Seismic and aseismic response to fluid injection

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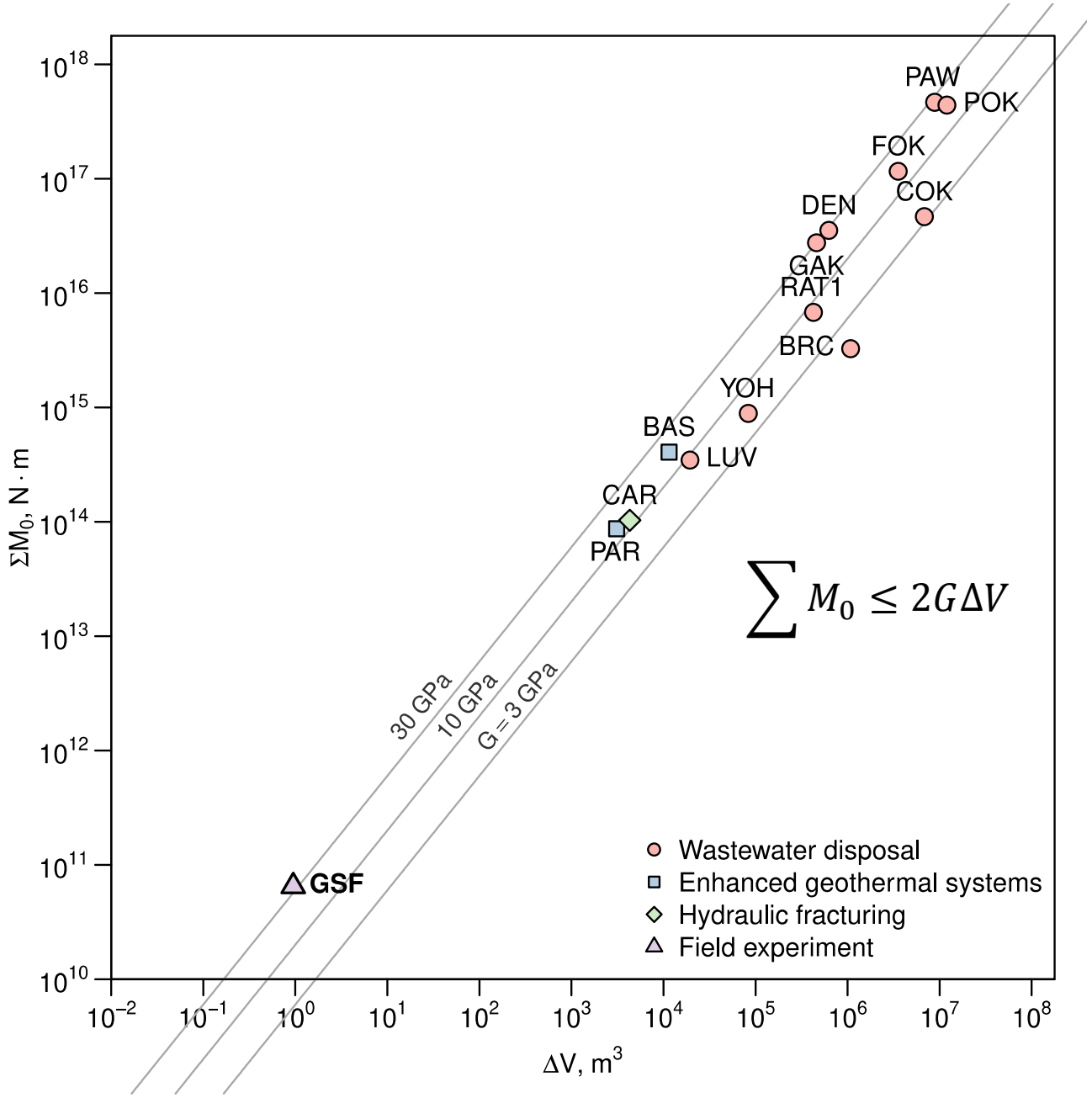
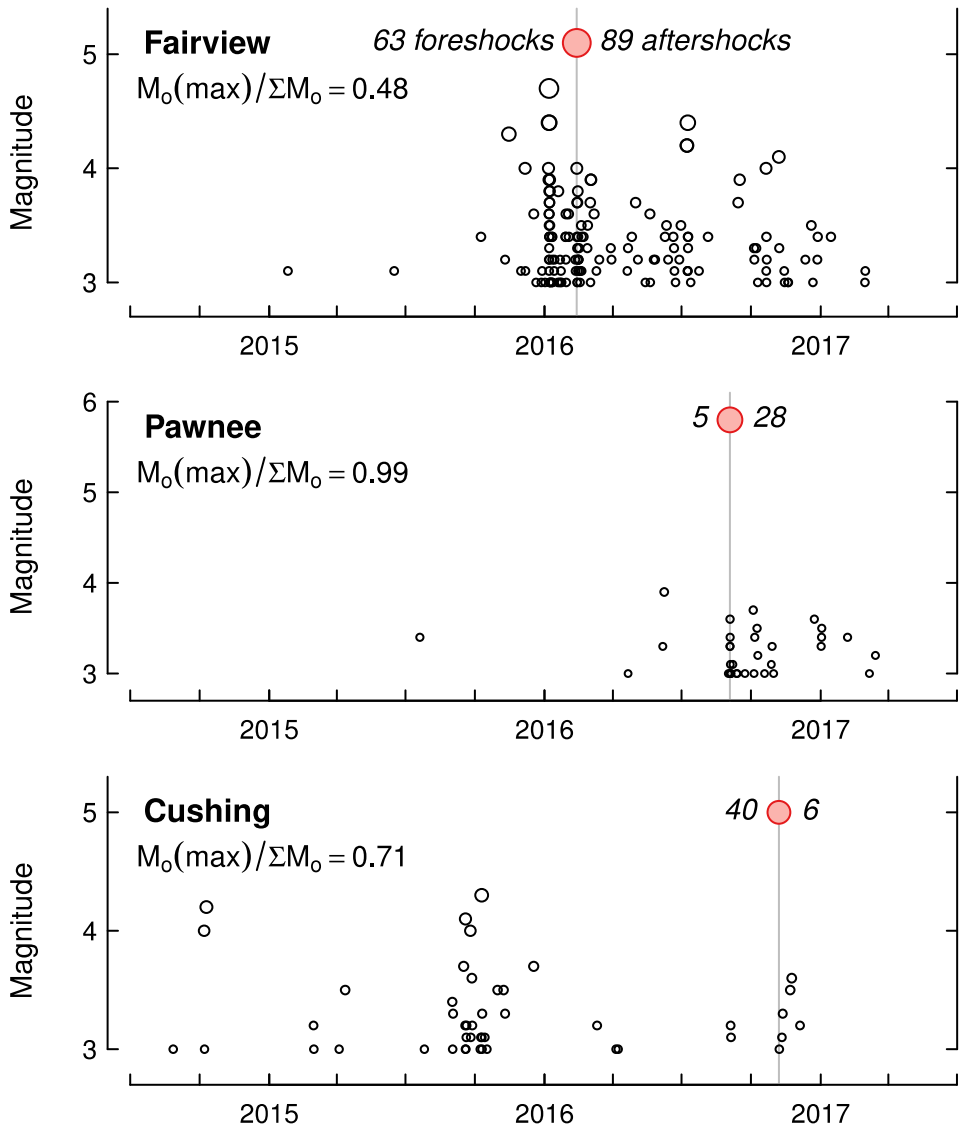
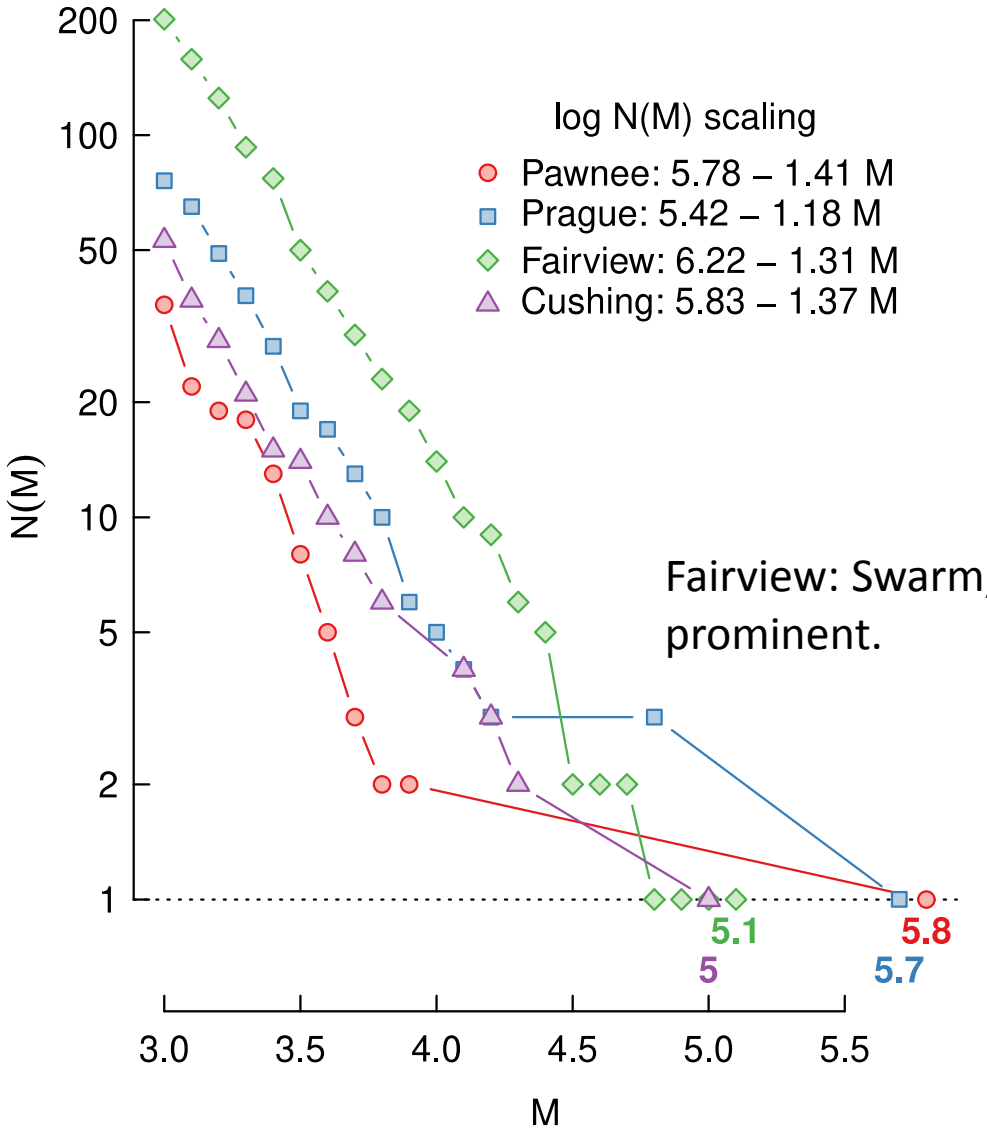
Questions and issues

