Induced seismicity: the creep route

Jean Schmittbuhl[1]

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Outline

- **Induced seismicity**:
  - a forcing term compare to natural seismicity : test causality issues
  - shalower, possibly easier to monitor
  - In-situ conditions (large scale experiments)
  - Expected to add information on the knowledge of earthquake nucleation processes

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  - Overview of the mechanisms
  - Pore pressure increase: the case of Soultz-sous-Forêts
  - Pore pressure decrease: the case of Lacq

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    - The 2000 stimulation at Soultz-sous-Forêts (large scale Vp changes)
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  - pre-aseismic fluid-induced slip:
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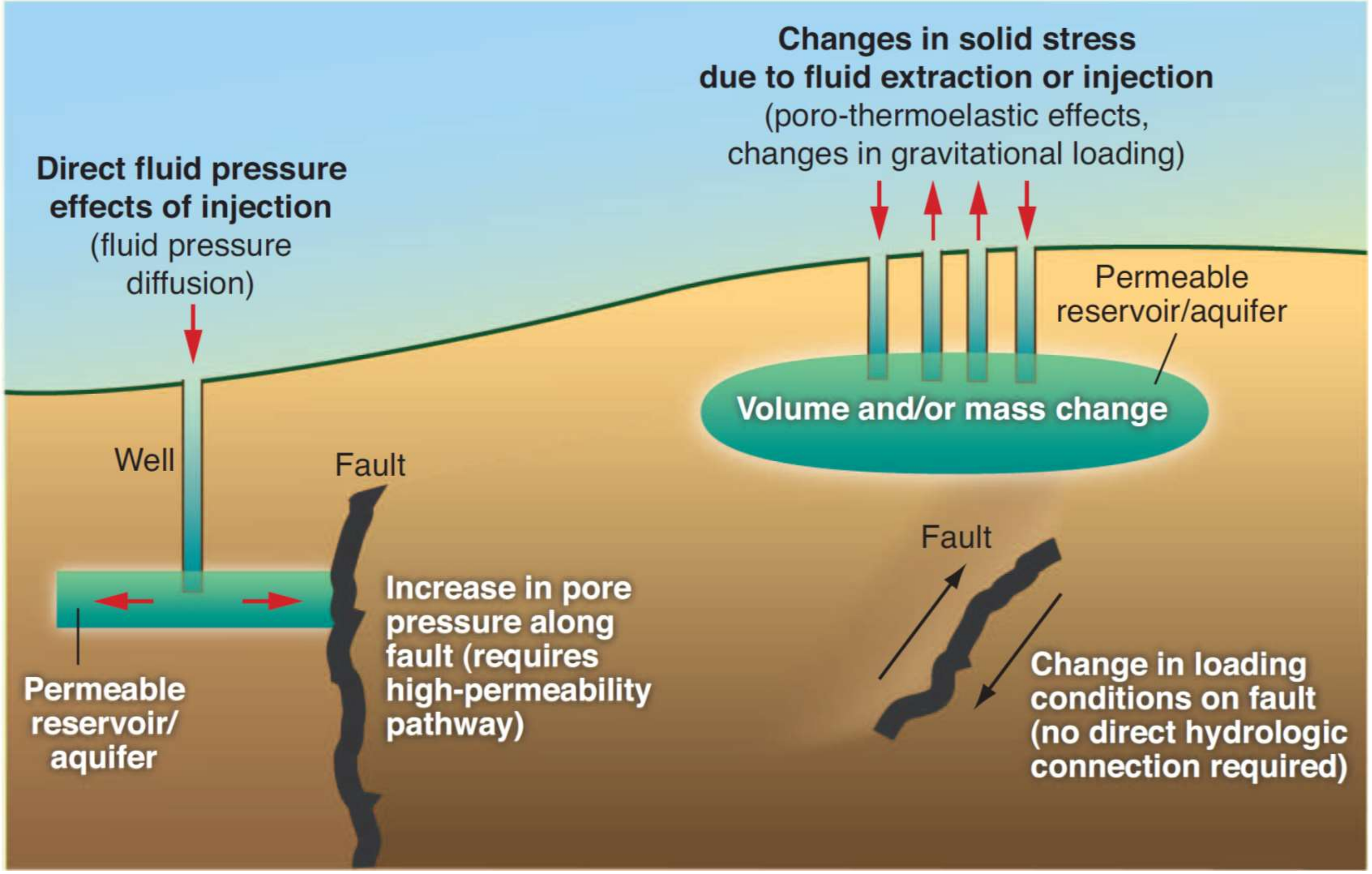
    - The rustrel experiment: at small scale
  - Fluid induced but… The 2010 Soultz-sous-Forêts circulation: long-term variable stress drop within multiplets
  - Pure creep induced seismicity: an experimental approach

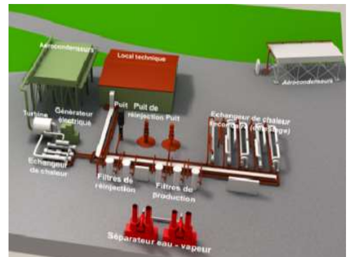
Mechanisms for fluid induced earthquakes

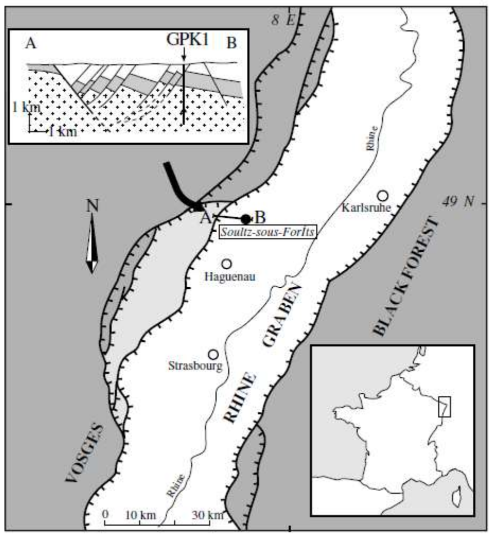


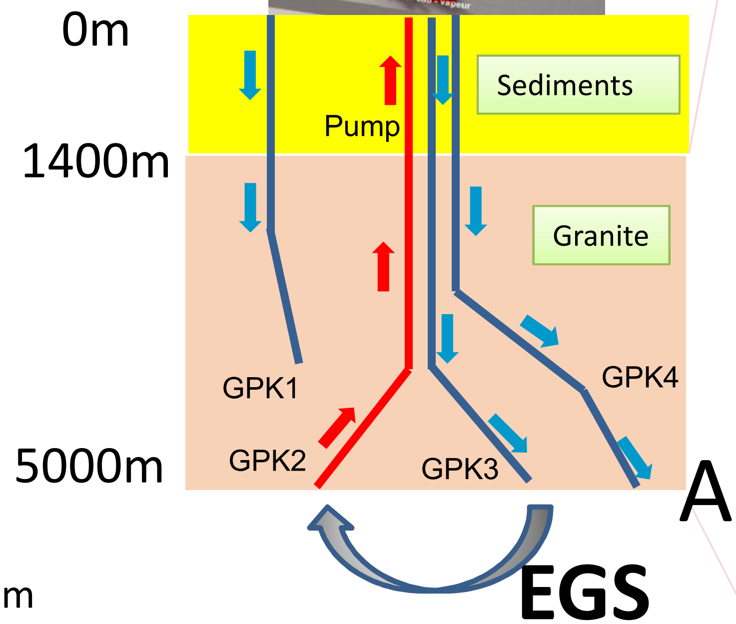
Ellsworth, Science, 2013

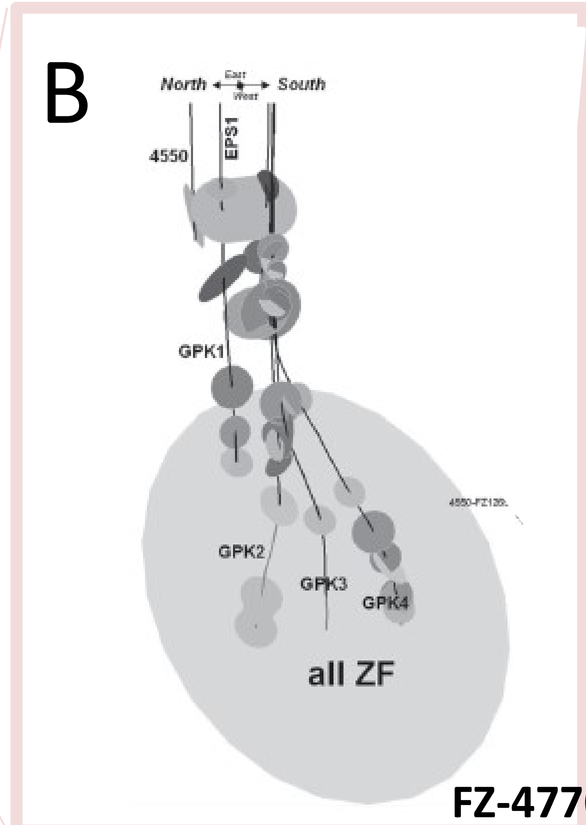
The deep geothermal reservoir of Soultz-sous-Forêts (GEIE EMC) (1987-)

- **Binary geothermal power plant** (ORC) 1.5 MWe net







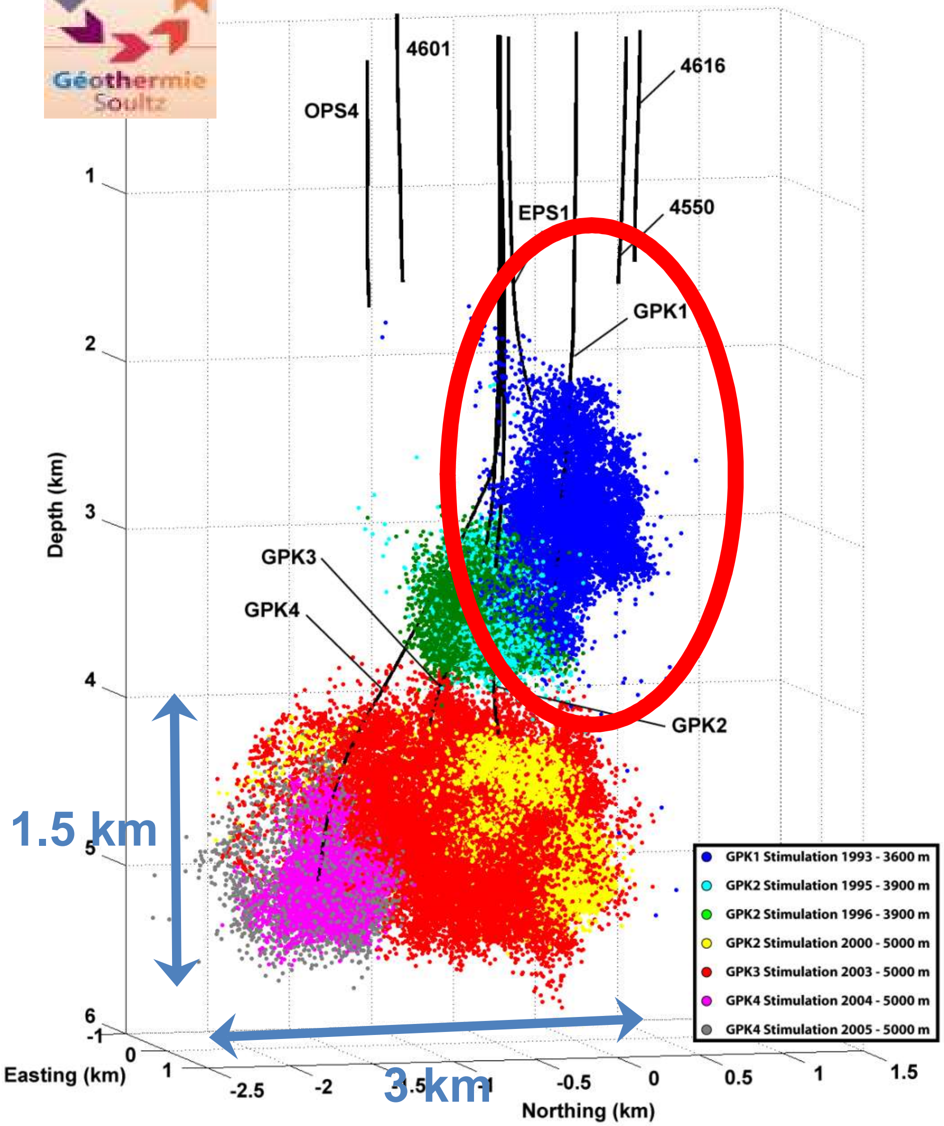


FZ-4770
GPK 1,2,3,(4)

Sausse et al, 2010

- Reservoir: 200°C @5000m
- A complex pre-existing 3D network (granite) + a major fault zone (most of the seismicity) **FZ-4770** in GPK3
- Abundant natural fluid (high salinity (~100g/l) – reservoir size ?

EGS stimulation and seismicity



- Target: Enhanced Geothermal System (EGS) – increase permeability of the reservoir from fluid stimulation
- A large number of induced seismicity (~10000 EQ/stimulation)
- A possible risk of felt EQ (if Ml > 2)
  - 2000 : Ml_{max}=2.6
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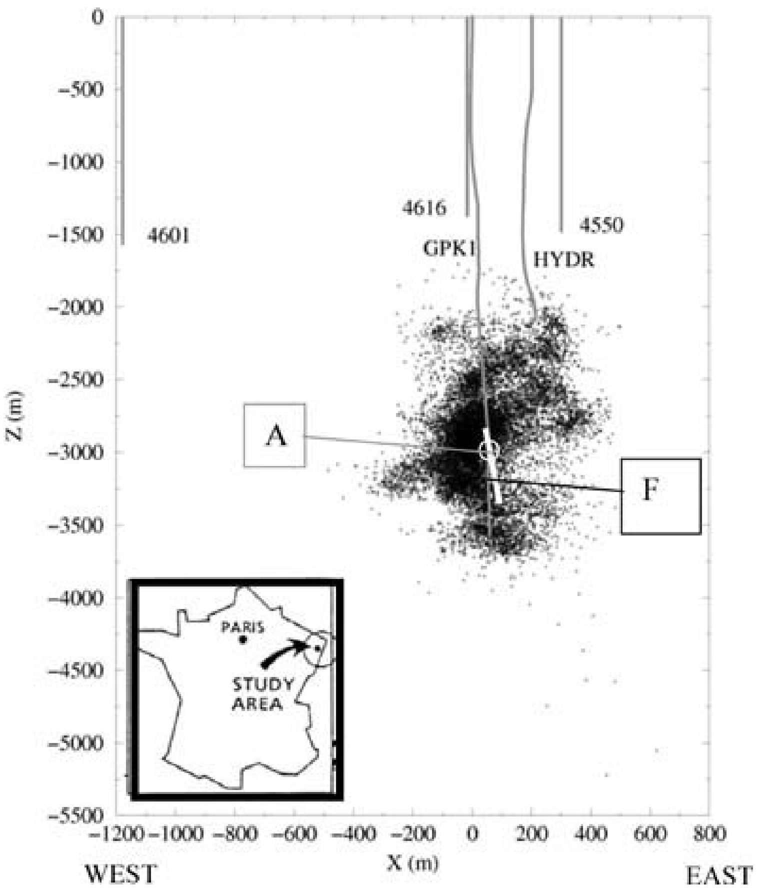
- A tool for reservoir imaging

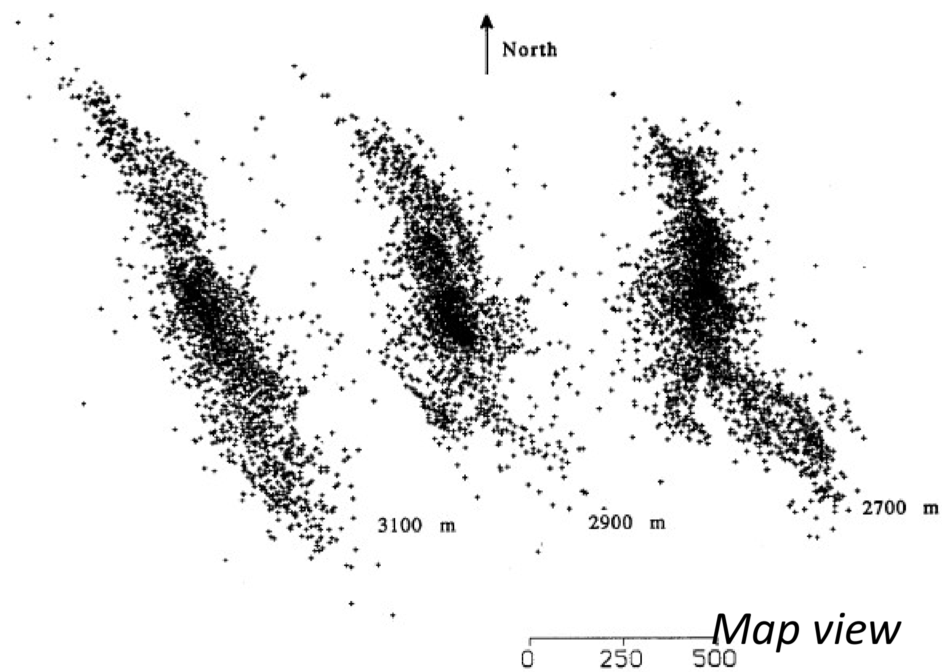
GPK1 stimulation at Soultz-sous-Forêts

injection of 25 000 m^3 during 16 days ~10000 located events



Bourouis and Bernard, 2007

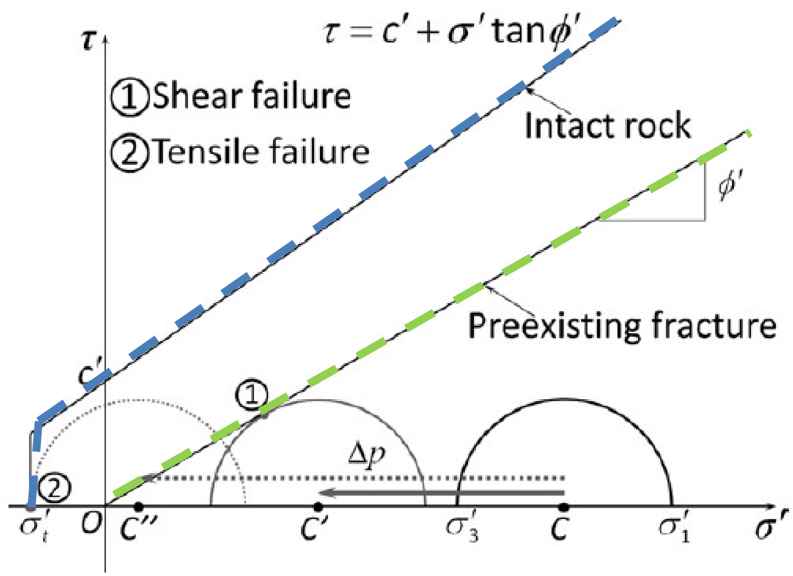
Cornet et al, 2007



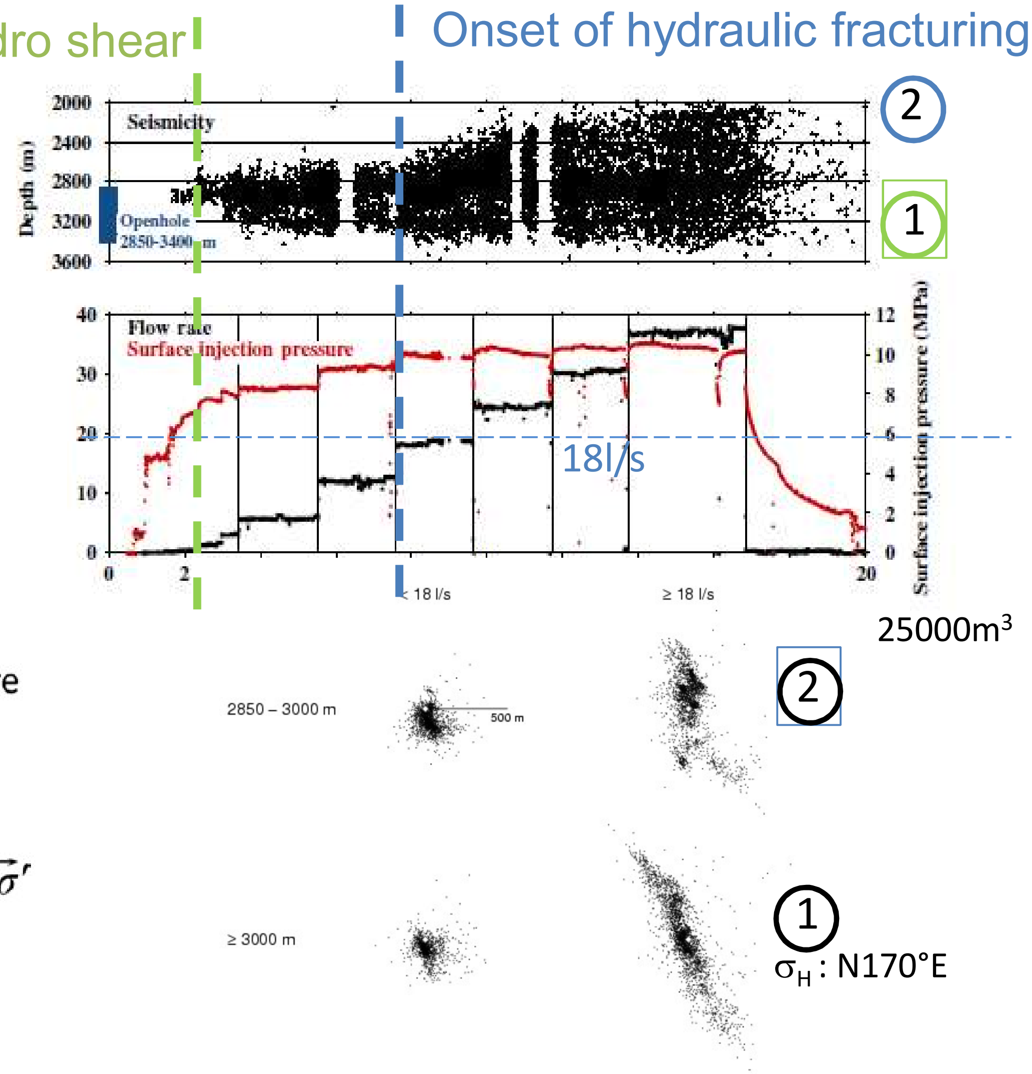
Depth interval (m)l	Mean azimuth	Mean dip (deg)	Number of events
2800–2900	N179°E	87	329
2900–3000	N165°E	67	402
3000–3200	N146°E	86	416

Fluid induced seismicity

GPK1 Stimulation (Sept-Oct 1993)



