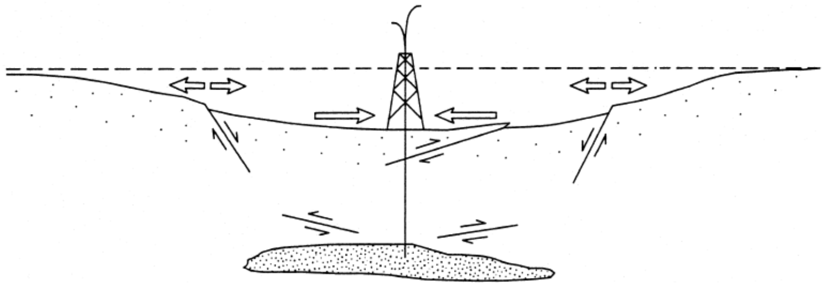
Spatial decay of seismicity during injection and active mitigation: Insights into fluid and rock coupling effects

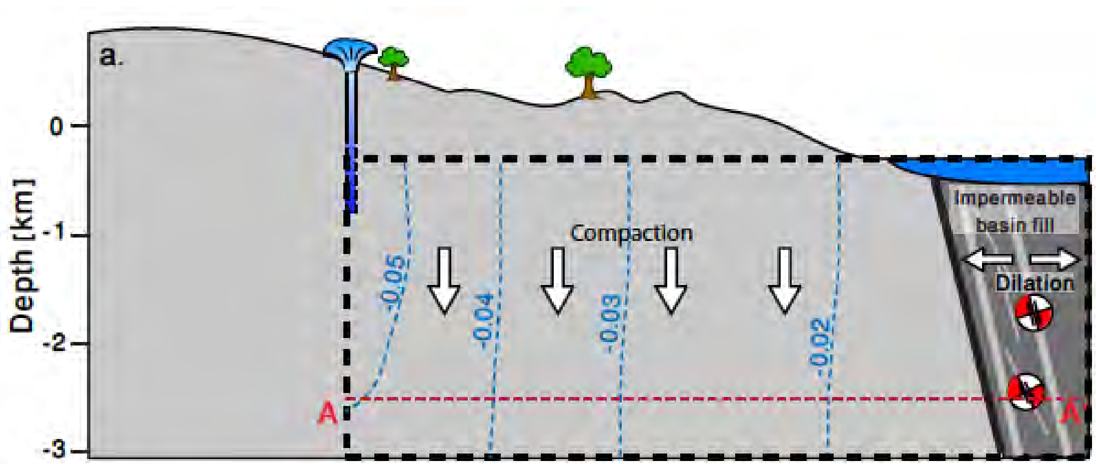
T.H.W. Goebel[1], E.E. Brodsky[1], M. Weingarten[2], X. Chen[3], J. Haffener[3], Zach Rosson[4], Jake Walter[4]

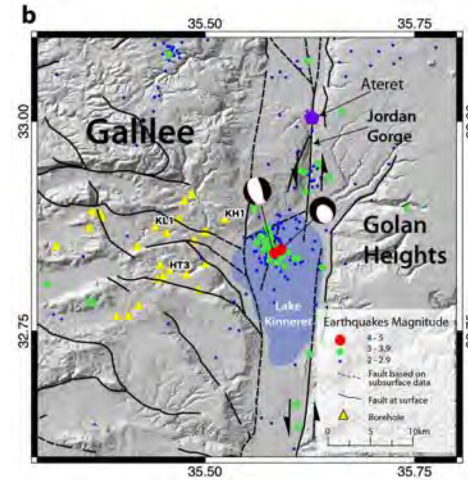
1-*University of California, Santa Cruz; 2-San Diego State; 3-University of Oklahoma, 4-Oklahoma Geological Survey*

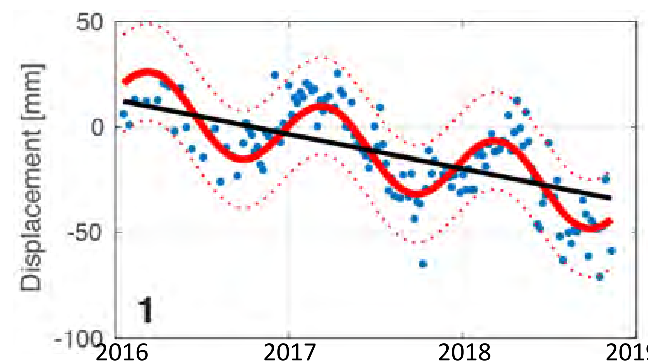
Fluid-rock coupling is important to explain extraction-induced seismicity



Segall *Geology*, (1989); Wang (2000)



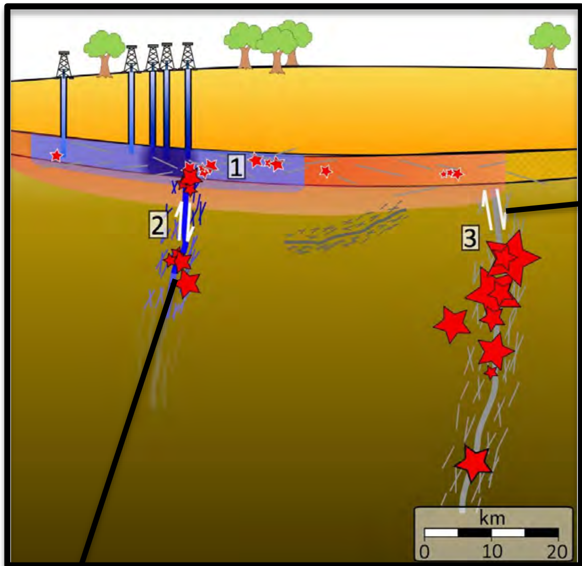




GEOLOGICAL SURVEY OF ISRAEL

Wetzler, Goebel, et al. (in prep)

Similarly, poroelastic effects should be considered for injection-induced earthquakes

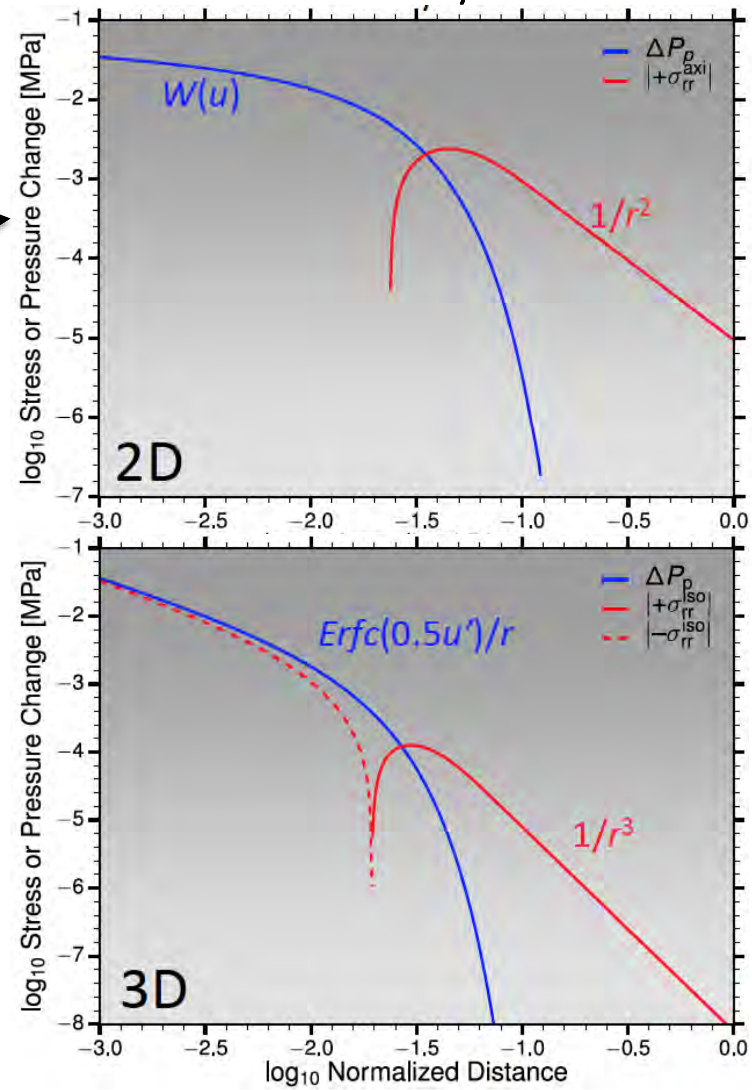


$$\Delta CS = \tau - \mu(\sigma_n - \alpha_{fl}\Delta p)$$

$\alpha_{fl} = 1 - A_r/A$

e.g. Hirth & Beeler, *Geology*, 2015

Induced stress-decay with distance:



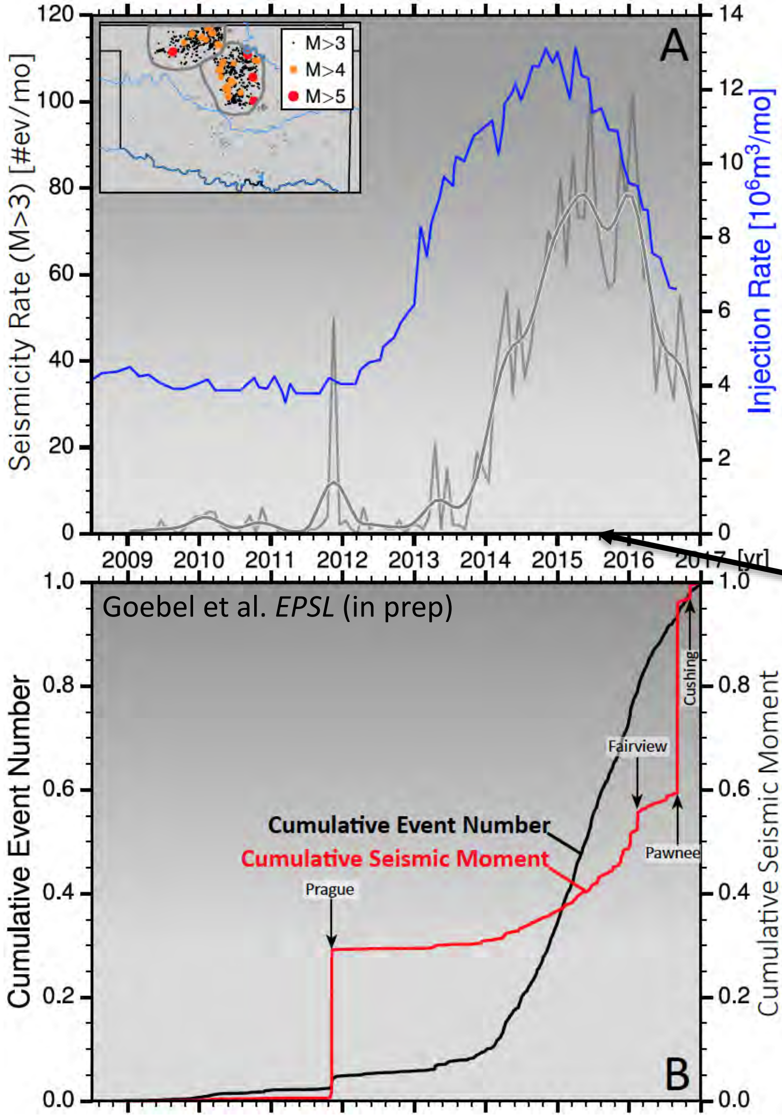
Goebel et al. *EPSL* 2017, see also Segall & Lu, *JGR*, 2015; Chang & Segall *JGR* 2016, Babour et al., *SRL*, 2017

Key questions

1. What is the seismogenic reach of injection-wells?
2. What the role of elastic stresses vs. direct pressure effects?
3. What are implications for seismic hazard?