- Scaling of moment release
- Highly-variable nature of injection-induced earthquake sequences
- Character of rupture in terms of distributions of asperities
- Pore pressure increase needed to reactivate pre-existing fault
- Seismic or aseismic response

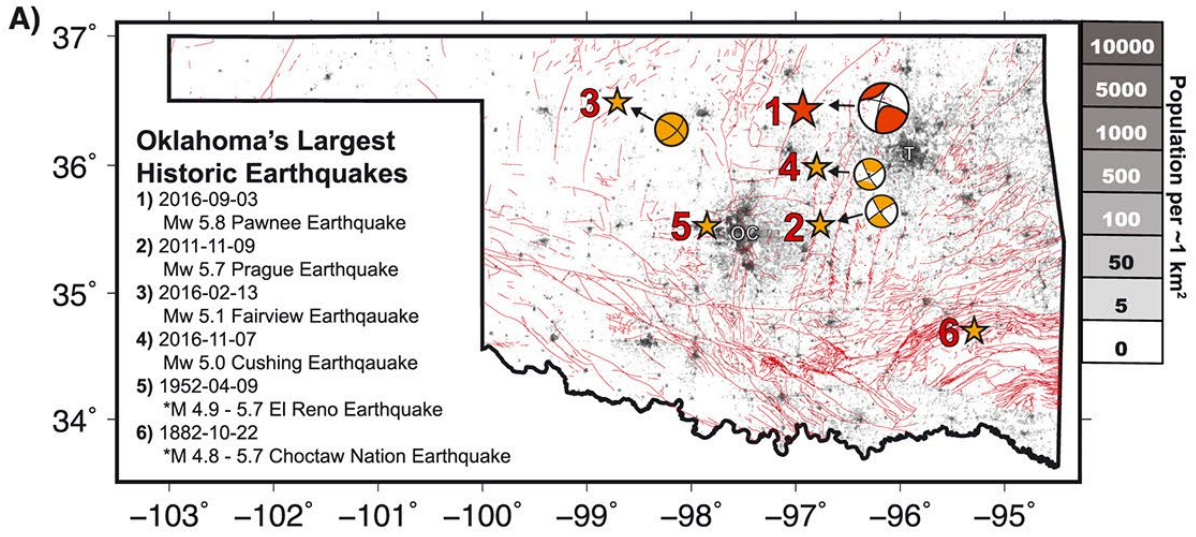

PAW
POK
FOK
COK
DEN
GAK
RAT1
BRC
YOH
BAS
LUV
CAR
PAR
GSF
30 GPa
10 GPa
G = 3 GPa
$\sum M_0 \leq 2G\Delta V$
Wastewater disposal
Enhanced geothermal systems
Hydraulic fracturing
Field experiment
ΣM_0, N · m
ΔV, m^3
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}