Vilarrasa et al, 2012



Cornet et al., IJRMMSc, 2007

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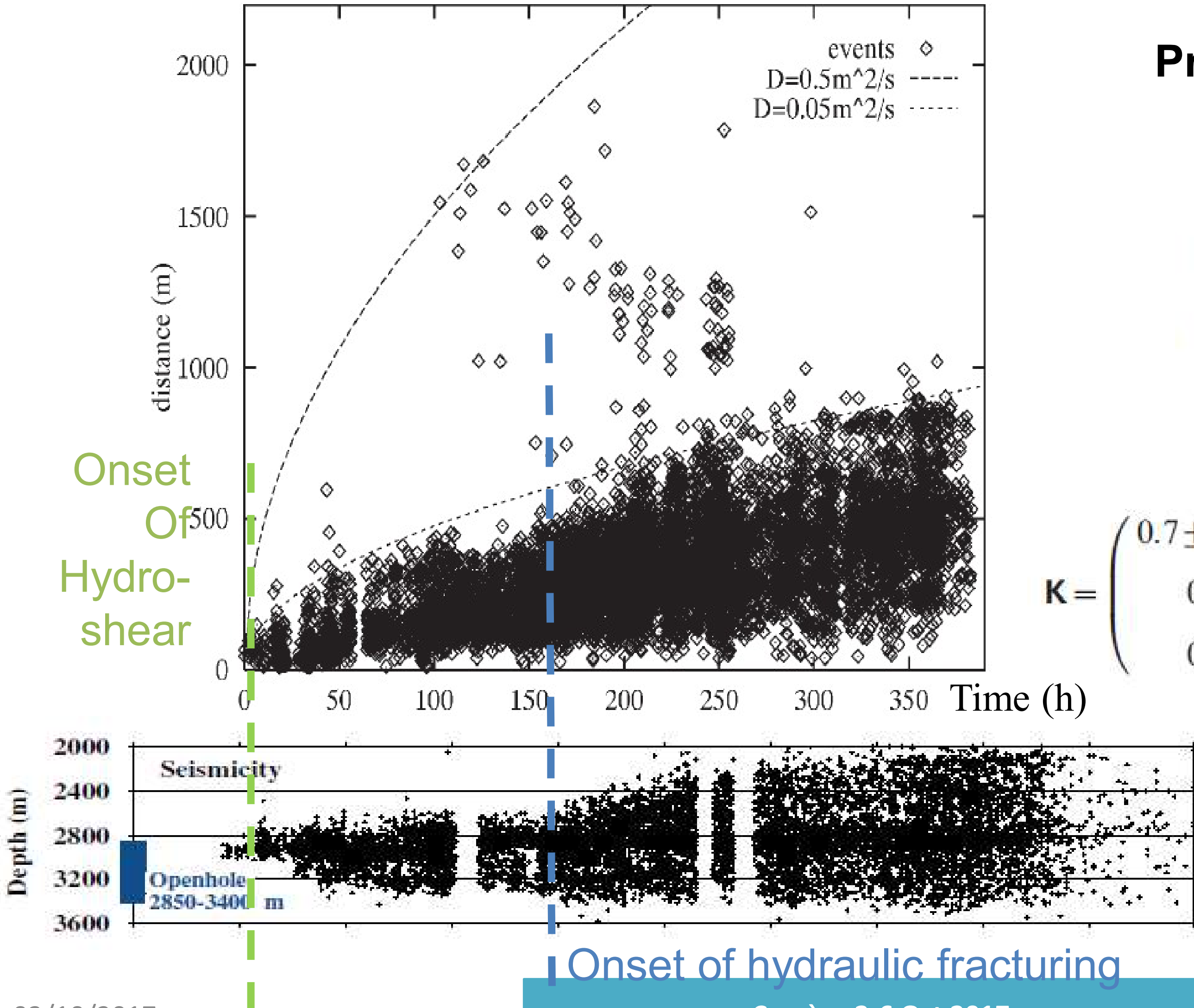


Pressure diffusion:

$$r = \sqrt{4\pi D t}$$

$$\frac{\partial p}{\partial t} = \sum_{i=1}^{3} D_{ii} \frac{\partial^2 p}{\partial x_i^2}$$

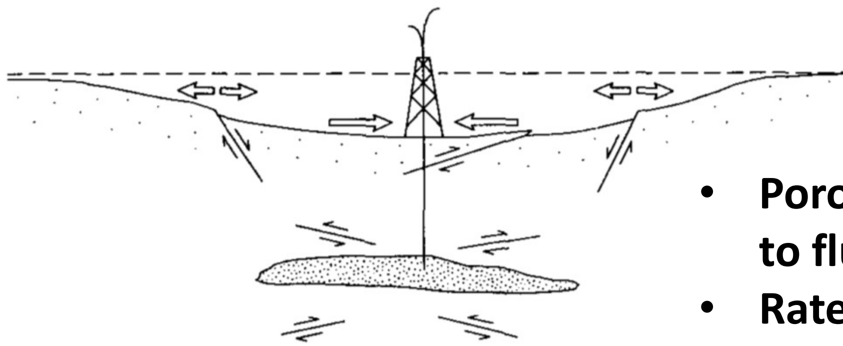
$$\mathbf{D} = N\mathbf{K}/\eta$$

$$\mathbf{K} = \begin{pmatrix} 0.7 \pm 0.2 & 0 & 0 \\ 0 & 1.9 \pm 0.3 & 0 \\ 0 & 0 & 5.2 \pm 2.6 \end{pmatrix} \times 10^{-17}\ \mathrm{m}^2$$

Shapiro et al, GJI, 1999

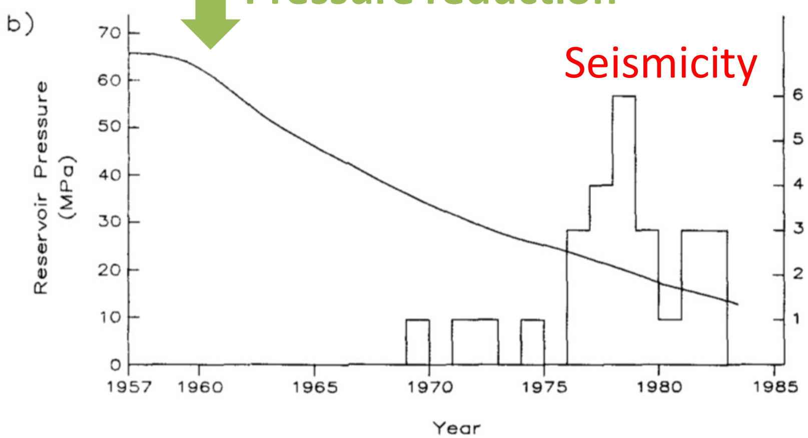
Earthquakes triggered by fluid extraction

Segall, Geology, 1989

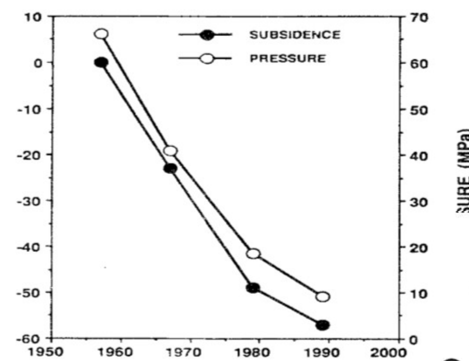


- **Poro-elastic effects related to fluid extraction**
- **Rate and state effects**

Pressure reduction

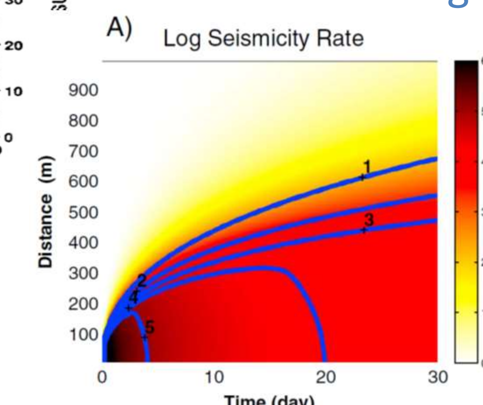


Grasso & Wittlinger, BSSA, 1990; Grasso, 1992



Aseismic deformation

PE+R&S modeling



Segall and Lu, JGR, 2015

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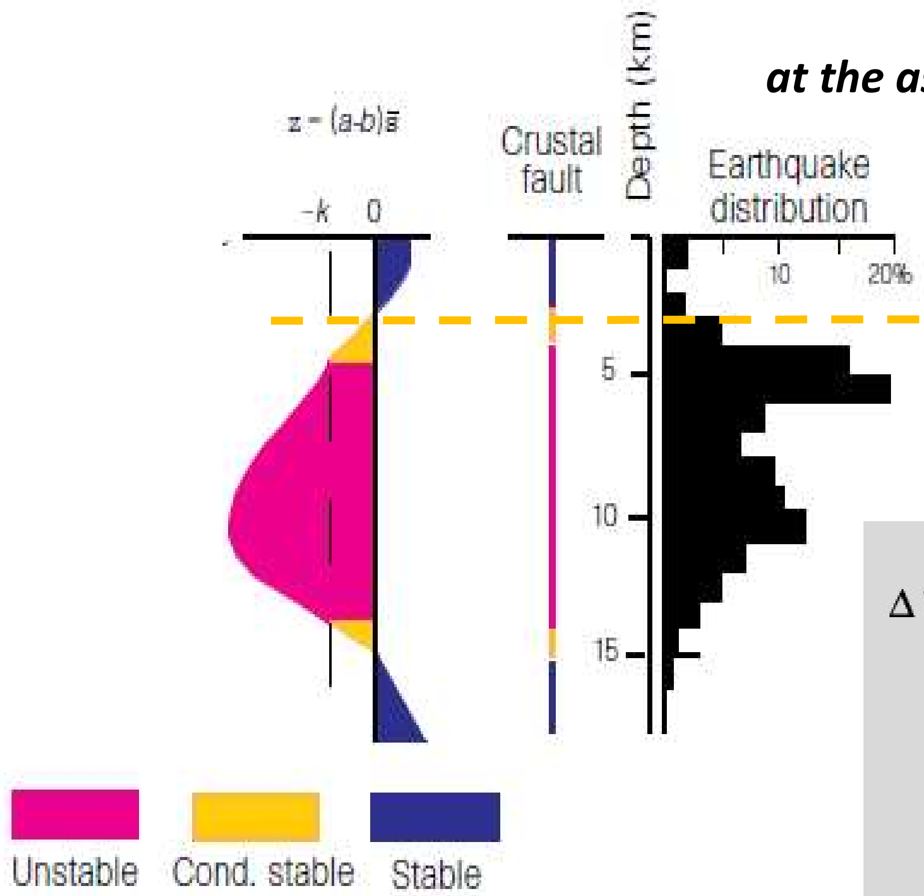
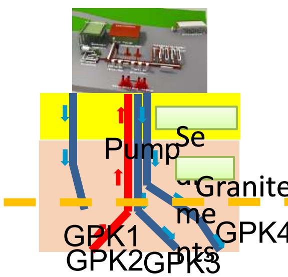
Seismic/aseismic behavior

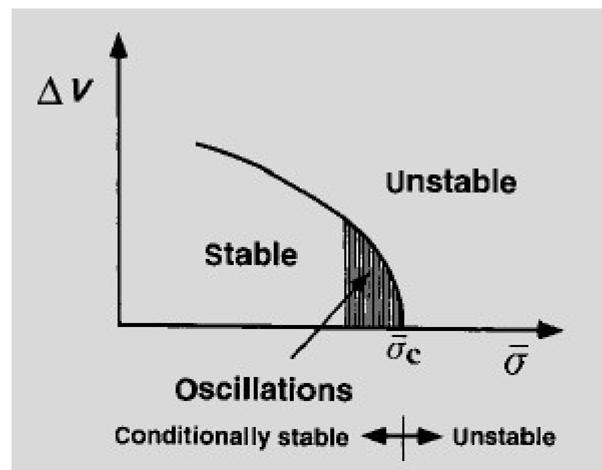
EGS reservoirs
at the aseismic/seismic transition





Aseismic

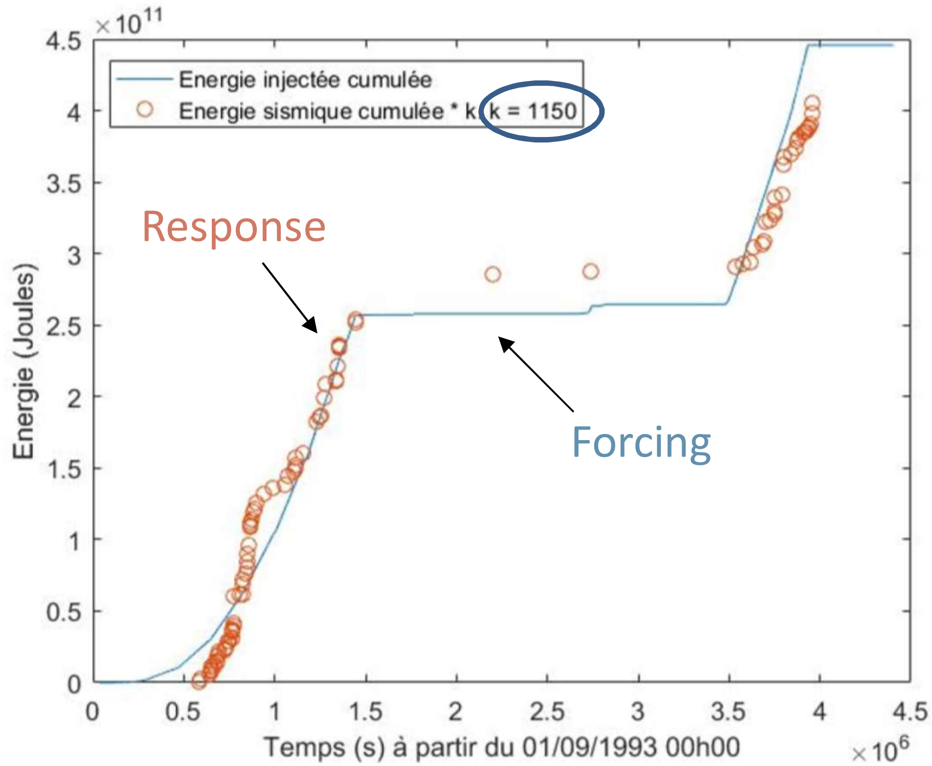
Seismic



Scholz, 1998

1993 Stimulation – Soultz-sous-Forêts

- Injected mechanical energy / radiated energy



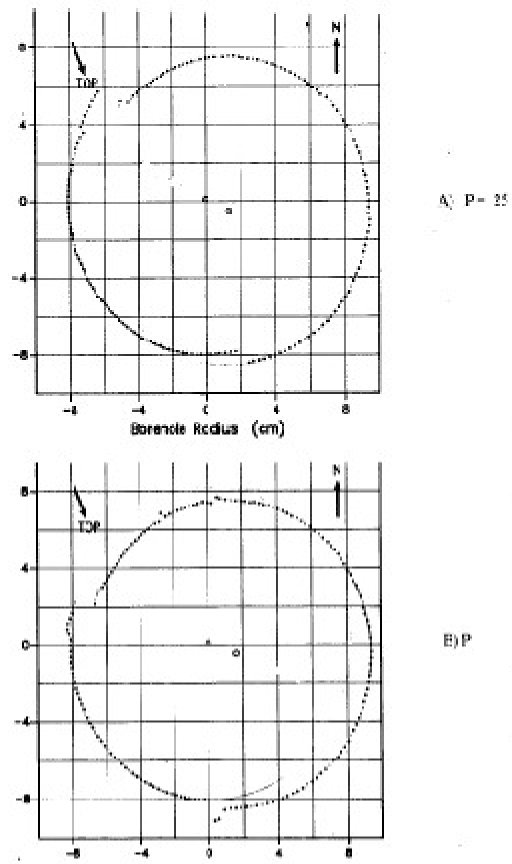
$$E_I = \int_{t_1}^{t_2} P(t) * Q(t)\, \mathrm{d}t$$

$$log_{10}(E_R) = 1.5 * M_L + 4.8$$

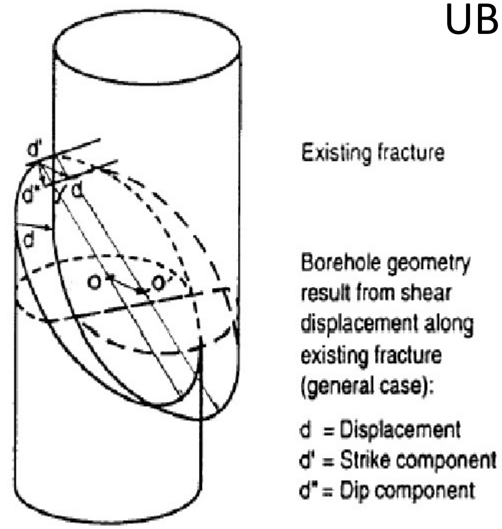
Rico et al, 2017

Before and after 1993 stimulation

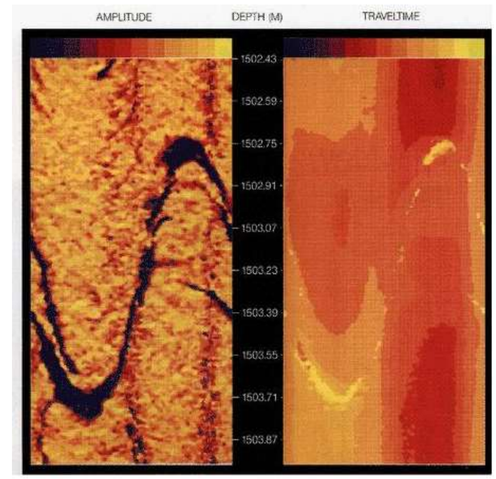
Cornet et al., 1997



M~4.2 >> M~1.9 (observed)



UBI



Determination of slip motions induced in the well GPK1 during the September–October 1993 injections. Z is distance from well head (in m) according to the logging depth meter, β is the dip direction of fracture plane (positive eastward), α is the dip of fracture plane, λ is the strike of the slip vector, A is amplitude of the slip motion (in cm). Uncertainties are noted ε with the respective subscript. SX is the mean amplitude of the slip vector measured within the cross section of the borehole. Frame of reference is north, east, vertical positive downward. Within the fracture plane, rotation is positive from strike direction toward dip (downward positive).

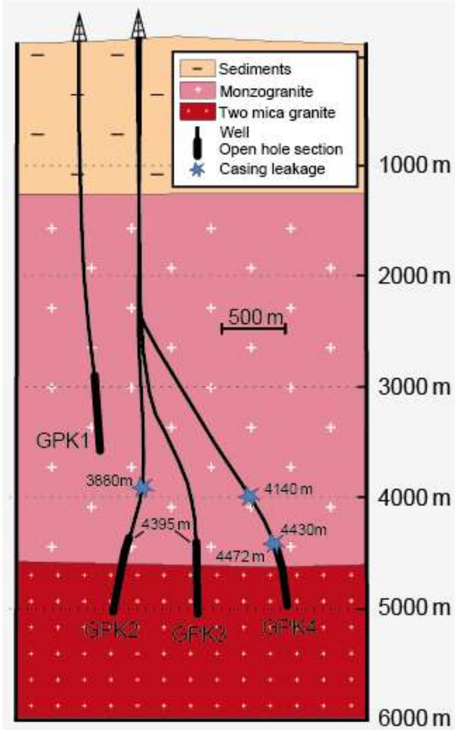
Z (m)	β	α	λ	A (cm)	ε_λ	ε_A (cm)	SX (cm)	ε_{SX} (cm)
2966	105	84	110	4.7	5	0.7	0.5	0.1
2867	259	62	304	2.2	3	0.1	1.45	0.07
2976	269	61	218	0.8	15	0.2	0.5	0.05
2887	298	75	271	0.85	8	0.3	0.28	0.1
2973	273	78	198	0.4	10	0.06	0.22	0.04
2925	48	86	99	4.3	13	1.3	0.5	0.14

F

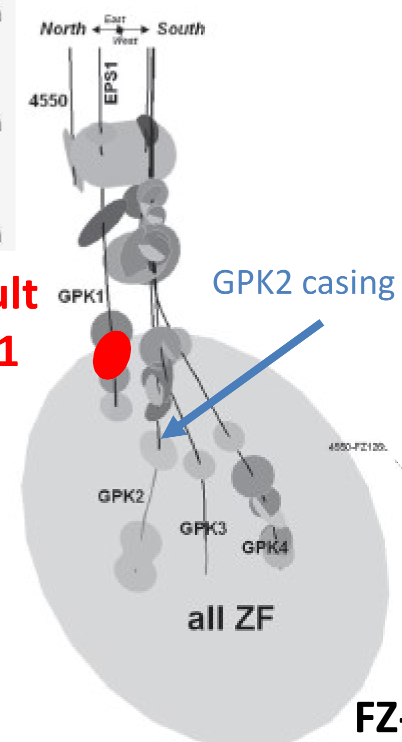
More than fluid induced shear or hydraulic fracturing:
fluid induced aseismic slip

Lessons from Soultz:

- A complex pre-existing 3D network (granite)
- A major fault zone (most of the seismicity) **FZ-4770**
- Shear and hydraulic fractures
- Evidenses of aseismic slip in **GPK1 F-2925**
- from GPK2 casing deformation along FZ-4770
- From casing deformation in GPK4 (Jung et al, 2010)



Held et al, 2013



F fault GPK1

Cornet et al, 1997

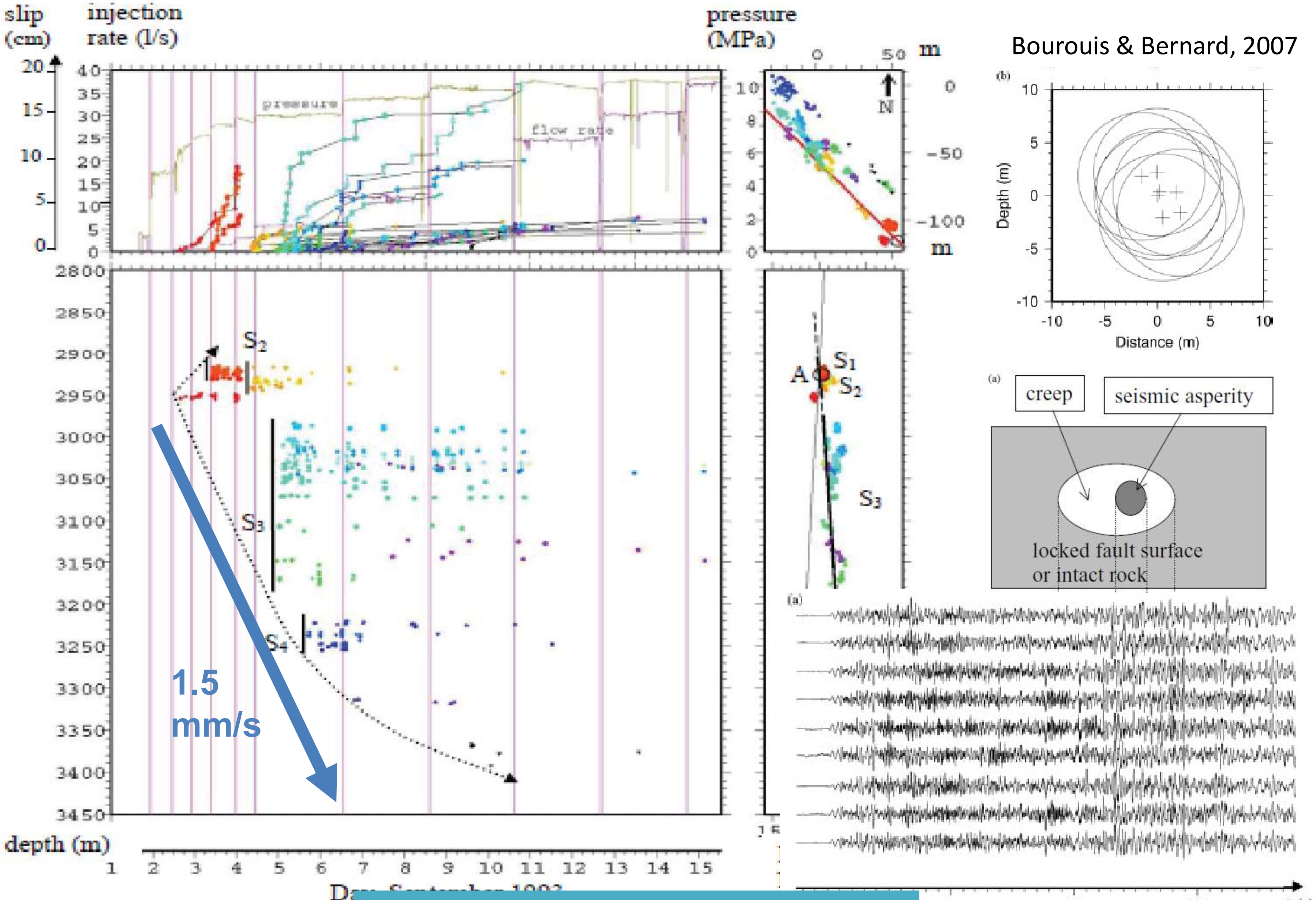
GPK2 casing shear

FZ-4770
GPK 1,2,3,(4)

