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Hydroshearing and permeability enhancement: Revisiting a fracture zone stimulation at Fenton Hill

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5 - 8 March 2019
DAVOS
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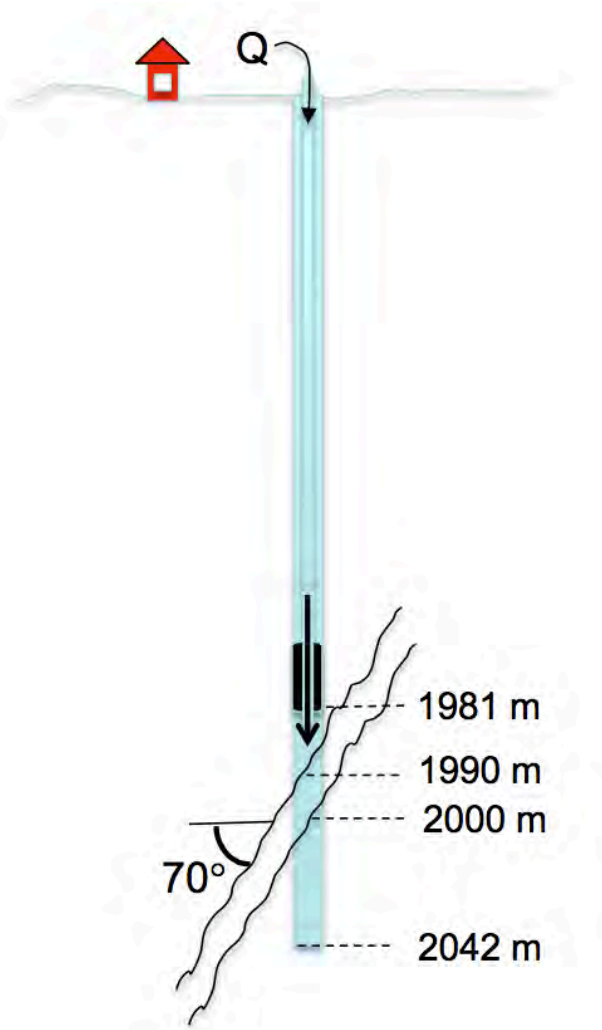
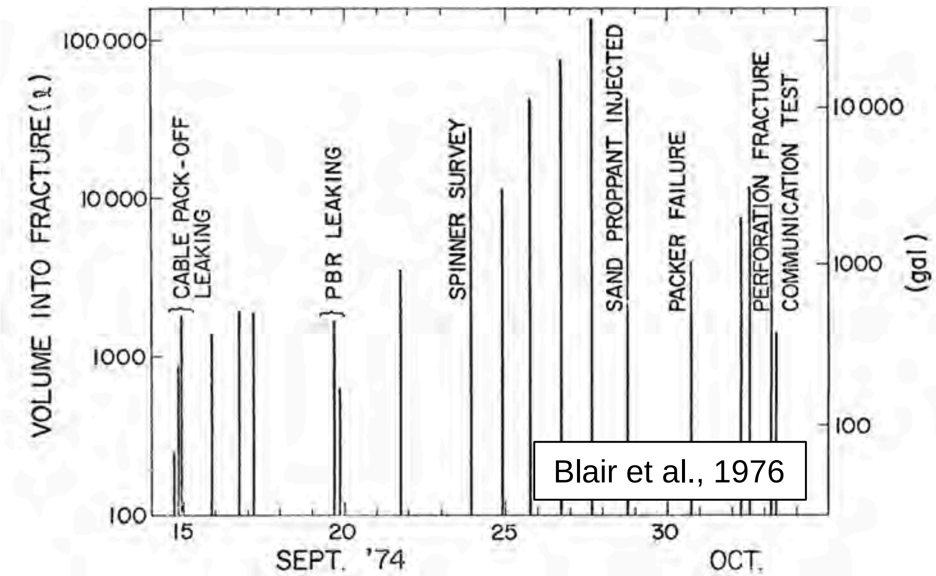
3rd Induced Seismicity Workshop

Fenton Hill Experiment: fracture inflation



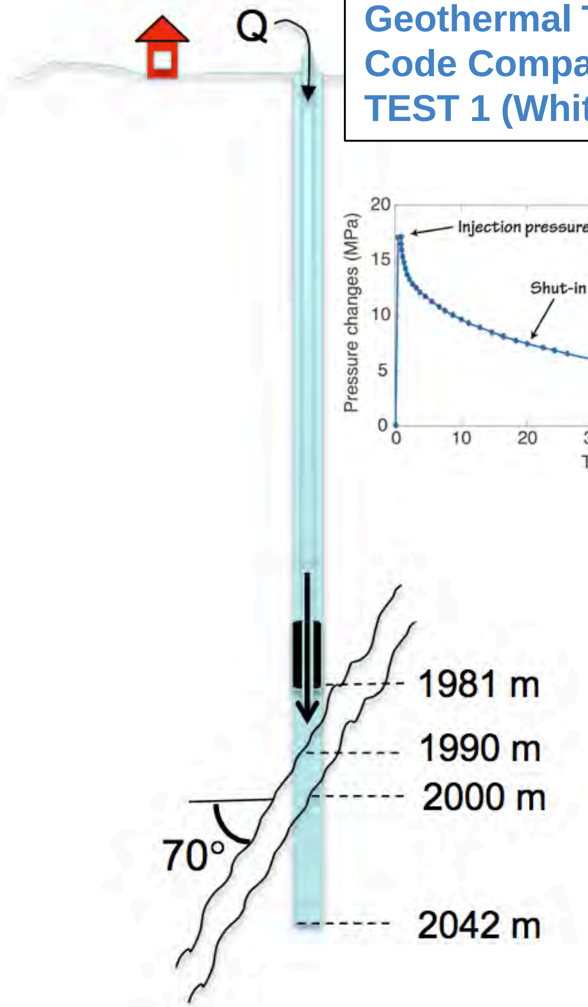
Fracture radius
Estimated to 270 m

Summary of GT-2 fracture inflation experiments

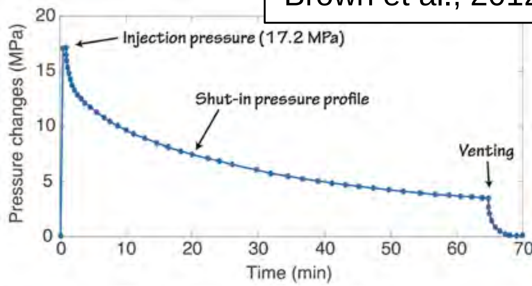


Fenton Hill Experiment: fracture inflation

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



Brown et al., 2012



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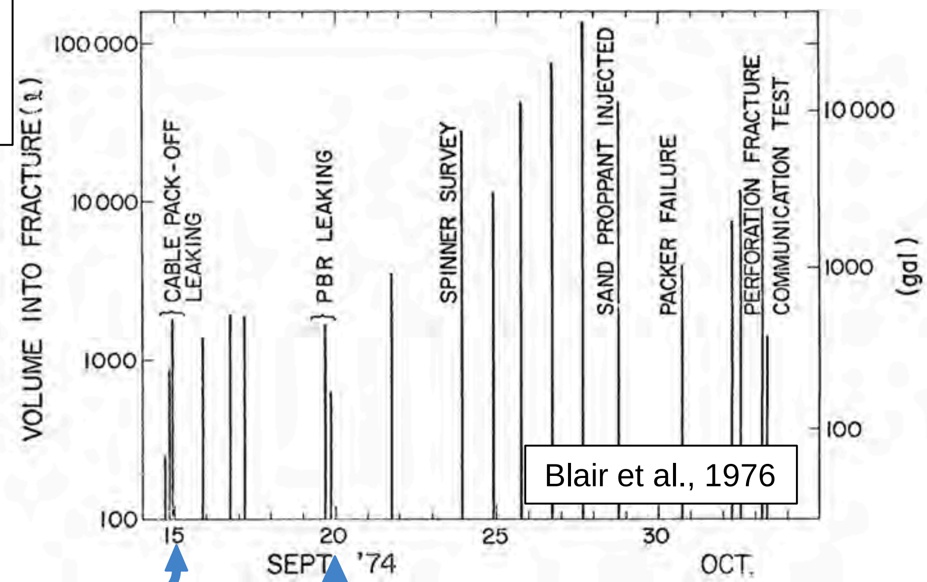
Summary of GT-2 fracture inflation experiments



Blair et al., 1976

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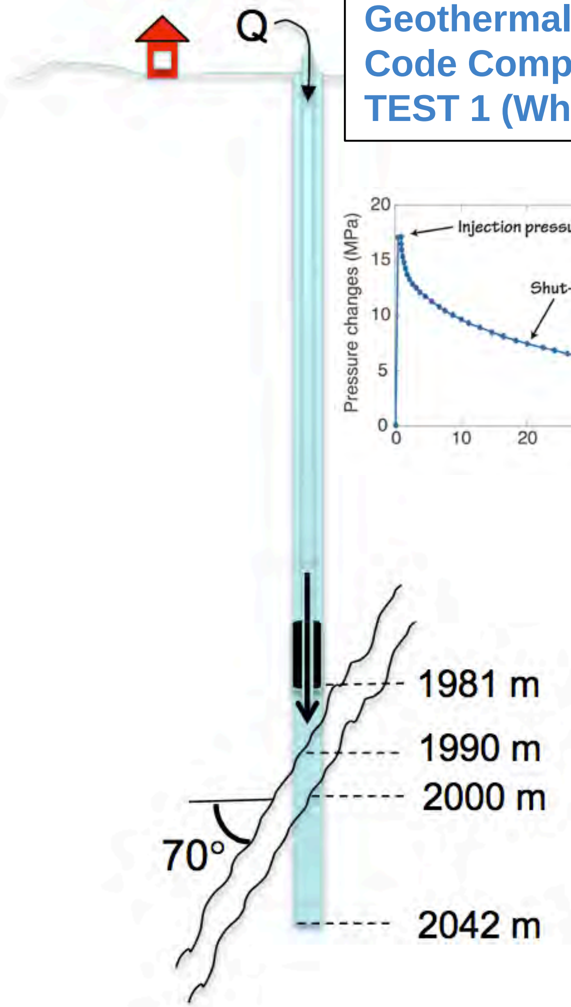
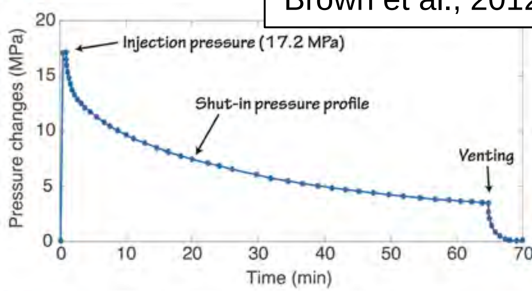
Geothermal Technology Office Code Comparison Study TEST 1 (White et al. 2016)