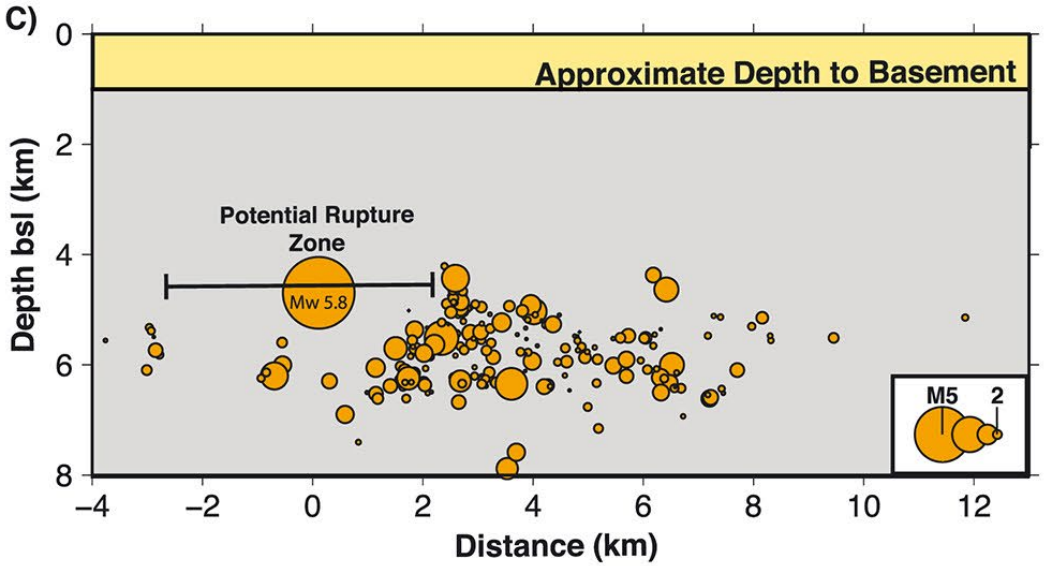

Fairview
63 foreshocks
89 aftershocks
$M_o(max)/\Sigma M_o = 0.48$
Pawnee
5
28
$M_o(max)/\Sigma M_o = 0.99$
Cushing
40
6
$M_o(max)/\Sigma M_o = 0.71$
Magnitude
2015
2016
2017

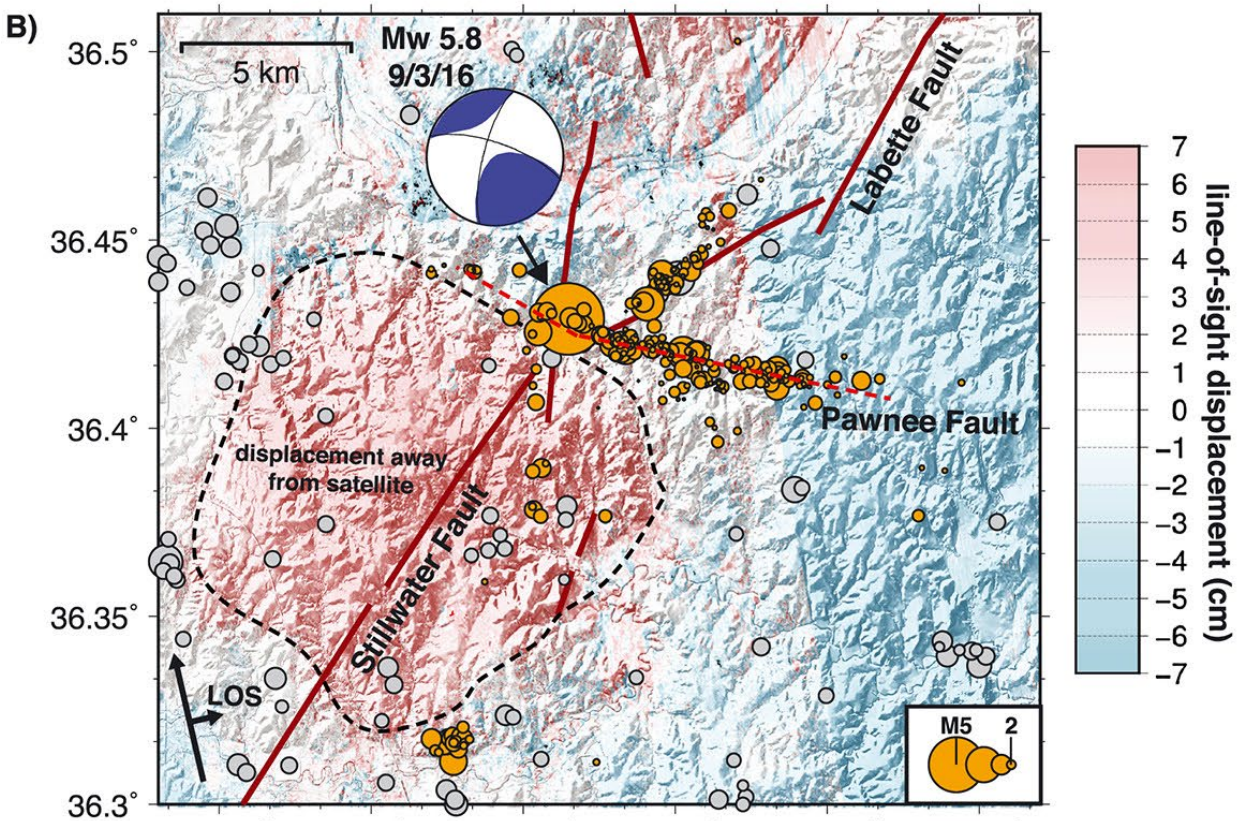
Pawnee: Rupture of single large asperity.



Fairview: Swarm, mainshock not very prominent.