A. Mitigation effects in Oklahoma

Two mitigation strategies in Oklahoma:



1. Injection rate reduction
2. Well plug-back to shallower depth

OKLAHOMA
Corporation Commission
P.O. BOX 52000
OKLAHOMA CITY OKLAHOMA 73152-2000

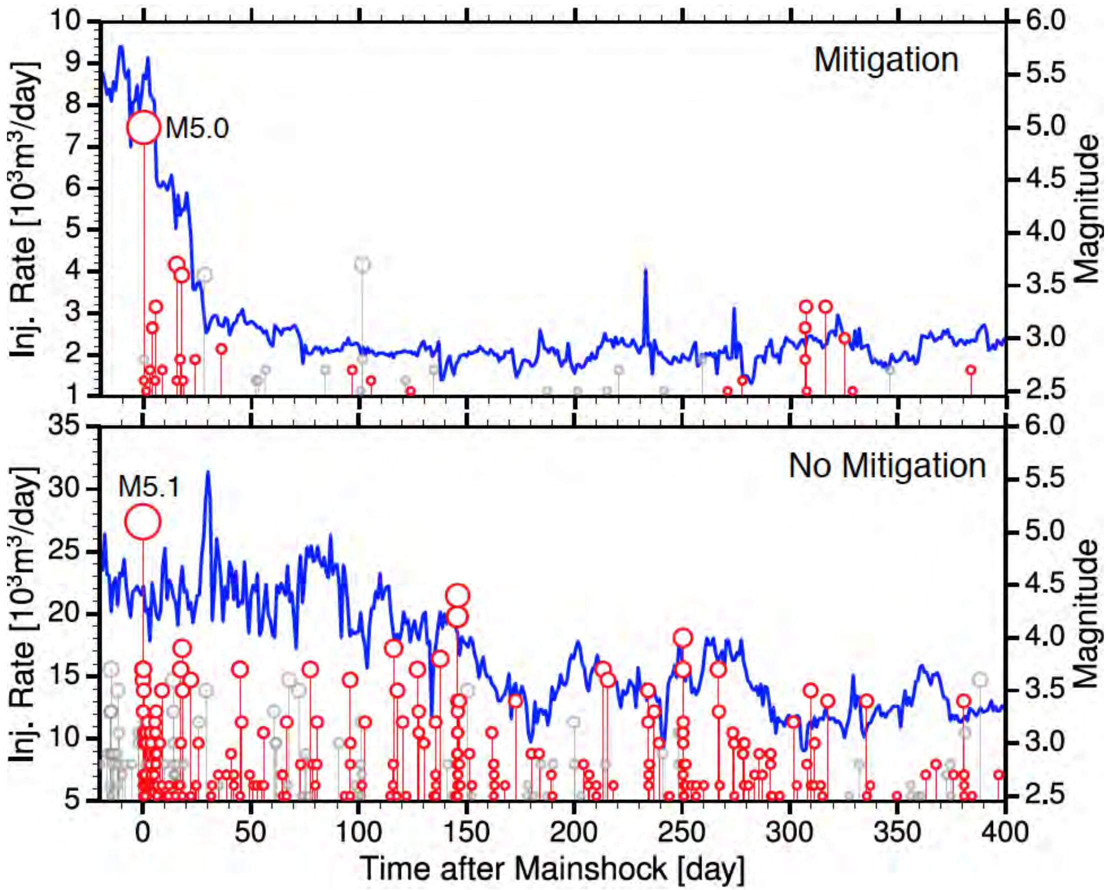
OIL & GAS CONSERVATION DIVISION

July 17, 2015

By July 2015 more than 120 wells, including wells near Fairview, had to be plugged-back to shallower formations from basement.

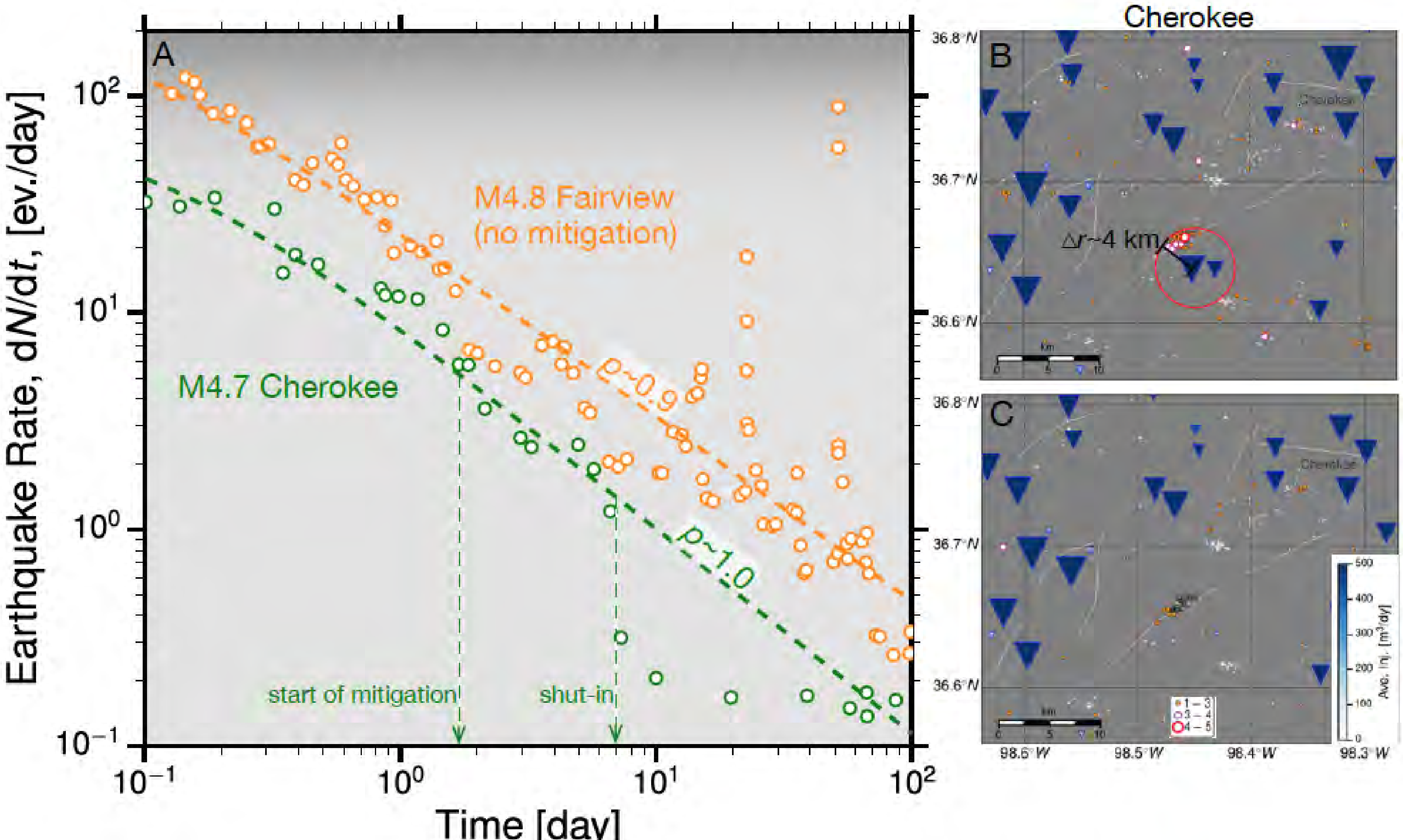
see also Yeck et al. *GRL* 2017, Goebel et al. Sci. Adv. 2017

Areas with reduced injection exhibit lower seismicity rates



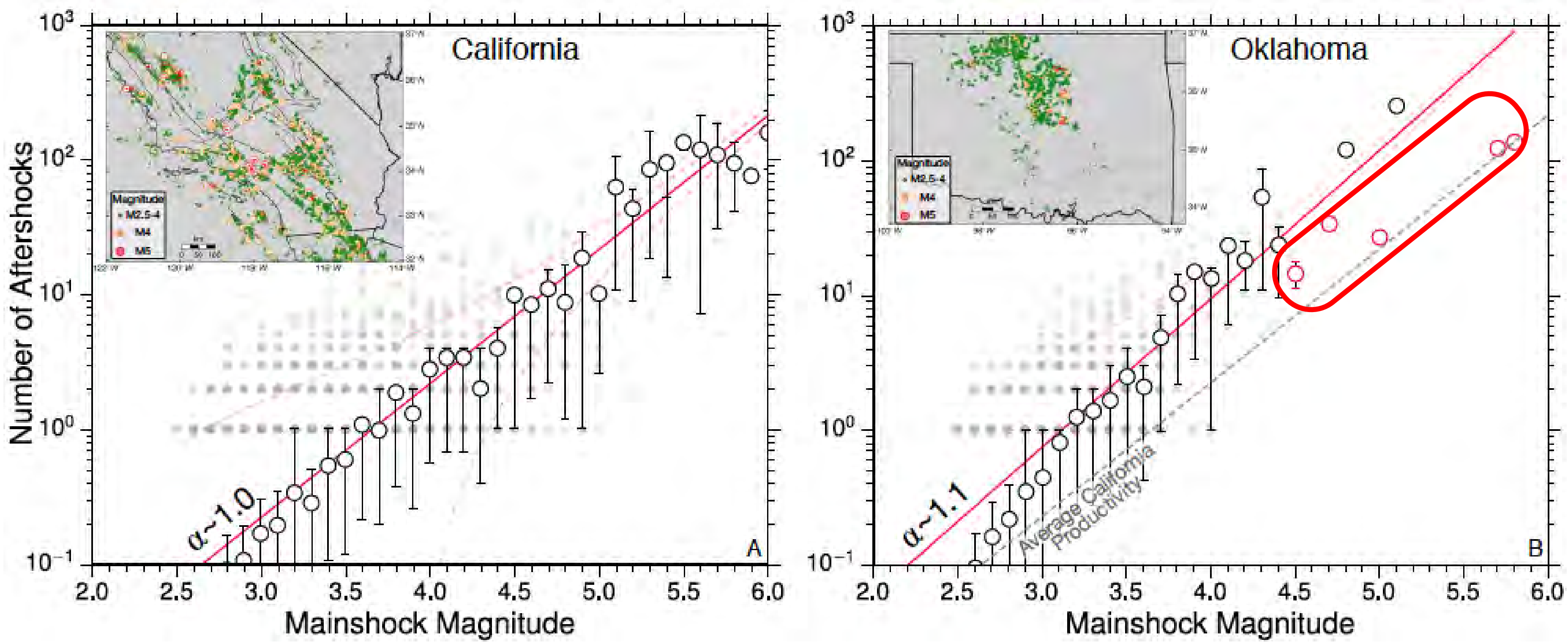
Goebel et al. *EPSL* (in prep)

Rapid mitigation affects unfolding aftershock sequences



Goebel et al. *EPSL* (in prep)

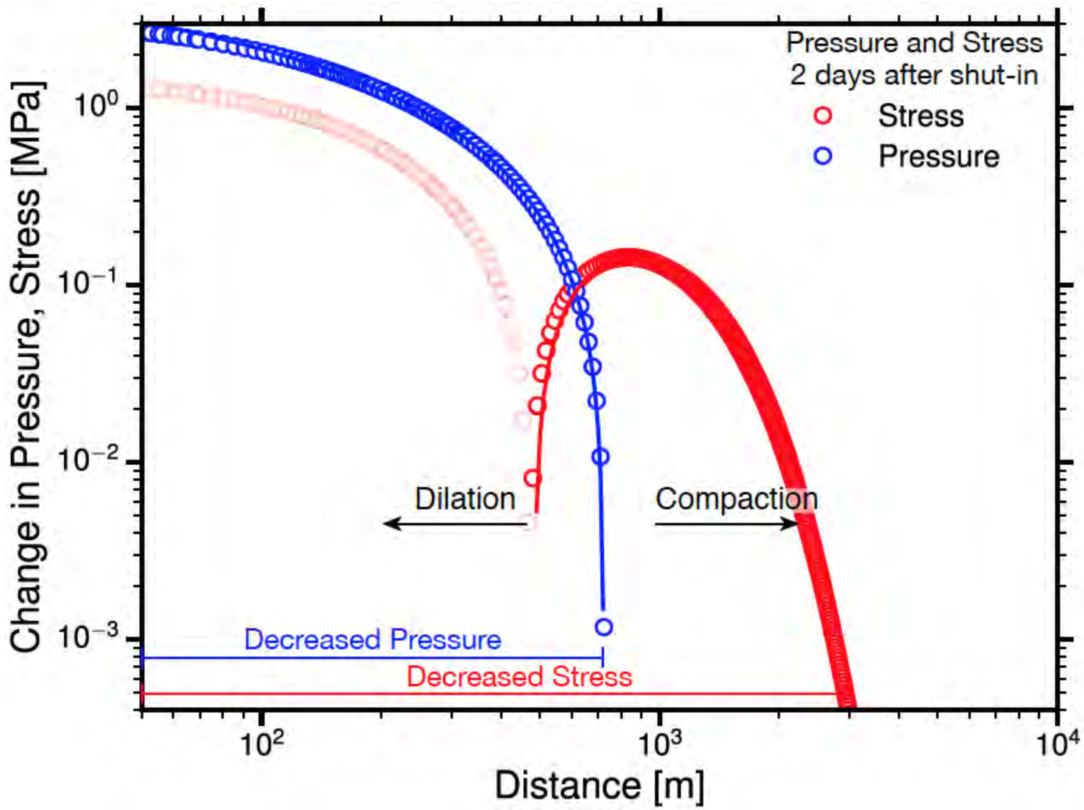
Mainshocks with rapid mitigation generally show low aftershock productivity



Goebel et al. *EPSL* (in prep)

Poroelastic effects may contribute to stopping aftershock sequences at large distances