Brown et al., 2012



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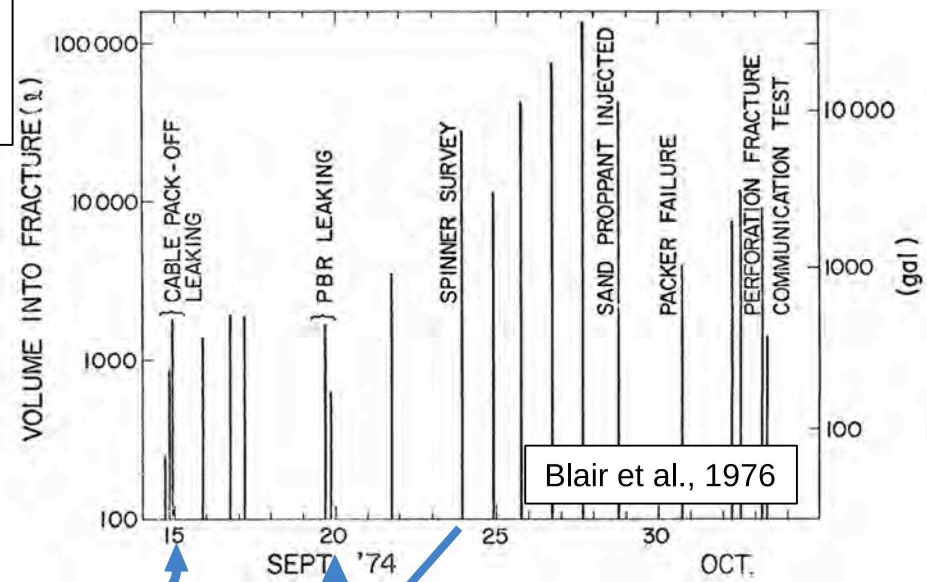

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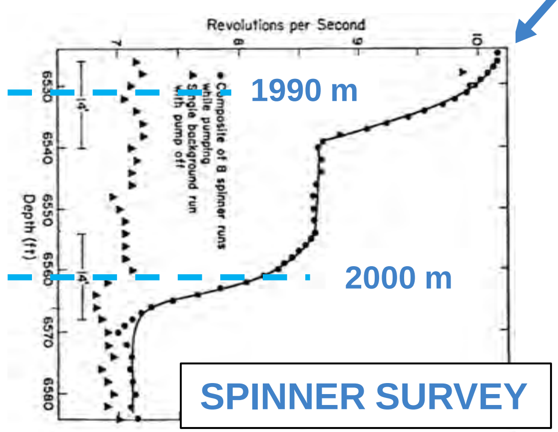


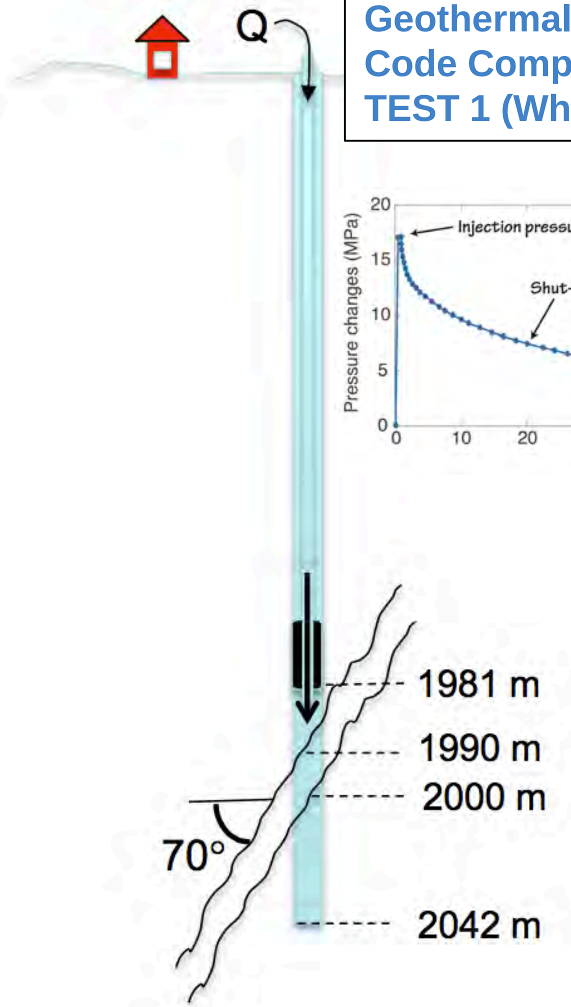
SPINNER SURVEY

Fracture radius
Estimated to 270 m

Fenton Hill Experiment: fracture inflation

Summary of GT-2 fracture inflation experiments

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



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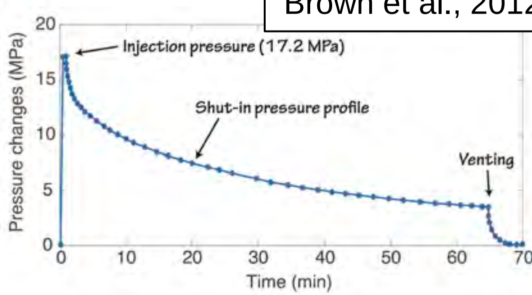

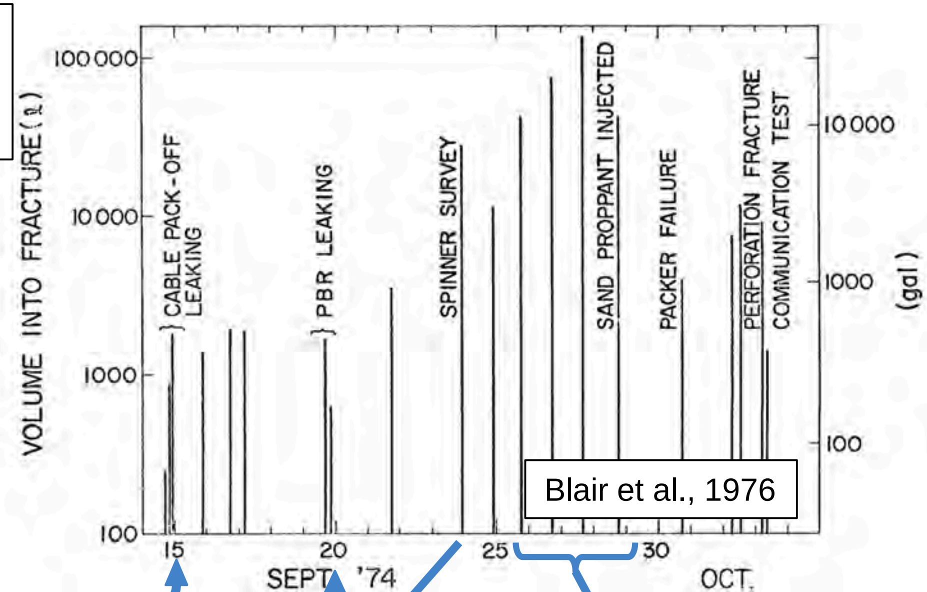

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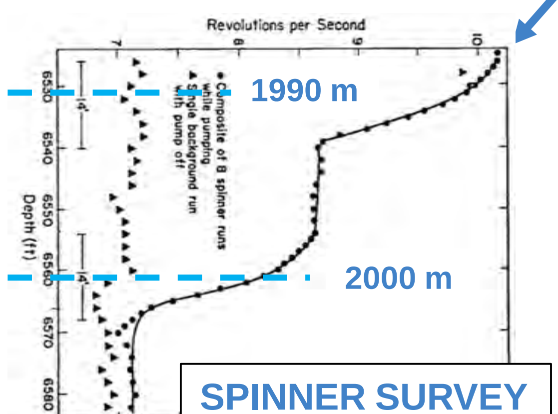


SPINNER SURVEY

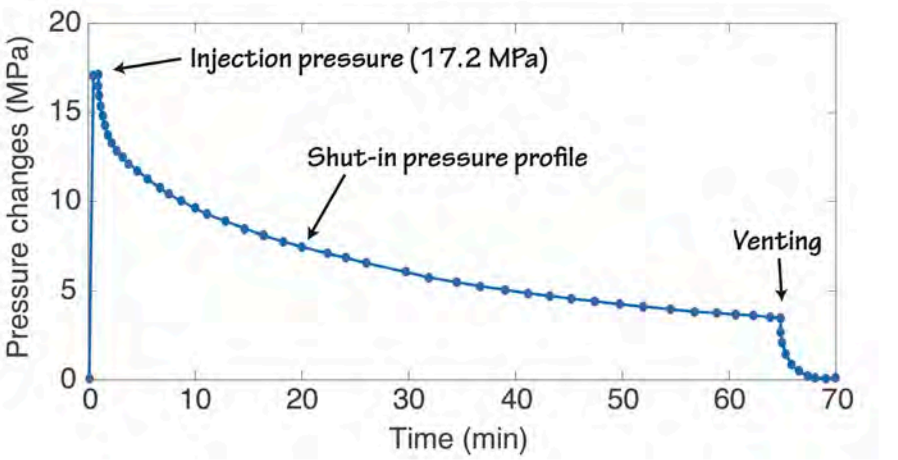
Geothermal Technology Office Code Comparison Study TEST 2 TO TEST 5

Fracture radius
Estimated to 270 m

GTO-CCS: problem #2

- **White et al., 2016: identify the correct opening mechanics**
- *Question*
  Assuming natural joints were being opened by the hydraulic stimulation, what are the hydro-mechanical responses of the joints to fluid injection, shut-in, and venting (flow-back)?
- *Metrics*
  Three key observations:

1. The pressure history during and following the first pressure-stimulation test – TEST1.
2. The observation that much less than half of the injected fluid was recovered in each of the three subsequent tests (pressure always below 17.2 MPa) – TEST2-4.
3. The observation that a much greater portion of the injected fluid was recovered after an injection experiment using proppants – TEST5.