Sausse et al, 2010

Evidence of repeaters related to aseismic slip

Bourouis & Bernard, 2007



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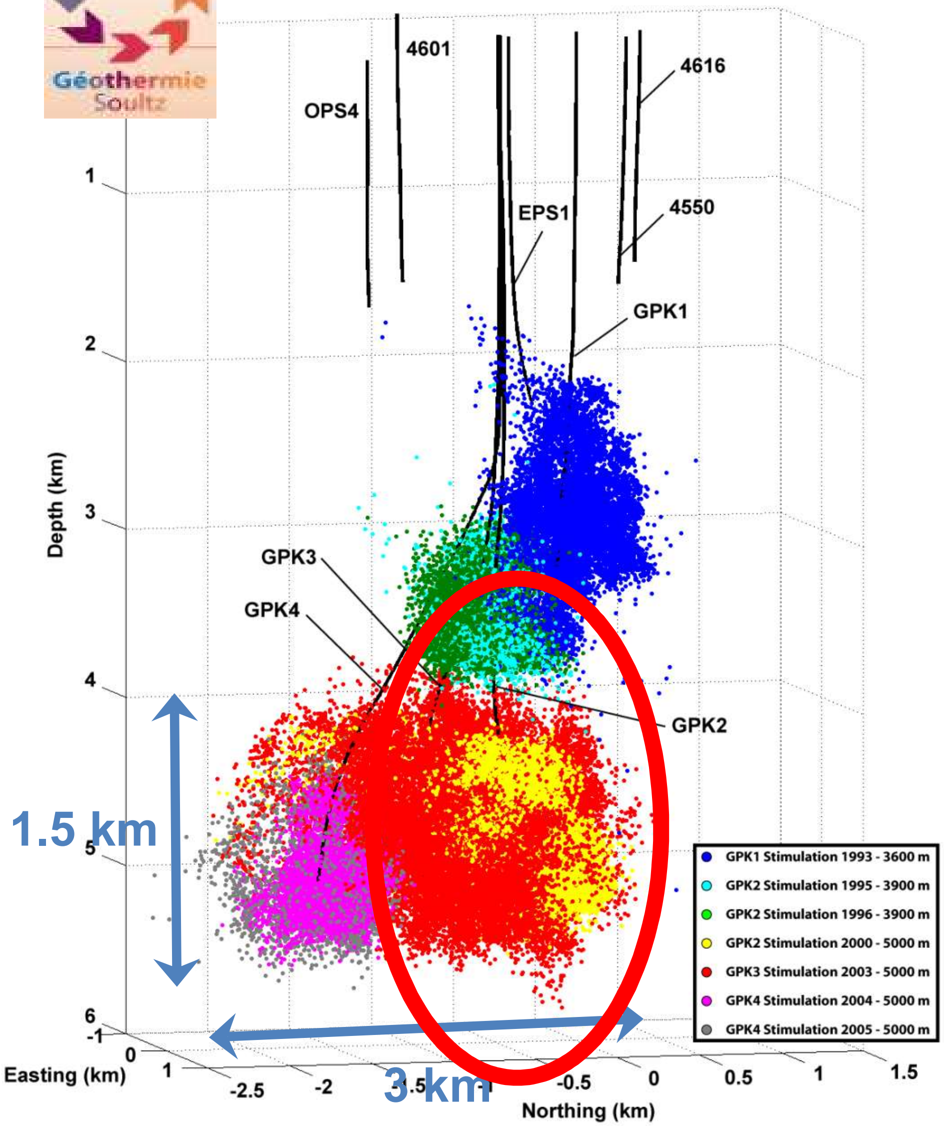

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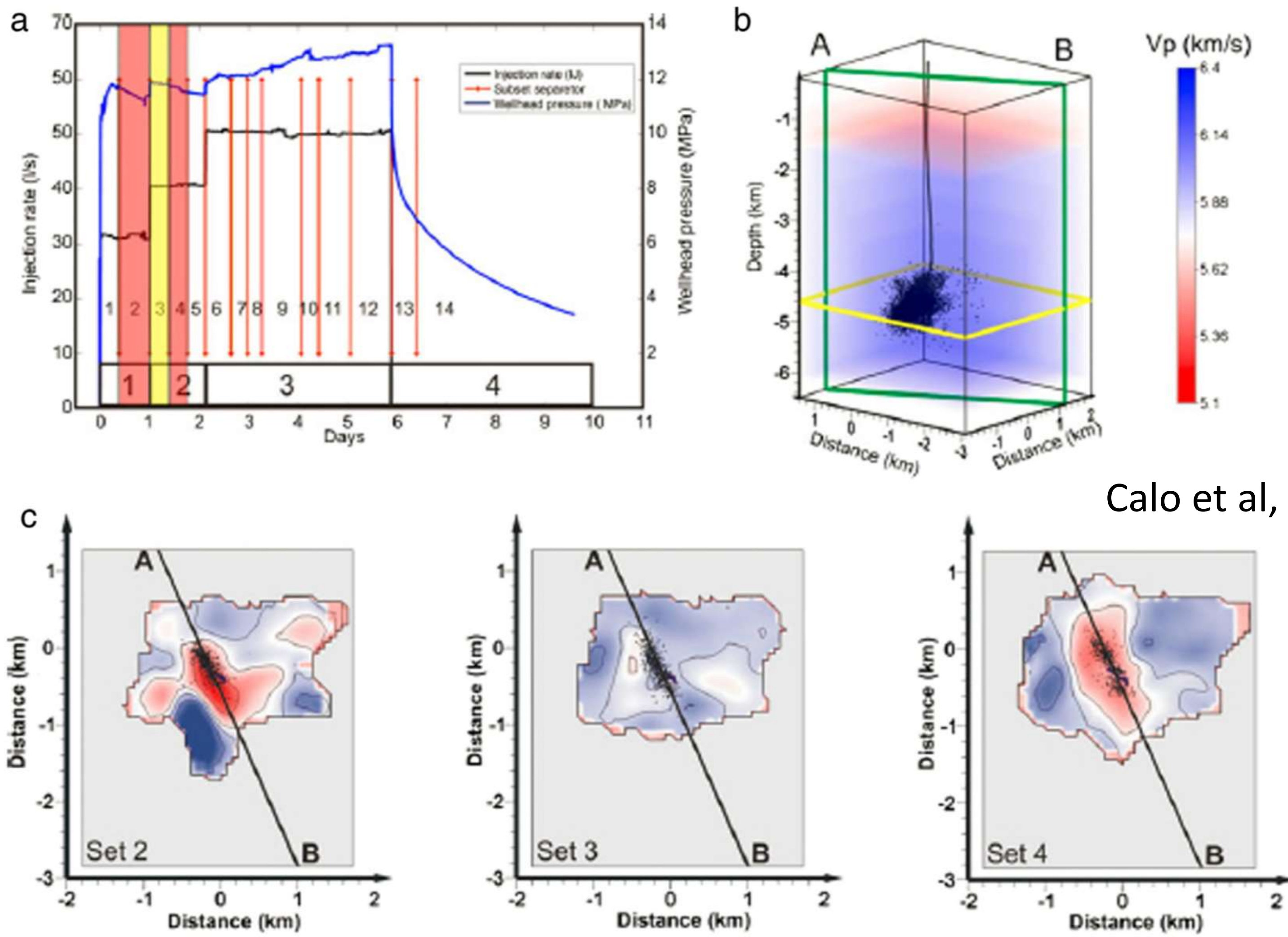
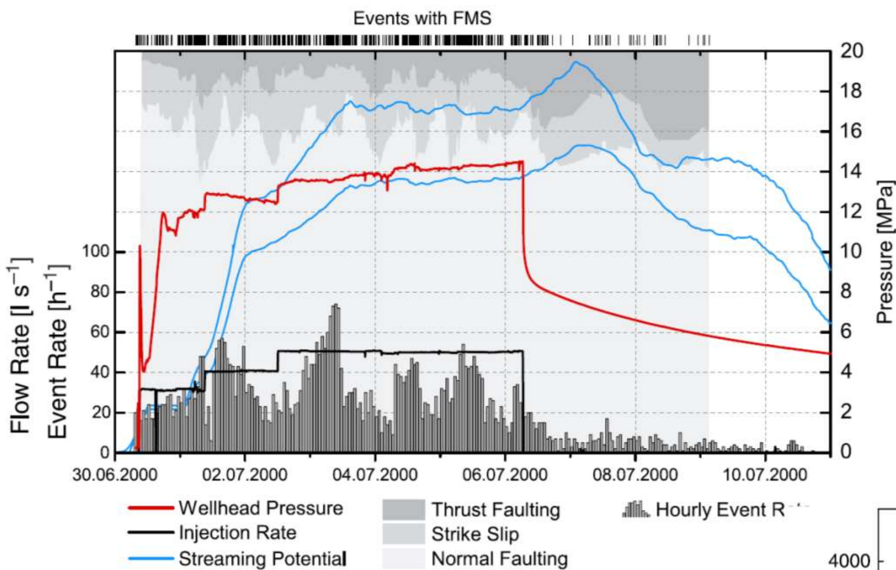
GPK2 stimulation: large scale Vp variation and aseismic slip



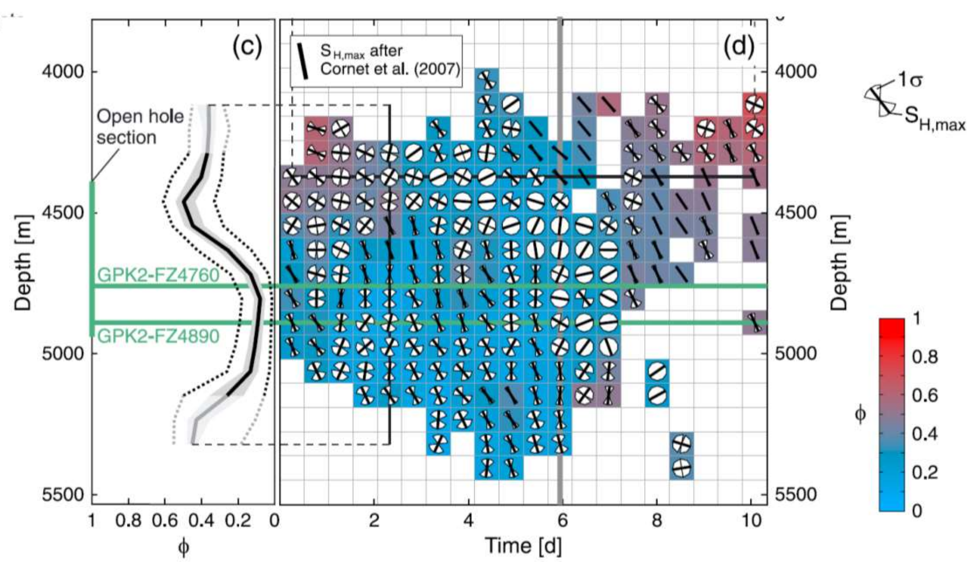
Calo et al, GJI, 2011

GPK2 stimulation: stress transfer from aseismic slip



7215 localized events (Mmax=2.5)
Stress inversion (715 events with M>1)

Schoenball et al, GRL, 2014



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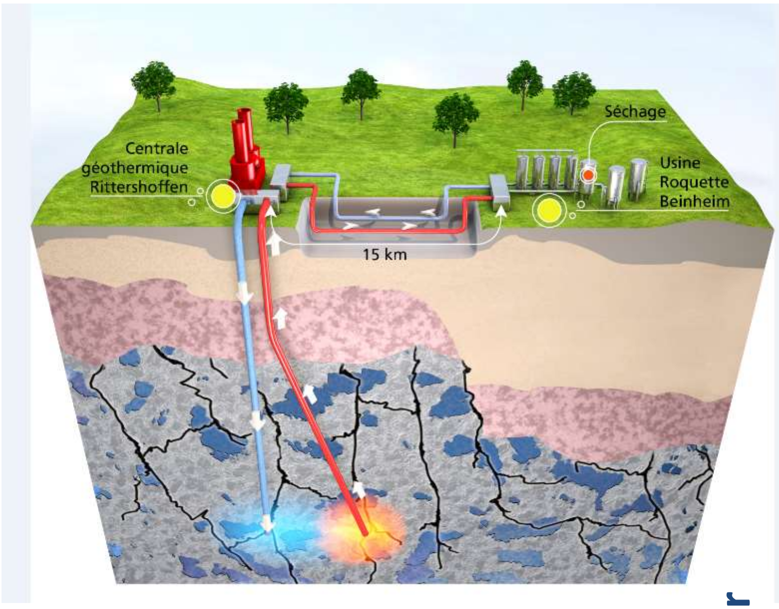
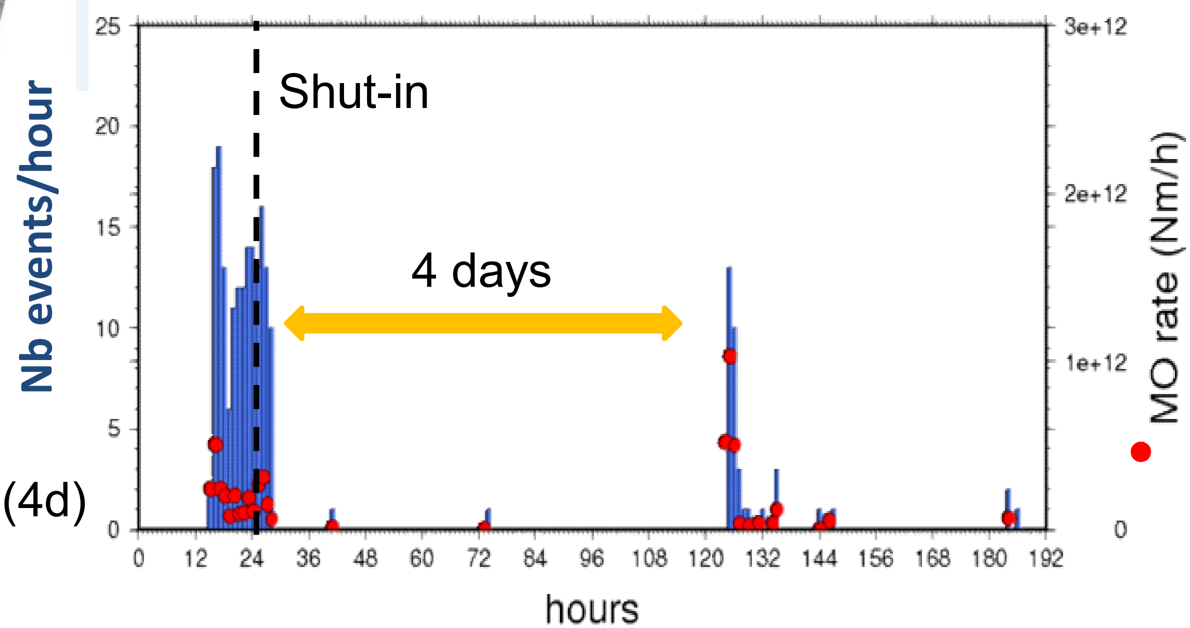
The case of GRT1 (ECOGI)



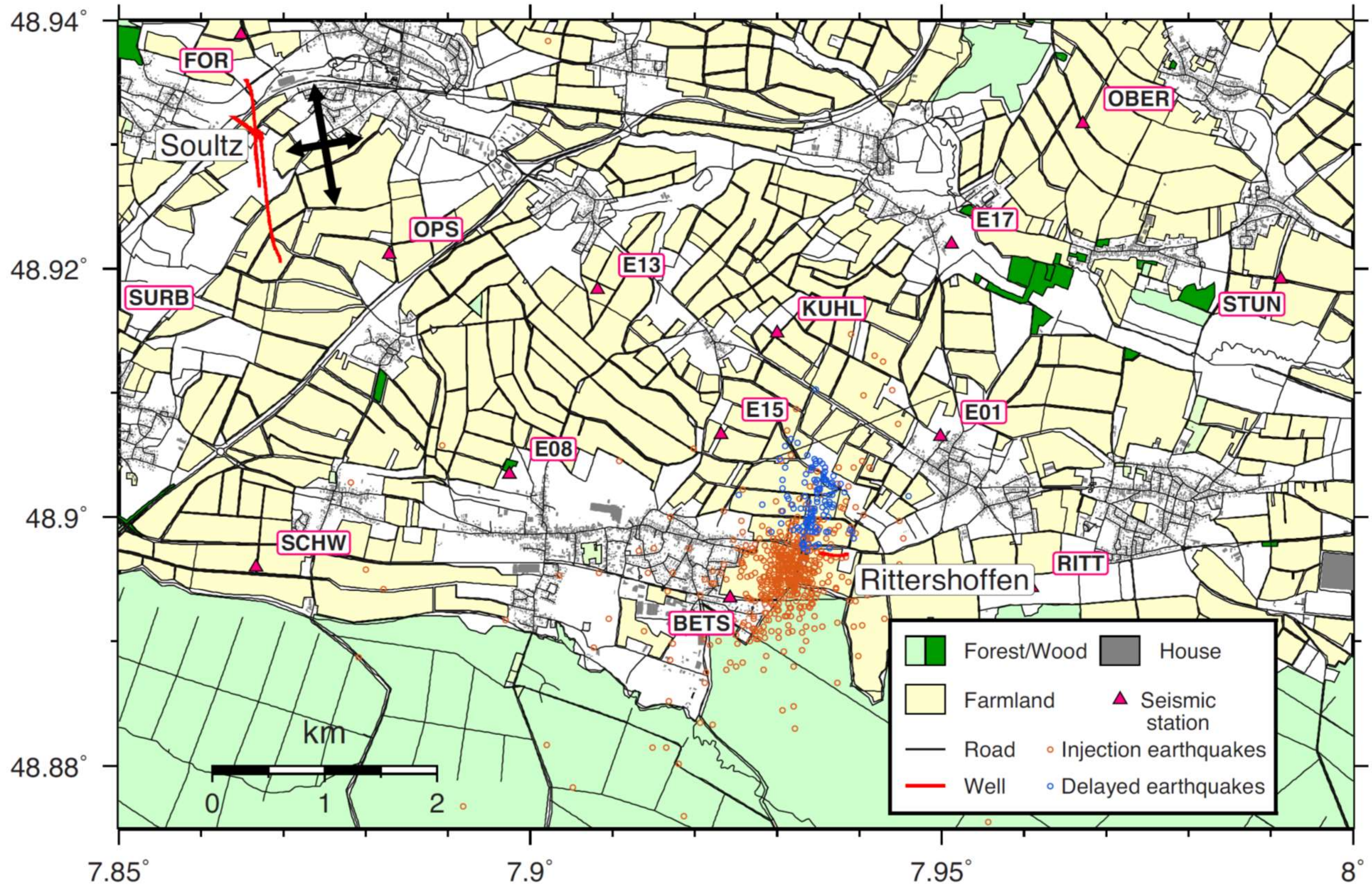
Rittershoffen (< 10 km Soultz)

Stimulation of GRT1
(June/July 2013)

second crisis ~100h after shut-in (4d)
with a larger moment rate

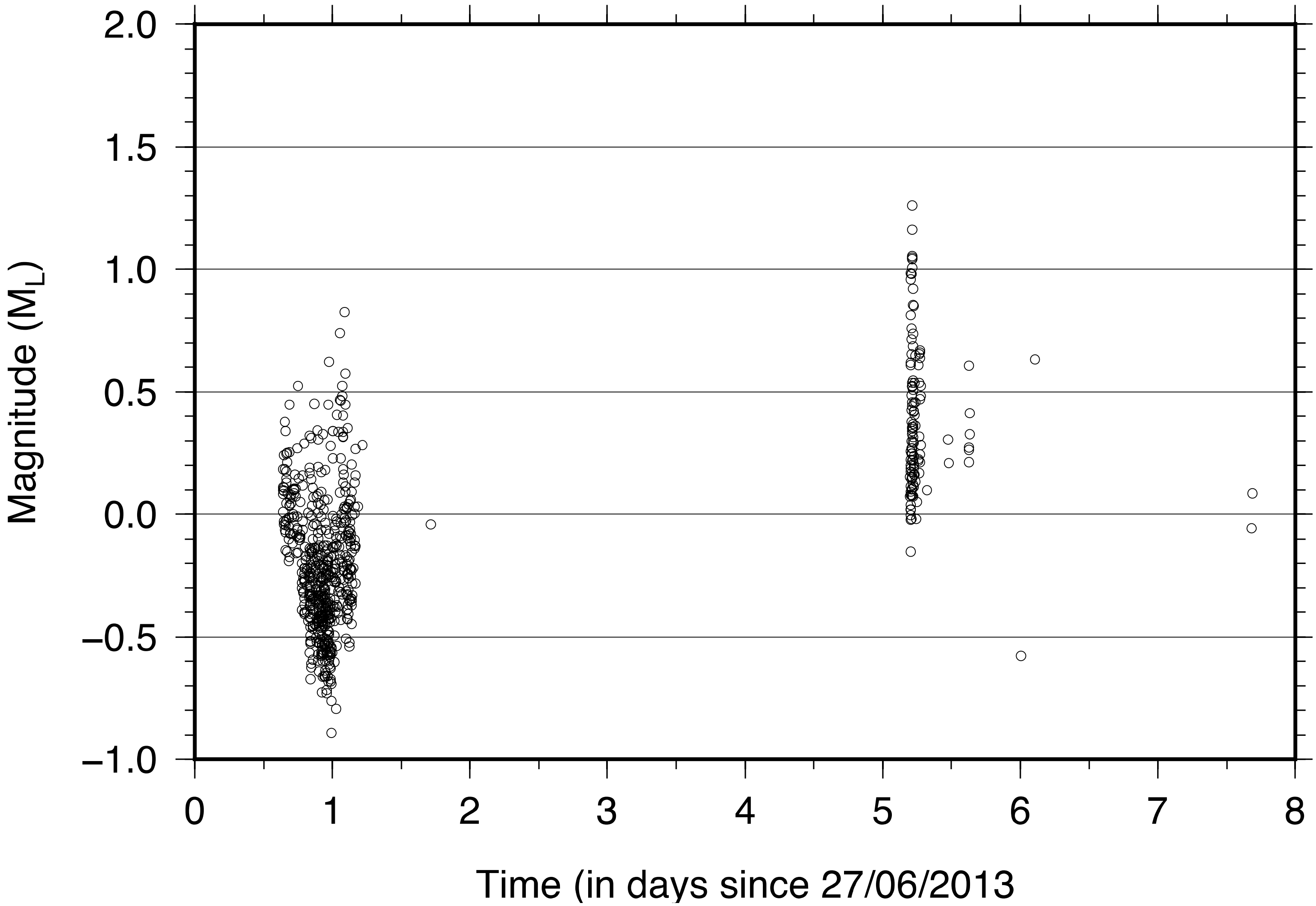


Seismological network



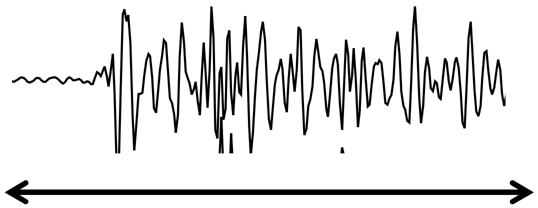
Maurer et al., 2013

Magnitude

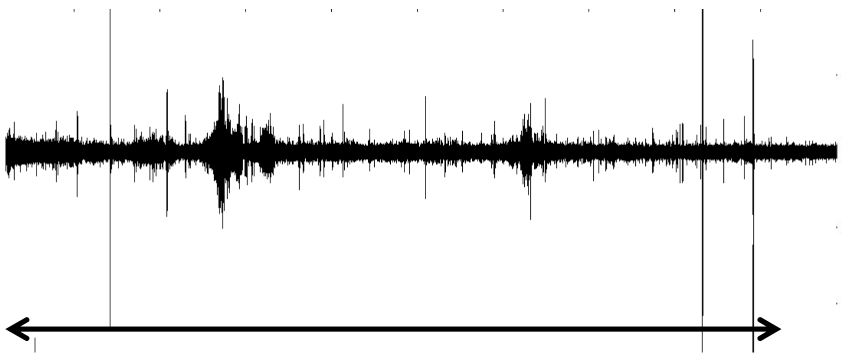


2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
Magnitude (M_L)
0
1
2
3
4
5
6
7
8
Time (in days since 27/06/2013