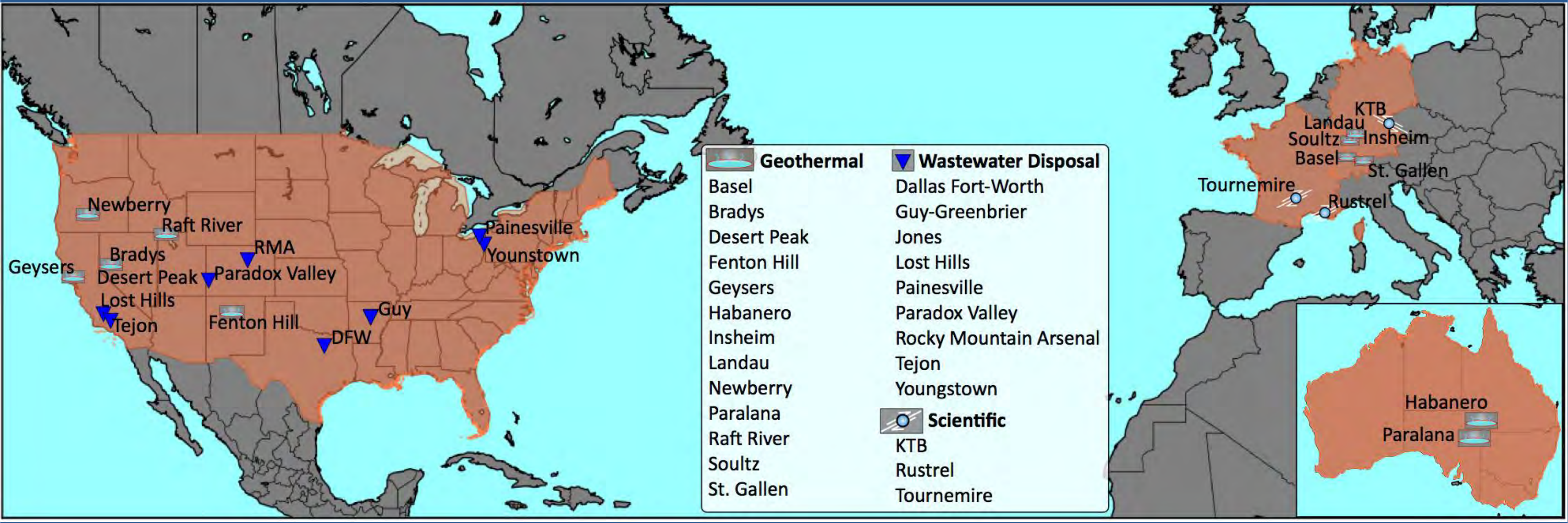
Spatial extent of poroelastic stress reduction 2days after shut-in



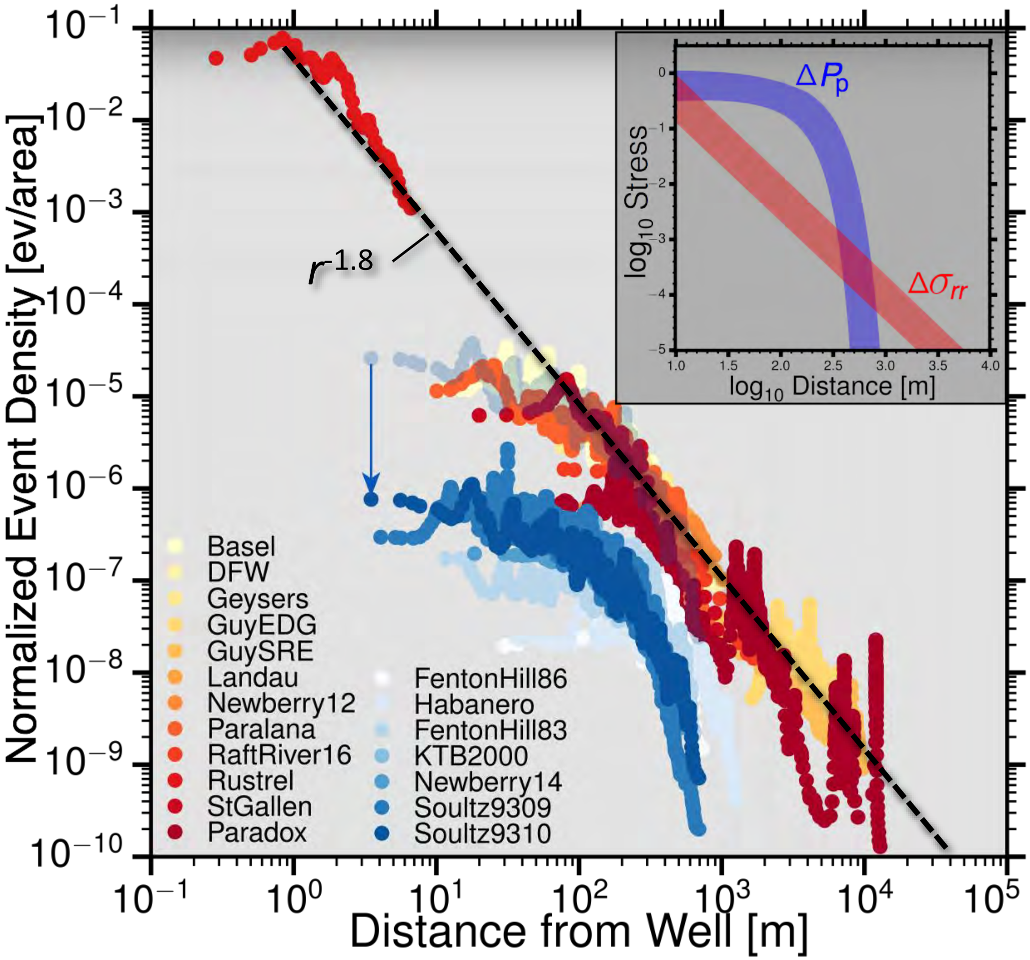
Stress changes as low as 0.01 to 0.1 MPa may affect an unfolding aftershock sequence, providing an upper threshold on triggering stresses

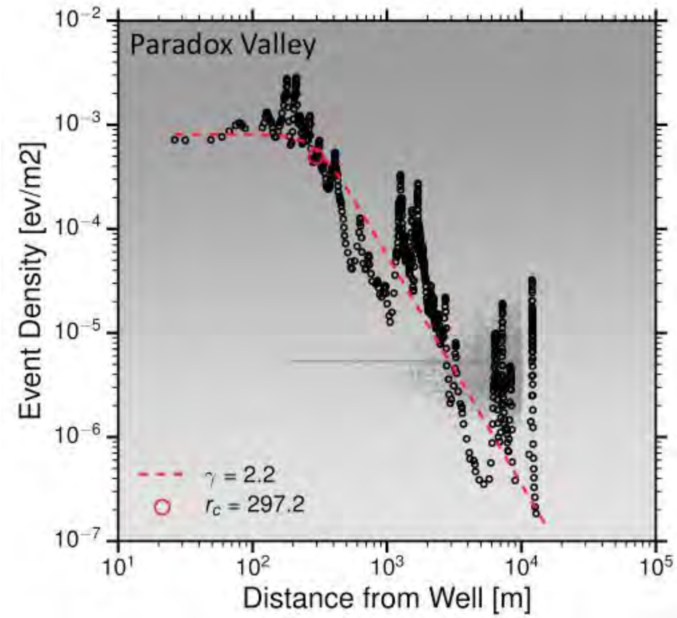
Goebel et al. *EPSL* (in prep)

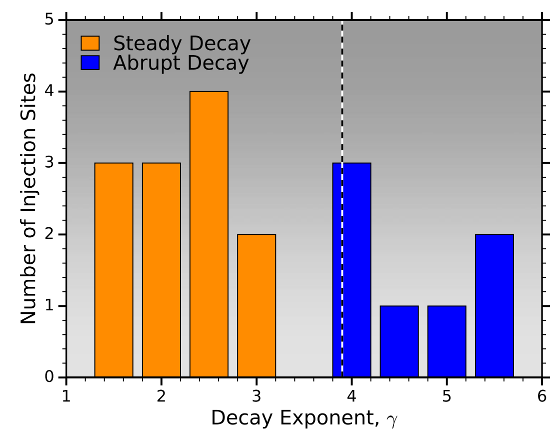
B. Global study of spatial seismicity decay from injection wells



Separation into sites with steady and abrupt decay based on spatial decay exponent







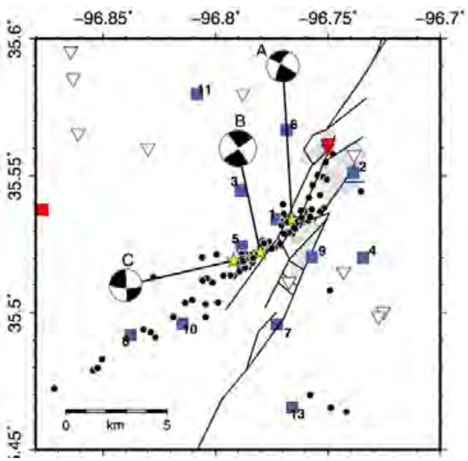
Goebel & Brodsky, *Science*, 2018

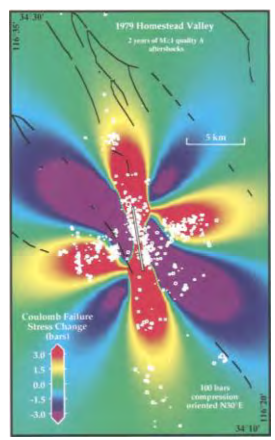
Additional mechanisms that may cause earthquake triggering are larger distances from wells

1. Dynamic permeability changes during slip

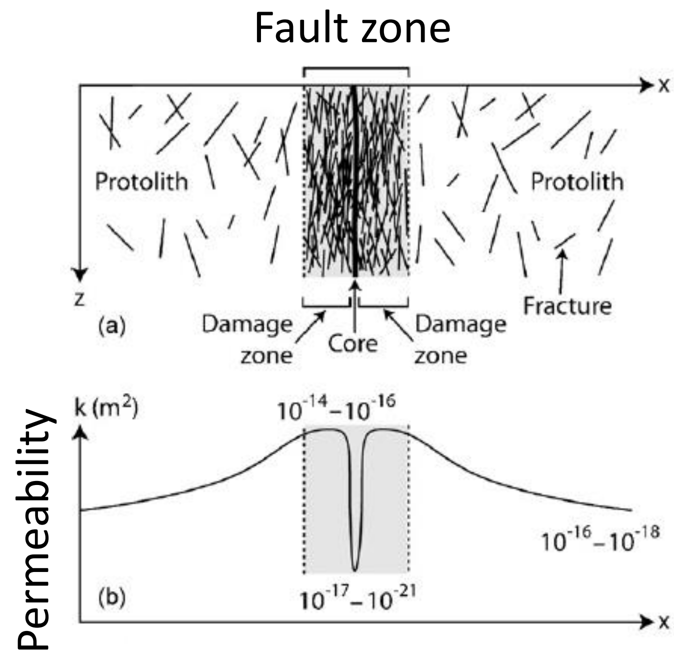
2. Event-event interactions

e.g. Sumy et al. JGR, 2014





King et al. *BSSA* 1994
Felzer & Brodsky *Nature* 2006



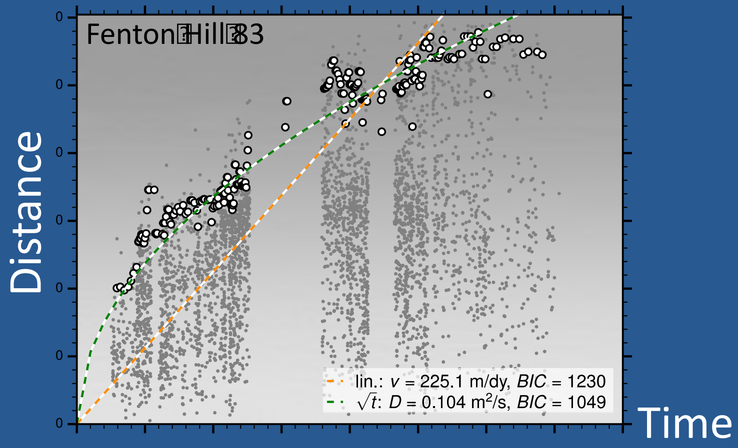
Cappa & Rutqvist 2010

Summary of observations from the global study:

Two populations of injection sites:

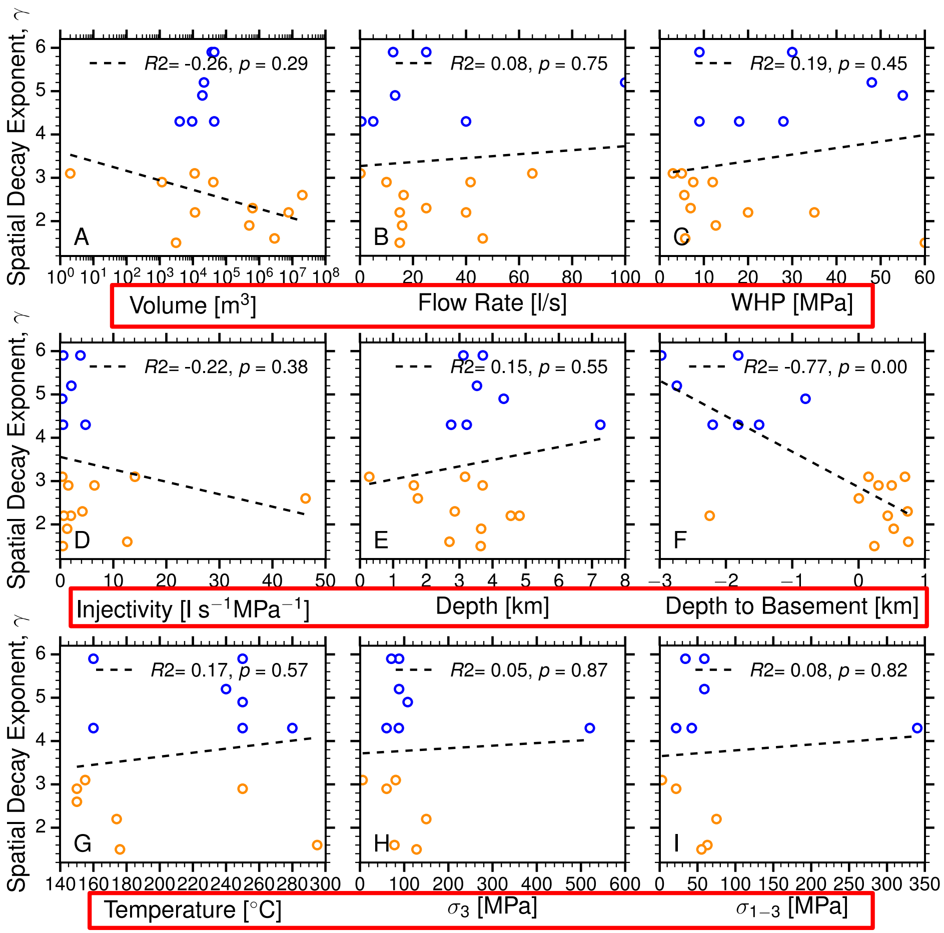
1) Abrupt decay with common square-root migration and smaller maximum magnitudes

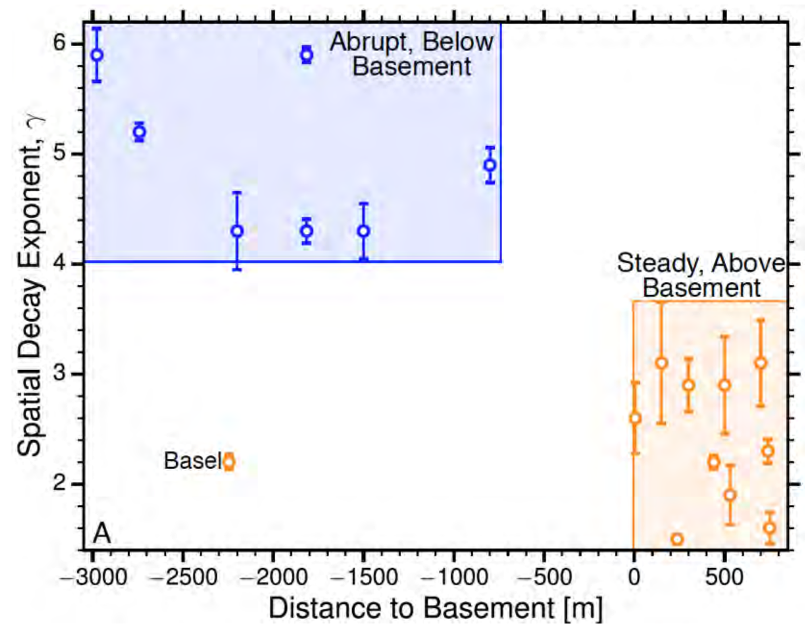
Basel



2) Steady decay with linear or no migration and larger maximum magnitude events

What controls the separation into abrupt and steady decay?





Sites with abrupt decay are solely located within the basement

Difference in fluid-rock coupling between sediment and basement

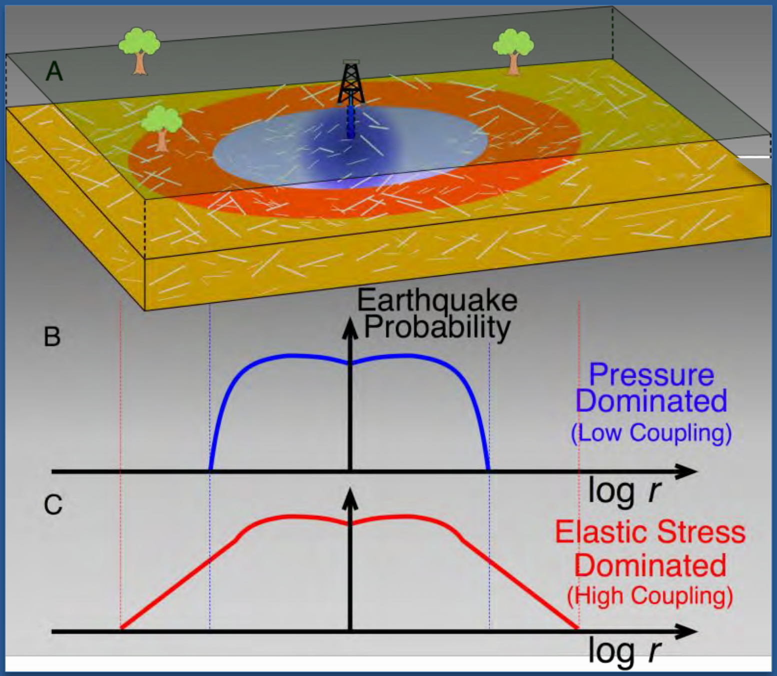
$$\alpha_B = 1 - K_B/K_s$$

Goebel & Brodsky, *Science*, 2018

Seismic hazard implications

- Spatial footprint is key: amplitude of stress change + number of available faults close to failure

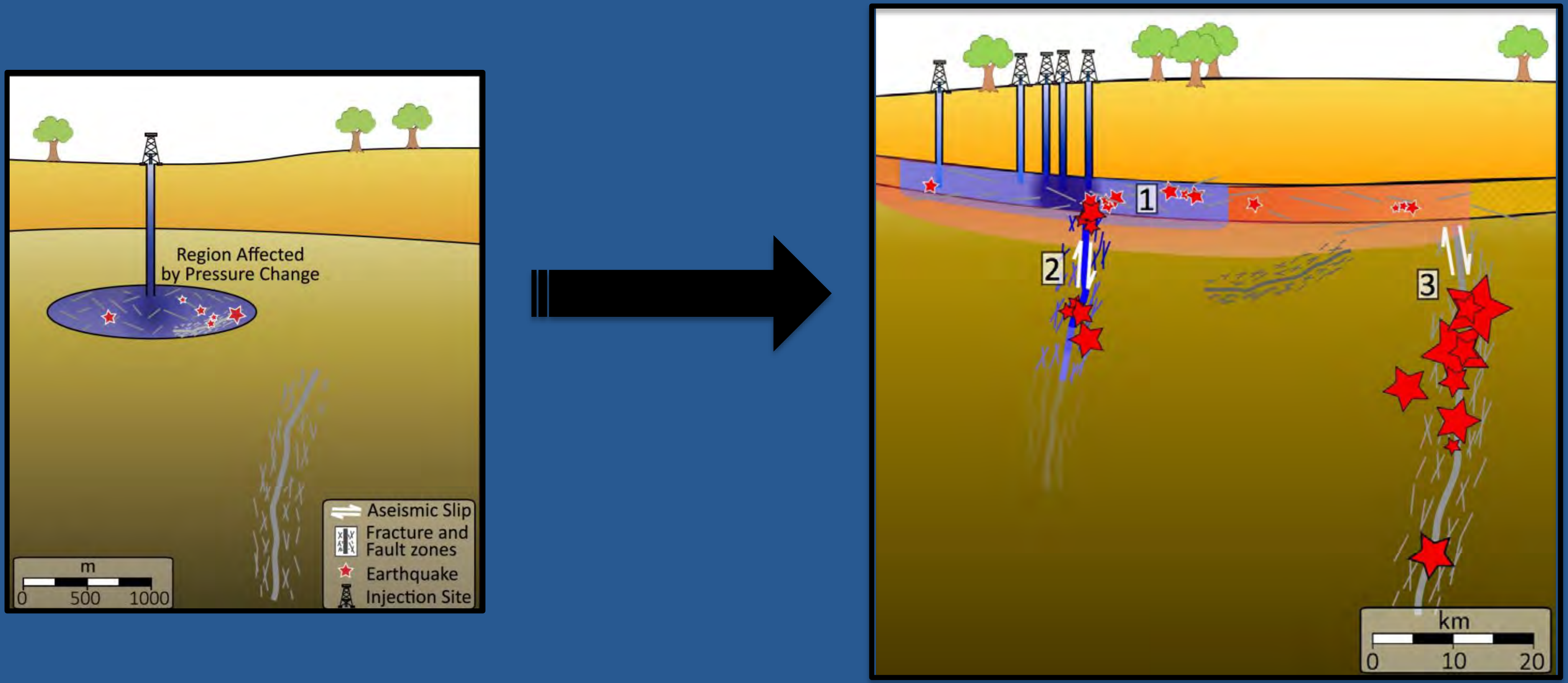
- Injection at shallower depth may increase seismic hazard due to larger zone of influence



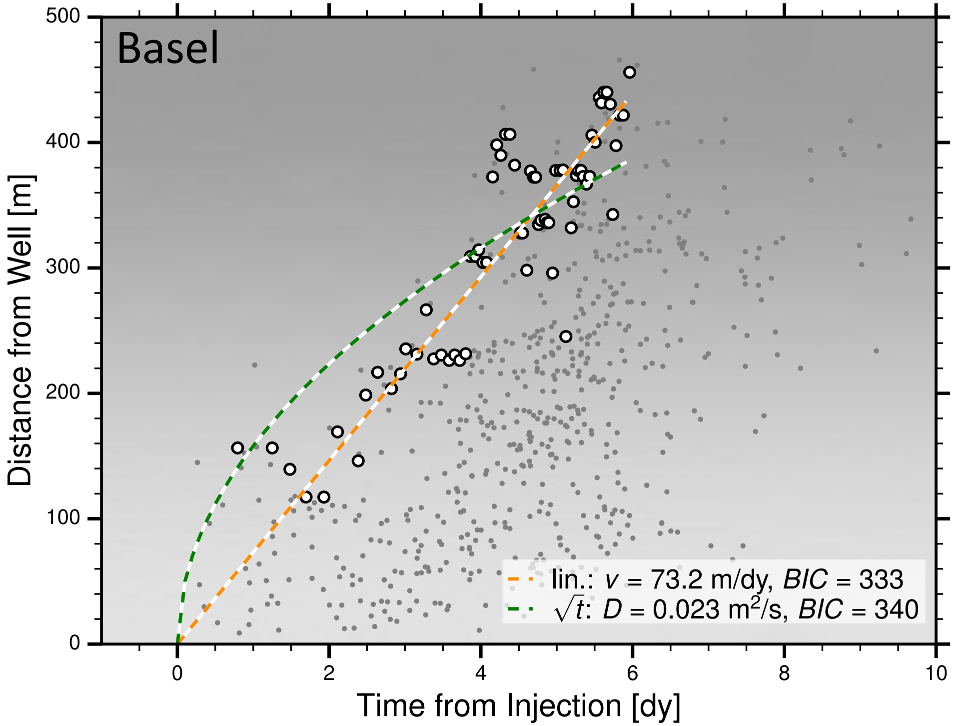
Additional Slides

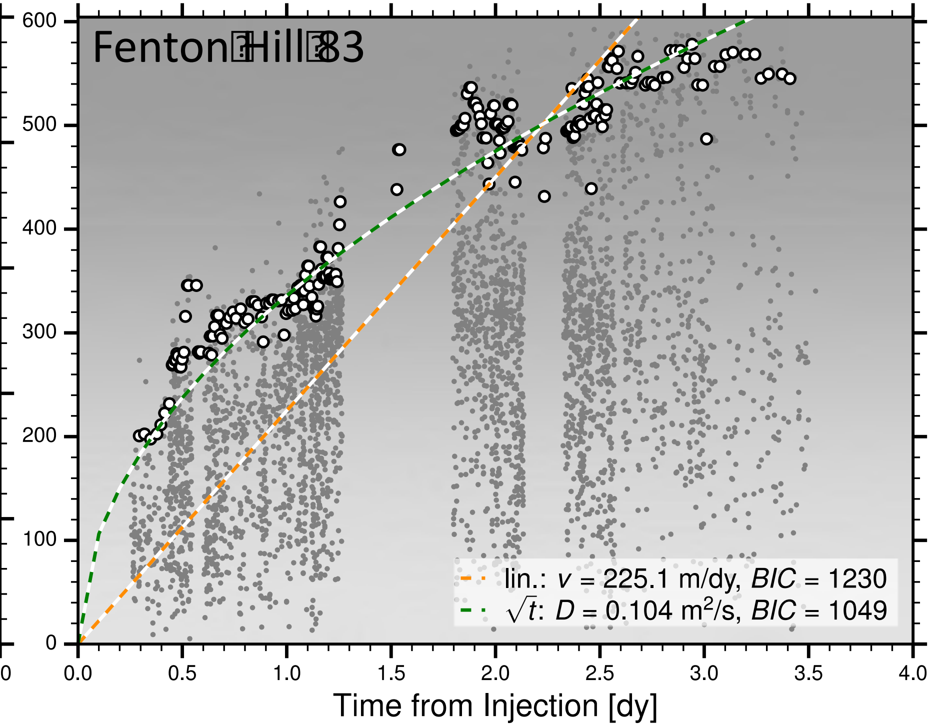
Key questions

1. What is the seismogenic reach of injection-wells?
   >10 km, potentially up to 40 km for multi-well injection
2. What are underlying triggering mechanisms?
   Fluid pressure and elastic stresses