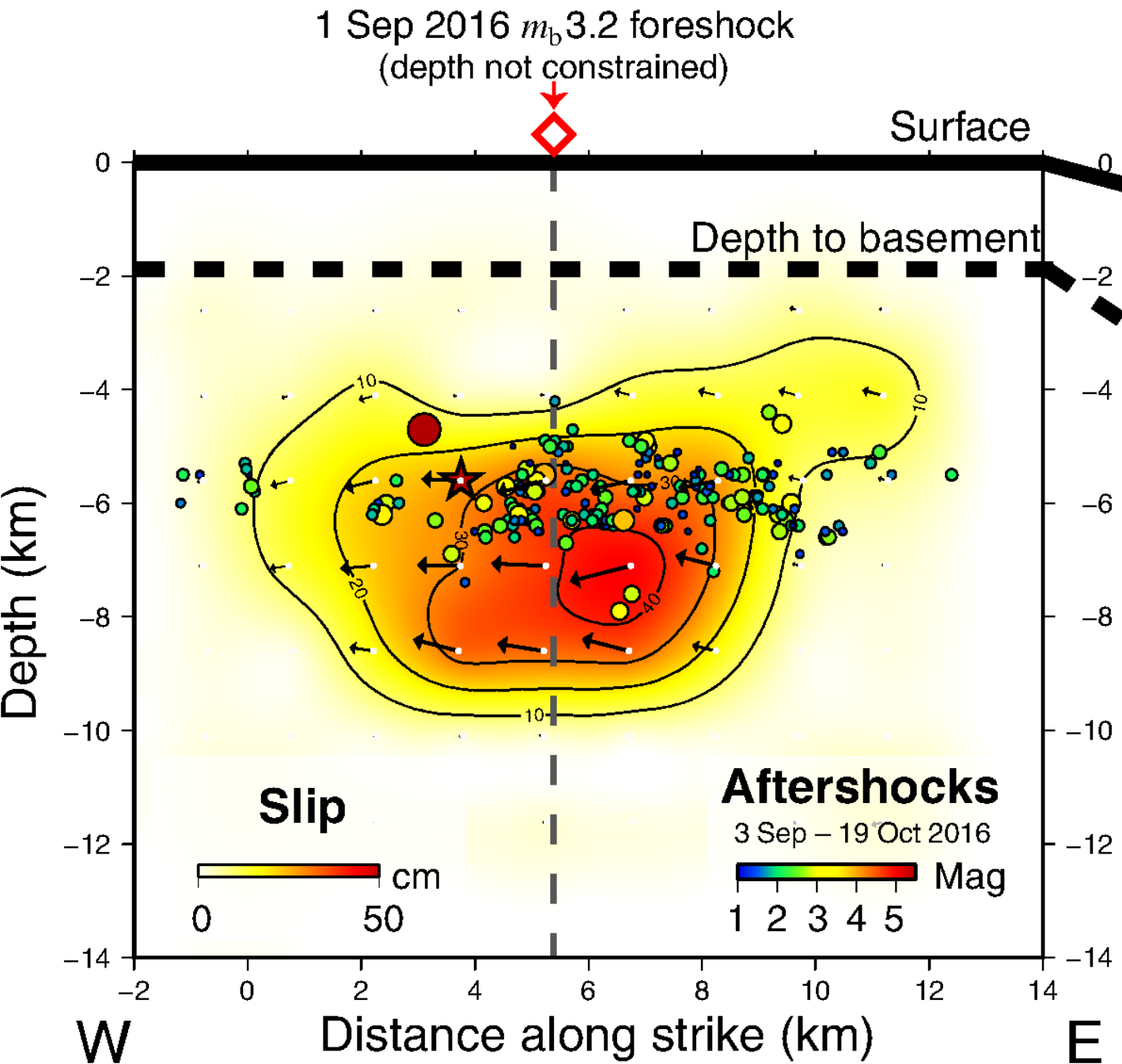


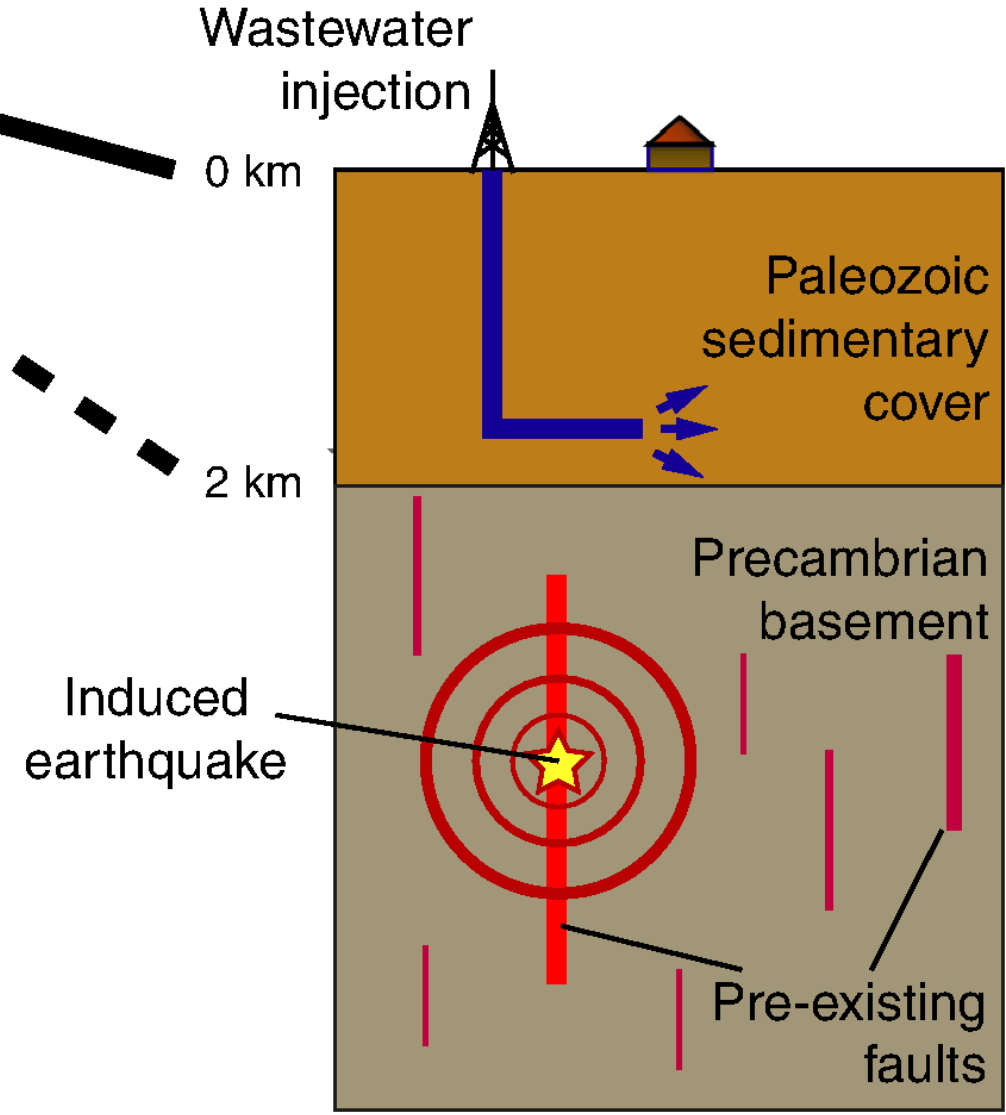
Yeck et al. (GRL, 2017)

Stress drop = 9.9 MPa

Single asperity, slip=1 m, radius 2.2 km, can account for M5.8 mainshock.