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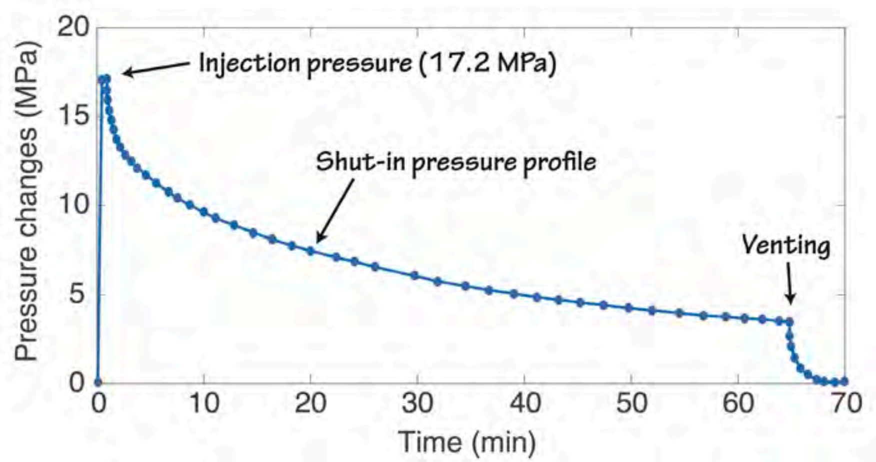
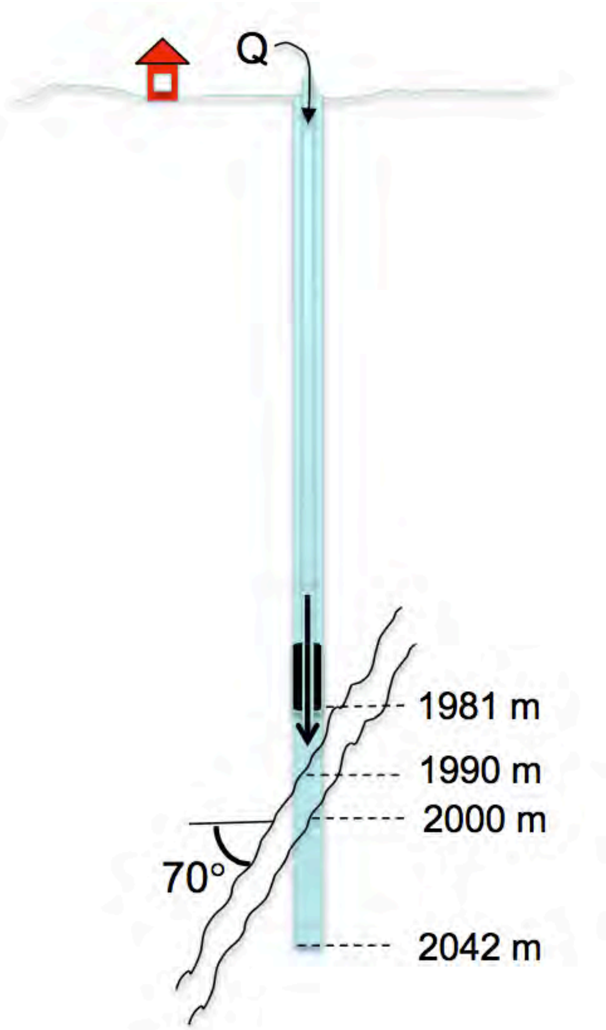
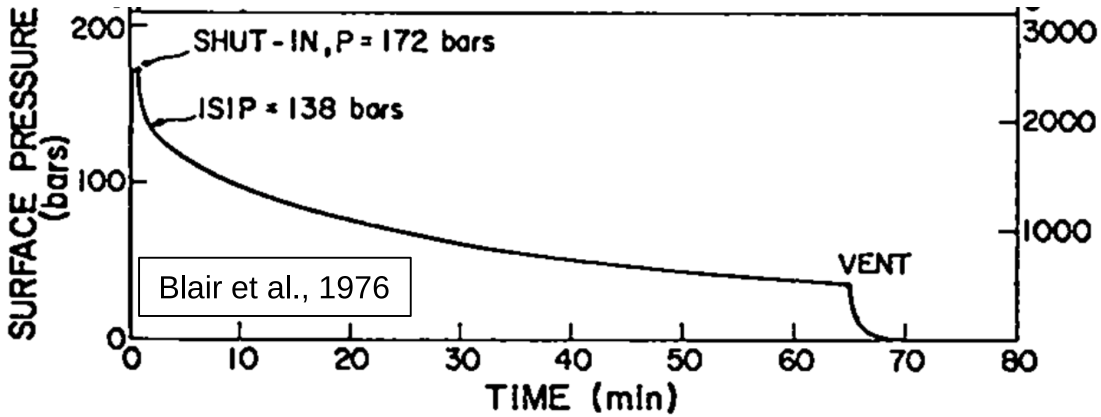


Potential shear reactivation?





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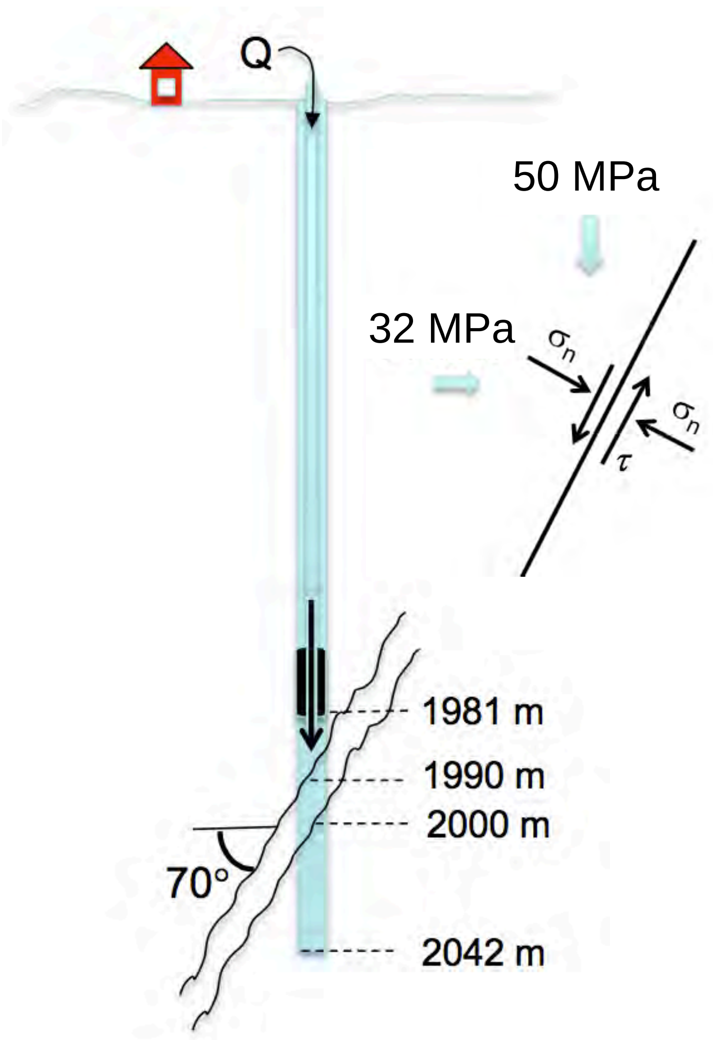
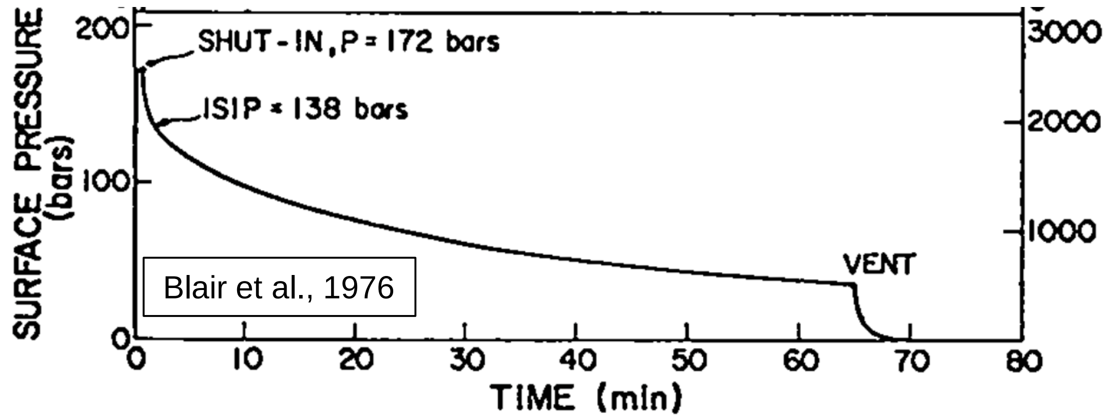
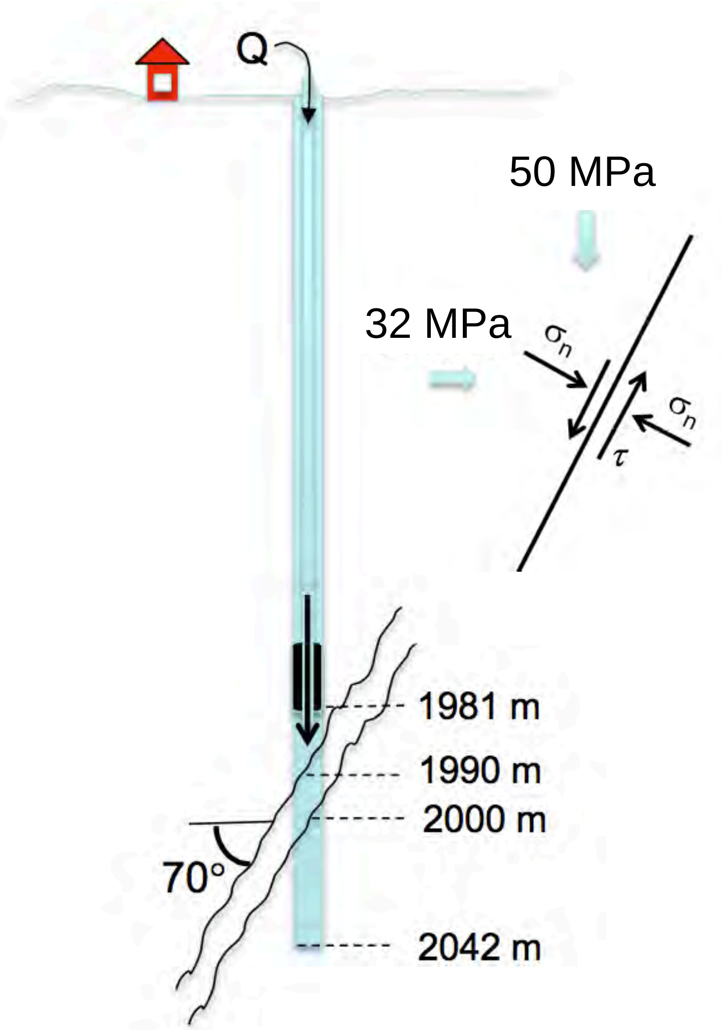


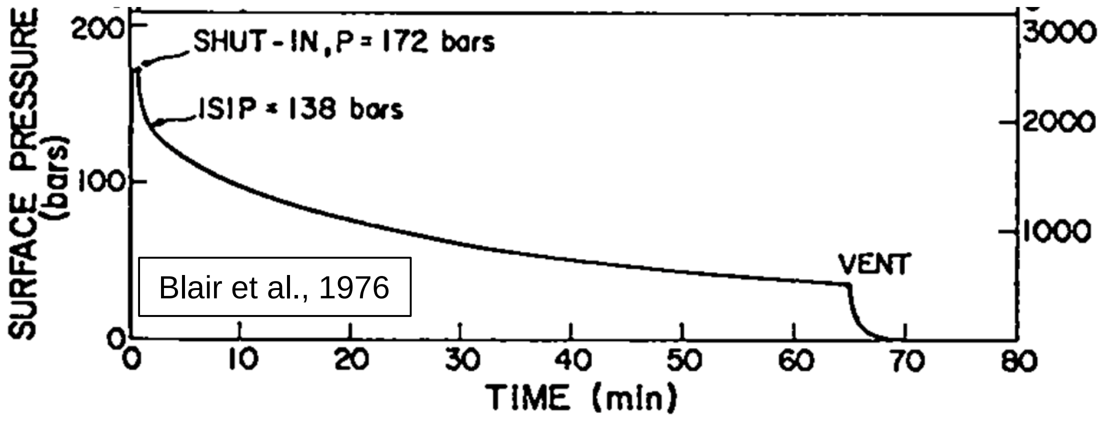


- ISIP = 138 bar ⇒σ_n=20+13.8 ~ 34 MPa
- Vertical stress ~ 50 MPa;
- Shear stress: 5.8 MPa

Fracture radius
Estimated to 270 m

Potential shear reactivation?





- ISIP = 138 bar $\Rightarrow \sigma_n$=20+13.8 ~ 34 MPa
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- Shear stress: 5.8 MPa

- Shear strength: $\tau_c = S_0 + \sigma'_n \mu$

  τ_c = 9.4 MPa, for S_0 = 1 MPa and μ = 0.6

Fracture radius
Estimated to 270 m

Potential shear reactivation?