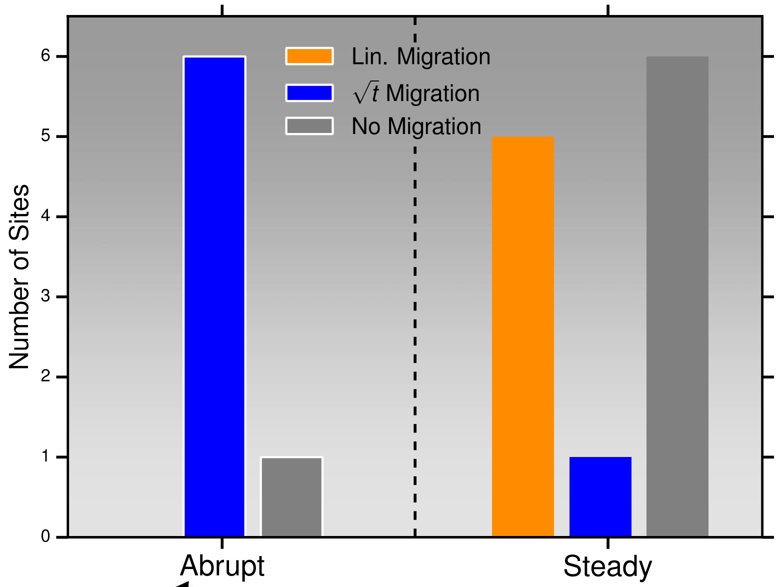
1. We observe evidence for both linear and √t - migration





Goebel & Brodsky, *Science*, 2018

√*t*-migration is dominant at abruptly decaying sites whereas sites with steady decay show more evidence for linear or no migration



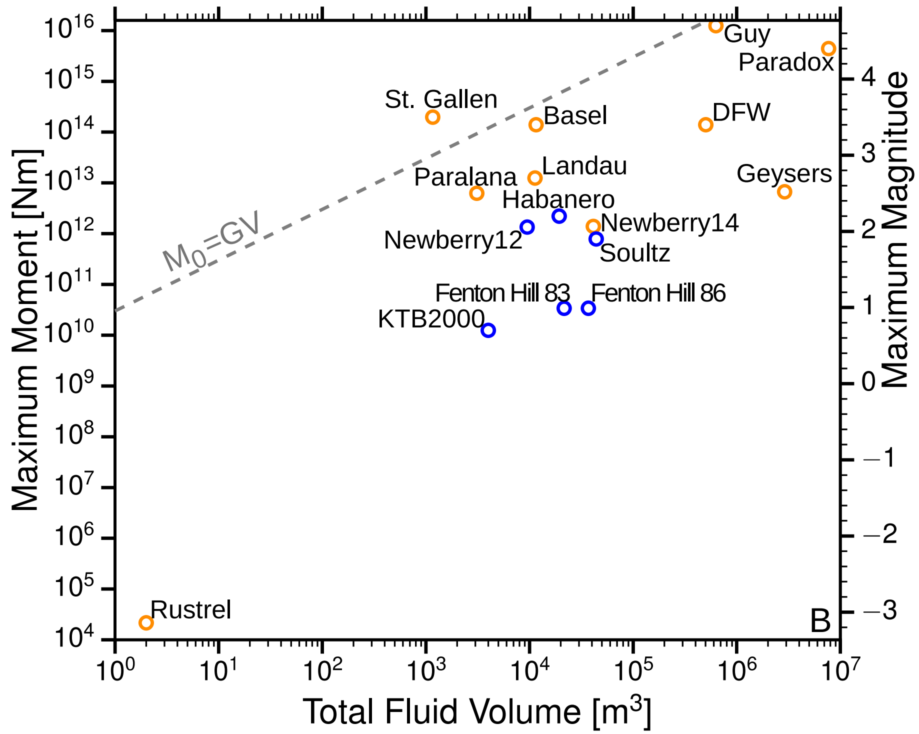
Square-root migration indicates dominance of pressure-driven seismicity

Goebel & Brodsky, *Science*, 2018

2. Maximum magnitude events are larger for sites with steady decay

pt, Below
sement

Steady, Above
Basement



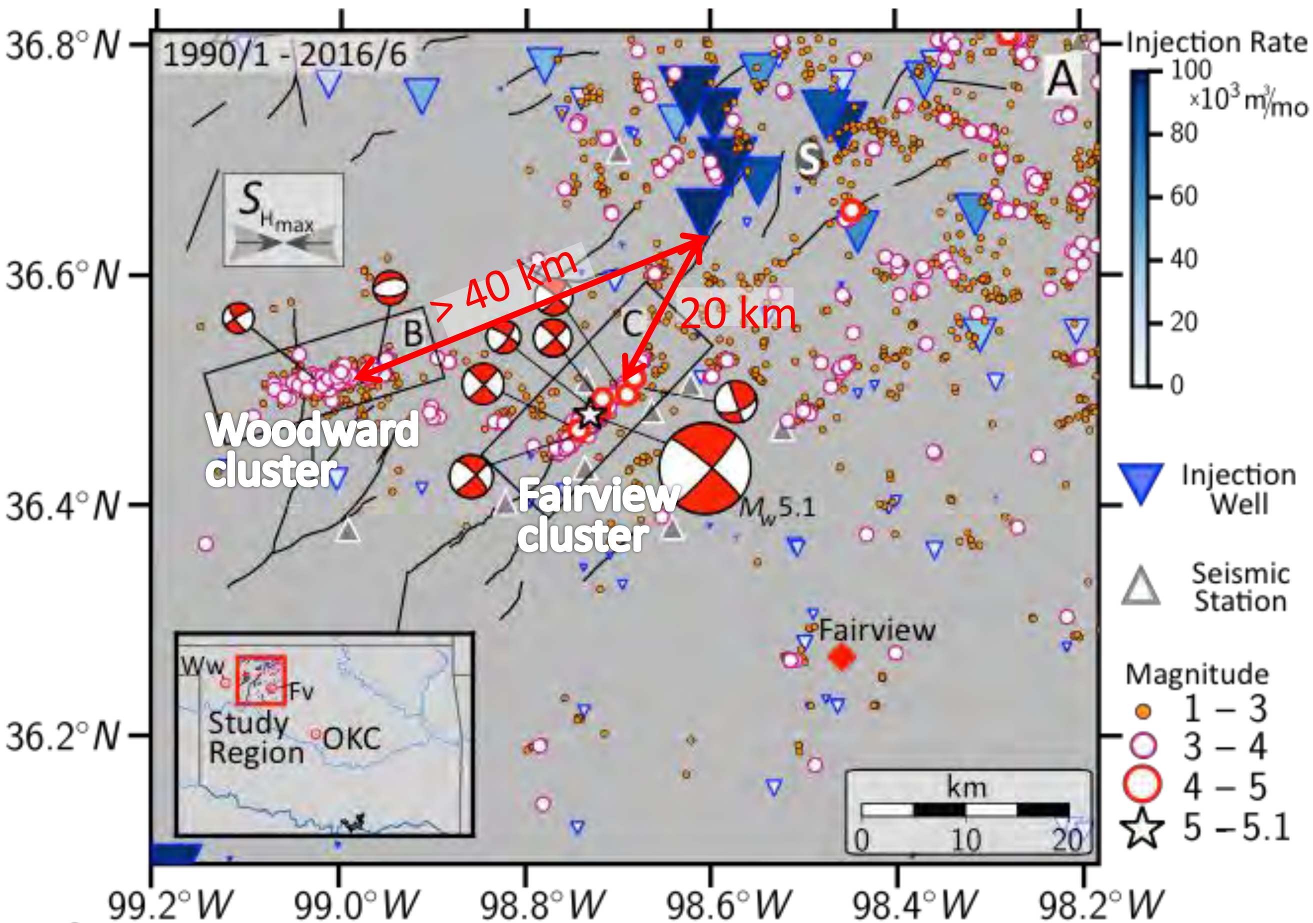
Recap - Two populations of sites:

1) Abrupt decay with common square-root migration and smaller earthquakes

2) Steady decay with linear or no migration and larger earthquakes

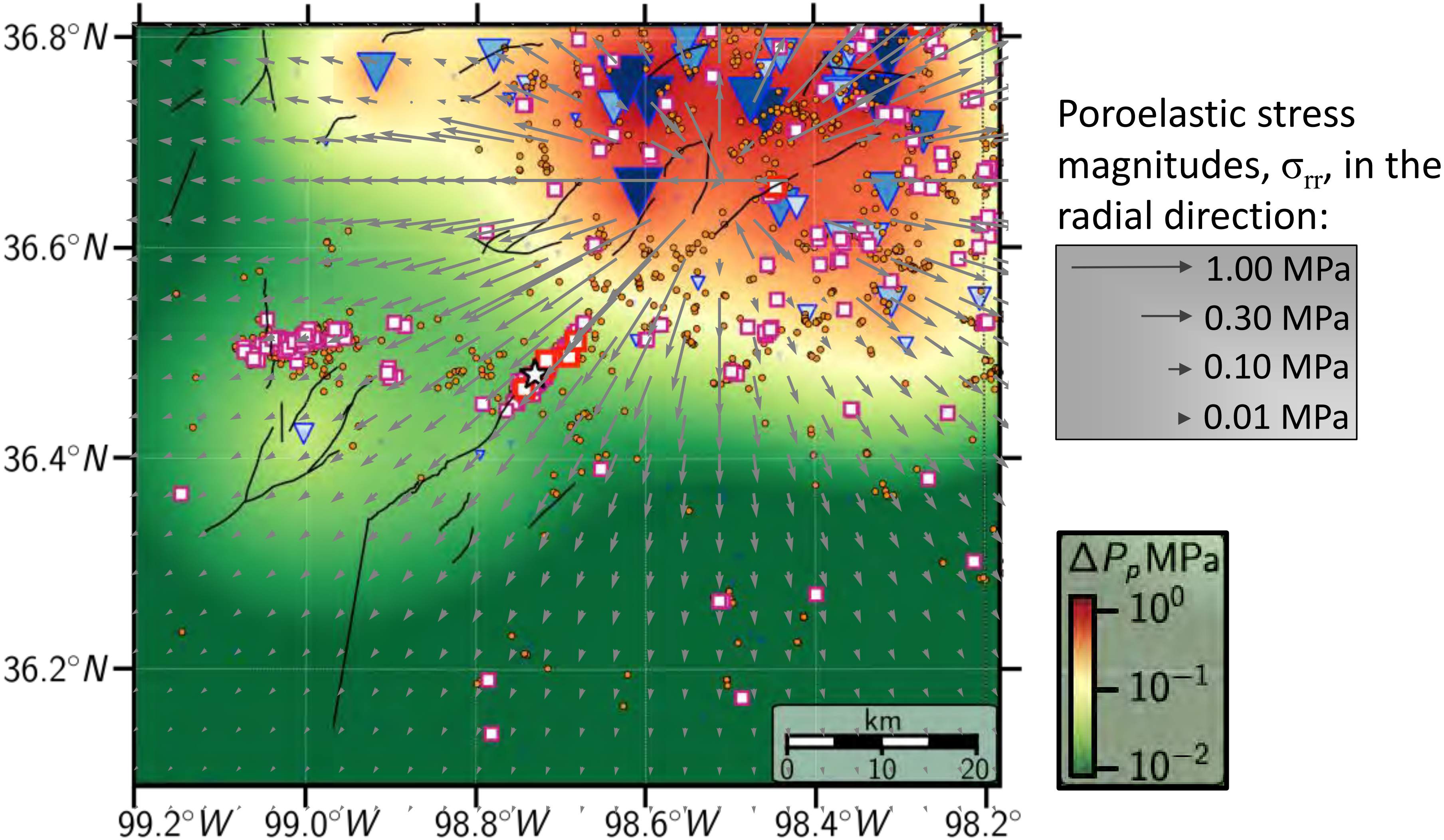
1. What is the the seismogenic reach of injection wells: Lessons from Oklahoma

