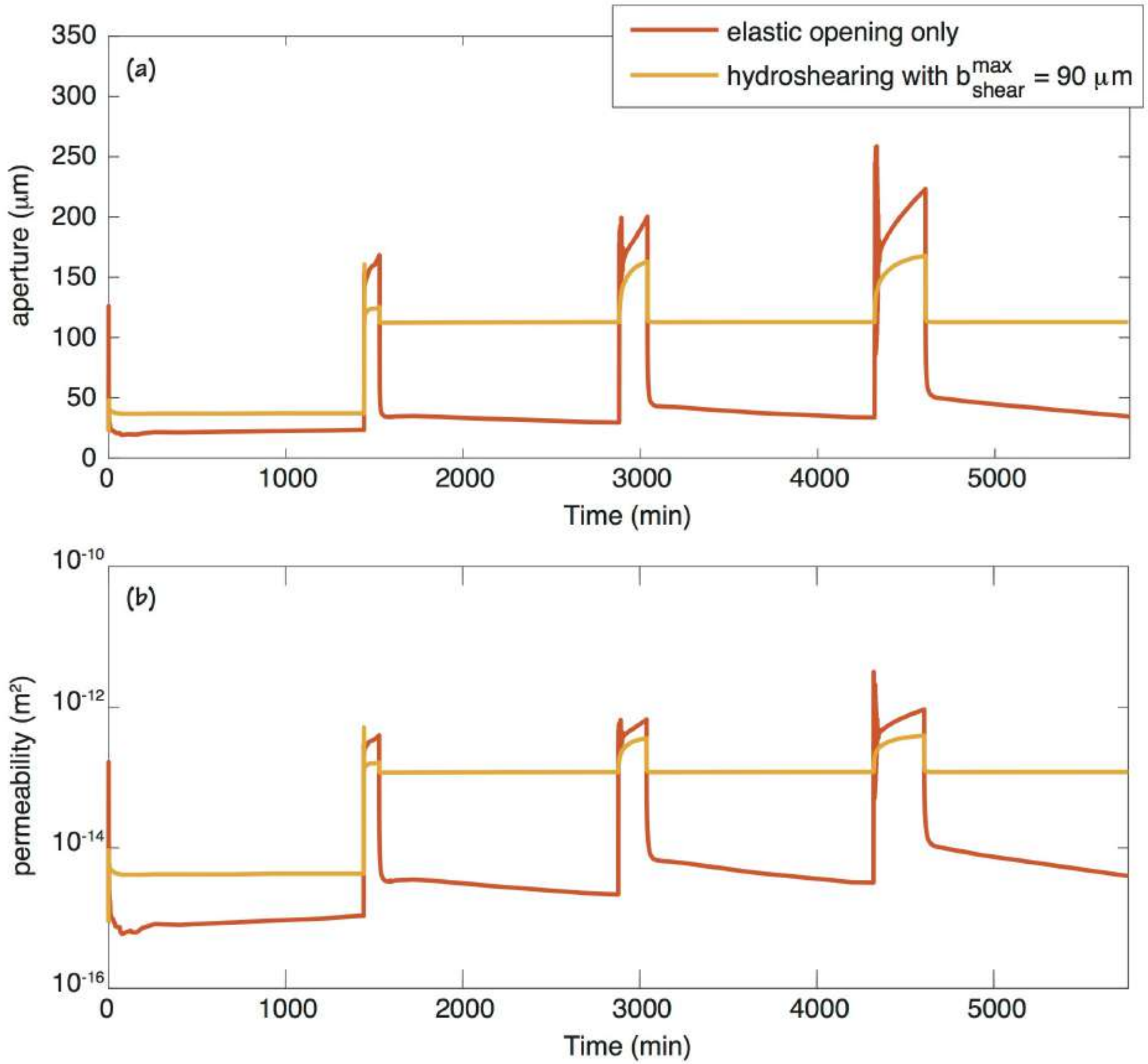


Hydroshearing or opening?
Flow back



Our interpretation of "much less than half" is in the order of few percent not less than 2%