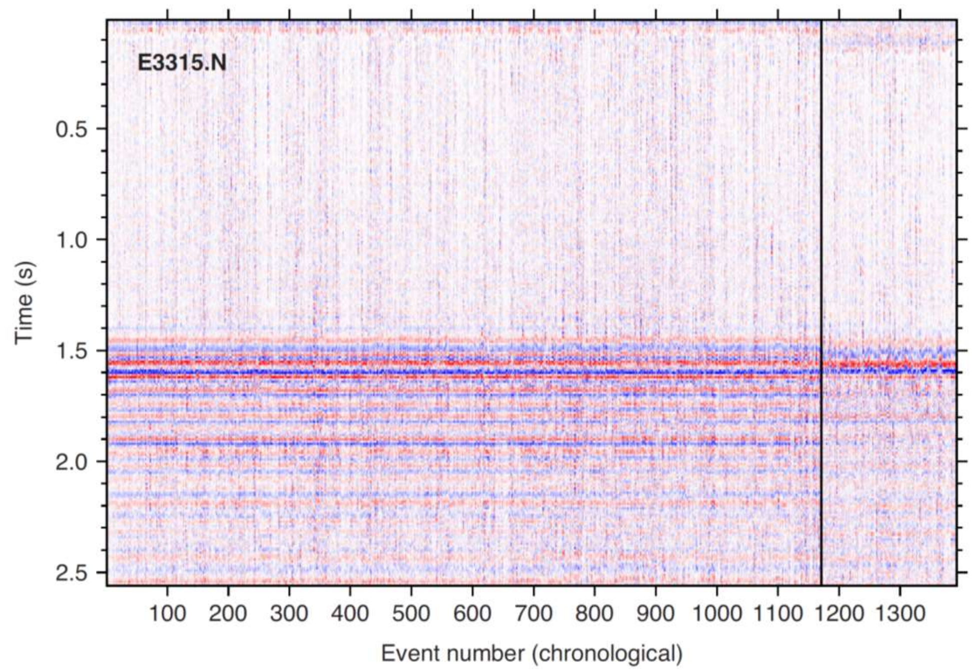
Template matching



2.5 seconds



4 hours



Lengliné et al, GJI, 2017

Temporal evolution

Temporal evolution of seismicty

682 identified and picked seismic events

557+0+125

1395 detected events with TM

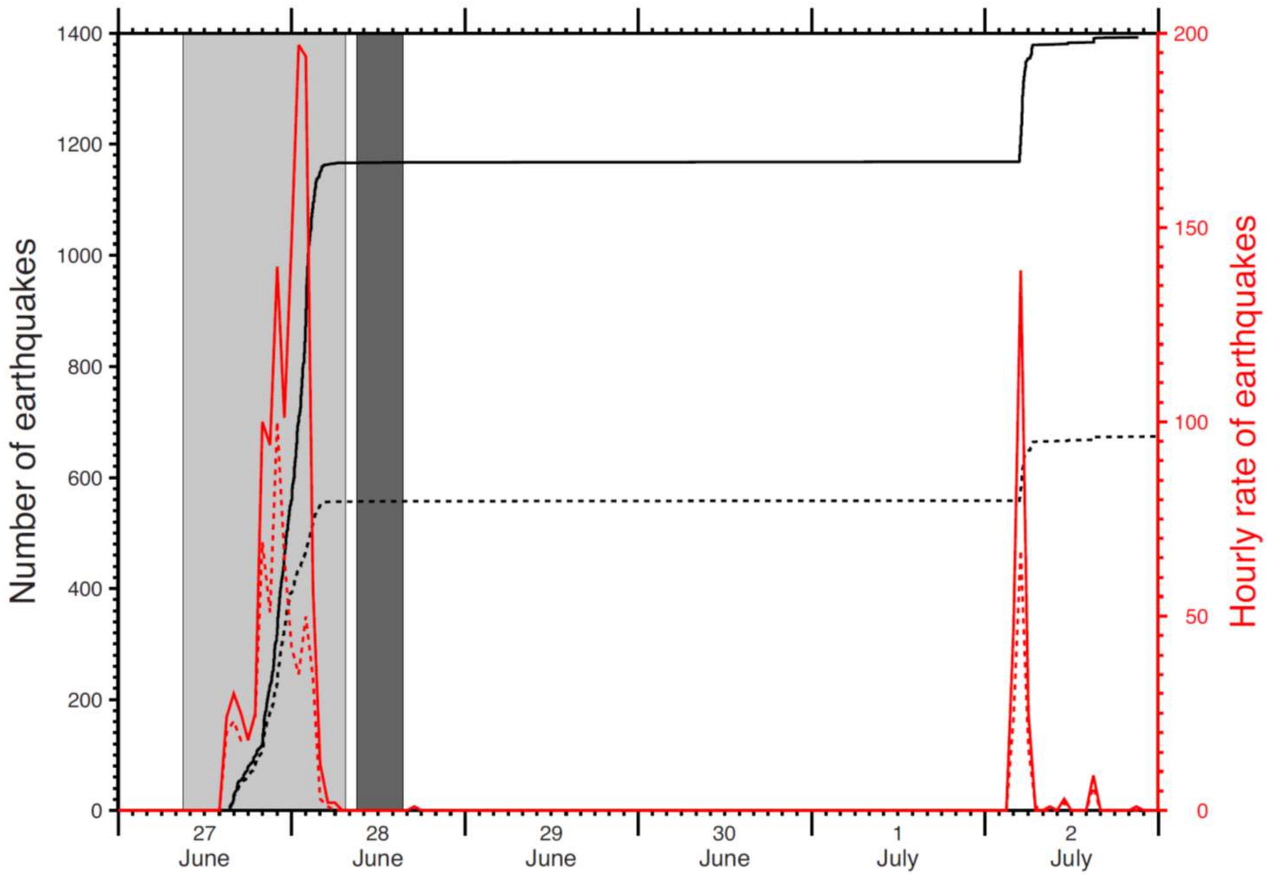
1169+1+225

Kaiser effet

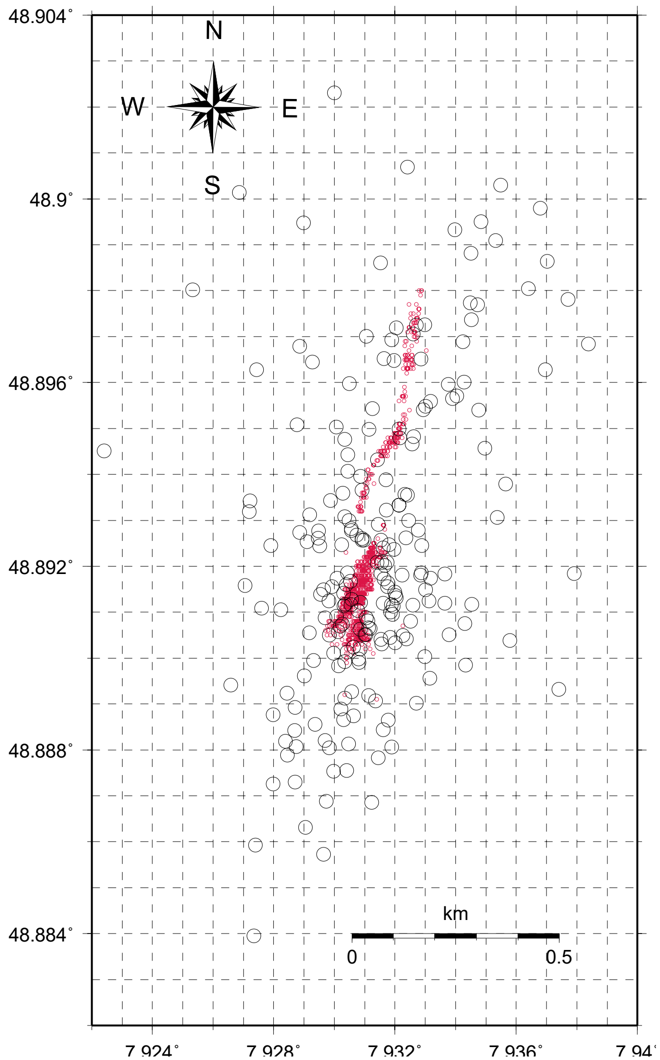
No seismicity for injection rate lower than previsously applied

2nd crisis

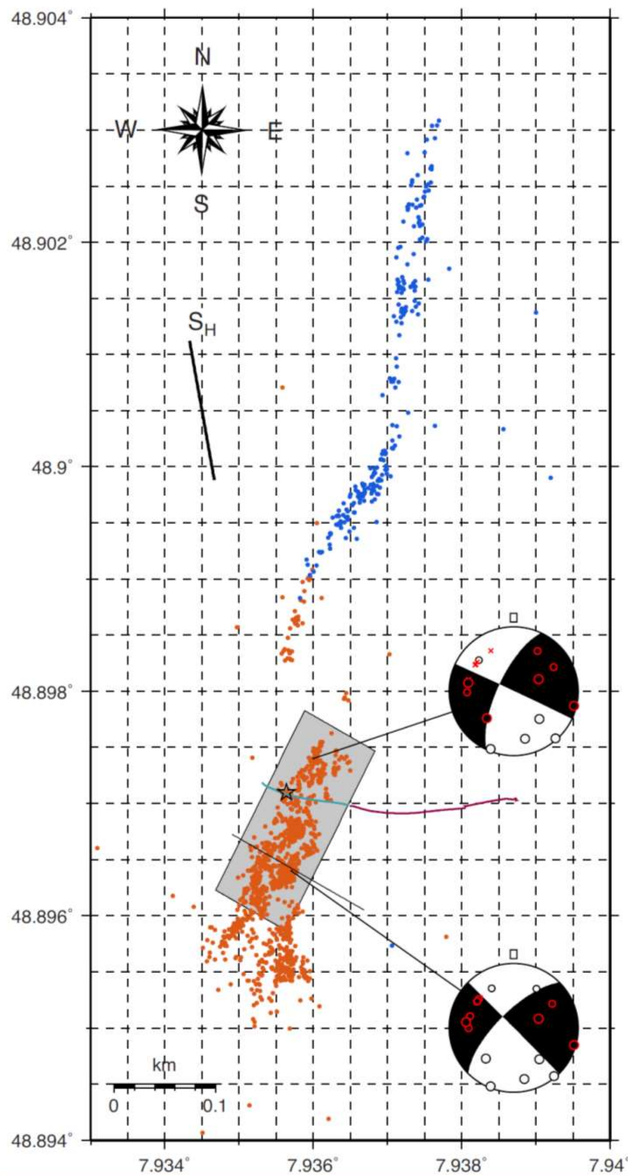
High seismicity level 3.5 days after shut-in. No earthquake during this interval

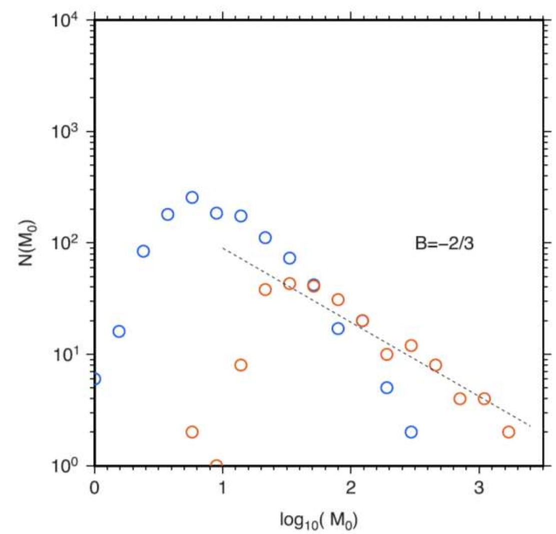


Relocations



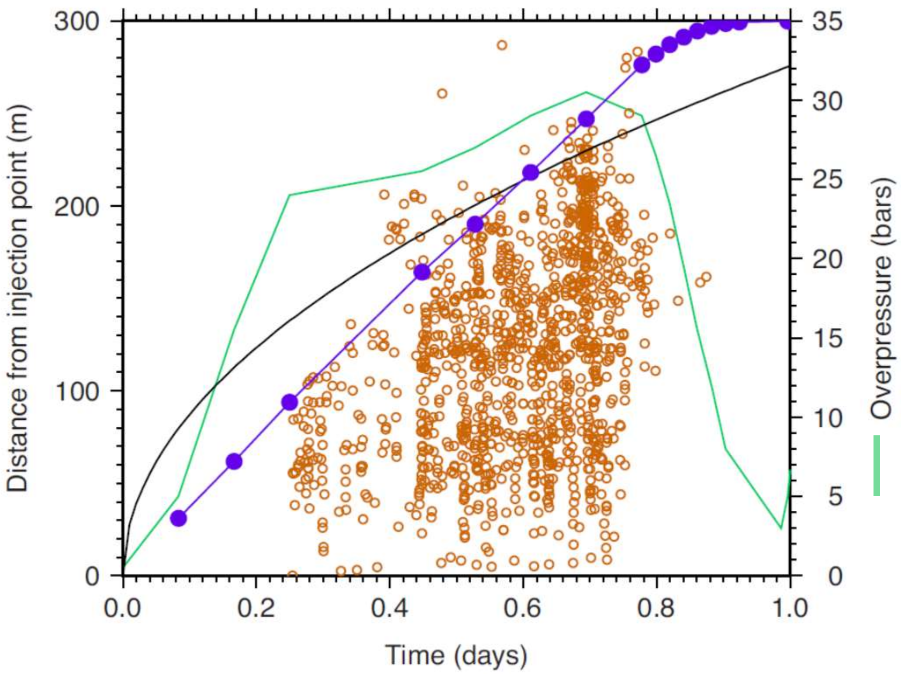
Seiscomp - realtime





Lengliné et al, GJI, 2017

Fluid induced: pressure induced or not ?



Pressure diffusion

$$r(t) = \sqrt{4\pi D t}$$

D=0.07m/s²

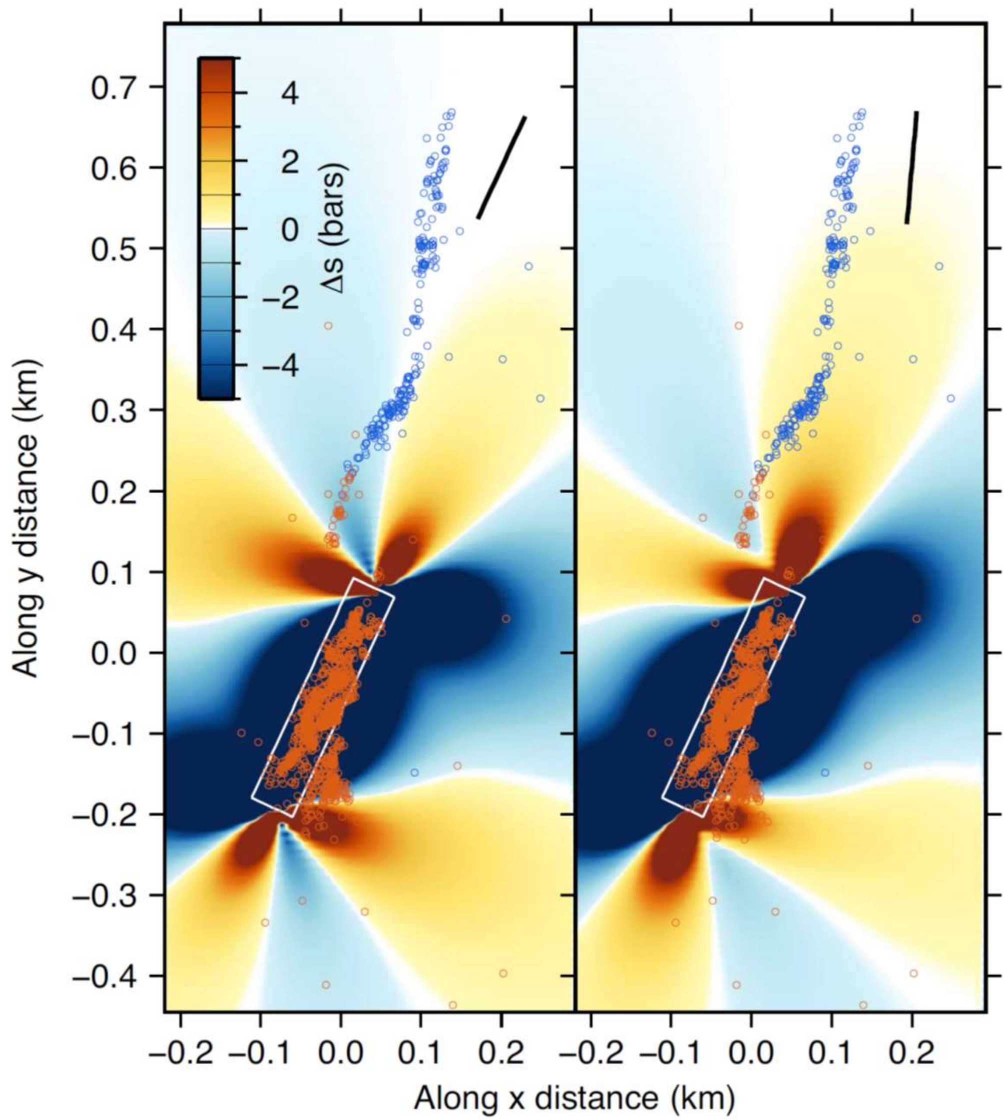
(*D*=0.05m/s² in Soultz, 1993)

No pressure diffusion

$$r(t) = \sqrt{\frac{\int_0^t Q(t')\,\mathrm{d}t'.}{\pi h}}$$

Stress transfer from aseismic slip (?)

Coulomb stress perturbation from a 1cm left-lateral aseismic slip



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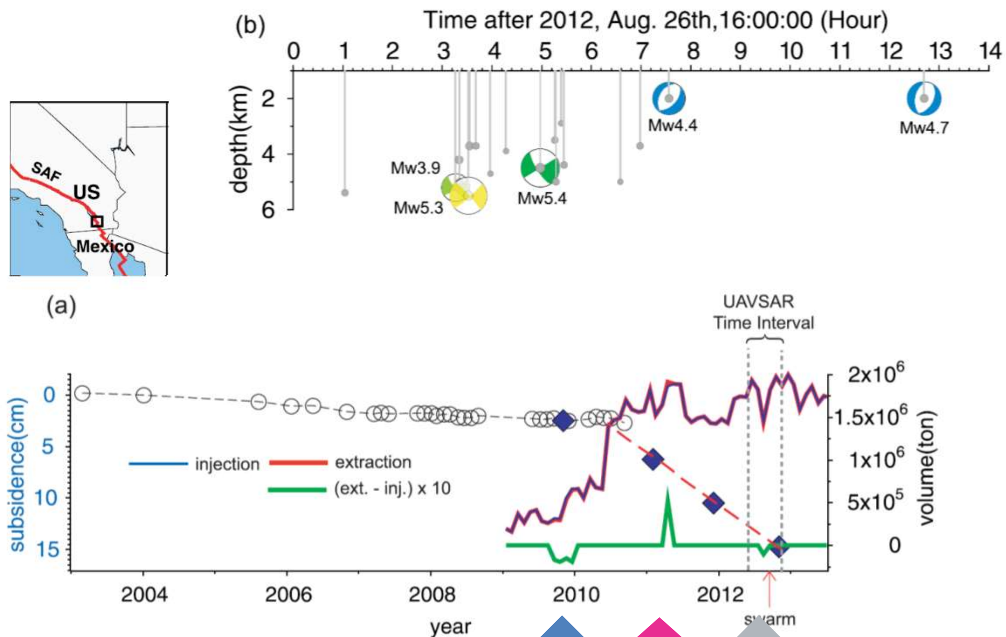
Fluid injection-induced aseismic slip



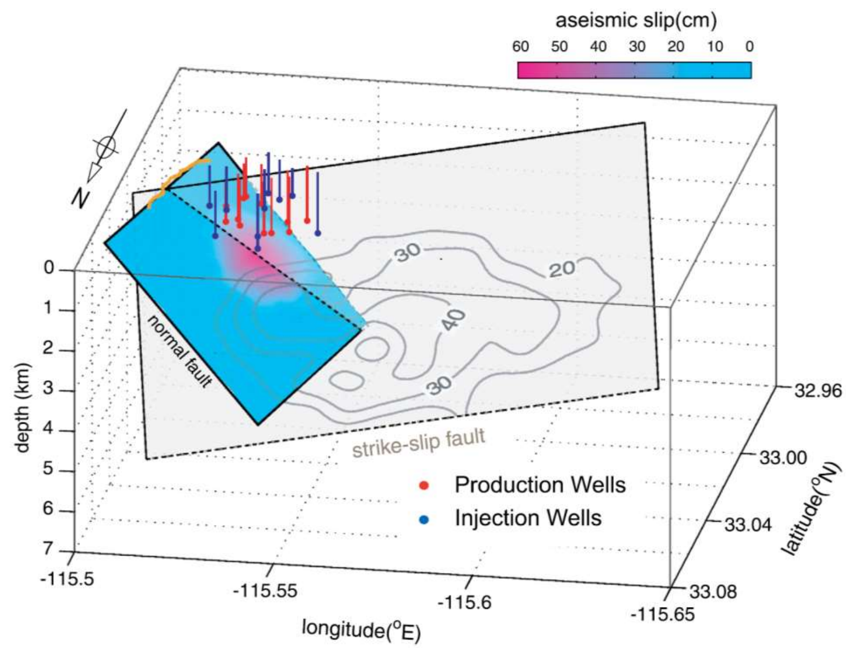
2012 Brawley swarm

Brawley geothermal field (Imperial Valley)