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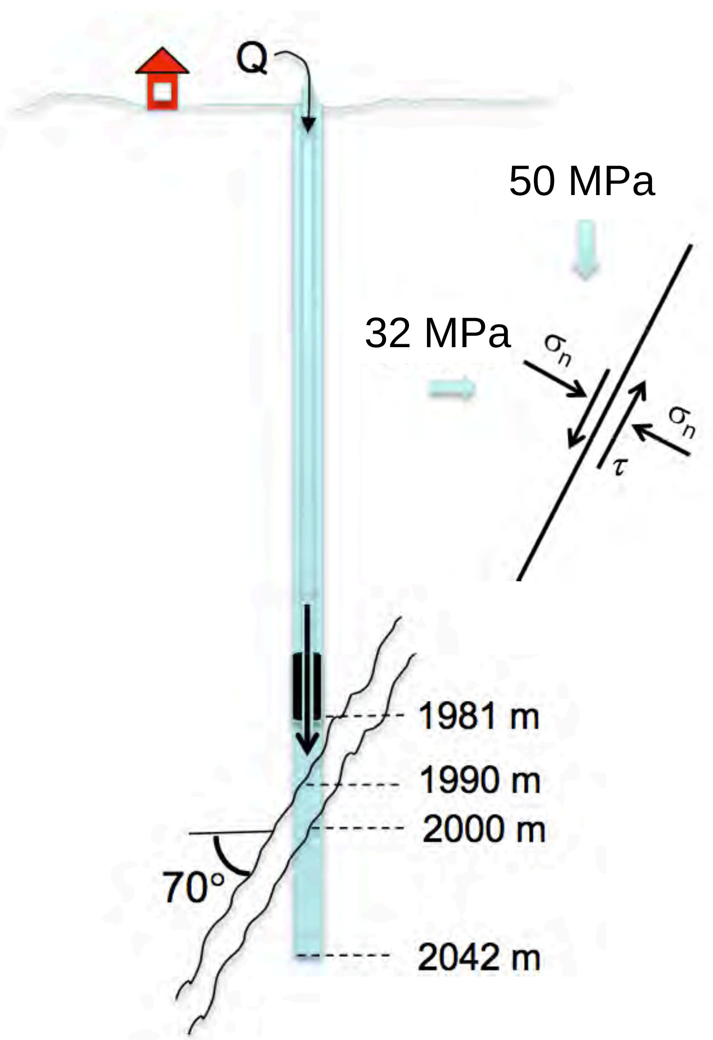

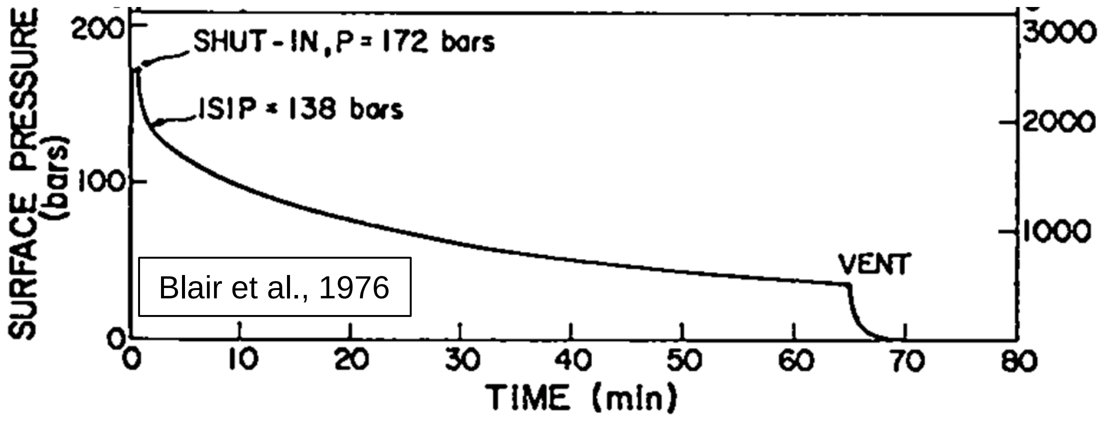

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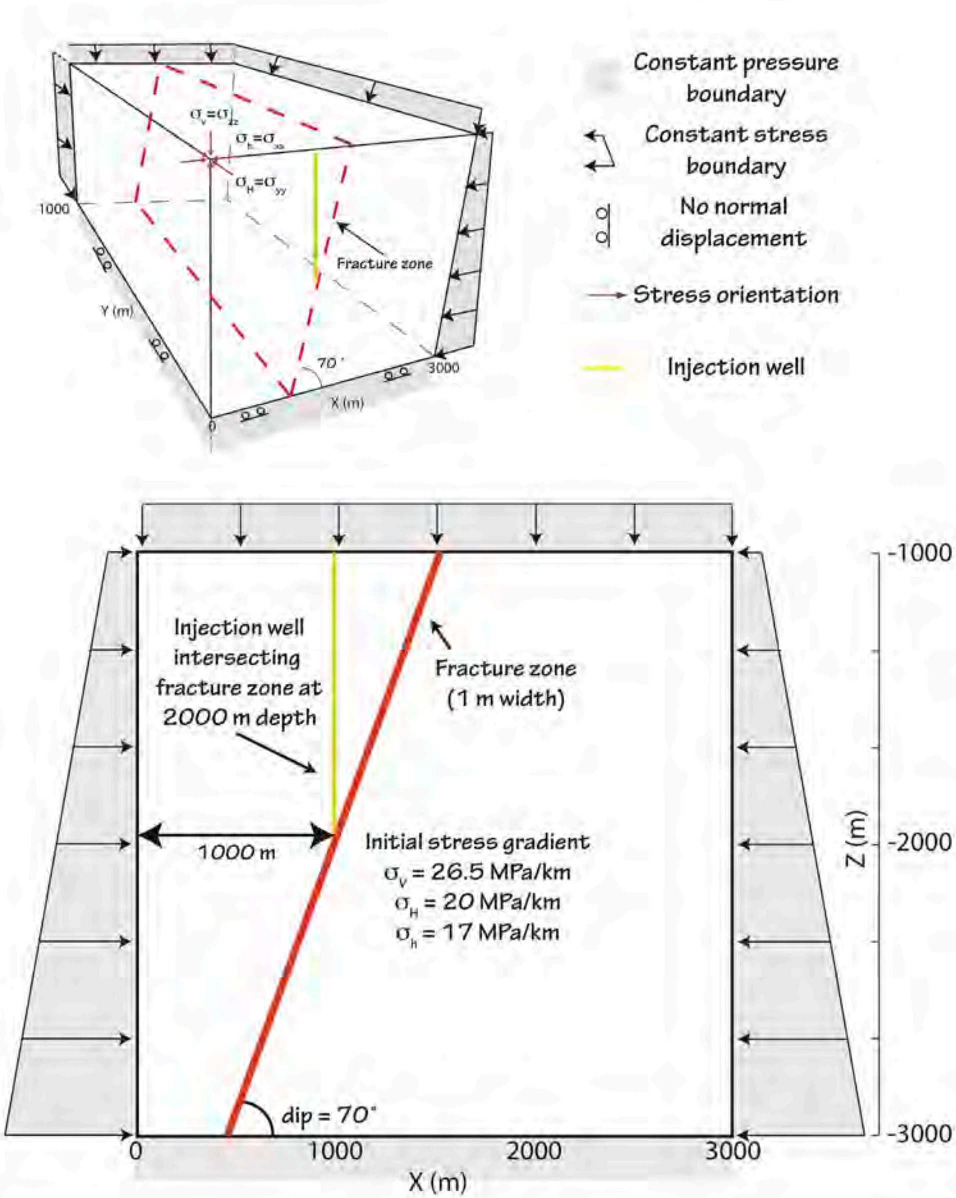
- Pressure at shear:

$$P = \frac{S_0 + \sigma_n \mu - \tau}{\mu} \Rightarrow P = 26 \text{ MPa}$$

Fracture radius
Estimated to 270 m

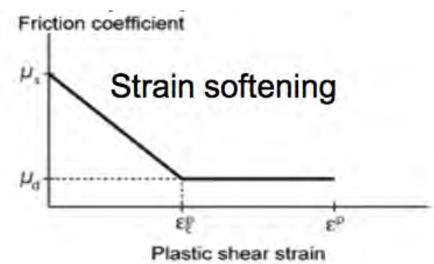
Shear slip occurs before fracturing!

Modeling Approach



TOUGH-FLAC
(Rutqvist et al., 2015; Rinaldi et al., 2015)

- Tests 1 – 4; at rate of 7.9 l/s. (0.4, 42, 76, 98 m^3; 105, 11000, 20000, 36000 gals)
- Fracture represented by finite thickness element
- Anisotropic plasticity model allowing shear (Coulomb) and tensile failure
- Strain-softening for sudden slip



- Cumulative seismic moment as:

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

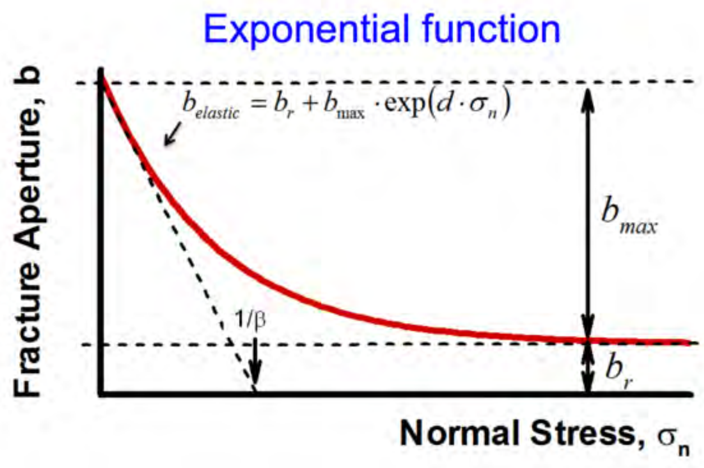
$$cumM_w = \frac{2}{3}\log_{10} M_0 - 6.1$$

Hydroshearing model for fracture zone

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

Elastic opening:

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



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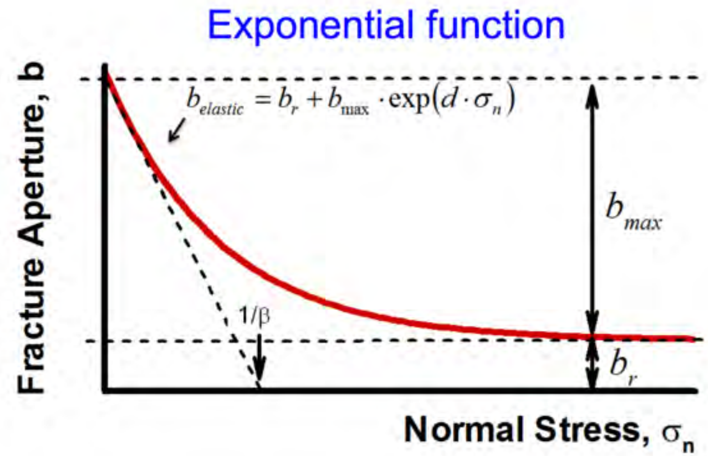
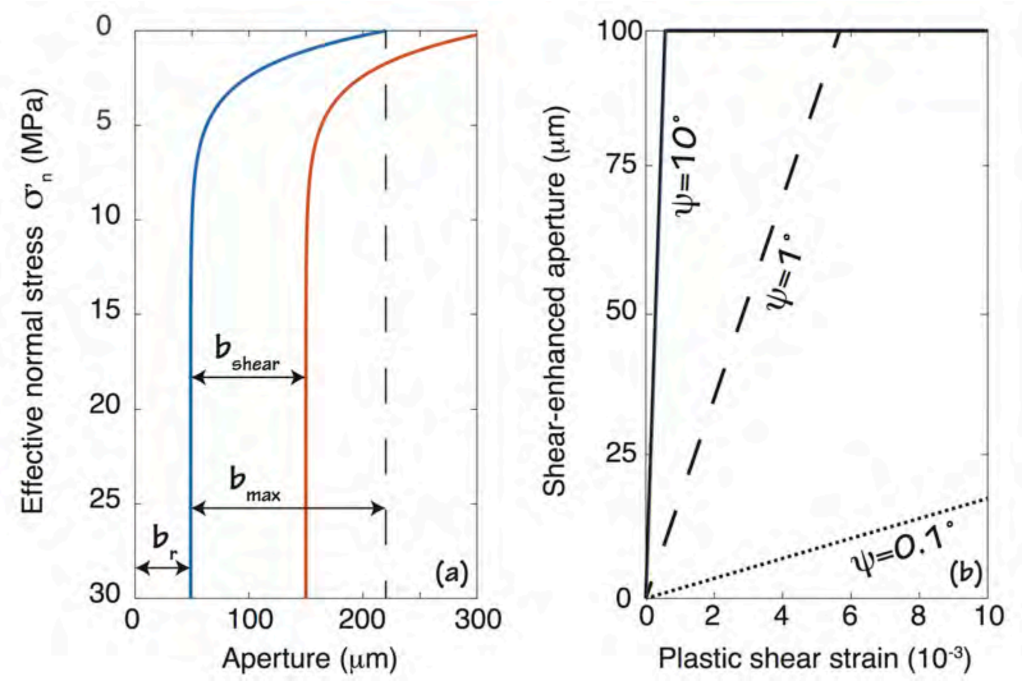
Shearing and tensile opening:

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

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





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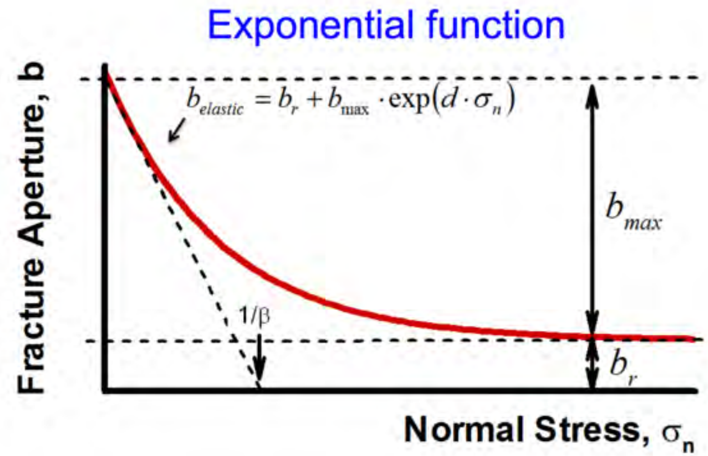
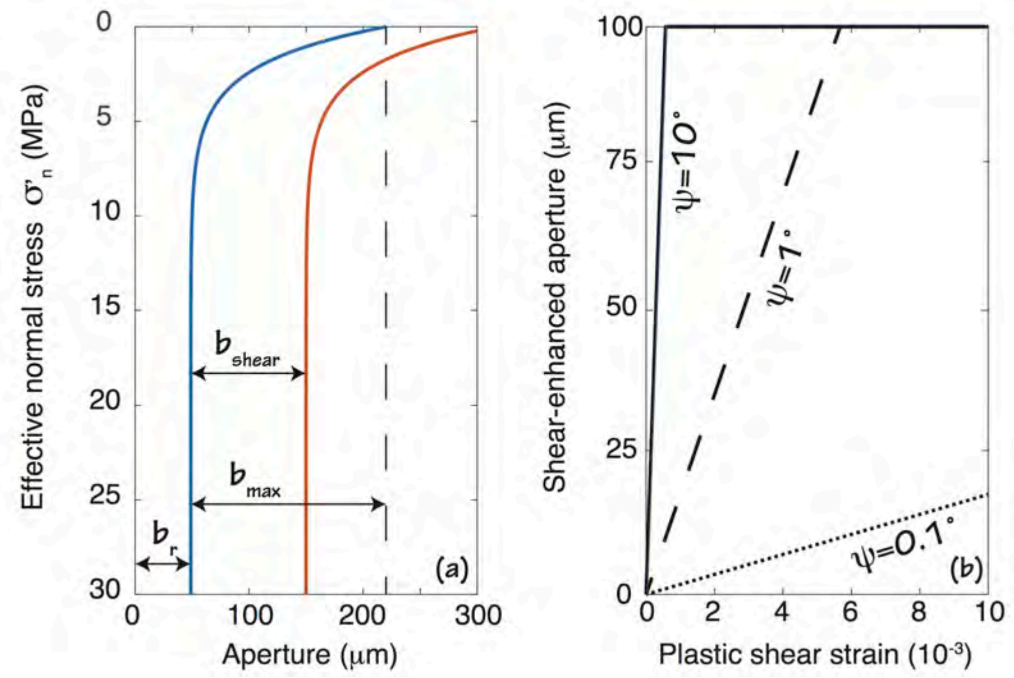
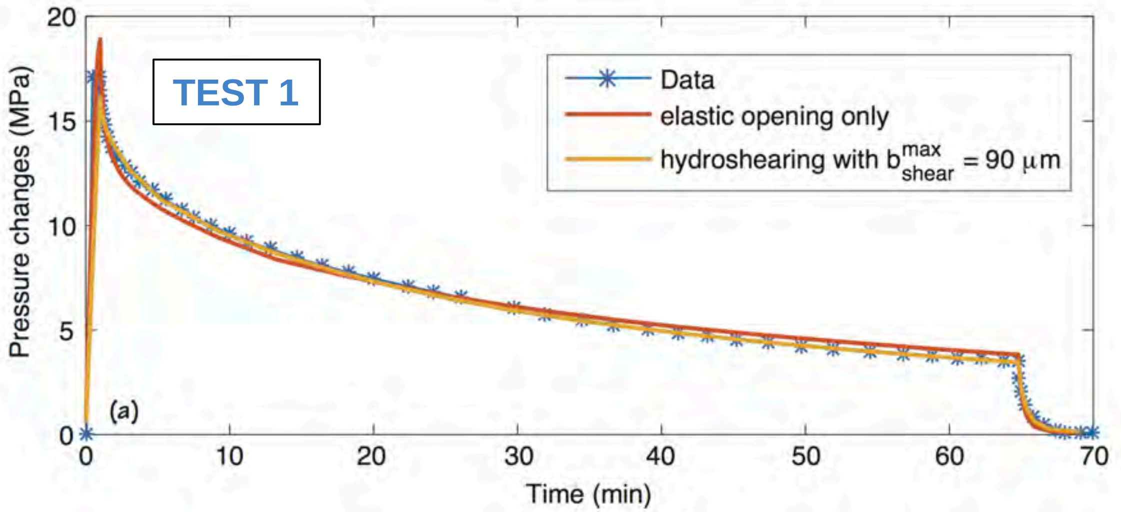
Fracture permeability governed by “cubic law”:

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





Hydroshearing or elastic opening?



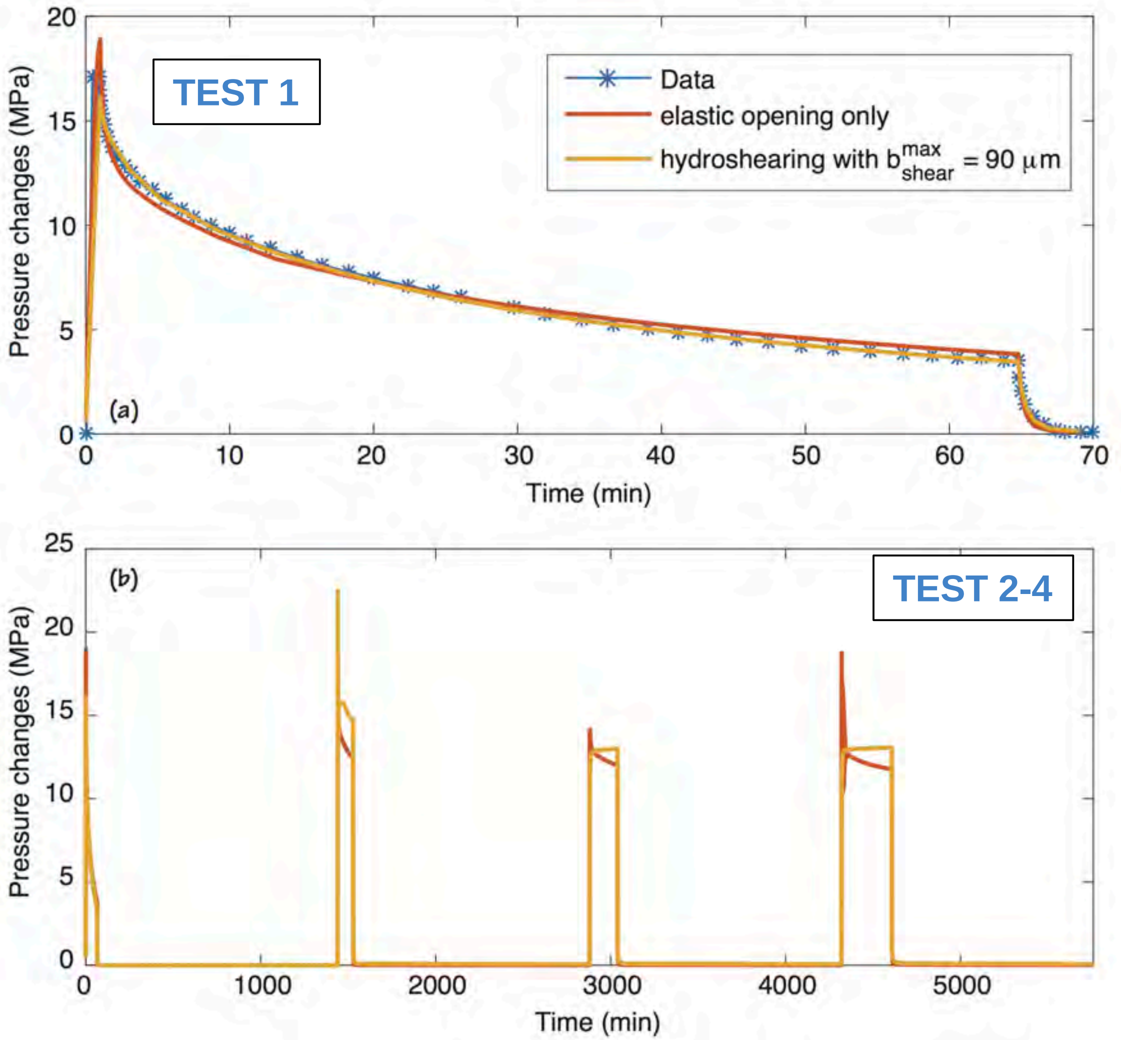
	EL	HS
residual aperture b_r (µm)	18.2	21.1
maximum aperture b_{max} (µm)	1300	569
stress dependency α (MPa^{-1})	0.37	0.45
maximum shear aperture b_{shear}^{max} (µm)	-	90
dilation angle ψ (°)	-	10