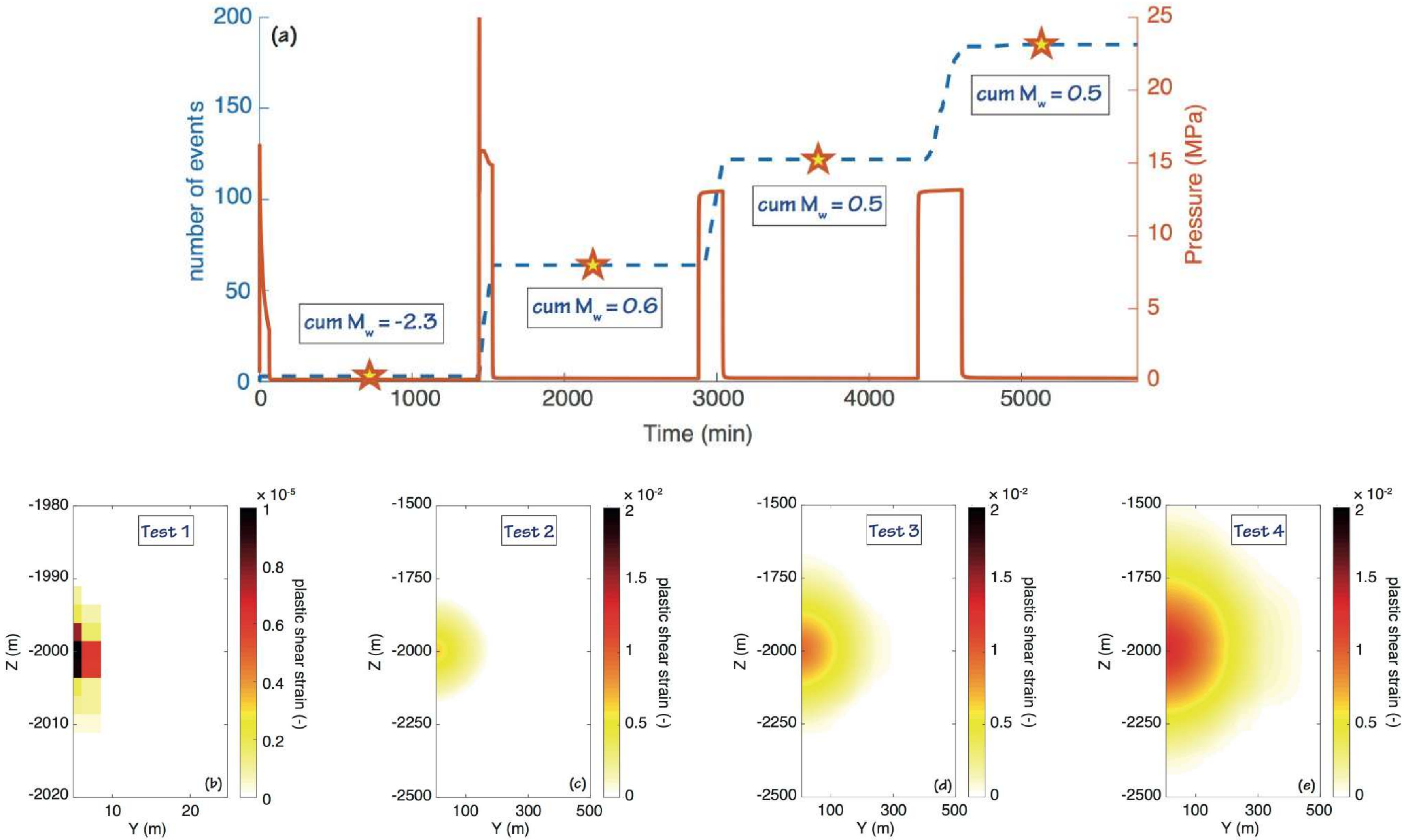
Hydroshearing or opening?
Permeability evolution