Injection

Induced aseismic slip

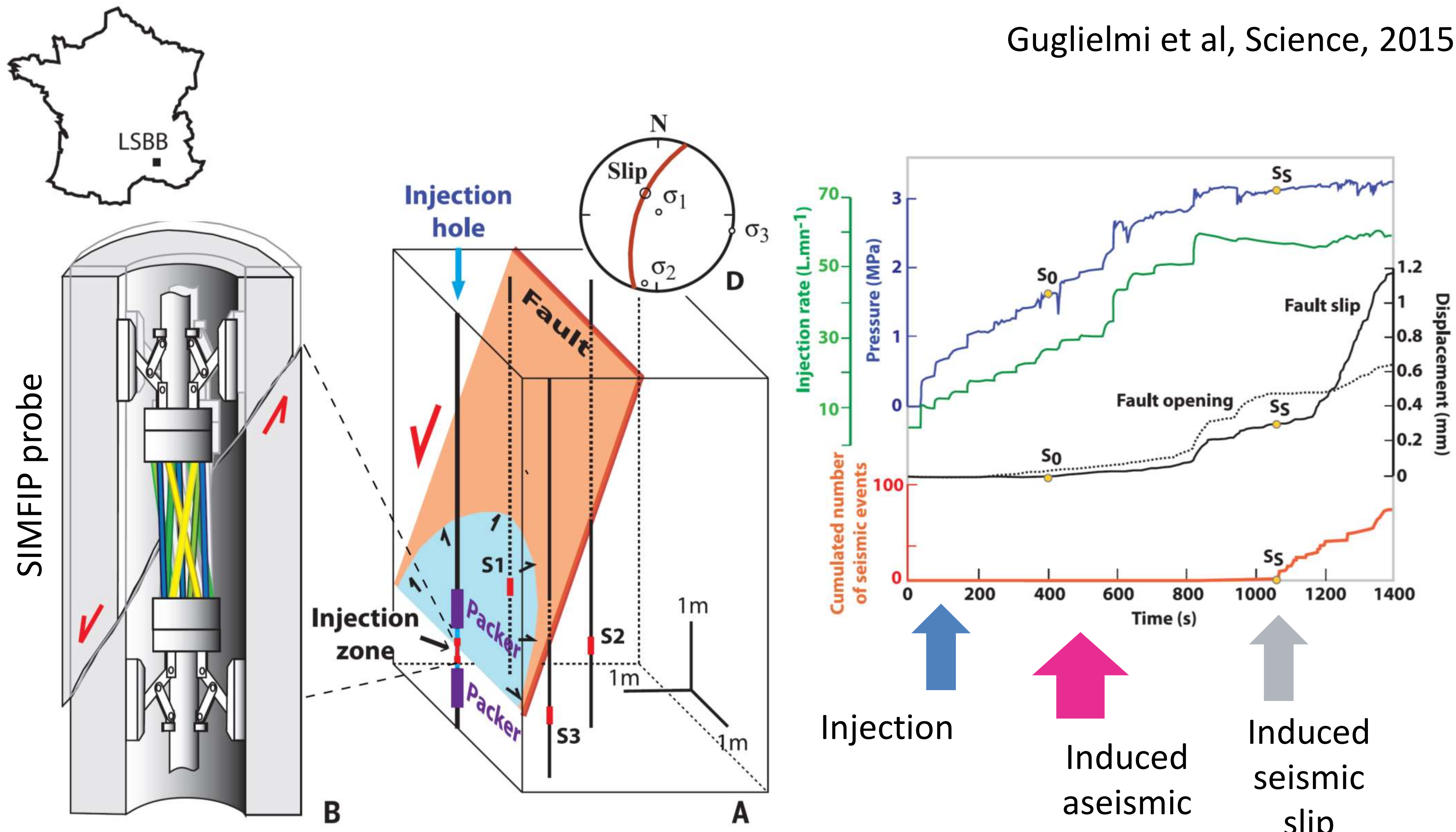
Induced seismic slip



Wei et al, EPSL, 2015

Fluid injection-induced aseismic slip

Guglielmi et al, Science, 2015



Injection

Induced aseismic slip

Induced seismic slip

Outline

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  - a forcing term compare to natural seismicity : test causality issues
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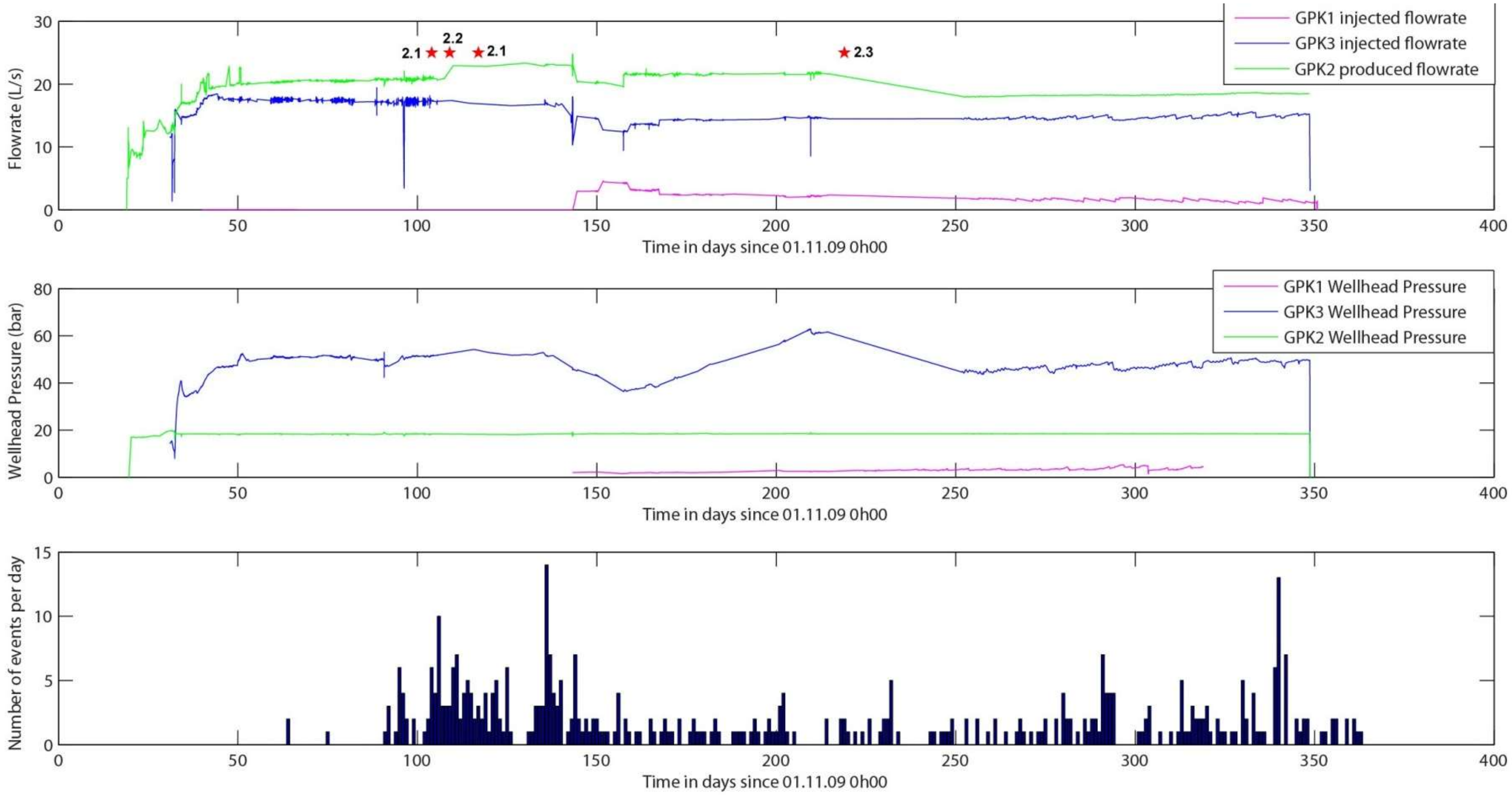
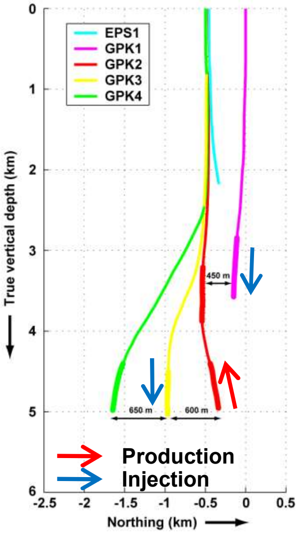
Soultz-sous-Forêts GEIE EMC
Hydraulic circulations in the lower reservoir (5 km)

	2005	2006	2007	2008	2009	2010	2011	2012	2013
Circul. days	160			80	240	330	160	50	140
Chem. Stim.		GPK4	GPK4						
Pump	No sub pump			Failure			Failure	Failure	
2 wells				1P, 1R	1P, 1R			1P, 1R	1P, 1R
3 wells	2P, 1R			2P, 1R	1P, 2R	1P, 2R	1P, 2R	1P, 2R	1P, 2R
4 wells					2P, 2R				
WHP R MPa	4 to 7	~7	~12	2 to 8	2 to 6	4 to 5	<2	<2	<1
Event	600	20	0 & 80	243	206	411	5	0	1
Mag Mx	2.3	1.9	- & 1.5	1.4 -1.7	1.7	2.3	1.7	-	0.3
Vol m3	205000	4500	4000	120000	200000	500000	300000	30000	150000

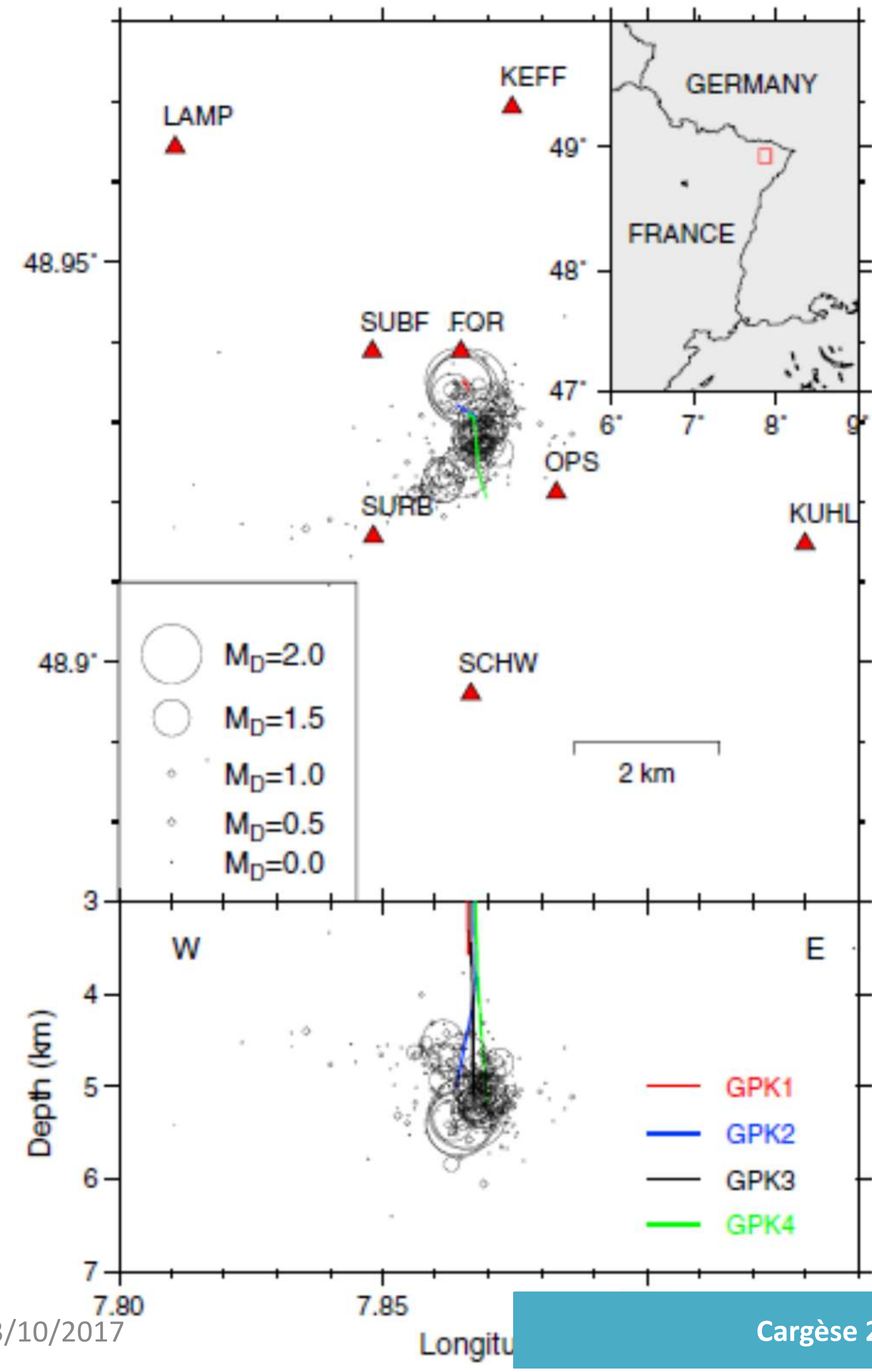
R = reinjection

2010 circulation test – Soultz-sous-Forêts





- ➢ 411 detected events, most intense activity when reinjection into GPK3 only
- ➢ Increase of activity at the end of the test, maybe due to the continuous rise of GPK3 injection pressure
- ➢ Remaining activity for 15 days after shut in
- ➢ 25 earthquakes of magnitude larger than 1 and 4 of magnitude larger than 2
  - a series of 3 occurred within a few days
  - the M=2.3 occurred 4 months after
- ➢ Not linked with significant hydraulic event



Data - Network

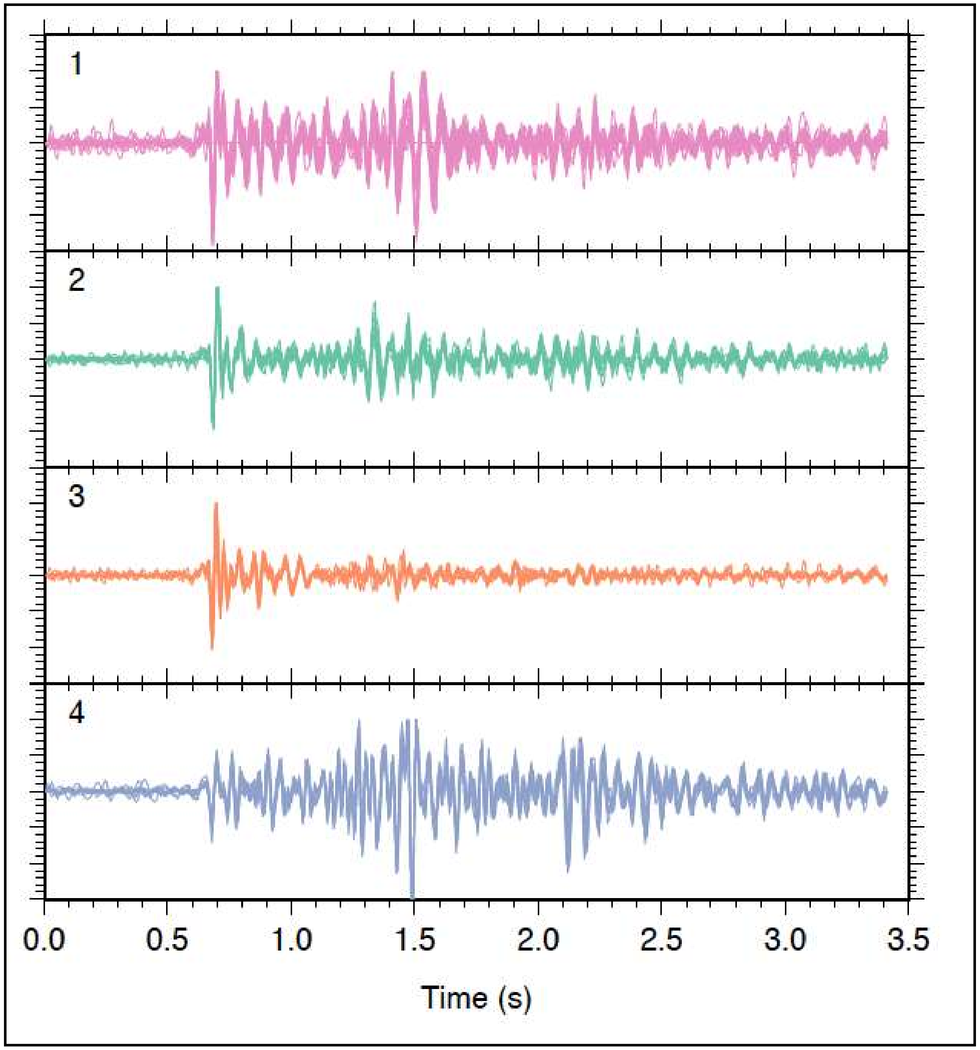
Sampling frequency 150 Hz
8 surface, short-period seismometers
Mostly vertical sensors

2009-2010 Circulation experiment

Water injected at 5 km depth
Starting 01/01/2009 - 11 months long
411 detected earthquakes
Automatic procedure M [-0.3 — 2.2]

Manually reviewing all arrival times
Localisation (393 events)

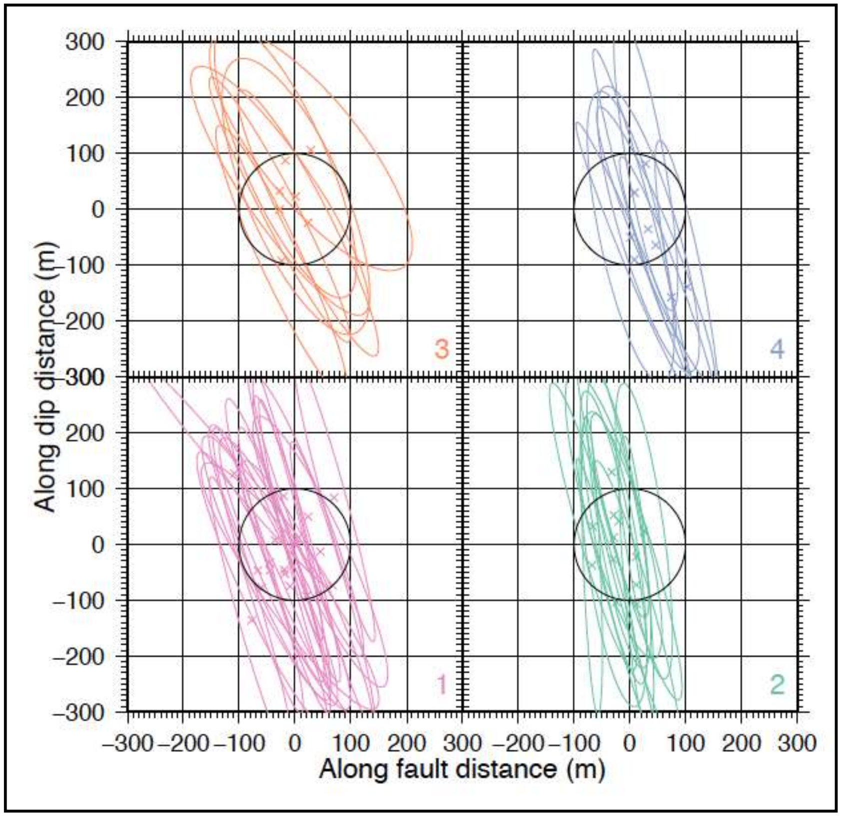
Repeaters



Similar Events

Coherency > 90% at two stations
Frequency range [10-40] Hz
Windows of 1.7 s around P (256 pts long)

Four groups with at least one M>1 earthquake ([-0.3:2.3])
# of events (19 /13 / 9 / 9)

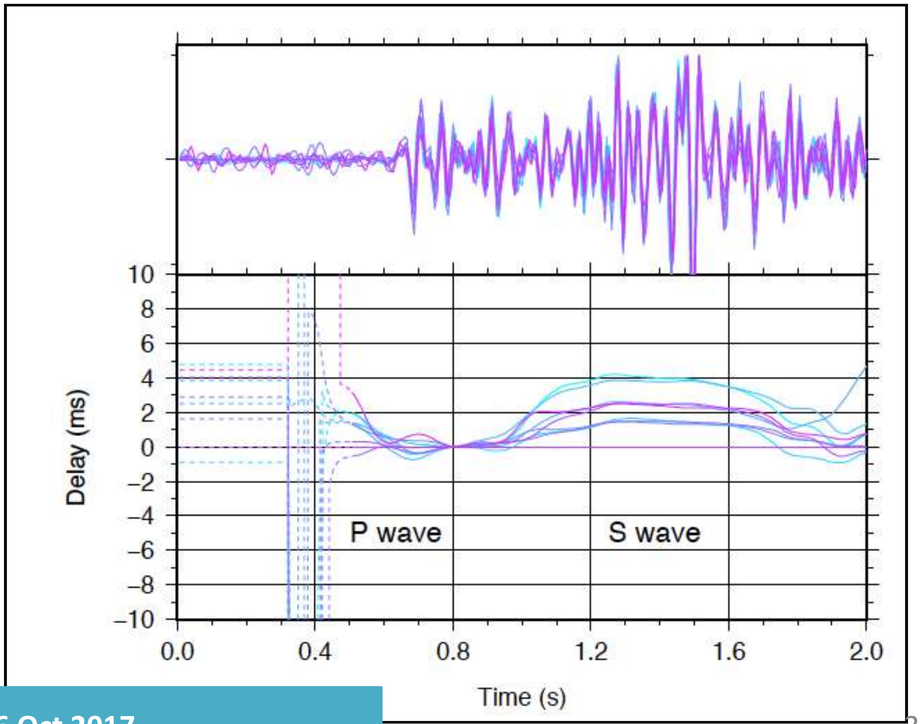


Earthquake double difference relative relocation

Cross-correlation P-wave travel times delays

Projected on the inferred fracture plane

Uncertainties computed from likelihood computed around the best solution – 95 % ellipse

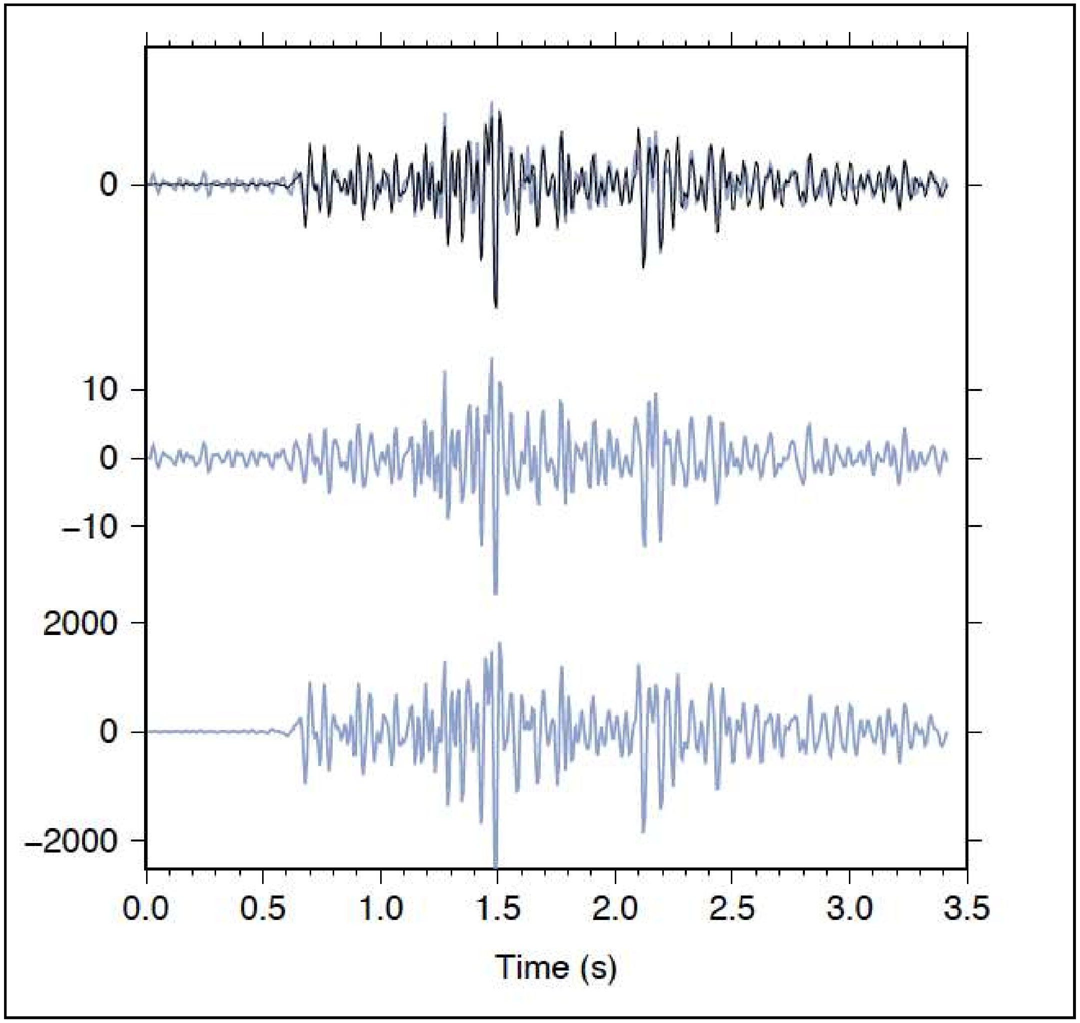


Running window correlation to validate results S-P travel time delays

Less than 3 ms delay for all groups at all stations

Distance in the ray direction less than ~23 m

Variation of moment for events in repeaters



Singular Value Decomposition Method [Rubinstein & Ellsworth, 2010]