Grandin et al. (SRL, 2017)



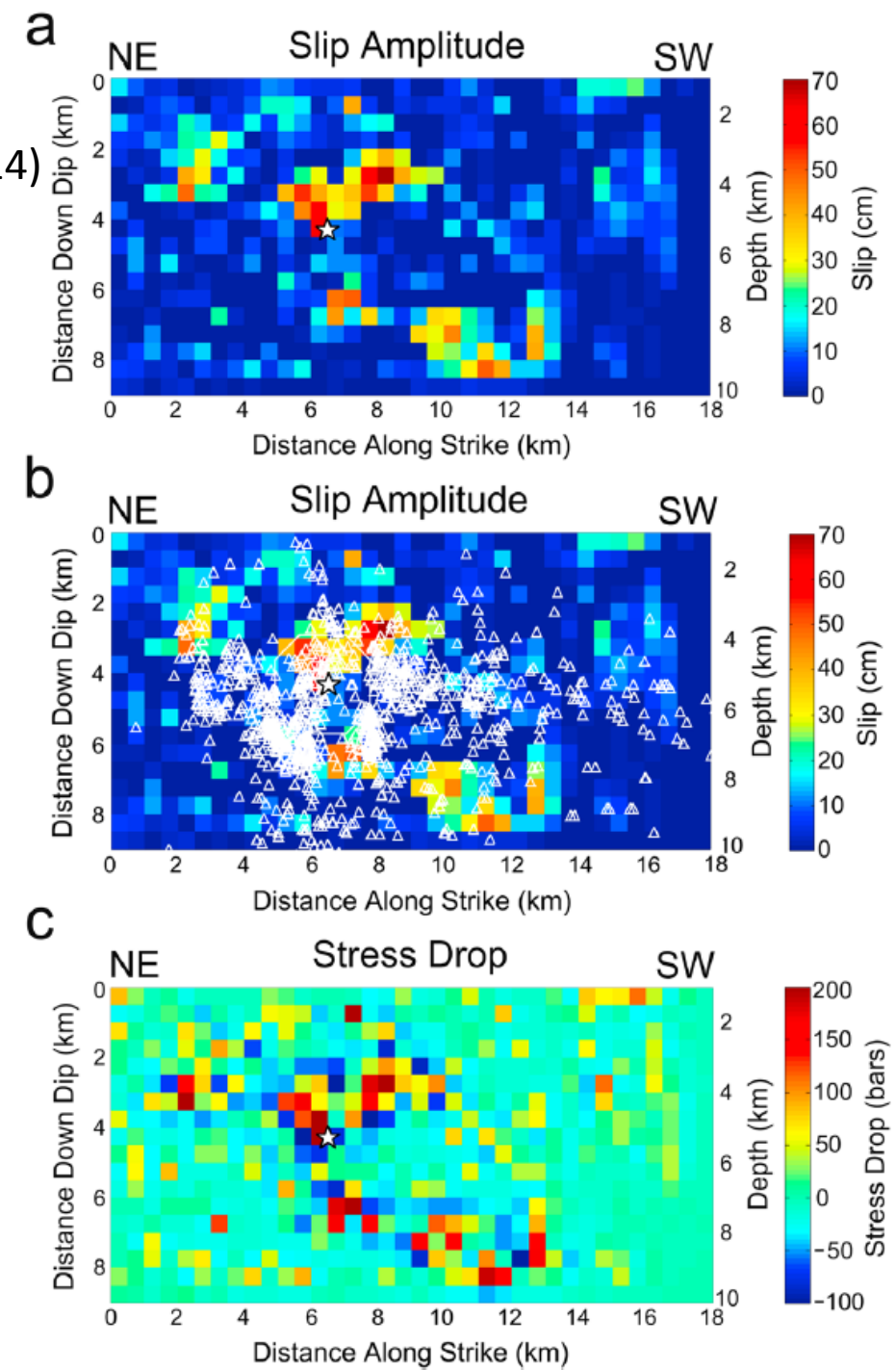


Sun & Hartzell (GRL, 2014)

2011 M5.7 Prague, OK Induced

Stress drop 9 MPa at hypocentral high-slip patch at depth 5 km.

2 asperities of radii 1.7 km and slip 0.7 m can account for M5.7 mainshock.