Two productive earthquake sequences at > 20 km distance from high-rate injection wells



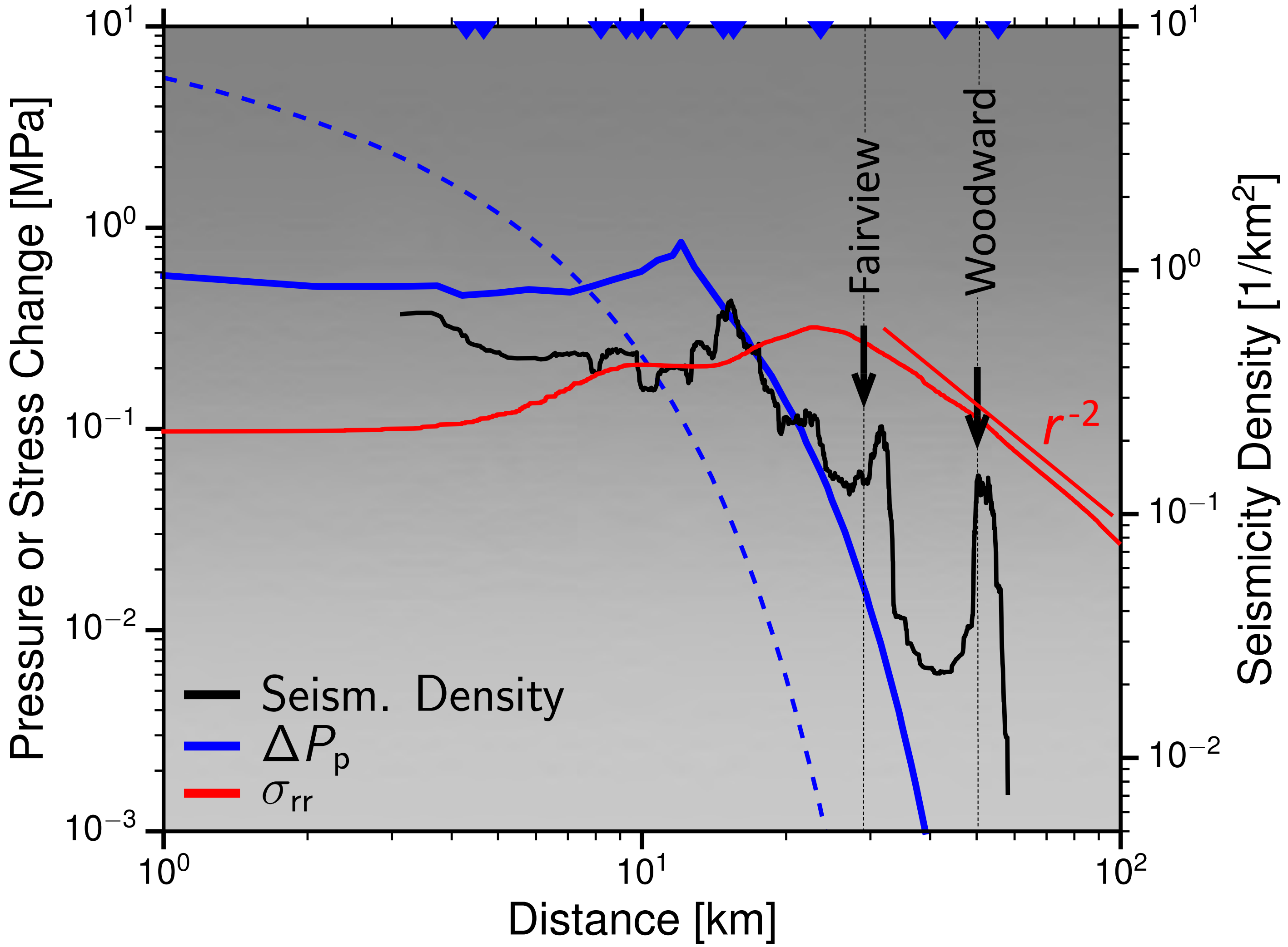
Goebel et al. *EPSL*, 2017

Sum of poroelastic stress changes from all wells within the targeted injection layer



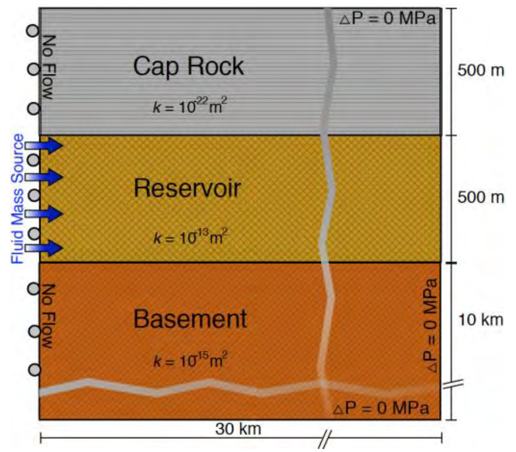
Goebel et al. *EPSL*, 2017

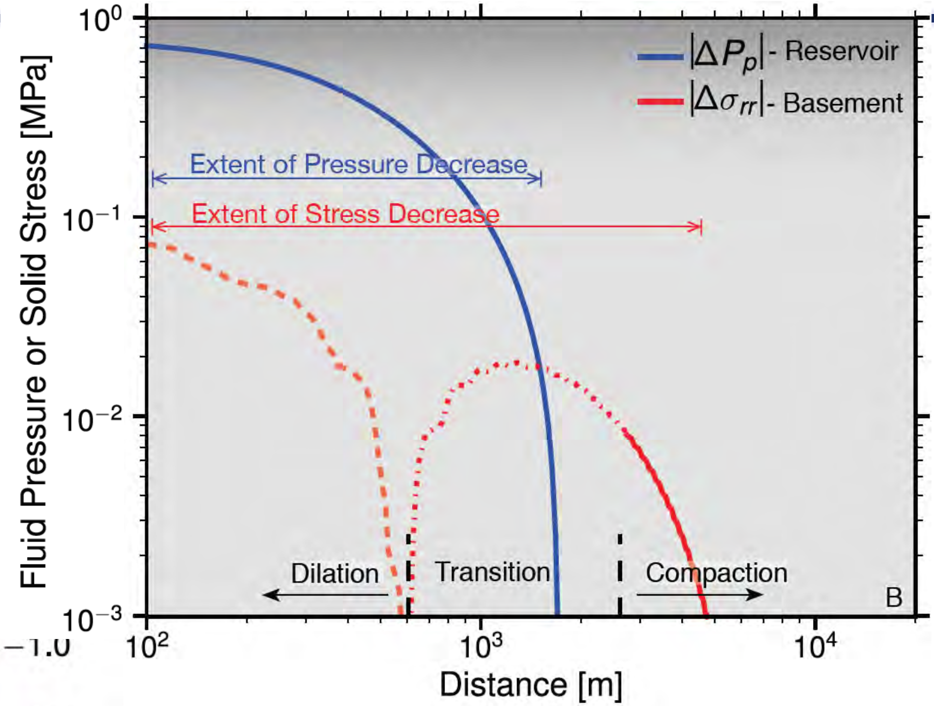
Poro-elastic stresses dominate at larger distances

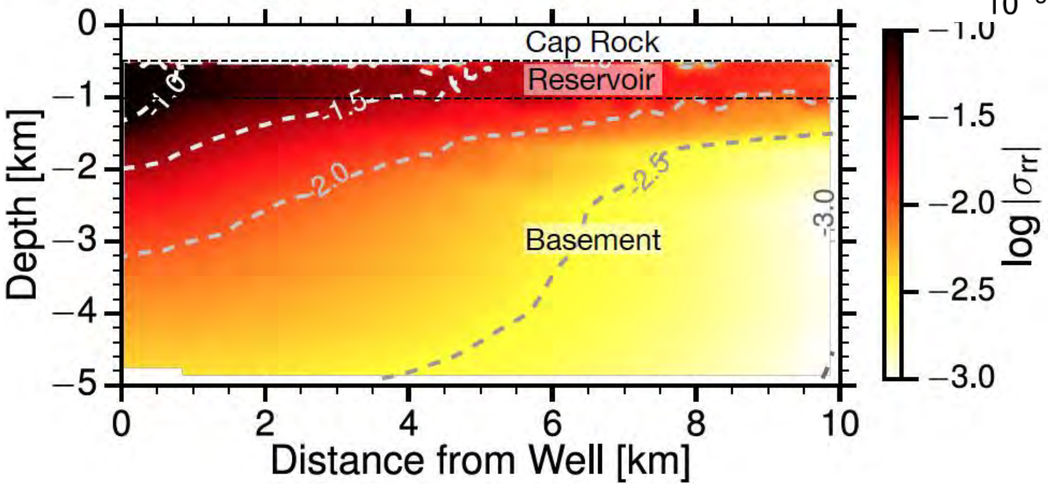


Goebel et al. *EPSL*, 2017

Poroelastic effects may contribute to aftershock sequence arrest at large distances



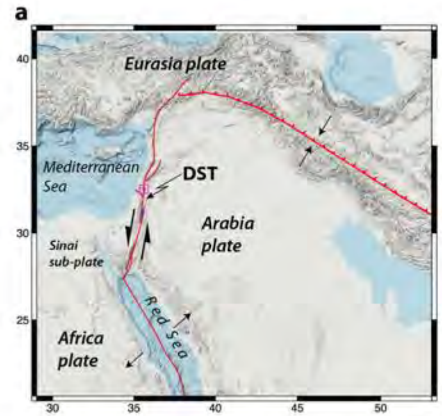


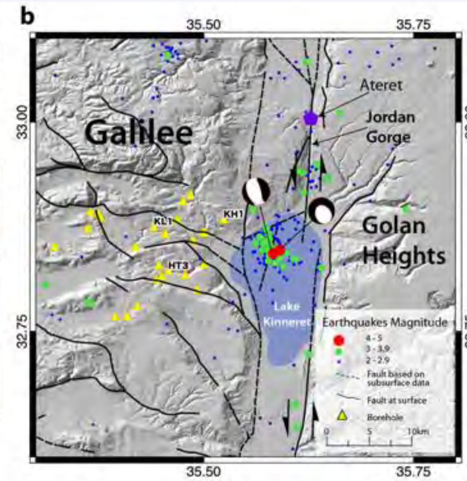


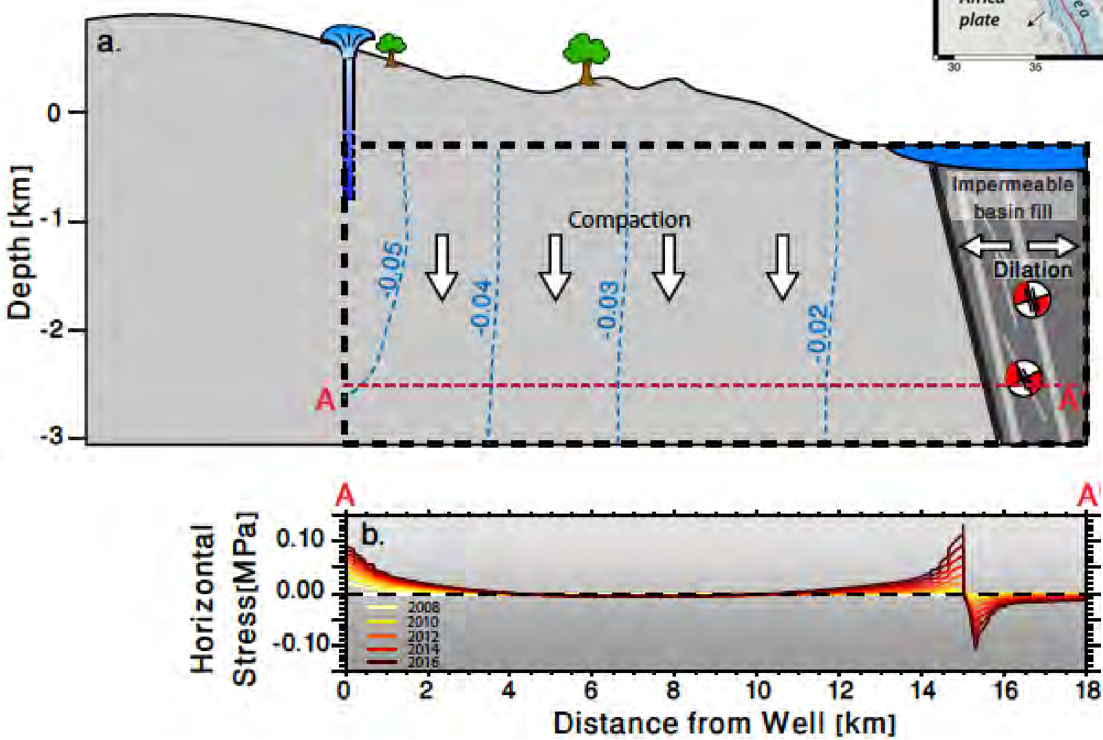
Goebel et al. *EPSL* (in prep)