Calibrated parameters

Calibration with iTOUGH2-PEST + TOUGH-FLAC

(Rinaldi et al., 2017)

Hydroshearing or opening?
Pressure evolution



Hydroshearing or opening?
Flow back

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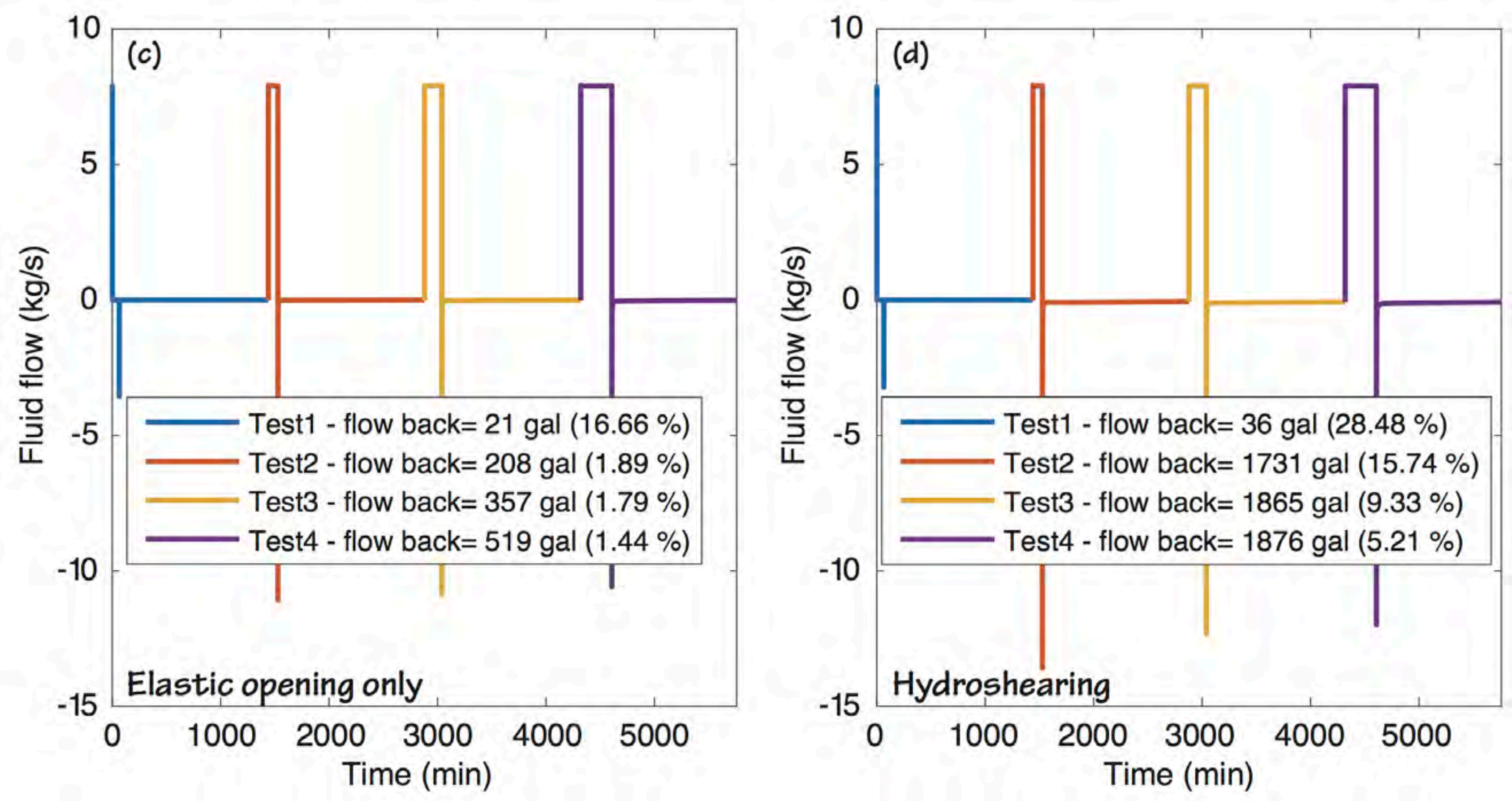
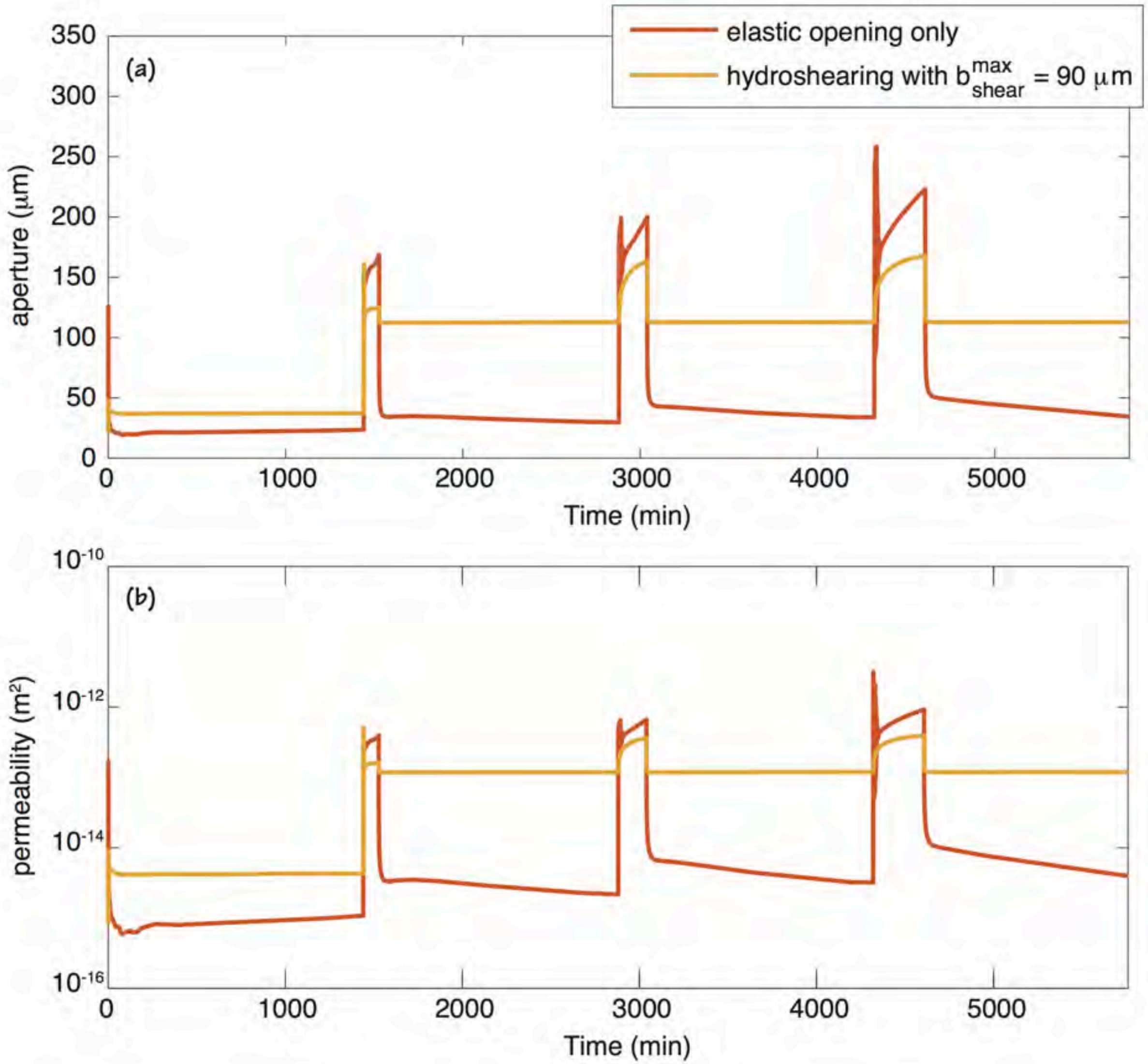
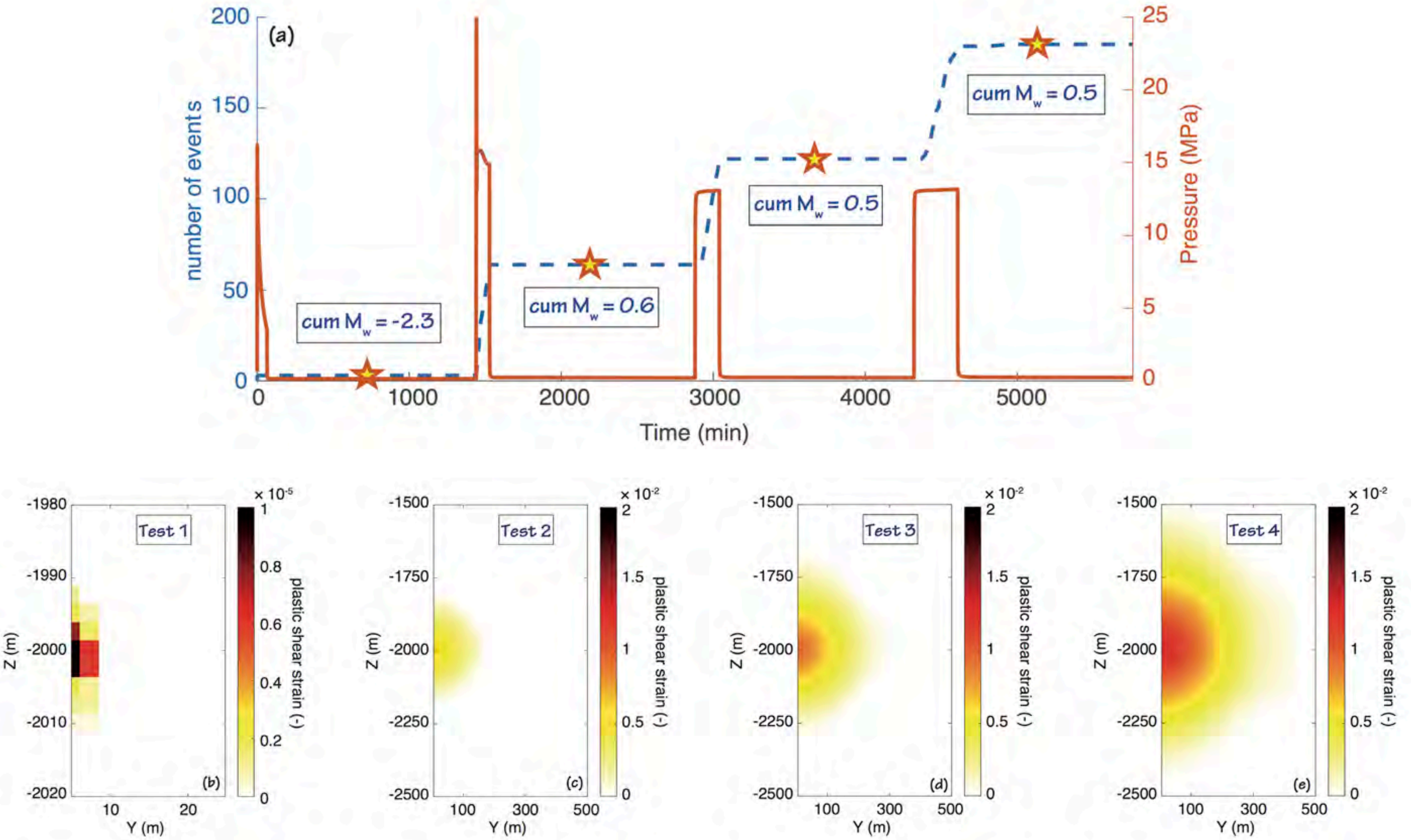