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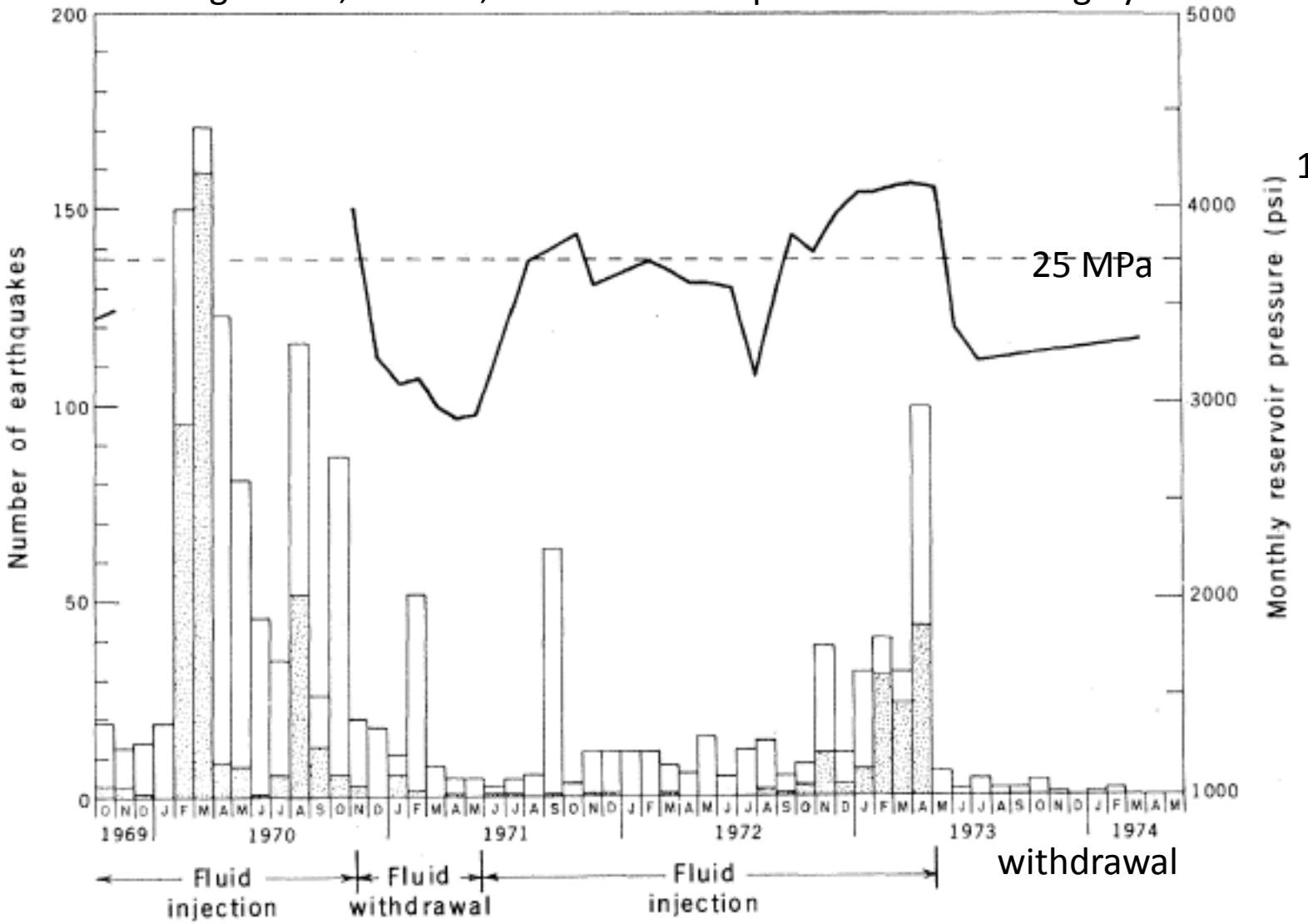
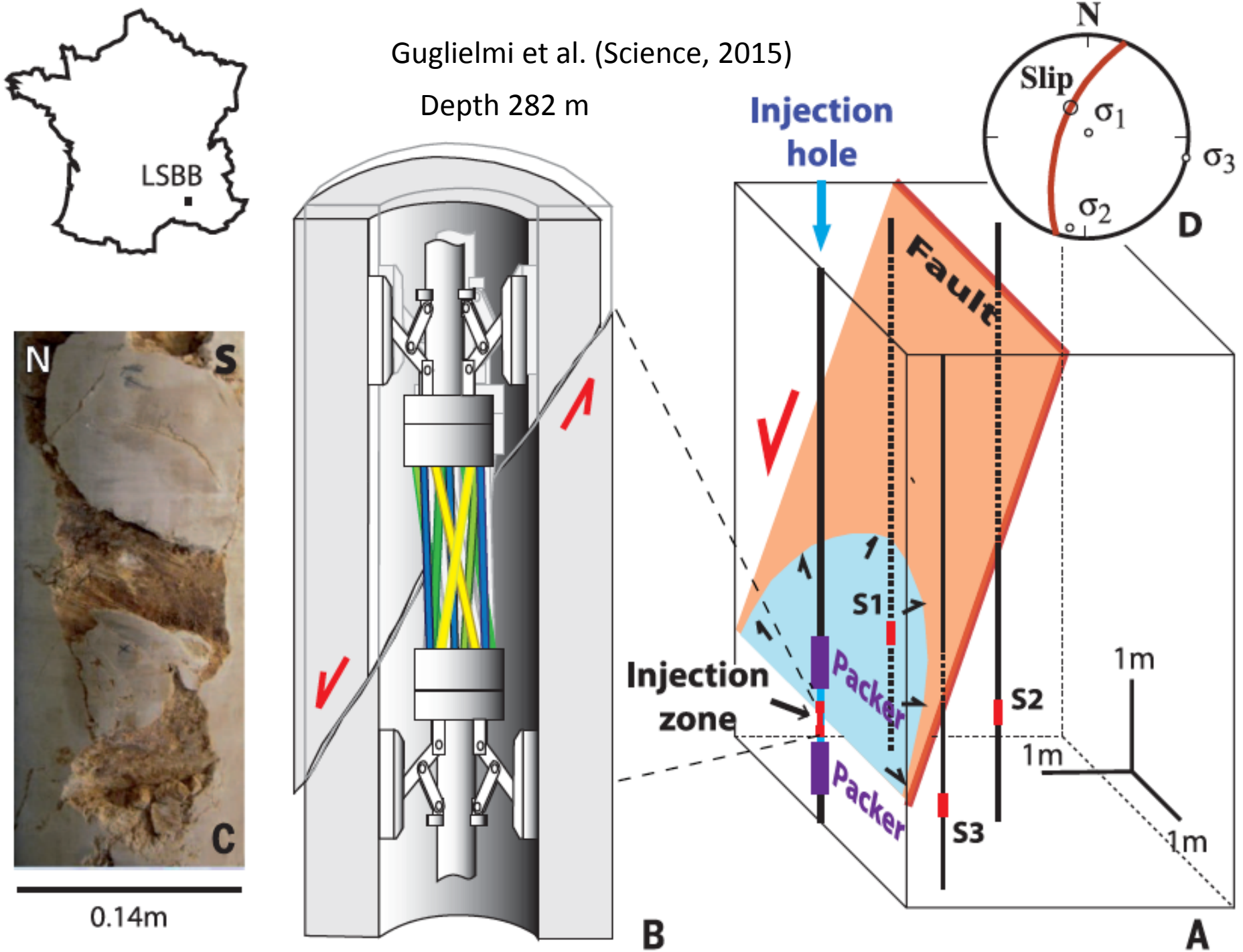
Earthquakes triggered by raising pore pressure 3 to 4 MPa above ambient. Earthquakes turned off by lowering pore pressure by 3 to 4 MPa below ambient.