Up to a factor x 300 of moment variation for one group

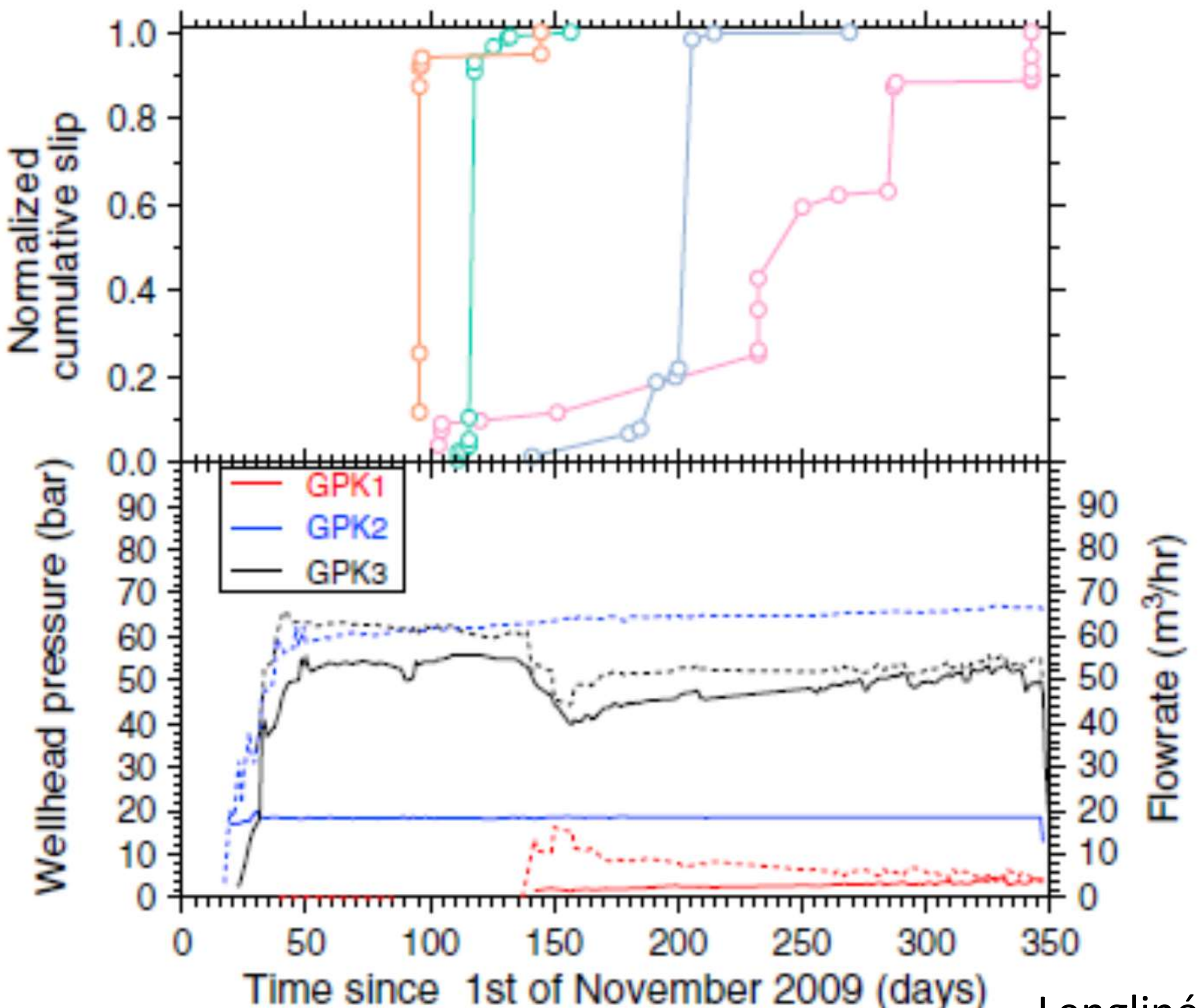
Corner frequency f_c [10-20] Hz – uncertainties are quite important

Rupture radius of 54-108 m assuming a circular rupture patch

Consistent with the estimated rupture size considering a typical stress drop of 1MPa

Lengliné et al, JGR, 2014

Link with fluid injection: fluid induced?



Time history of the seismic slip on the 4 asperities

Lengliné et al, JGR, 2014

Outline

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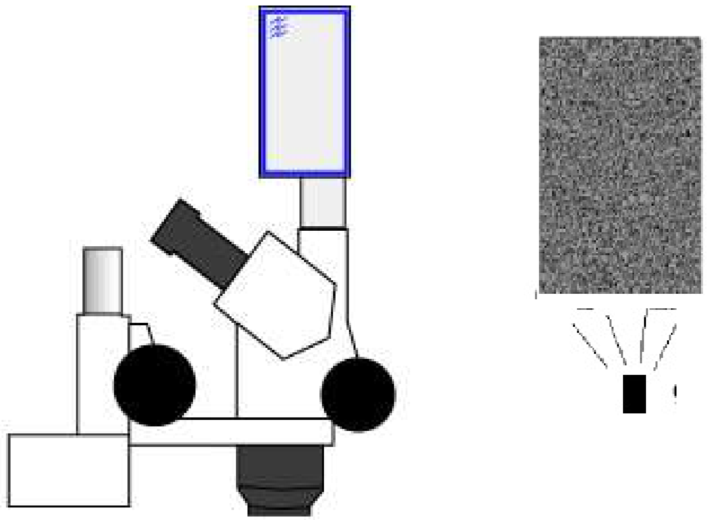
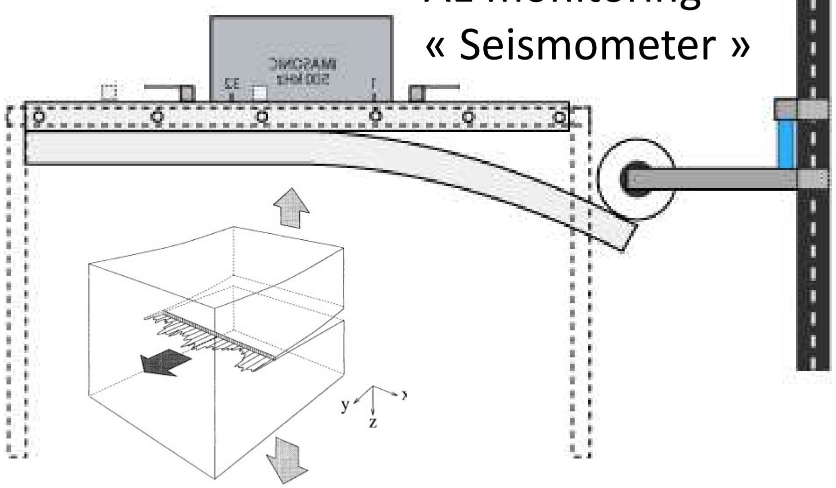
  - **Pure creep induced seismicity: an experimental approach**

An experimental approach of creep induced seismicity without fluid

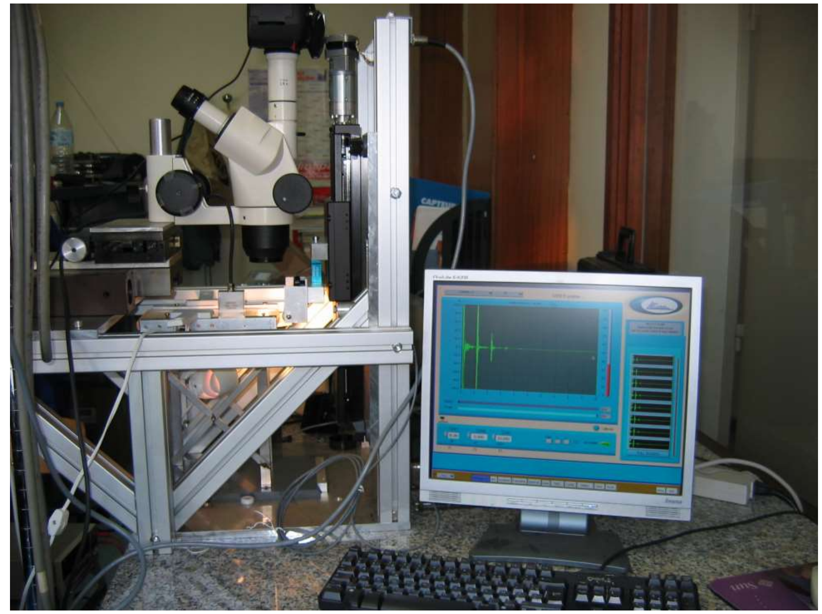
Optical monitoring
« aseismometer »

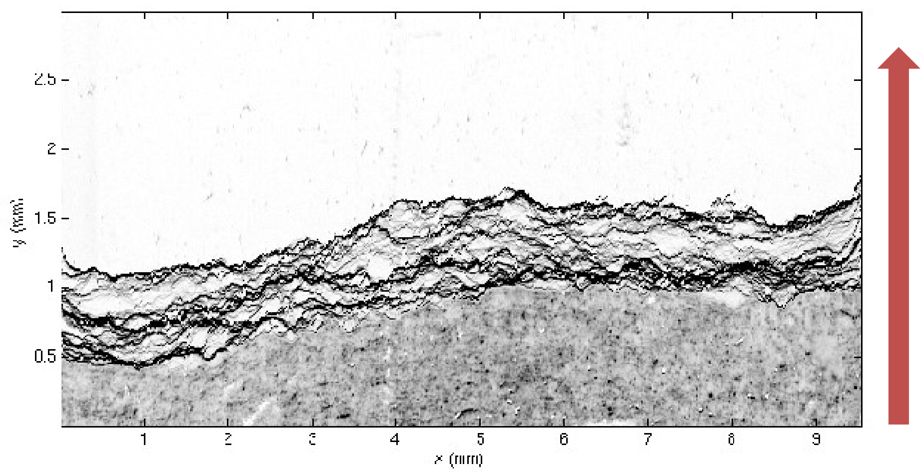


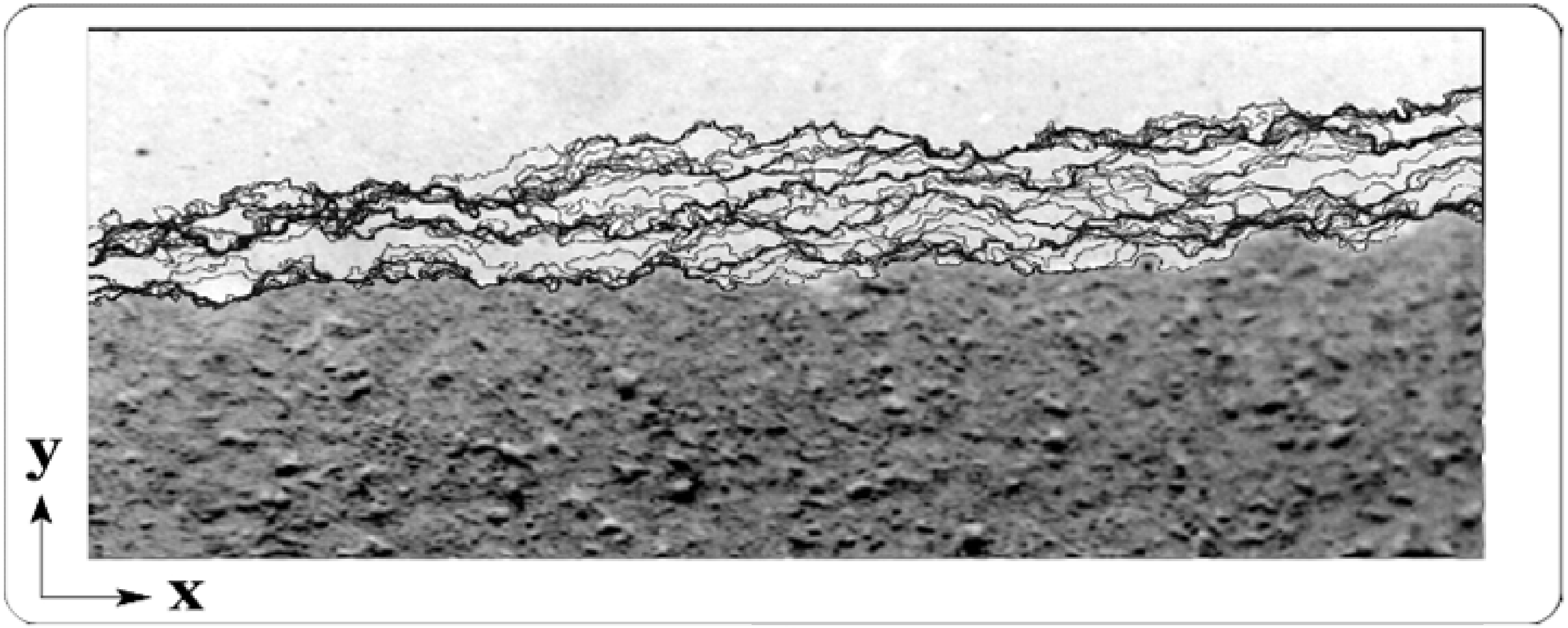
AE monitoring
« Seismometer »



Material: PMMA – subcritical Mode I fracture







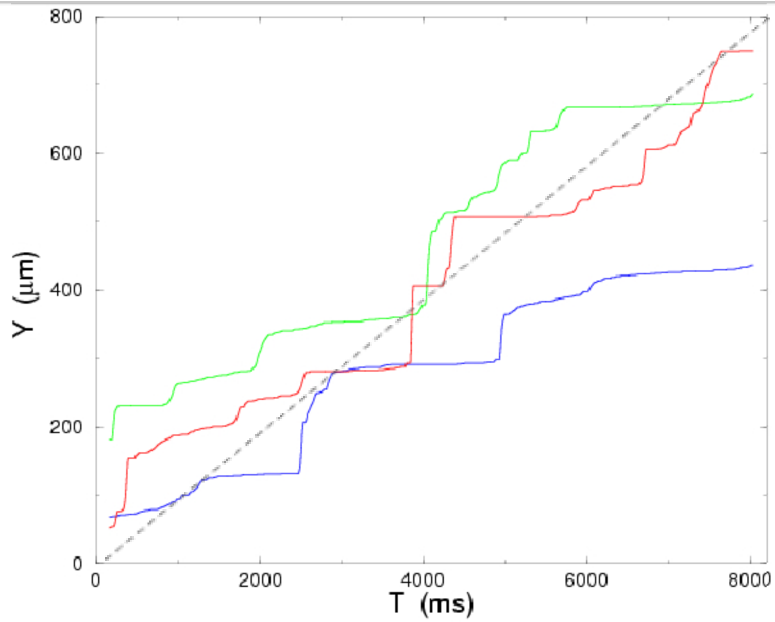
Microscopic behavior

Pining/Depining

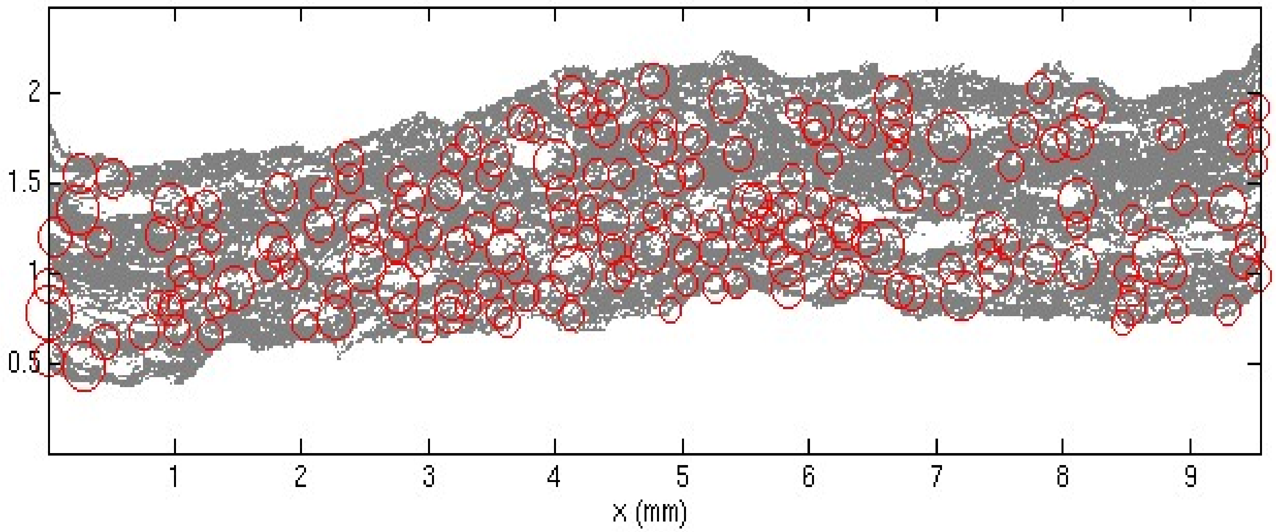
Local stick-slip motion

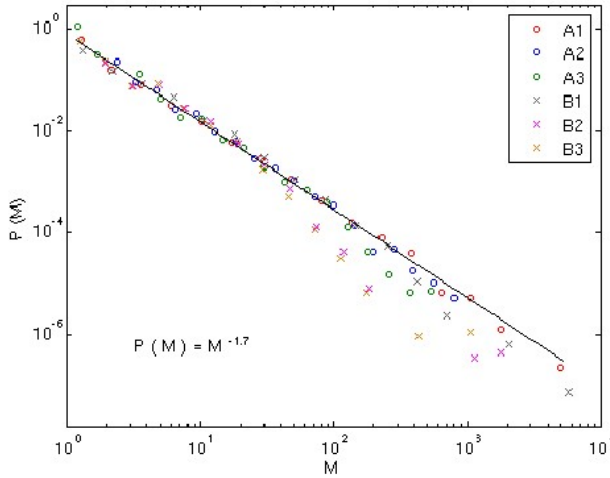
⟨v⟩~ 100 μm/s

Maloy et al, PRL, 2001



Slow slip events (optical events)