Our interpretation of "much less than half" is in the order of few percent not less than 2%

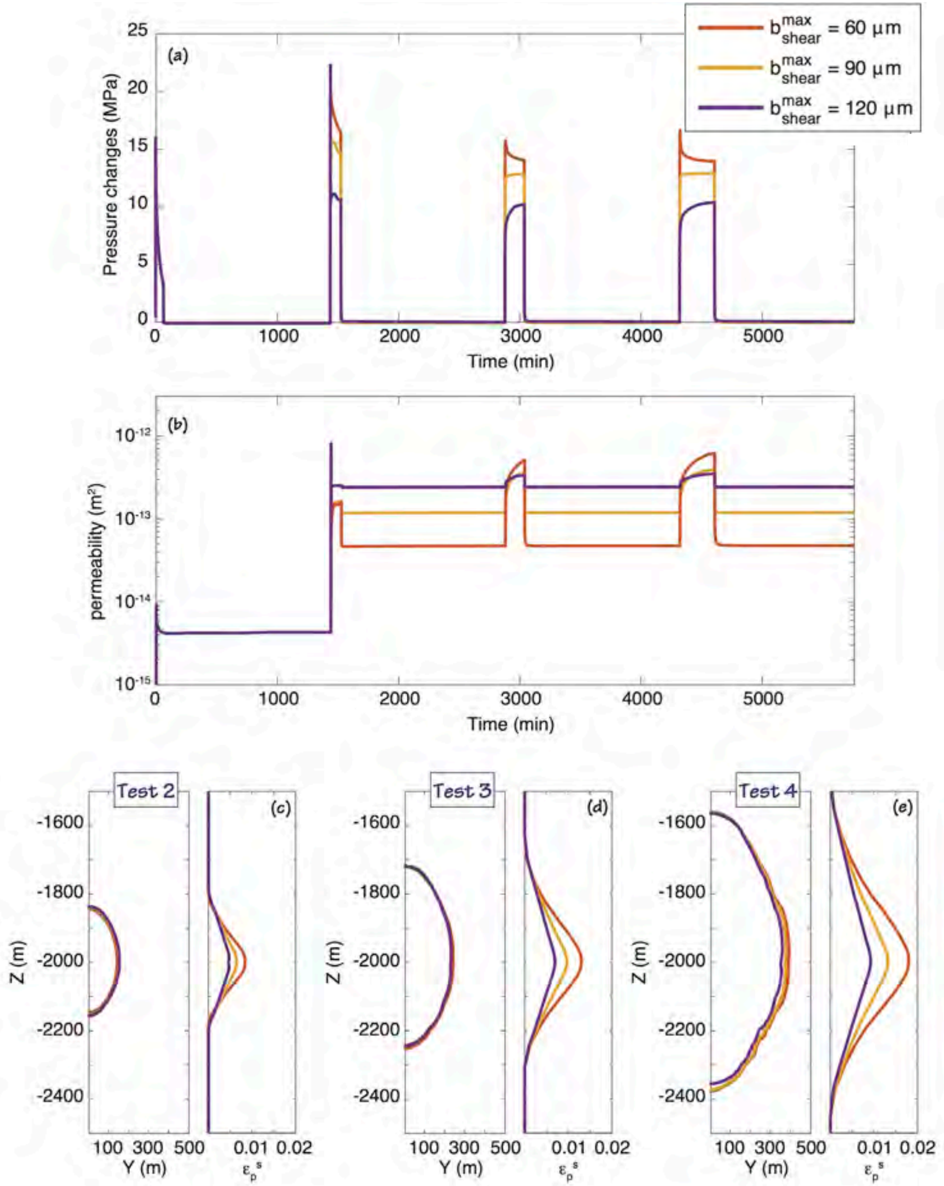
Hydroshearing or opening?
Permeability evolution



Hydroshearing or opening?
Sheared zone and seismicity



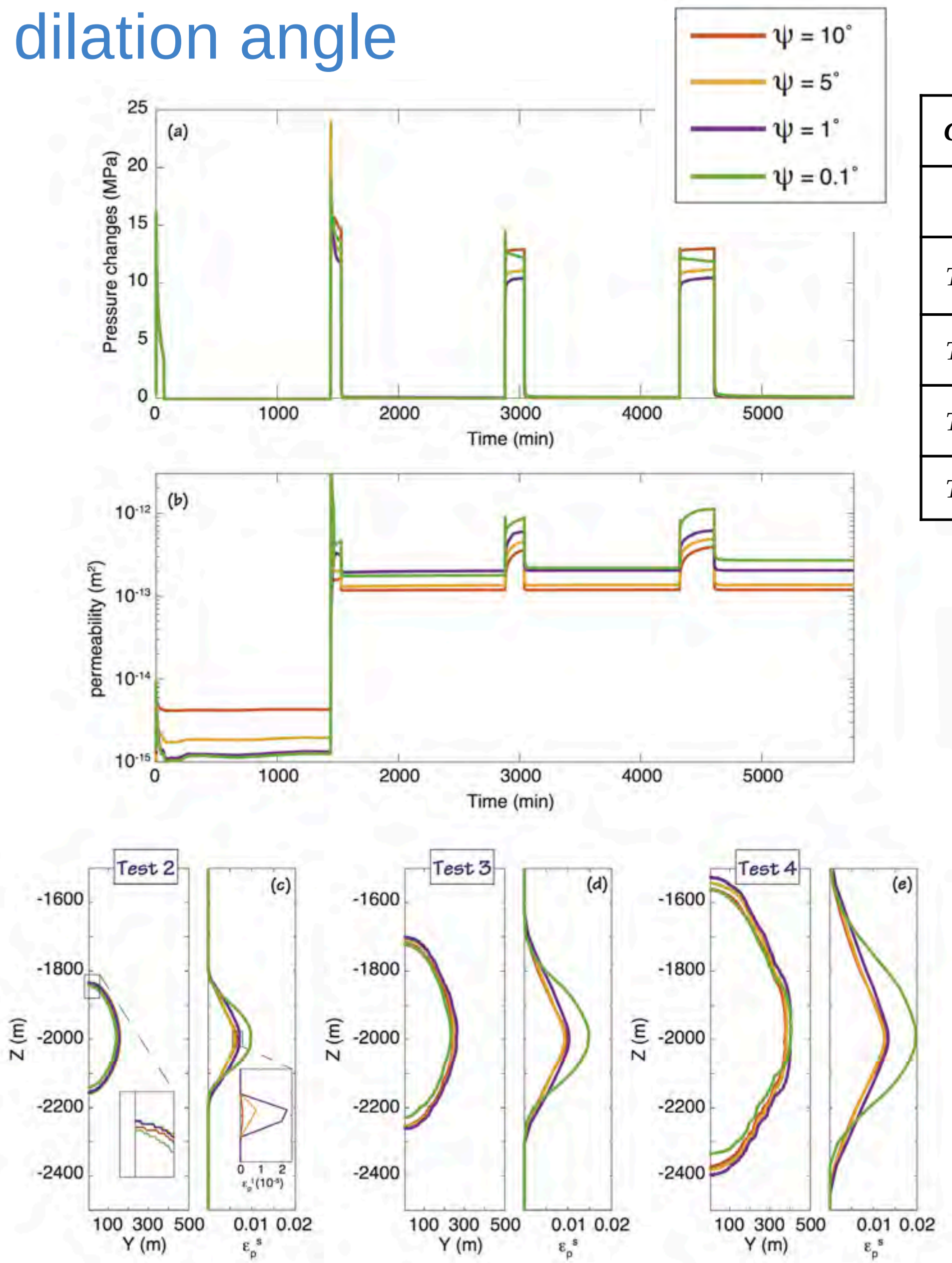
Sensitivity analysis 1
maximum shear aperture



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)

Sensitivity analysis 2
dilation angle



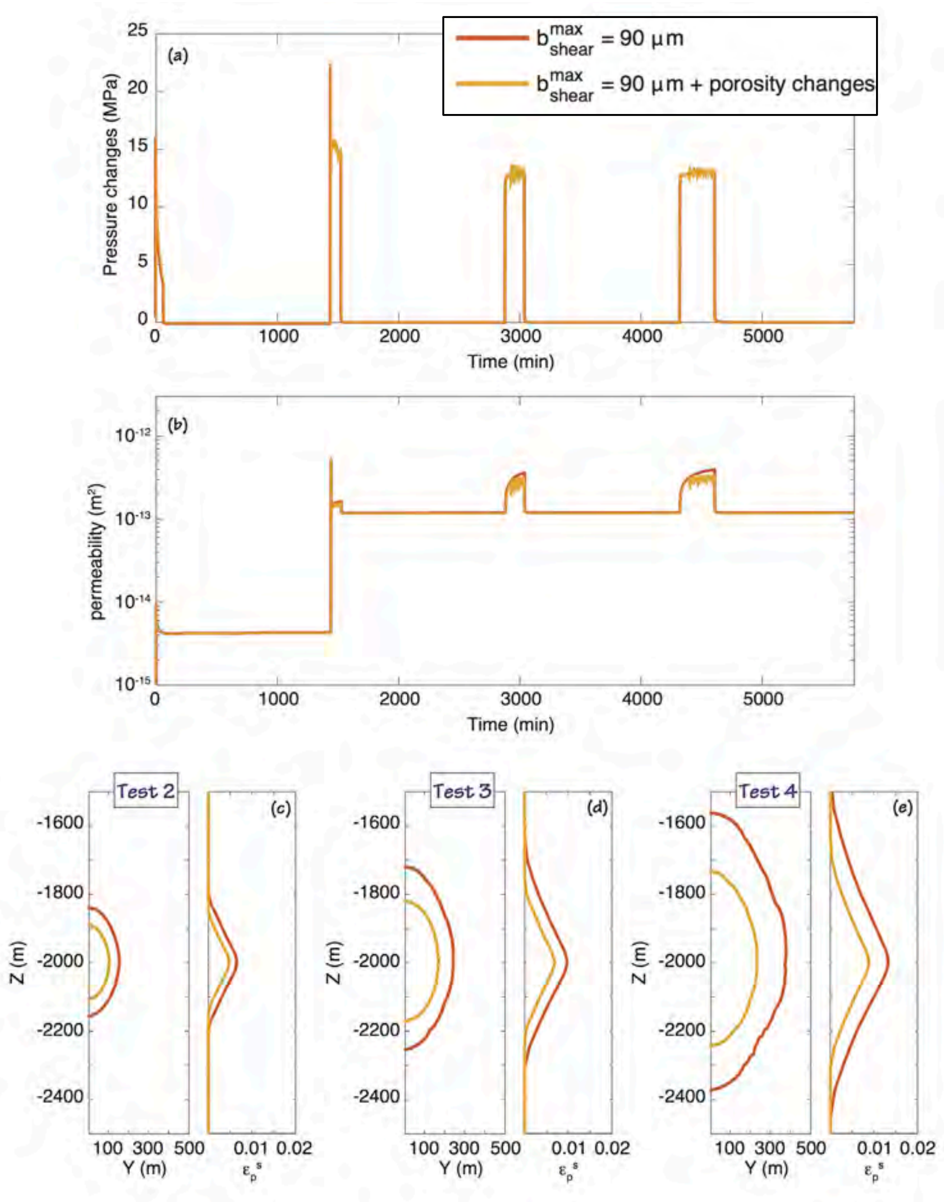
CASE	**10**			**5**			**1**			**0.1**		
	(%)	M_w	n_{ev}	*(%)*	M_w	n_{ev}	*(%)*	M_w	n_{ev}	*(%)*	M_w	n_{ev}
Test 1	28	-2.3	3	25	-2.2	3	23	-2.3	3	22	-2.4	1
Test 2	16	0.6	61	17	0.6	66	22	0.7	70	15	0.7	72
Test 3	9.3	0.5	58	10	0.5	59	15	0.6	65	15	0.7	66
Test 4	5.2	0.5	63	5.8	0.5	77	8.5	0.6	70	12	0.7	69