Raleigh et al., Science, 1976 Earthquake control in Rangely Oil Field

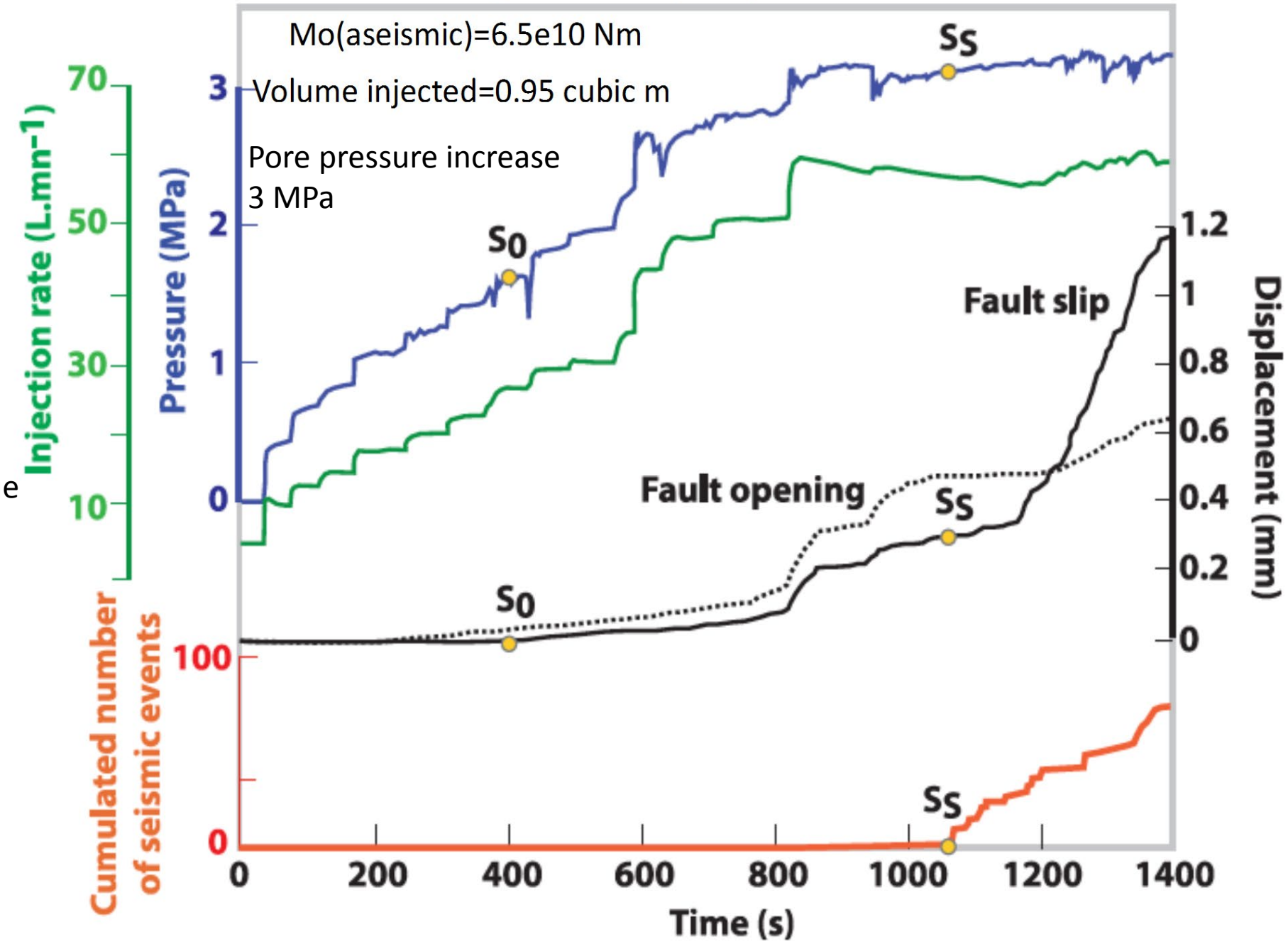


Depth 2 km

1000 psi=6.8 MPa

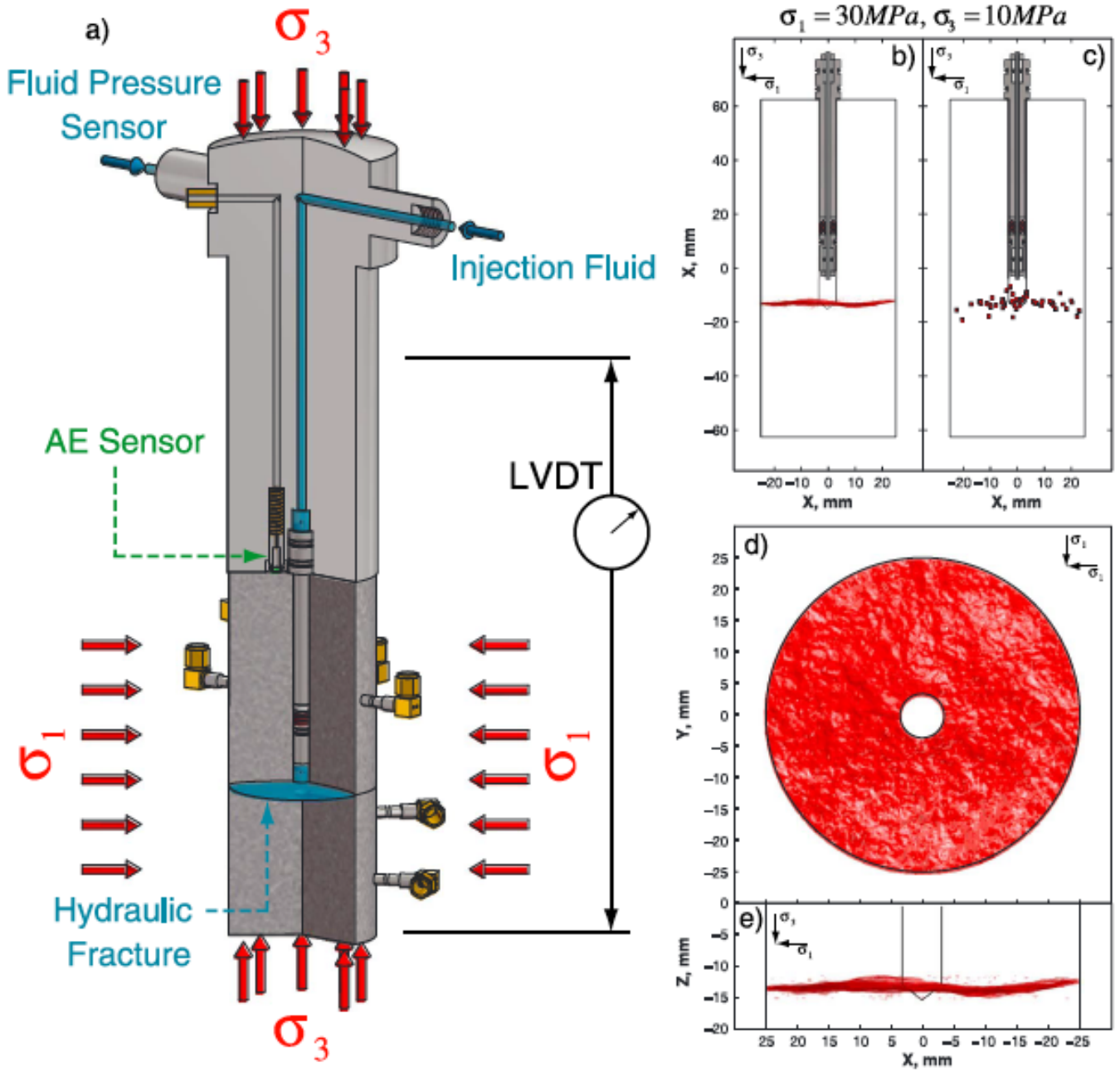

LSBB
N
S
C
0.14m
Guglielmi et al. (Science, 2015)
Depth 282 m
Injection hole
N
Slip
σ1
σ3
σ2
D
Fault
V
S1
Injection zone
Packer
Packer
S2
S3
1m
1m
1m
B
A

Guglielmi et al. (2015)