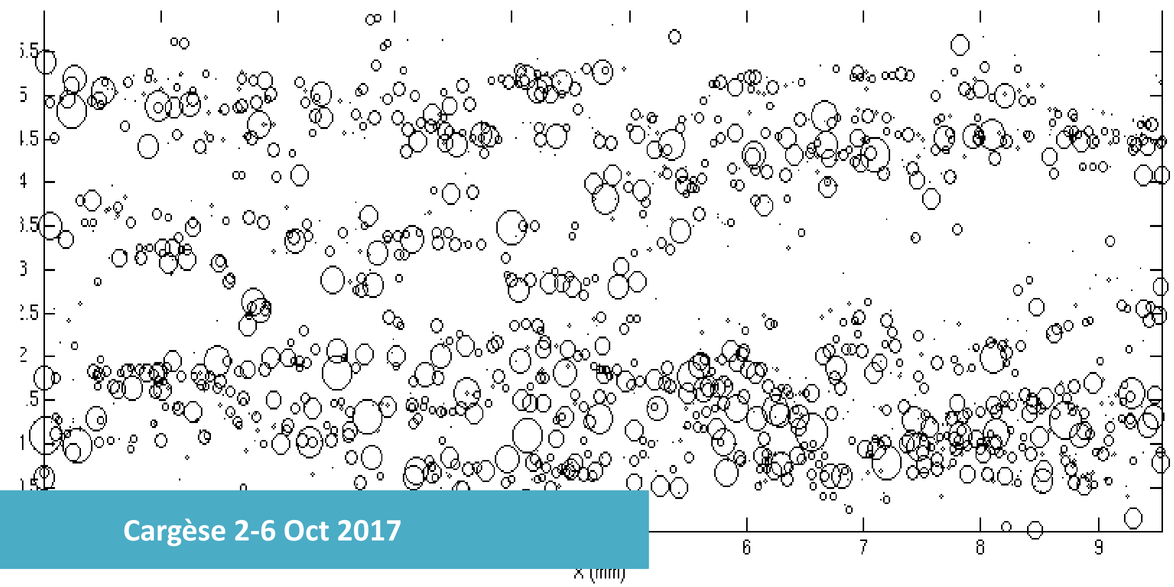




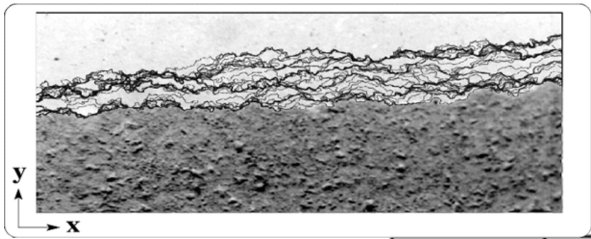
Grob et al, PAGEOPH, 2009

Local speed threshold:
v > 10*<V>

$$M \approx E\ S \times \delta$$

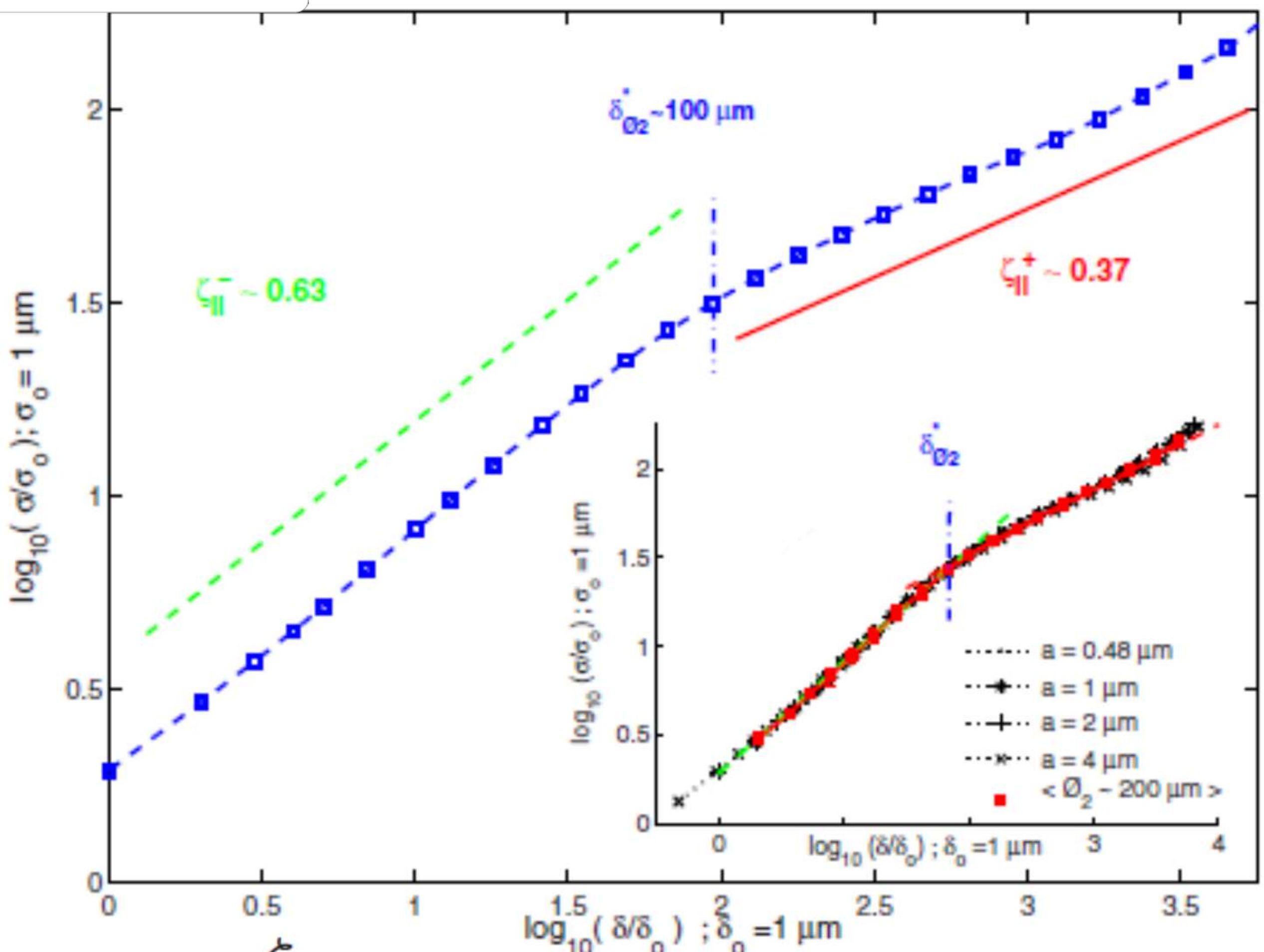


Circles = events
Diameter of circles = $\log_{10}(M)$



Scaling of the fracture front

$$\sigma(\delta) = \langle \Delta y^2(\delta) \rangle^{1/2}$$

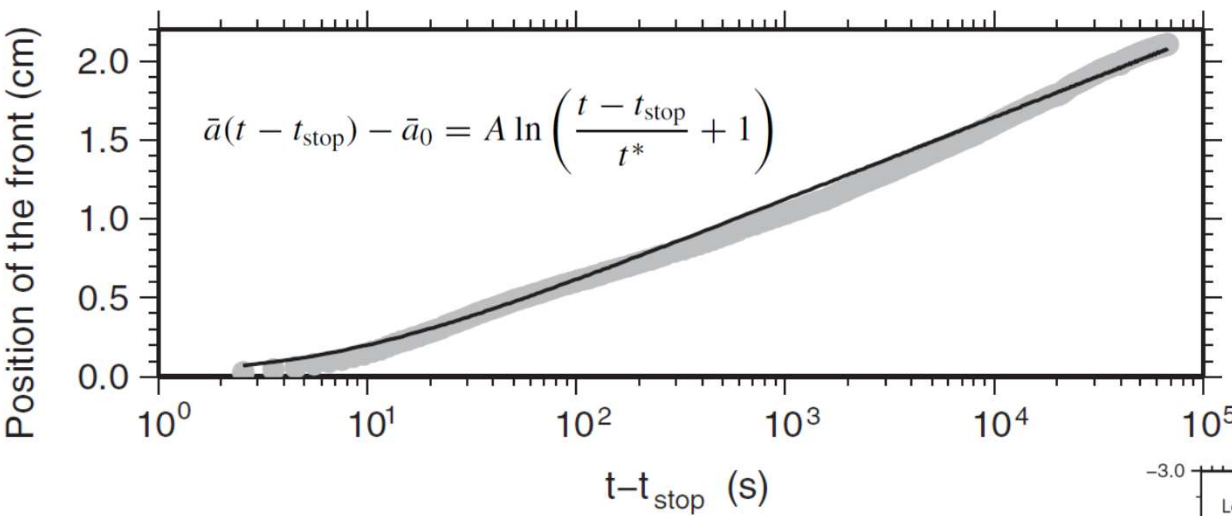


$$\sigma(\delta) \propto \delta^{\zeta}$$

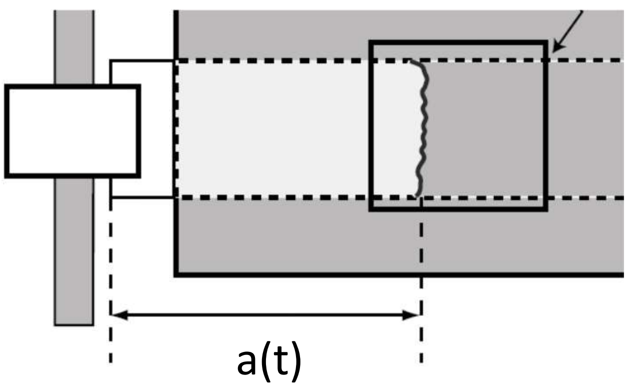
$\zeta \equiv$ roughness exponent

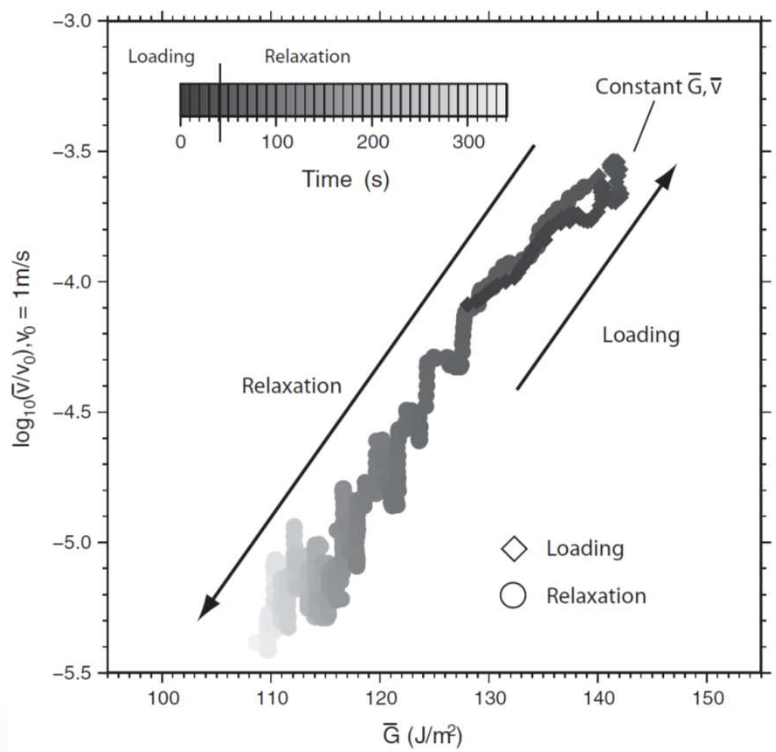
Santucci et al, EPL, 2010

Macroscopic creep behavior



Lengliné et al, PRE, 2011



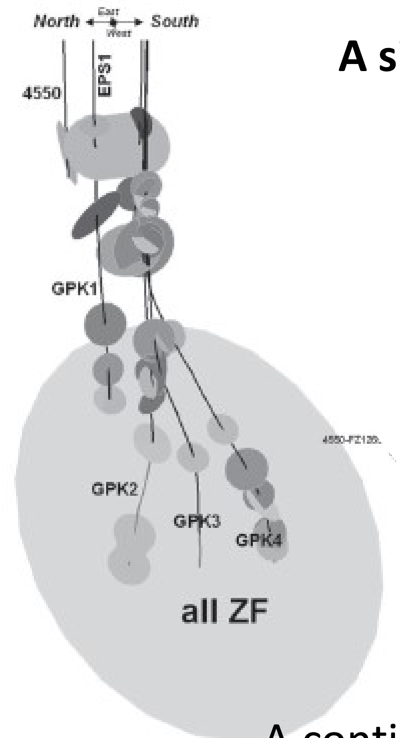


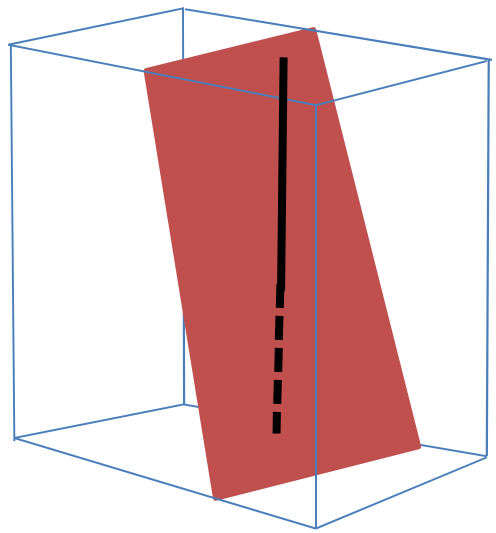
$$\bar{v} = \chi \exp[-\alpha^2(\bar{G}_c - \bar{G})/k_B T]$$

[Stormo et al, GE, 2015; Frontiers in Physics, 2016]

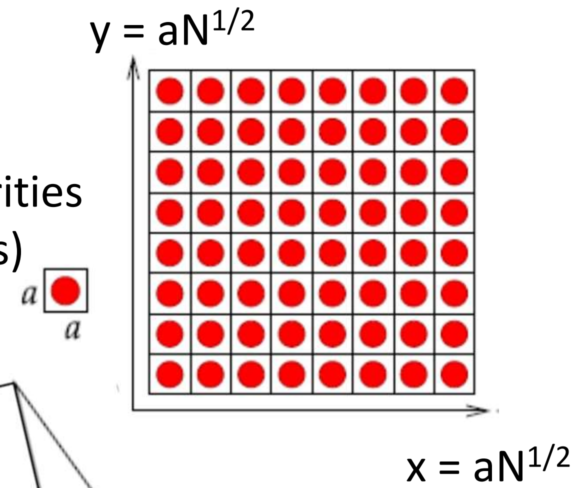
BEM+fiber bundle modelling

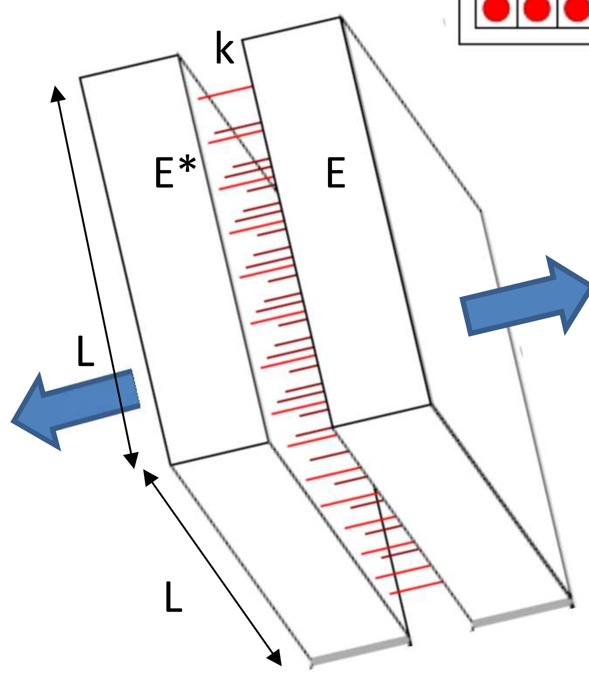
A single fault approach





N asperities (fibers)





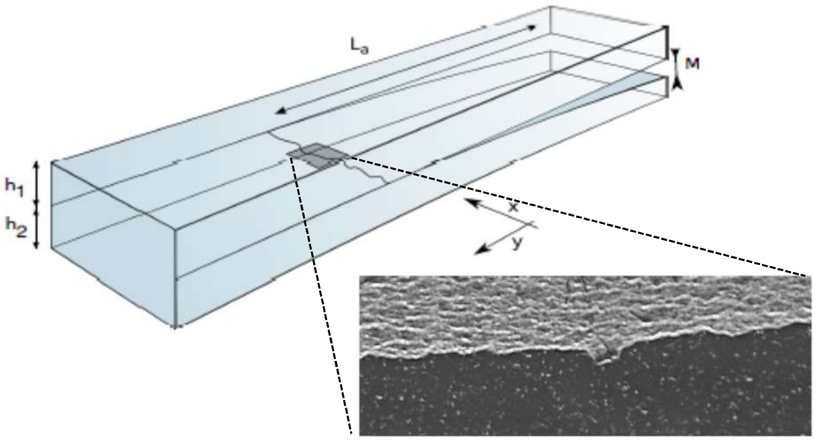
Injection
= imposed
displacement

A continuous elastic bulk
with long range interactions (k_b=E*L)
+
A discrete elastic/brittle interface
with fibers (k_i=N*k)

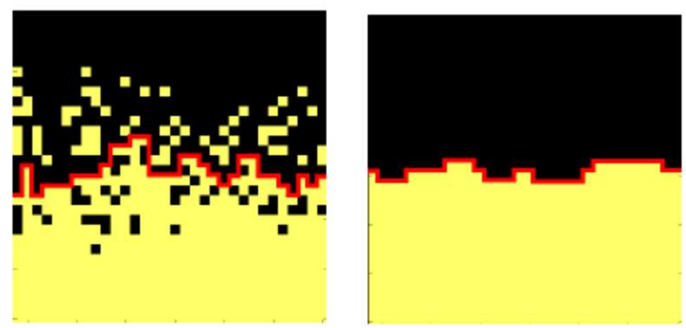
Stiffness ratio:

$$e = \frac{k_b}{k_i} = \frac{EL}{Nk}$$

Experimental / numerical comparision
Interfacial crack front

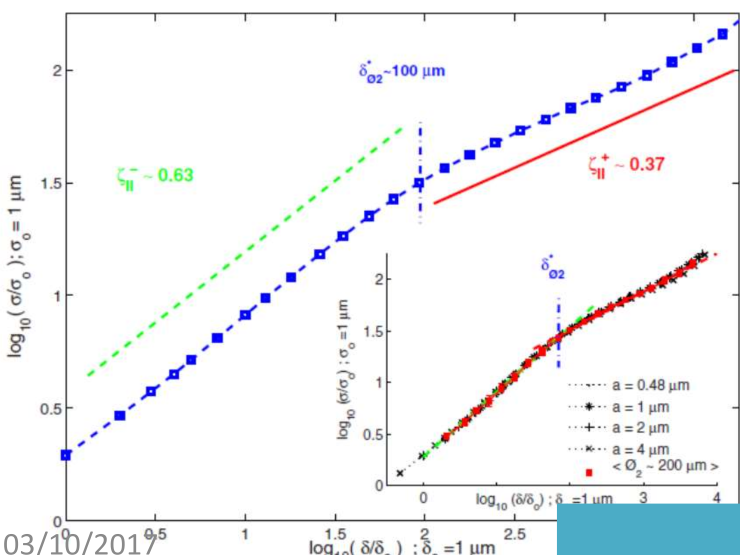


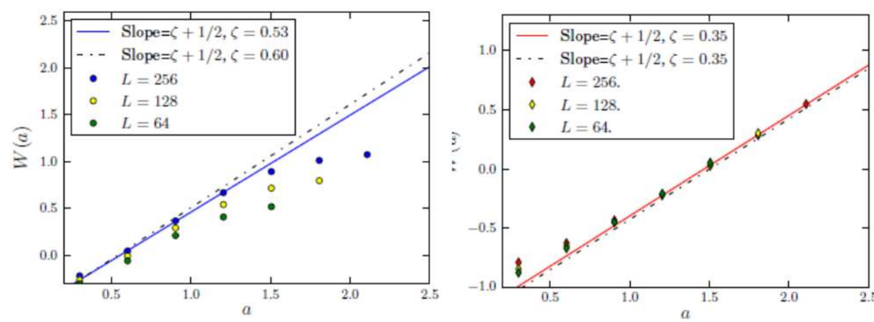
Stormo et al, FP, 2016



« Stiff »

« Soft »





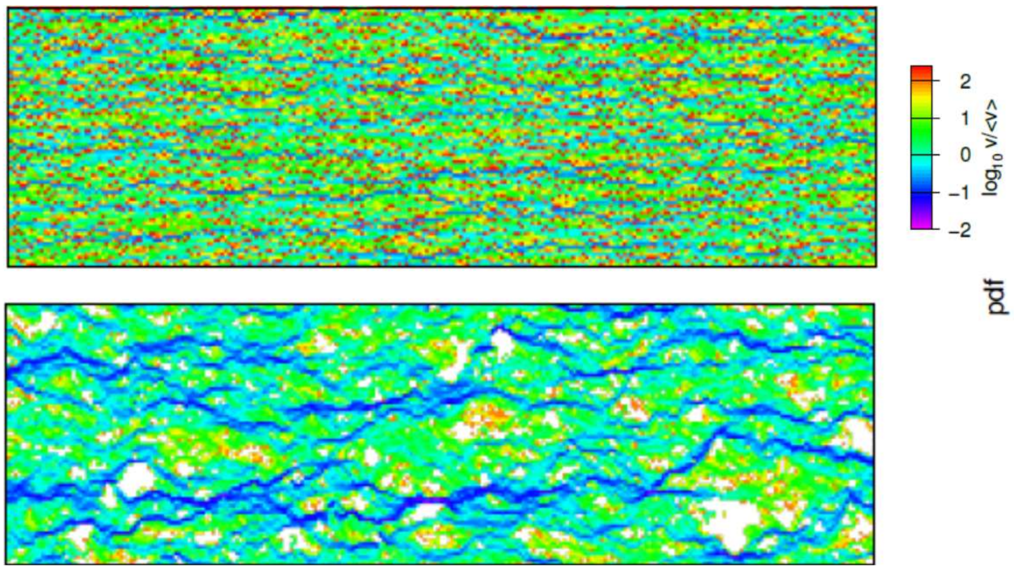
$$W(a) \propto a^{\zeta+1/2}$$

ζ = 0.35

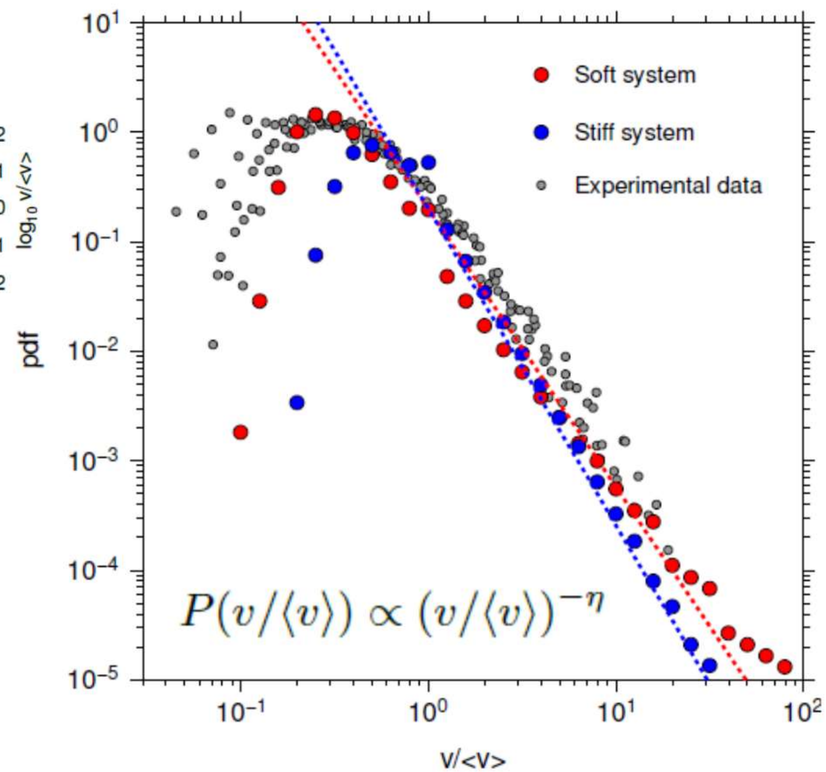
Local velocity distribution

[Stormo et al, Frontiers in Physics, 2016]