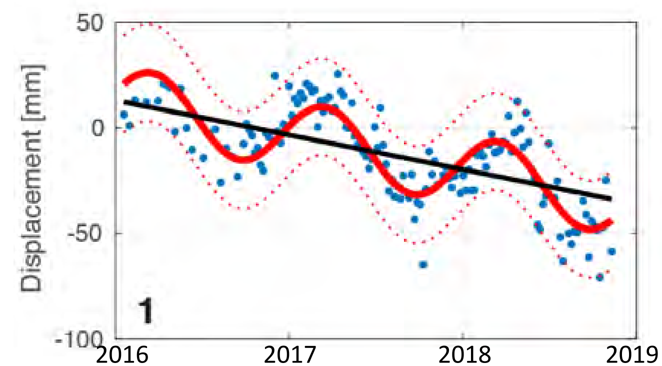
Groundwater pumping and pore-space collapse in Galilee

GEOLOGICAL SURVEY OF ISRAEL









Wetzler et al. (in prep)

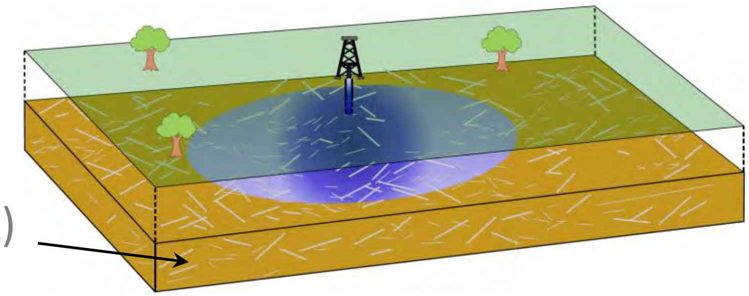
Spatial decay can be explained by pressure vs. elastic stress contributions

$$\rho_{eq} = N_{eq}/\Delta A \sim \Delta\sigma(r) \times N_{fl}/\Delta A \sim r^{-1.8}$$

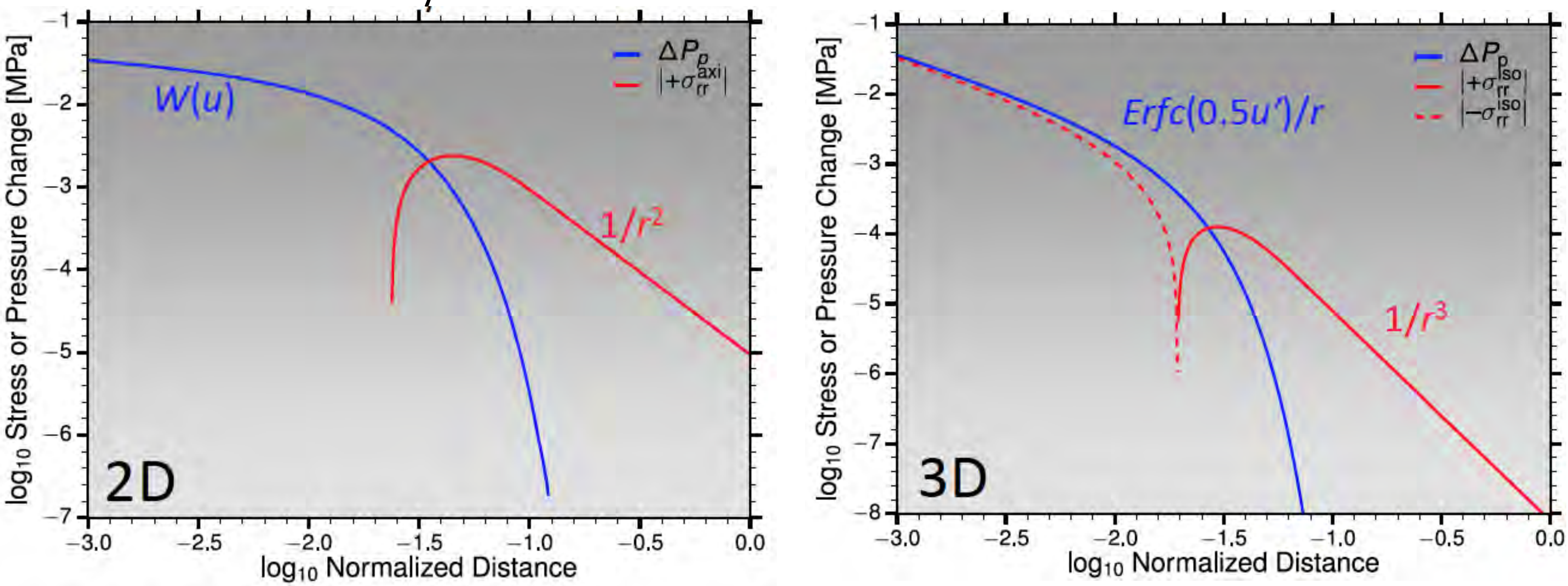
Felzer & Brodsky, *Nature*, 2006

Stress term

Geometric term (fault network)



Induced stress-decay with distance:



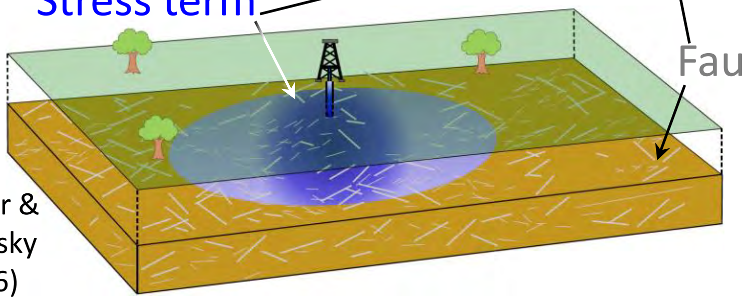
see also Segall & Lu, *JGR*, 2015

Density decay can be explained by stress change × no. of available faults

$\rho_{eq} = N_{obs}/\Delta r \sim \Delta\sigma(r) \times N_{fl}/\Delta r \sim r^{-1.8}$, $N_{fl}/\Delta r \sim r^{(df-D)}$, d_f – *fractal dimension of the fault network*

D = 2.0 (geometric dimension of density measurement)

d_f=1.0-1.6 (Kagan & Knophoff 1980; Hirata 1987; Davidsen & Goertz, 2004)

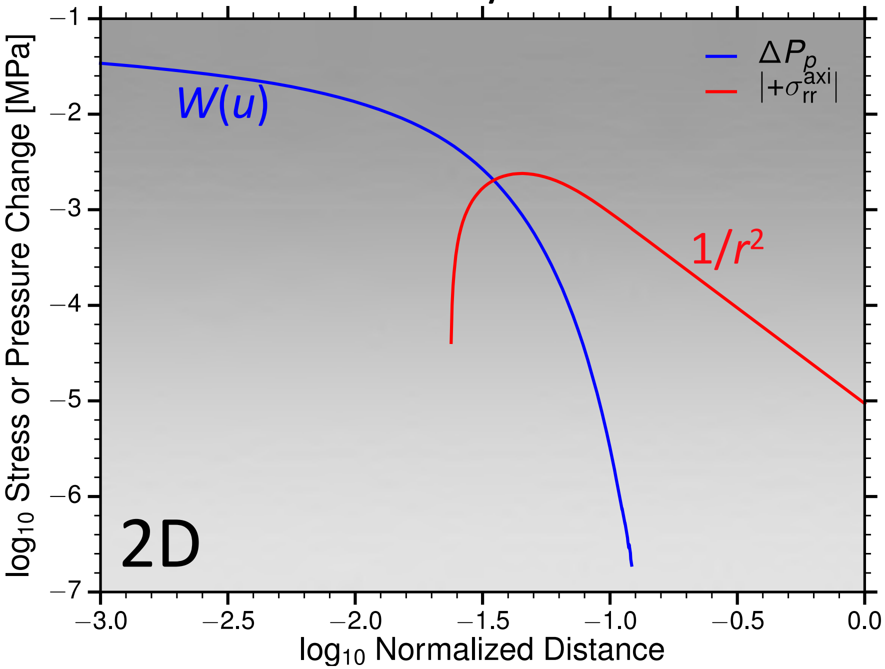


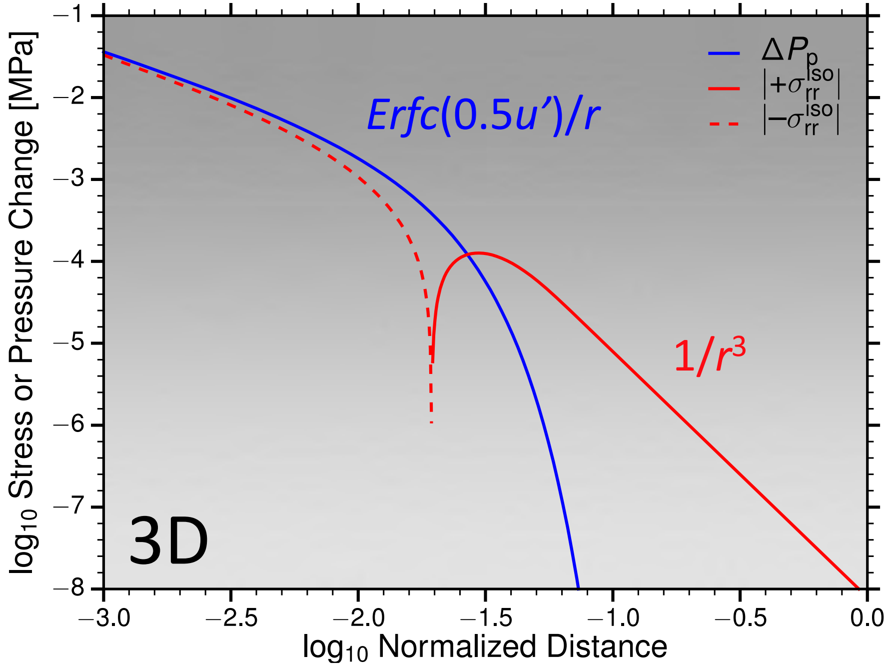
Felzer & Brodsky (2006)

For $\Delta\sigma(r) \sim r^{2.0}$, $\rho_{eq} \sim r^{-1.8}$

→ d_f=2.2

Induced stress-decay with distance:

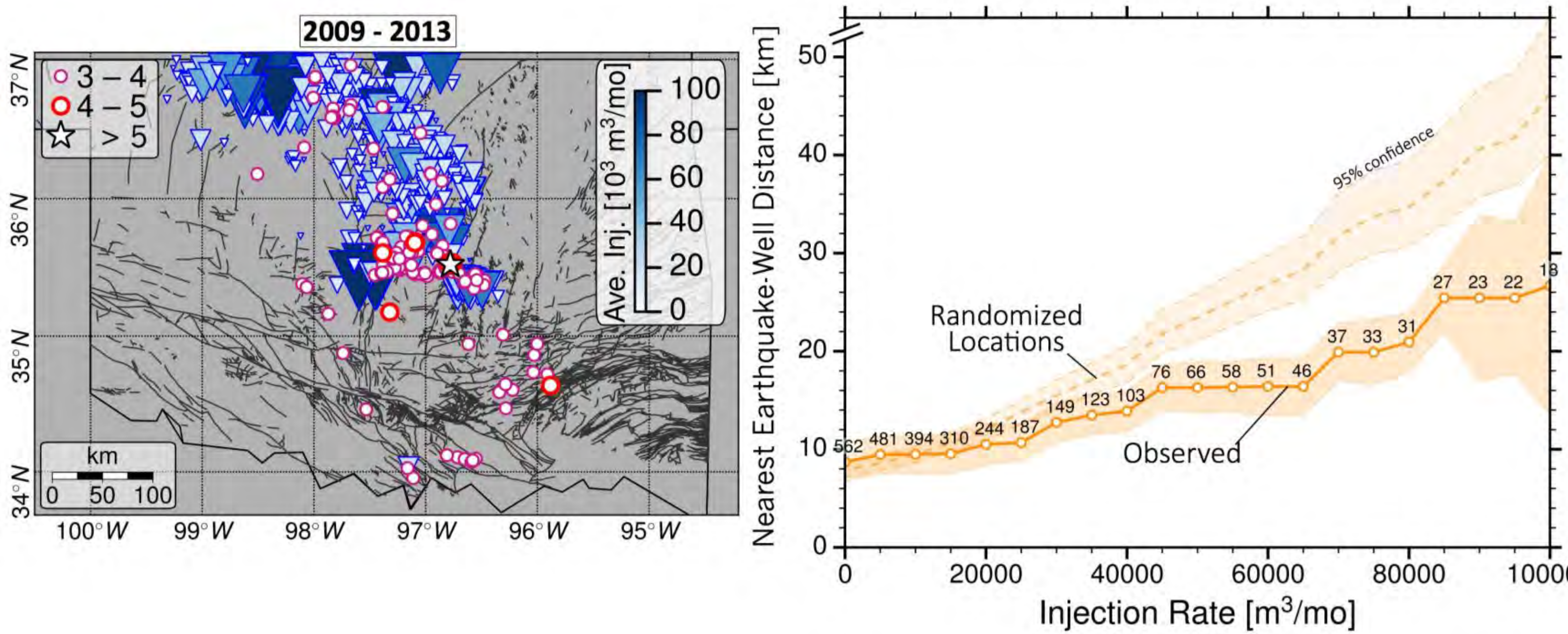




$W(u) = \int_u^\infty \frac{\exp(-u)}{u} du$, $u = r^2/(4Dt)$

$u' = r/(Dt)^{0.5} = 2u^{0.5}$

1) Induced earthquakes frequently occur at large distances from injection wells



Goebel *TLE* 2015

See also: Horton et al. 2012; Bao & Eaton 2016; Yeck et al. 2016; Goebel et al. *GRL* 2016

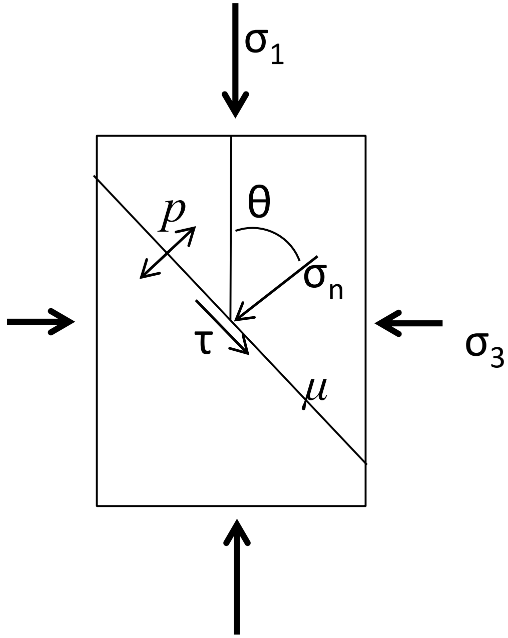
Changes in elastic stresses can directly trigger earthquakes

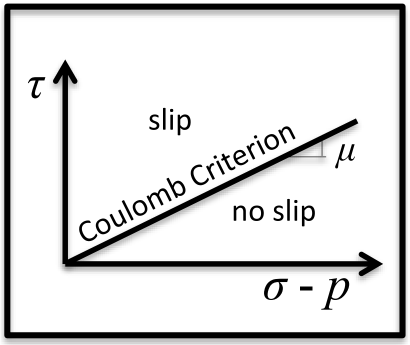
Coulomb stress change:

$\Delta CS = \tau - \mu(\sigma - \Delta p)$

Δp = change in pore pressure

$\sigma - \Delta p$ = effective normal stress





Healy et al. 1968, Raleigh et al. 1976, Ellsworth 2013

3) Poroelastic coupling of fluid and solid stresses close to the injection well

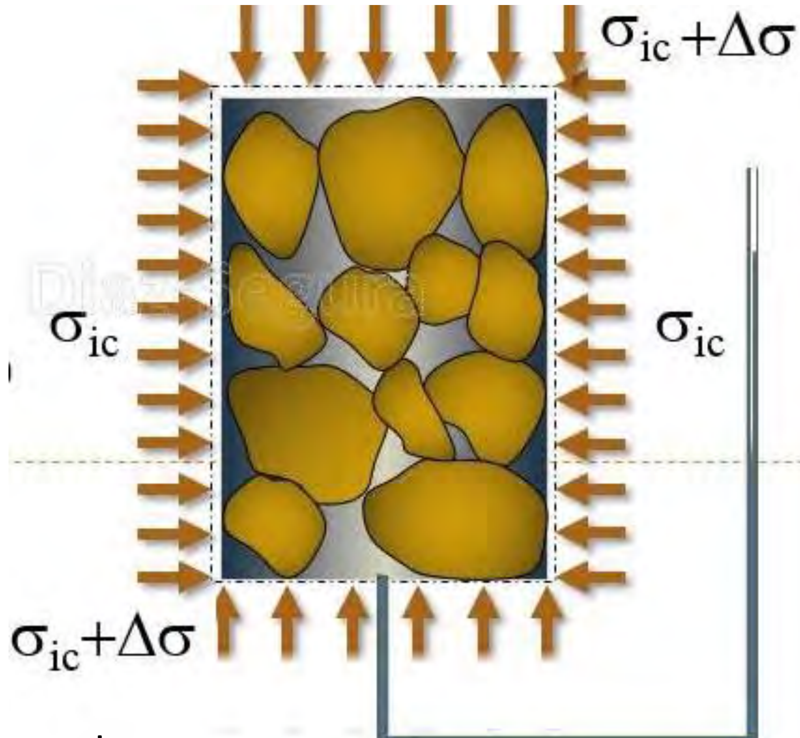
Constitutive relation for isotropic poroelastic medium:

$$e = \frac{1}{K} s + \frac{a}{K} p$$

Linear elasticity + pressure

$$DV = ae + \frac{a}{K_u B} p$$

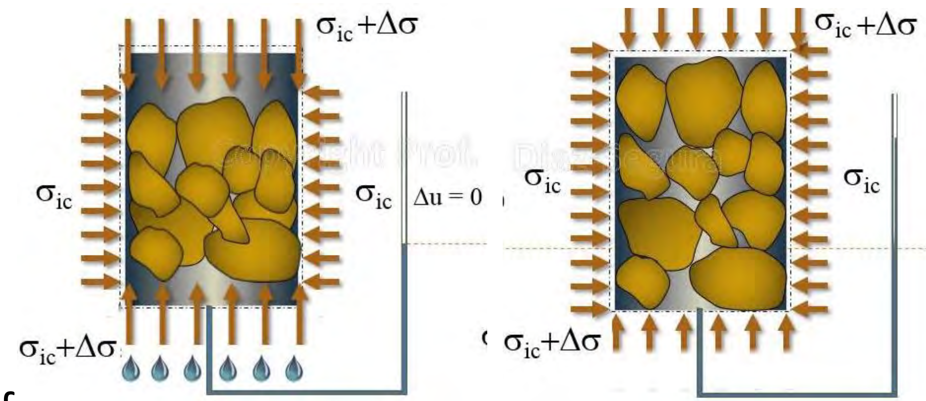
Change in (solid) stress and (fluid) pressure due to adding/removing increment of fluid ($\Delta\varsigma$)



Segall & Lu, *JGR* (2013); Wang (2000)

Poroelastic stress changes in the solid and fluid during fluid injection operations

drained condition



undrained condition

Constitutive relation for isotropic poroelastic medium:

$$1) \rightarrow \varepsilon = \frac{1}{K}\sigma + \frac{\alpha}{K}p \quad \longrightarrow \quad \alpha = 1 - \frac{\partial\sigma/\partial\varepsilon|_p}{\partial p/\partial\varepsilon|_s} = 1 - \frac{K}{K_s}$$

at $p = 0$ (for K); at $\sigma = 0$ (for K_s)

Linear elasticity + pressure

α - strain due to change in solid and fluid stresses

$$2)(V_p - V_f)/V = \zeta = \alpha\varepsilon + \frac{\alpha}{K_u B}p$$

→ Partitioning of change in (solid) stress and (fluid) pressure due to adding/removing increment of fluid (Δm)

Segall & Lu, *JGR* (2013); Wang (2000); Ma & Zoback *JGR* (2016)

Quantitative description of density decay at individual sites

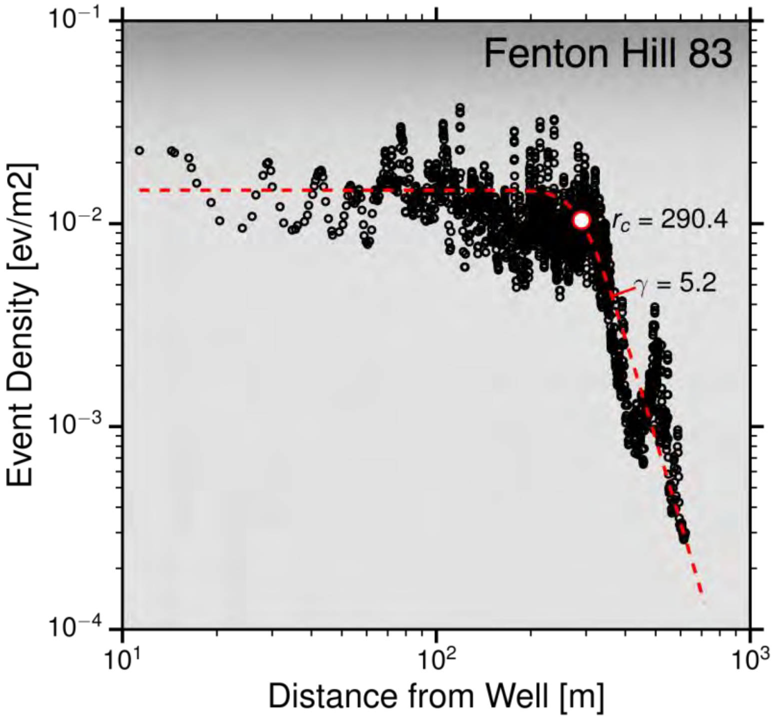
Functional form of decay: $$r = r_0 \frac{1}{\left(1+(r/r_c)^{2\gamma}\right)^{1/2}}$$

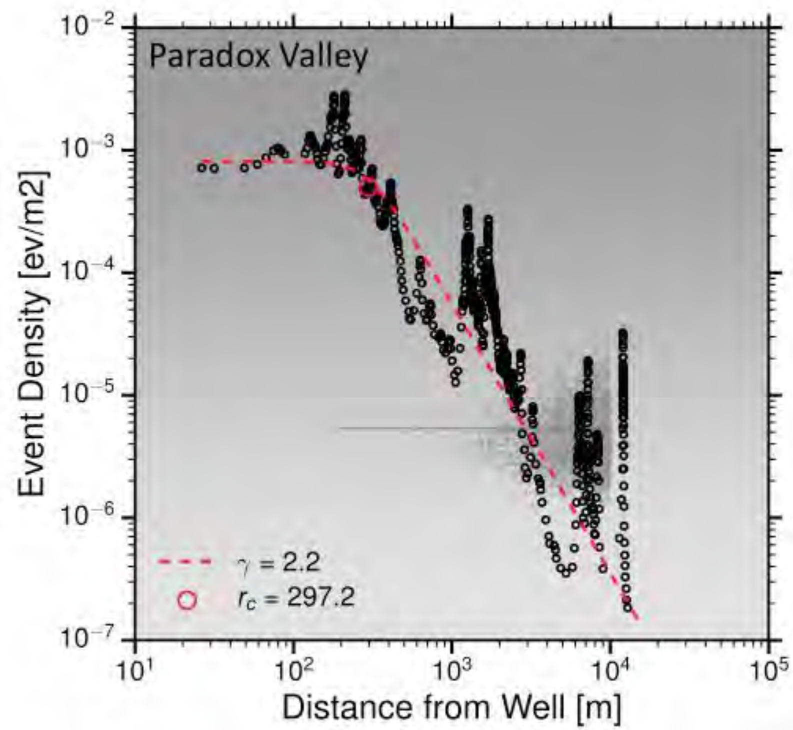
short distance plateau (→ r_0)

corner distance (→ r_c)

decay exponent (→ 2γ)

Determine γ and r_c from MLE assuming Poissonian counting errors in each distance bin





Goebel et al. *(in prep.)*