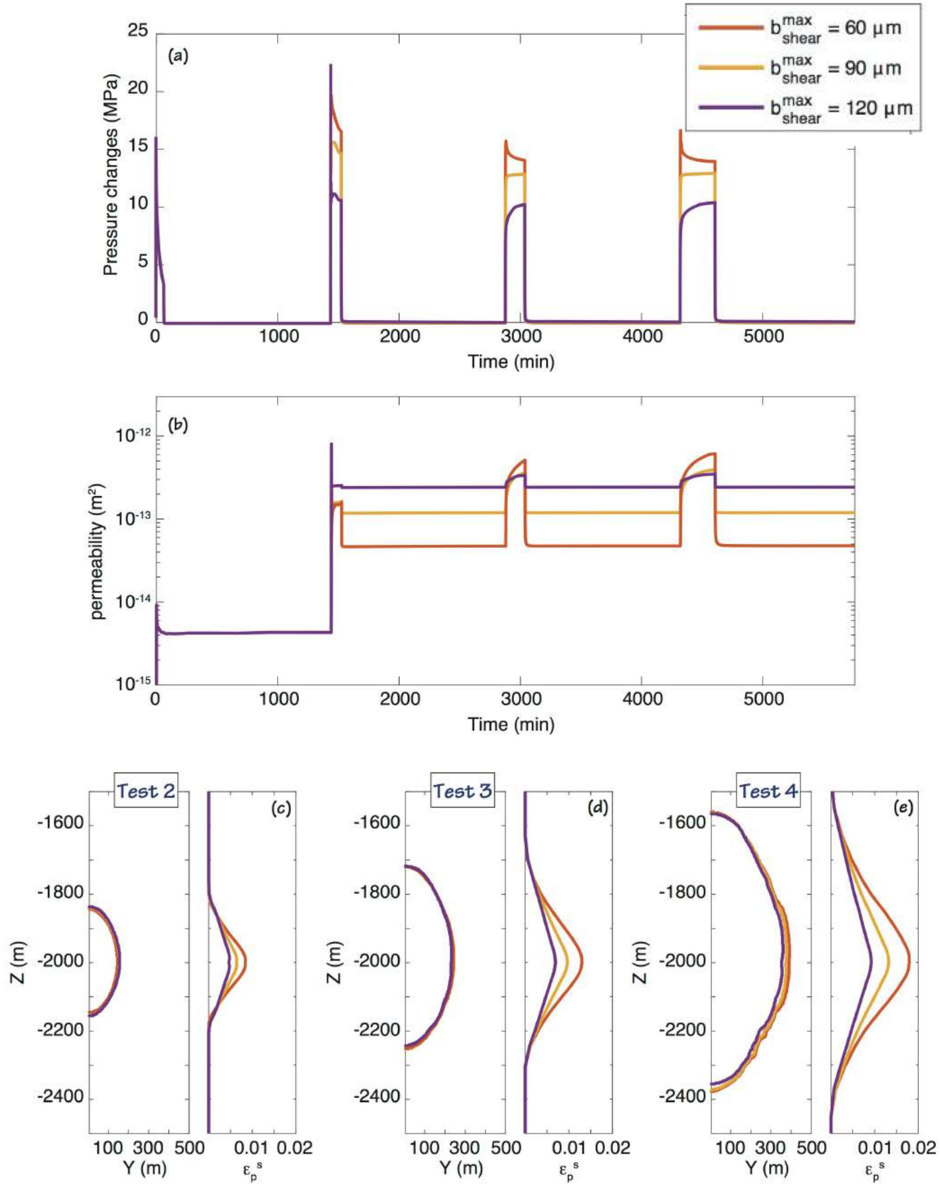
Hydroshearing or opening?
Sheared zone and seismicity