Lower dilation allows for more tensile opening, hence more flow back, but also larger cumulative seismic magnitude. The case of 0.1° shows progressive increase in residual permeability near well

Concluding remarks

- The flow-pressure response with stated maximum pressure and flow rates at one of 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**. Sensitivity analysis of the dilation angle evidences a very complex interaction among fluid flow, pressure, and seismic activity
- **Assuming appropriate conditions**, the simulation results suggest that fluid circulation could 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 (or with seismic magnitude below measurable threshold) creation of permeable pathway compromising the sealing capacity of a given site.

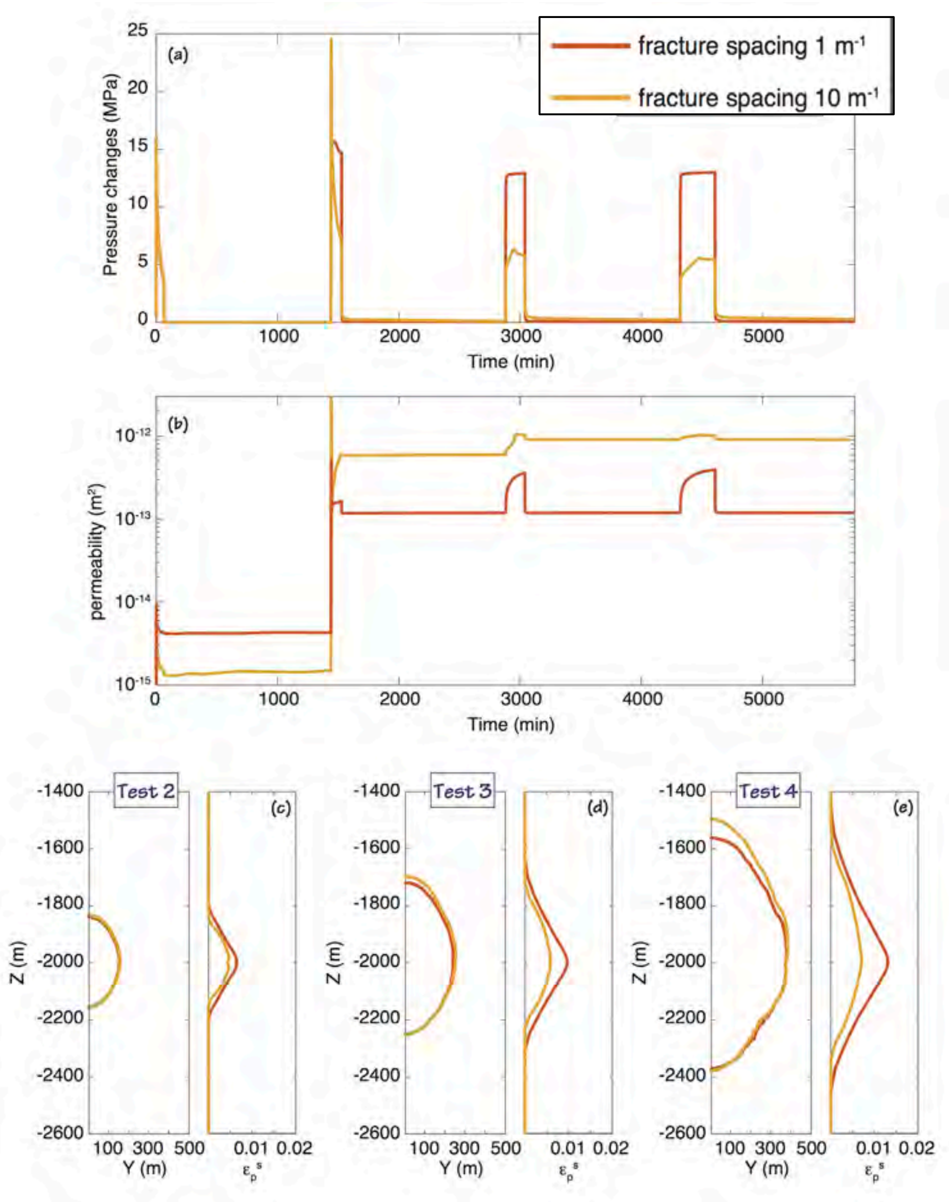
Extra: porosity changes



CASE	**Base case**			**Porosity changes**		
	(%)	M_w	n_{ev}	*(%)*	M_w	n_{ev}
Test 1	28	-2.3	3	28	-2.3	3
Test 2	16	0.6	61	13.3	0.4	51
Test 3	9.3	0.5	58	8.4	0.4	37
Test 4	5.2	0.5	63	4.9	0.5	55

Porosity changes result in larger storage volume. The extent of the reactivated fracture zone is much smaller for the case with porosity changes, resulting in smaller flow-back percentage.

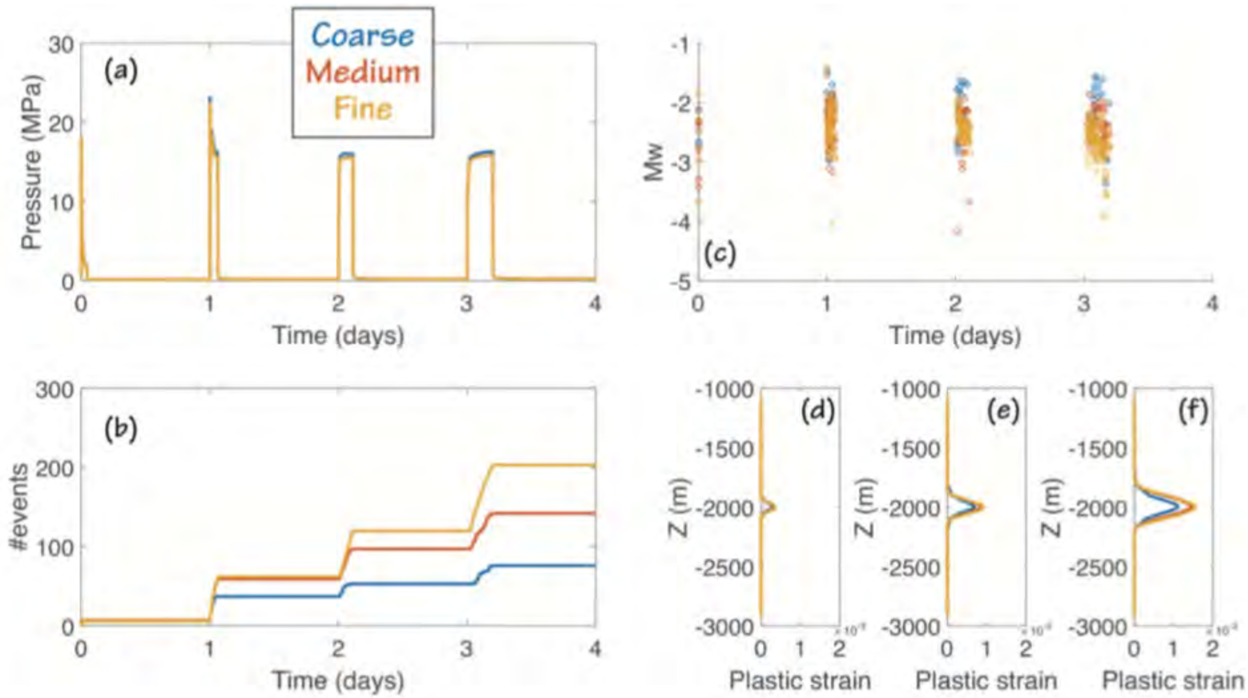
Extra: fracture density

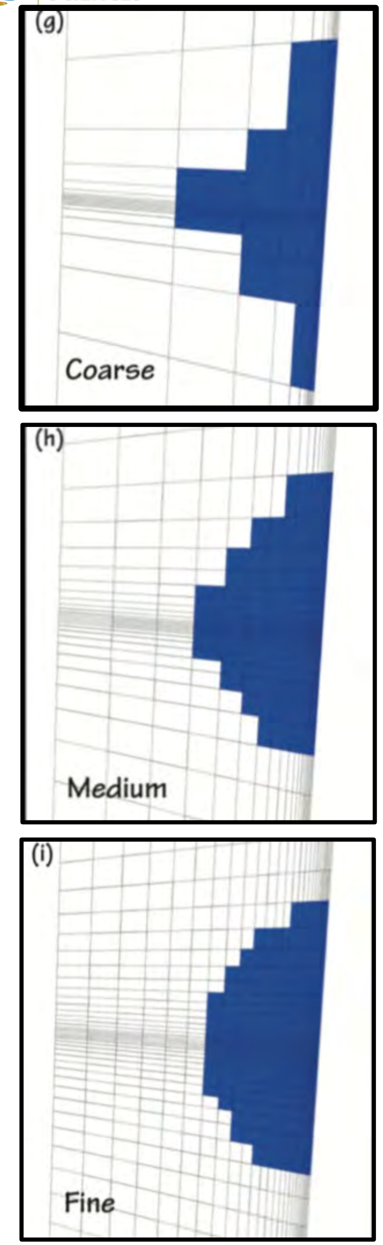


CASE	**Base case**			**Fracture density 10x**		
	(%)	M_w	n_{ev}	*(%)*	M_w	n_{ev}
Test 1	28	-2.3	3	28	-2.3	3
Test 2	16	0.6	61	13.3	0.4	51
Test 3	9.3	0.5	58	8.4	0.4	37
Test 4	5.2	0.5	63	4.9	0.5	55

Higher joint density results in a slightly larger fracture zone toward shallow depths, larger number of reactivated patches enlarging the stimulated region and much higher flow back.

Extra: mesh discretization





CASE	coarse		medium		fine	
Variables	$cumM_w$	n_{ev}	$cumM_w$	n_{ev}	$cumM_w$	n_{ev}
Test 1	-1.79	6	-1.84	7	-1.74	6
Test 2	-1.09	31	-1.08	52	-1.04	56
Test 3	-1.10	16	-1.22	38	-1.18	58
Test 4	-1.04	23	-1.20	45	-1.27	83