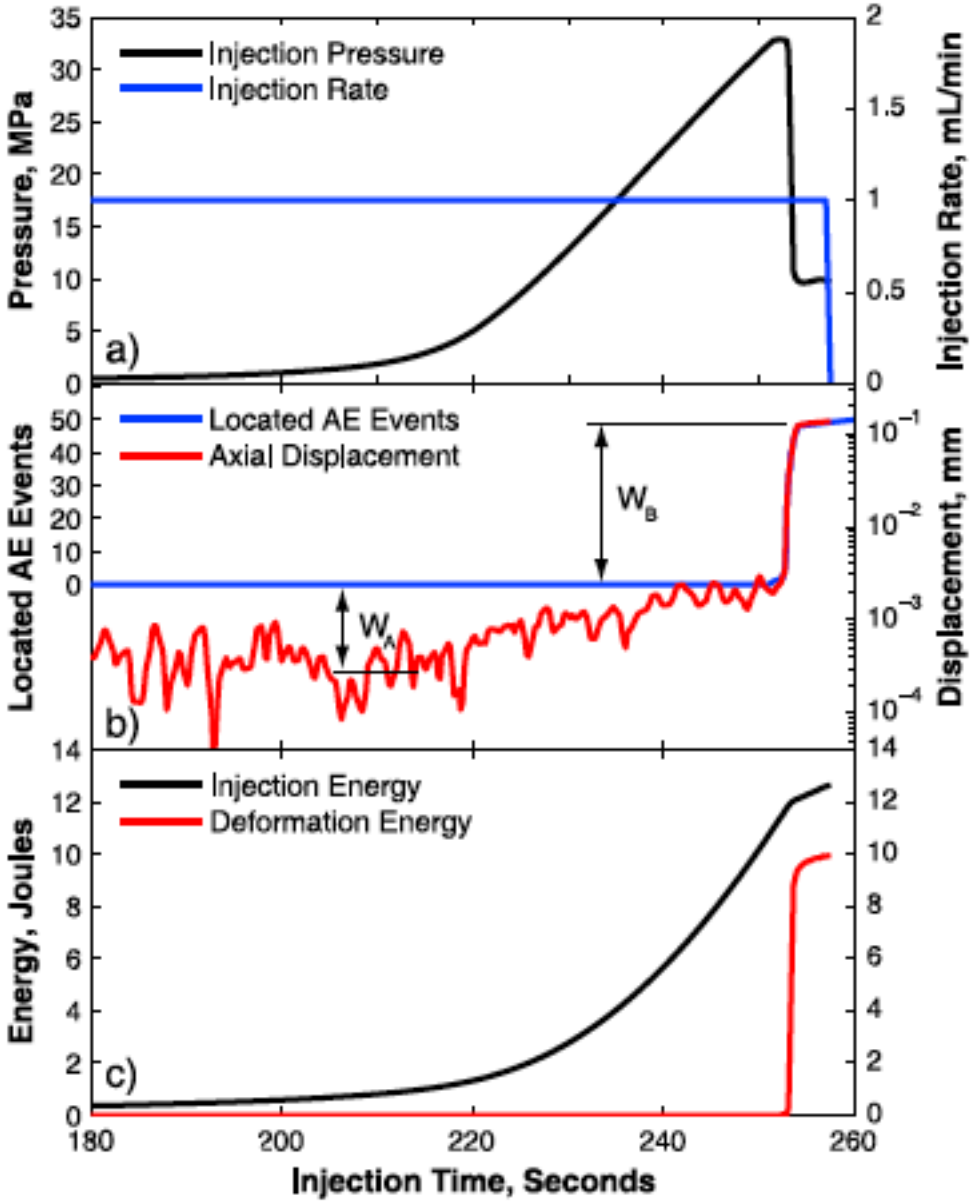


Aseismic slip due to rheology of limestone at shallow depth?

Goodfellow et al. (GRL, 2015)



Goodfellow et al. (GRL, 2015)



Experiment SR4

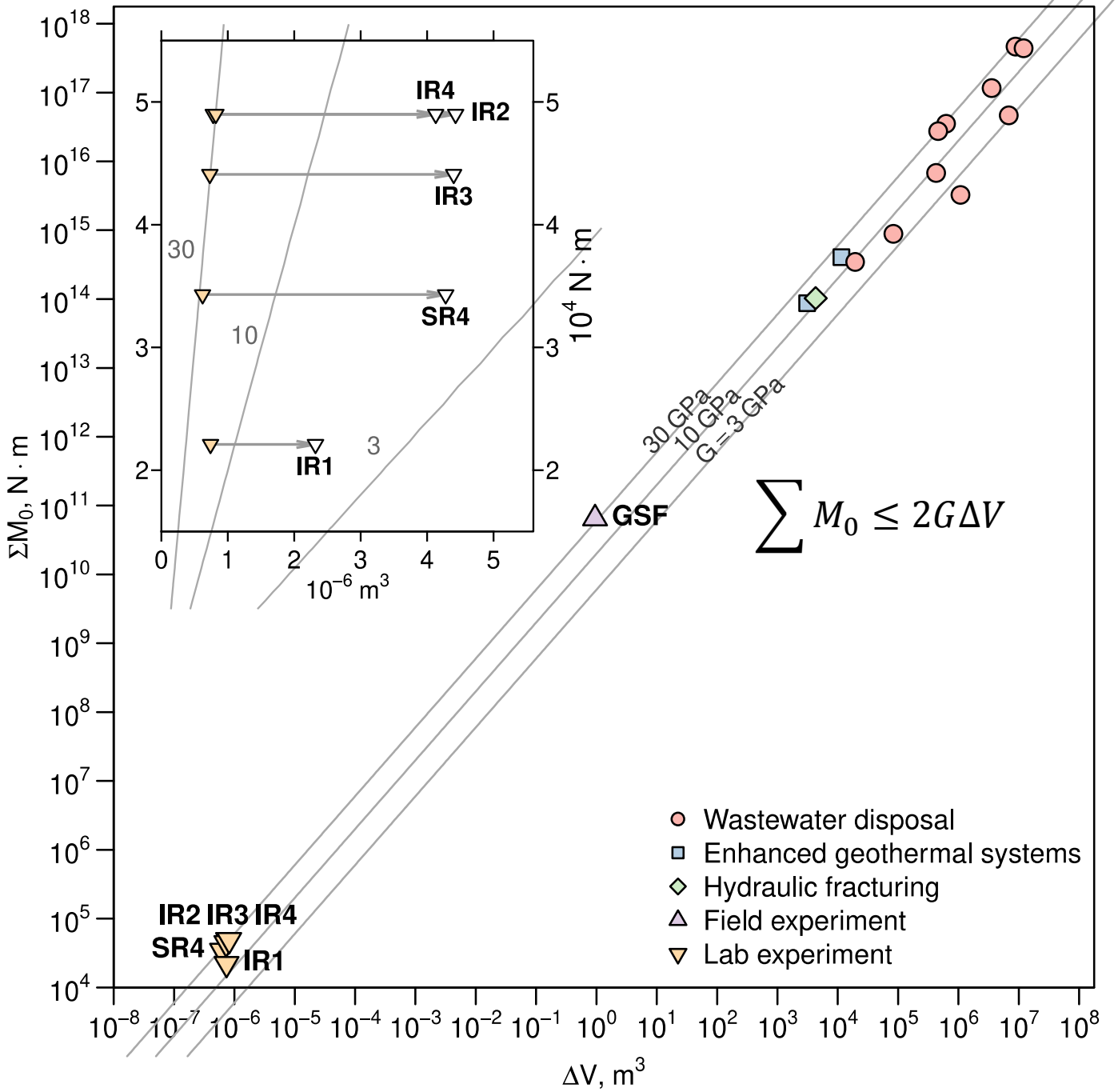
$\sum M_0(aseismic)$=3kAu

$$k = \frac{3\lambda + 2G}{3} \cong \frac{5G}{3}$$

$$\Delta V = 0.62x10^{-6}m^3$$

$$\sum M_0 = 3.43x10^4 \text{Nm}$$

Deformation rate limited by rate of fluid flow into cracks.


ΣM0, N·m
ΔV, m3
30 GPa
10 GPa
G = 3 GPa
GSF
$\sum M_0 \leq 2G\Delta V$
IR2 IR3 IR4
SR4
IR1
Wastewater disposal
Enhanced geothermal systems
Hydraulic fracturing
Field experiment
Lab experiment
IR4
IR2
IR3
SR4
IR1
30
10
3
10−6 m3
10^4 N·m

A few conclusions

- Upper bound moment release scales linearly with injected volume, but debate is probably not over due to a few reported outliers.
- Magnitude distributions of sequences appear to reflect size distributions of asperities at depth.
- Distribution of asperities also controls nature of rupture. Is there a single dominant asperity?
- Pore pressure increases of the order of a seismic stress drop can reactivate a pre-existing fault well oriented for slip in ambient stress state.
- Aseismic moment release may be due to fault zone rheology or to hydraulic fracturing response to injection.