www.seismo.ethz.ch

EARTH & ENVIRONMENTAL SCIENCES



Changing the maximum shear aperture

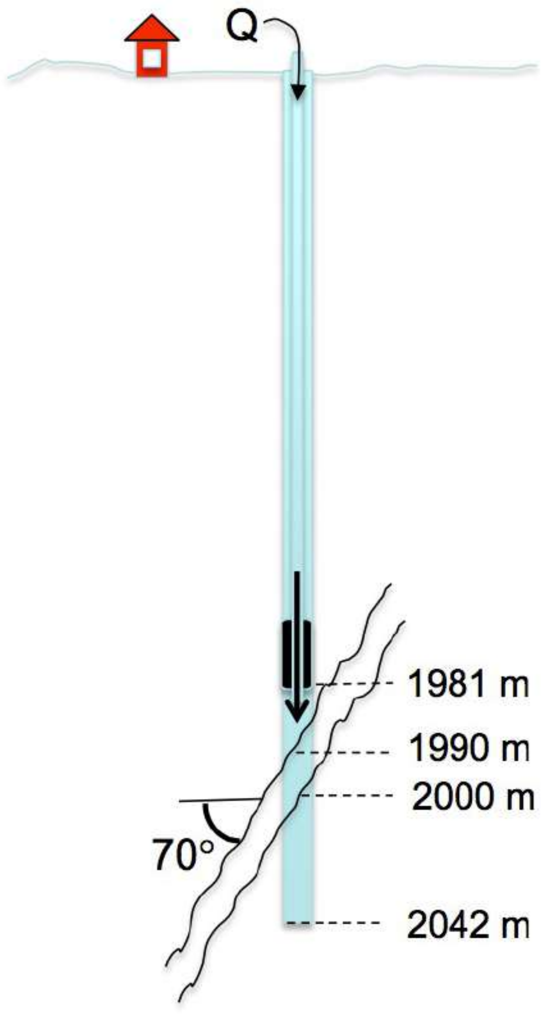


CASE	60 μm			90 μm			120 μm		
	(%)	M_w	n_{ev}	(%)	M_w	n_{ev}	(%)	M_w	n_{ev}
Test 1	28	-2.3	3	28	-2.3	3	28	-2.3	3
Test 2	8.5	0.6	72	16	0.6	61	23	0.5	63
Test 3	5.2	0.6	66	9.3	0.5	58	15	0.4	59
Test 4	3.4	0.6	65	5.2	0.5	63	8.3	0.5	58

Larger maximum shear aperture allows larger flow back, with slightly smaller cumulative seismic magnitude (less pressure)

Conclusion – part 3

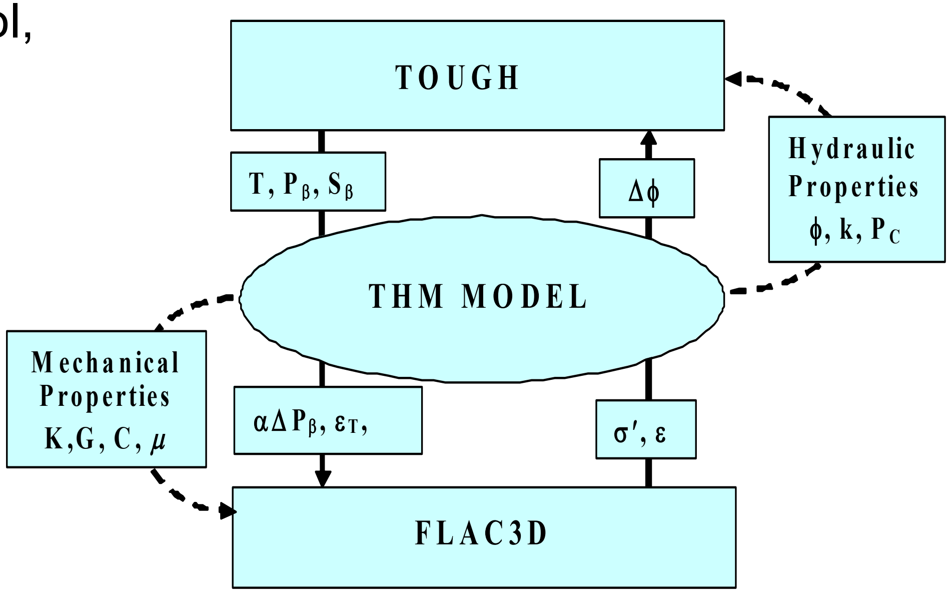
- The Fenton Hill experiments could be explained by **combined effects of shear dilation and non-linear elastic fracture opening**
- **Results are quite sensitive to parameters variation**.
- **Assuming appropriate conditions**, the simulation results suggest that permeability can be enhanced without inducing large seismic events.
- But results also highlight the importance of **monitoring not only for seismic activity**, in particular for storage projects, given the possible aseismic creation of permeable pathway compromising the sealing capacity of a given site.



Conclusive remarks

- Understanding the physics behind fault reactivation and **induced seismicity is not trivial.**
- Currently we still miss a full understanding on **how to exploit the underground and at the same time avoid dangerous seismicity**
- Modeling can help, but **right assumptions are needed** otherwise easy misinterpretation.

- TOUGH-FLAC reliable and flexible tool, despite being “semi”-commercial and with some technical limitations
- Just to list few of them
  - Not fully accounting for explicit fracture network
  - No flexibility on solver for the mechanical part
  - The approach may be unstable for complex coupling relationships



Thank you!