Experiment



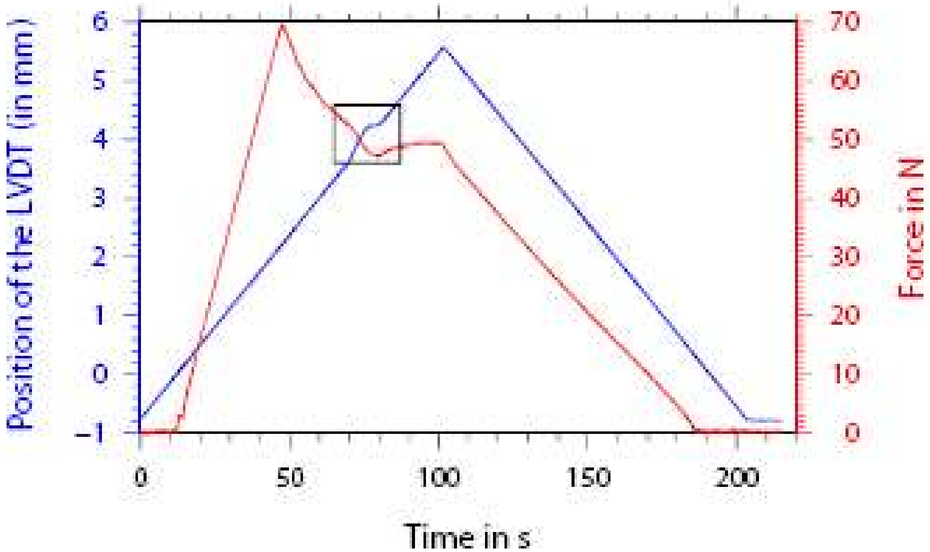
Model

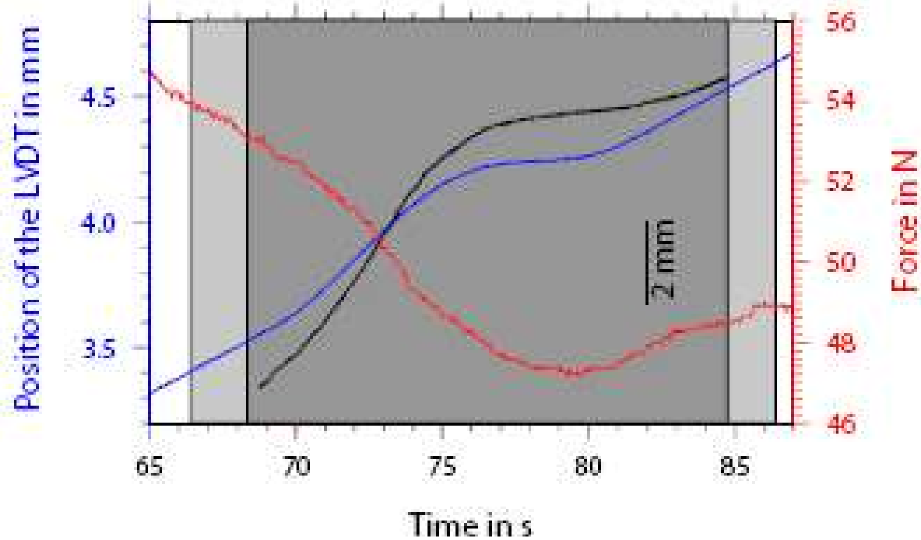


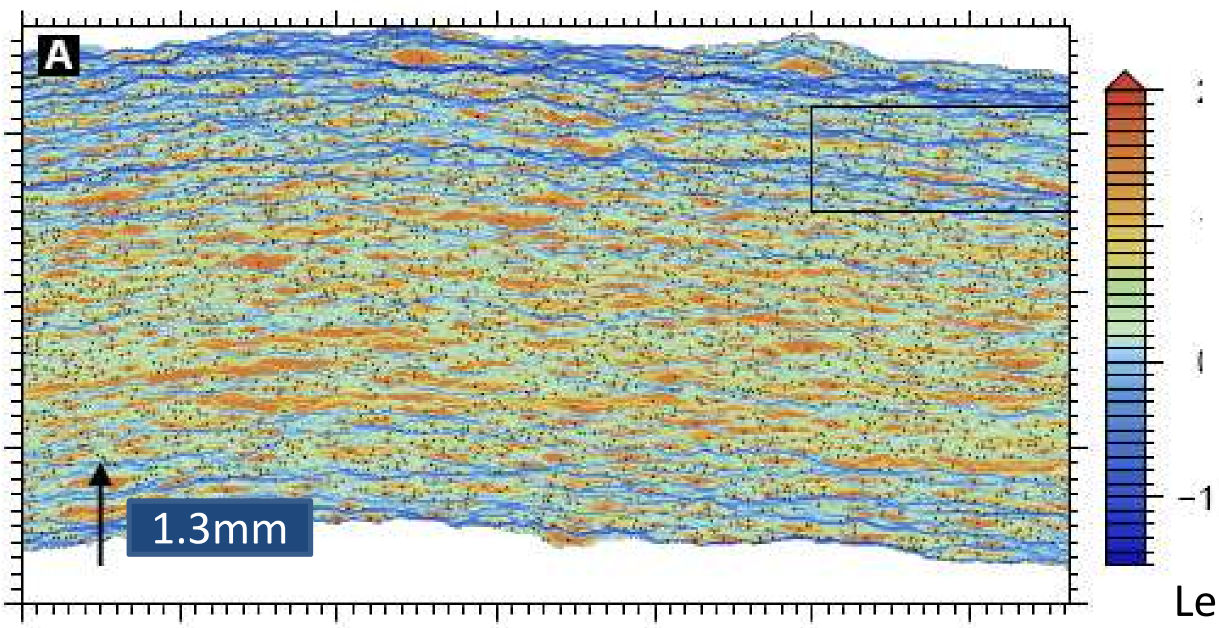
η_{exp} **=2.55** η_{stiff} **=2.89** η_{soft} **=2.54**

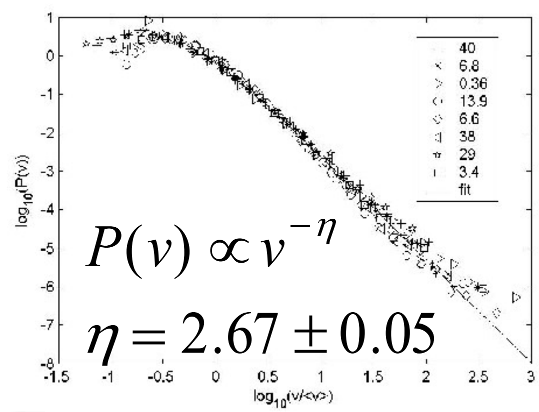
No pore pressure change

A loading perturbation – No fluid





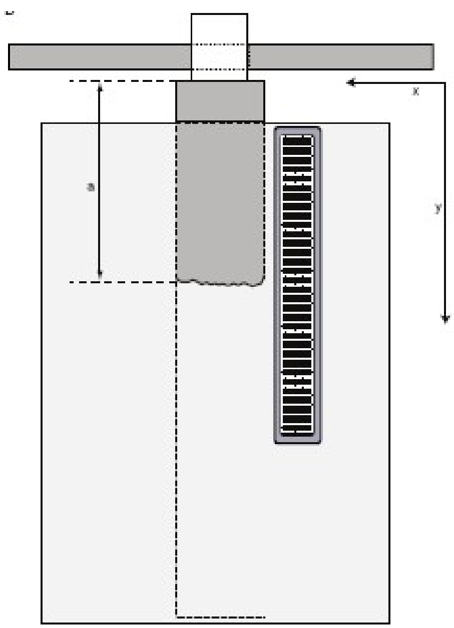


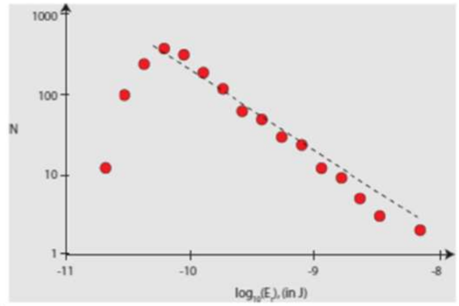


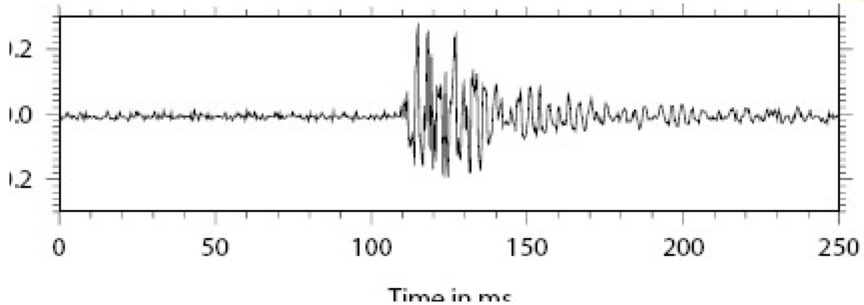
A power law distribution over 3 orders of magnitude: a continuum of time scales

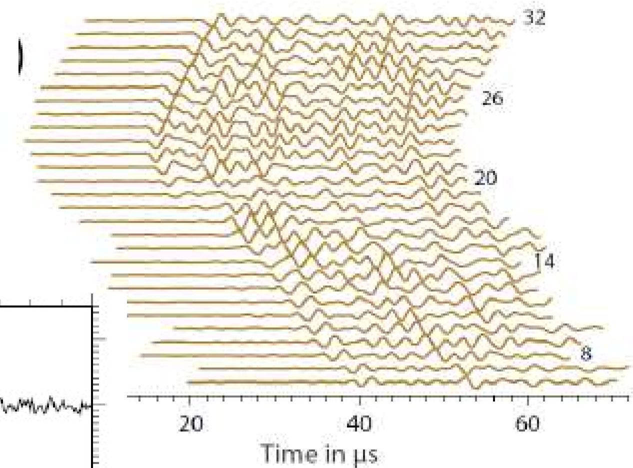
Lengliné et al, EPSL, 2012

Seismic events (acoustic emissions)

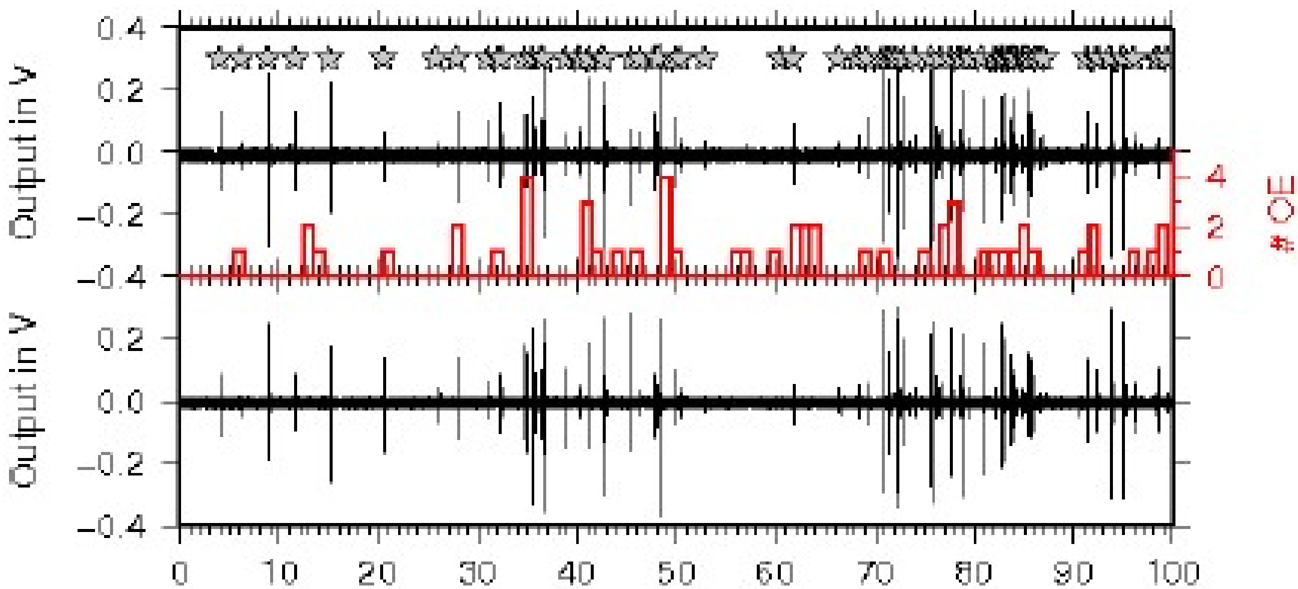




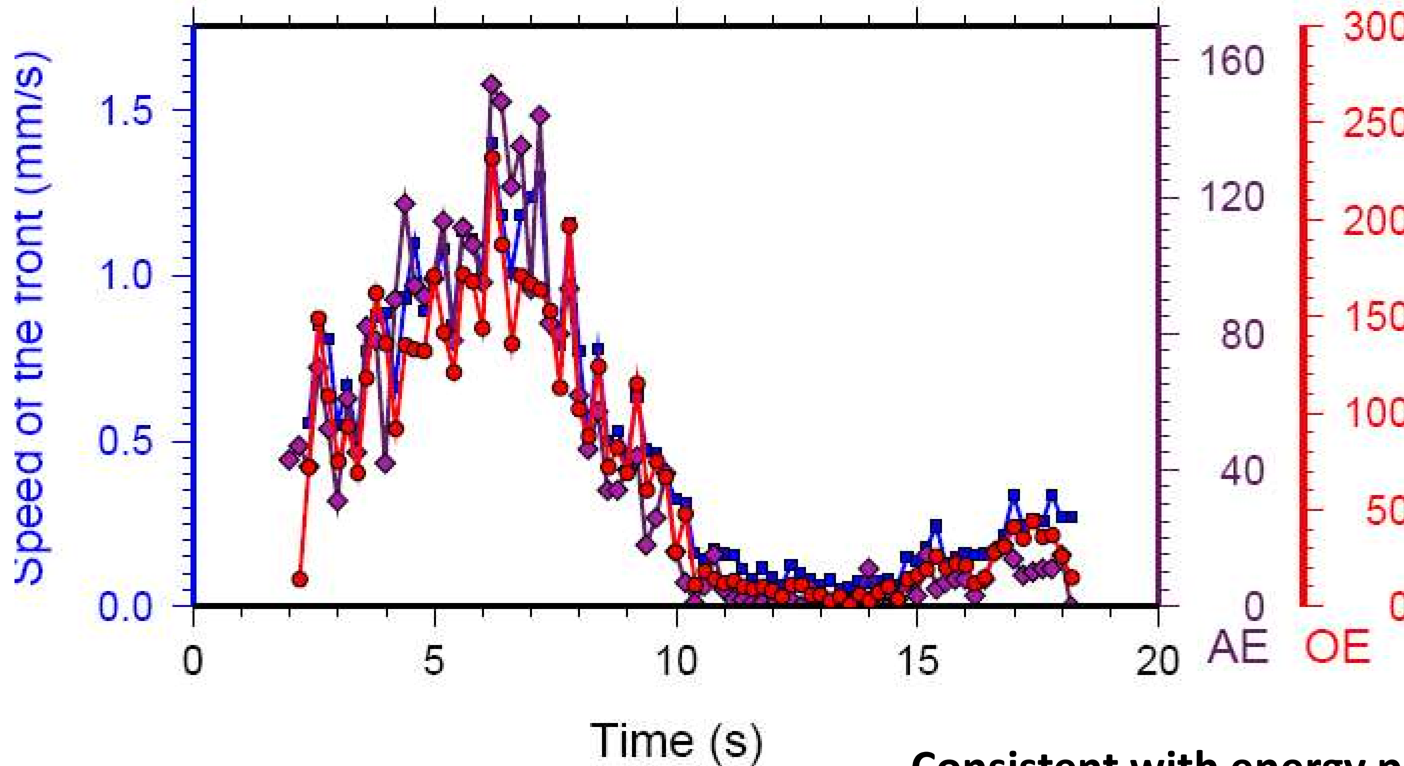




STA/LTA detection
(STA=20µs/LTA=100µs)



A creep induced seismicity



Average velocity of the front (mm/s)

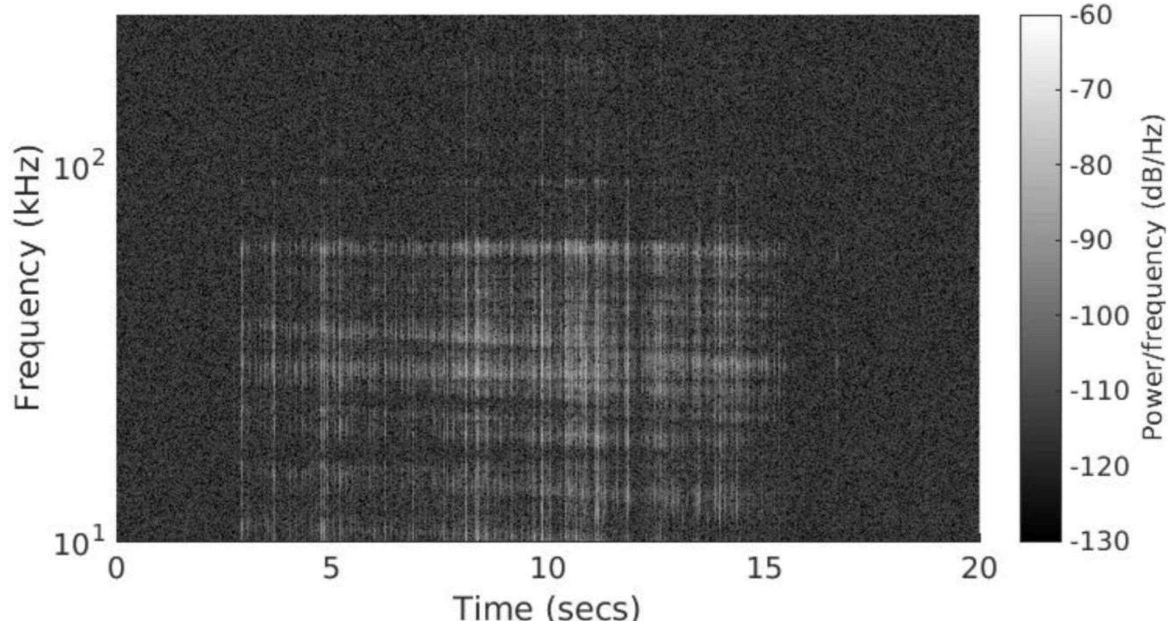
Number of acoustic events (**seismic**)

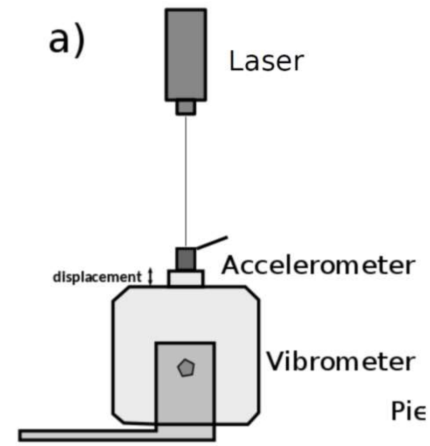
Number of optical events (**aseismic**)

Consistent with energy partition:
$E_{radiated} \sim M_0/20000$

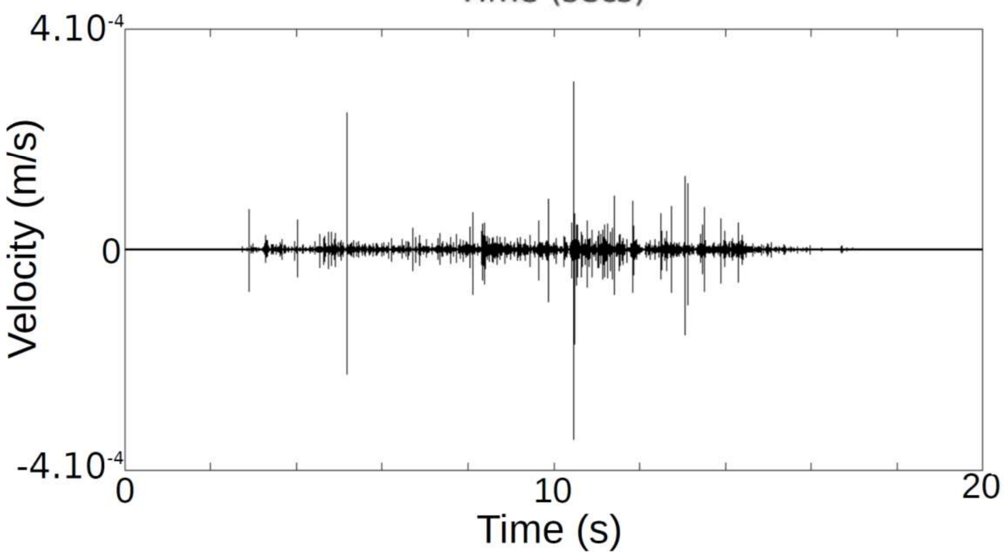
Lengliné et al, EPSL, 2012
Schmittbuhl et al, GE, 2014

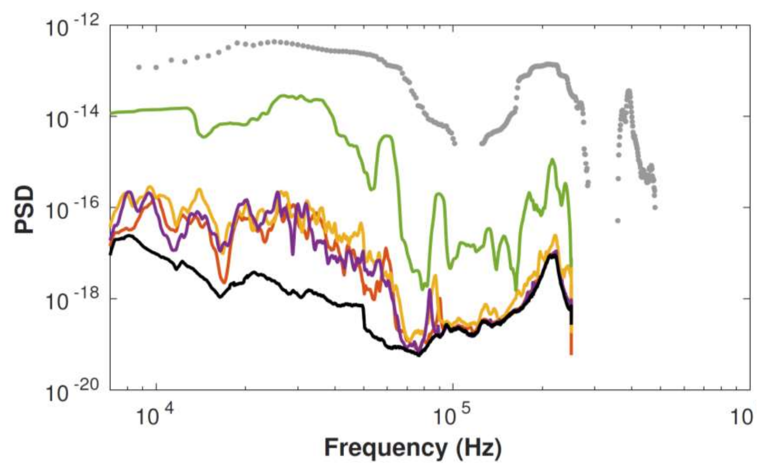
Low frequency signals



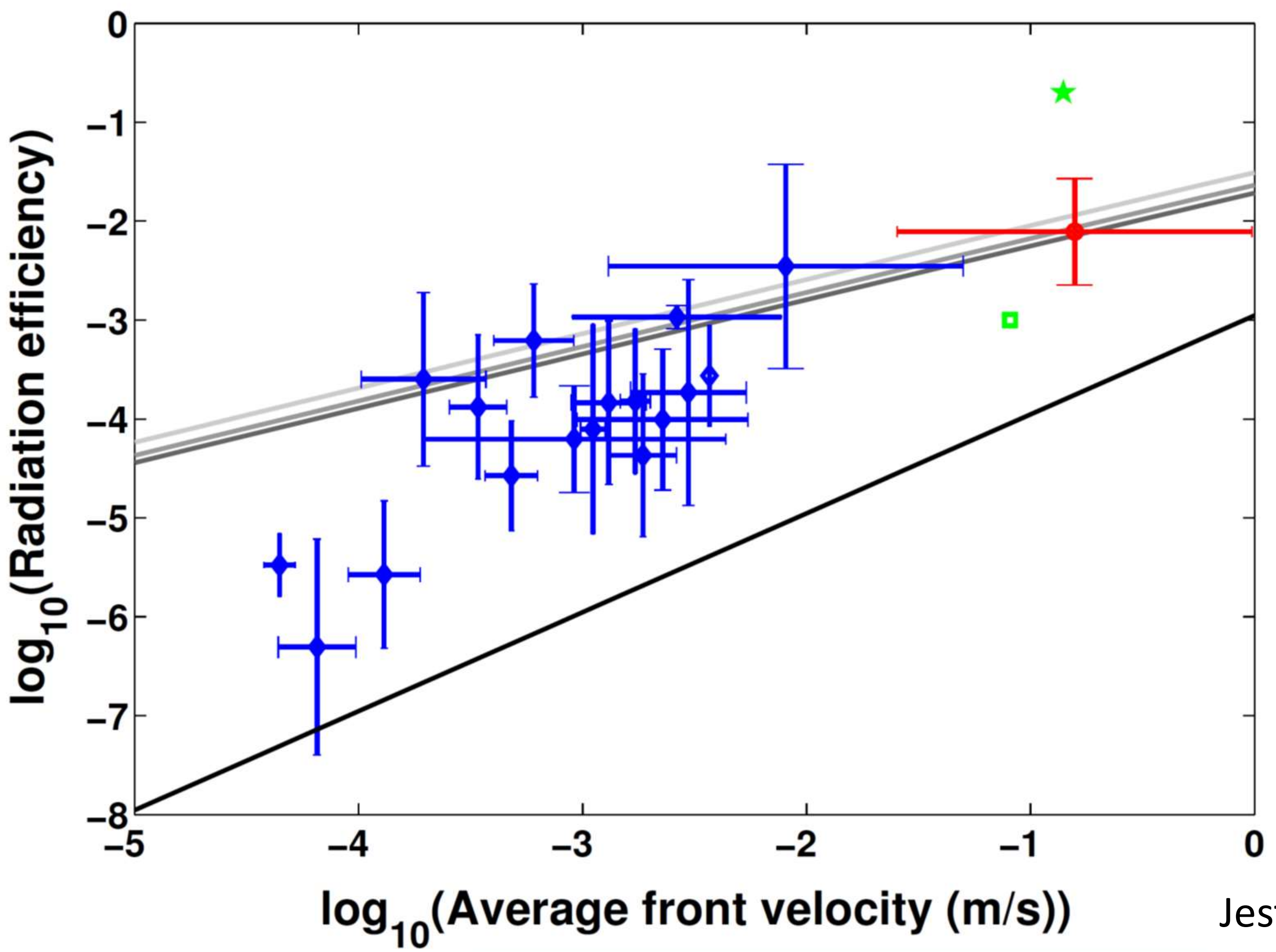


Jestin et al, 2017





Seismic/aseismic energy



Radiation efficiency

$$\eta_R = \frac{E_R}{E_R + E_G}$$

Jestin et al, 2017

Induced seismicity