Induced seismic and aseismic slip in EGS reservoir: Case studies from Alsace, France

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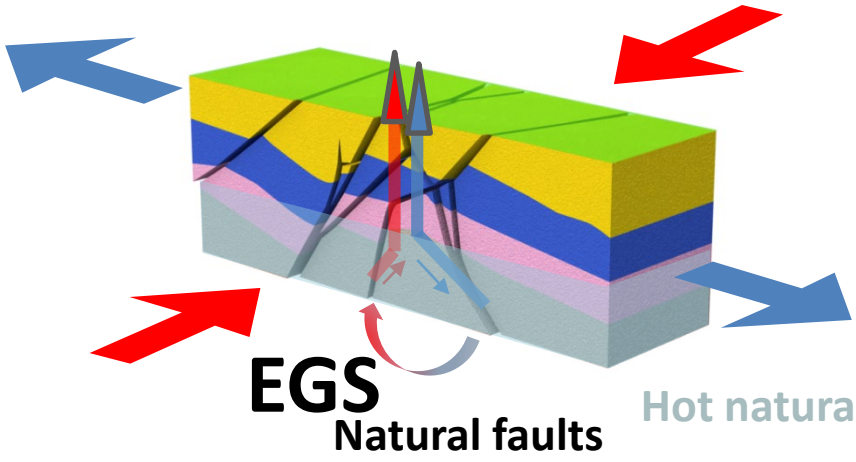
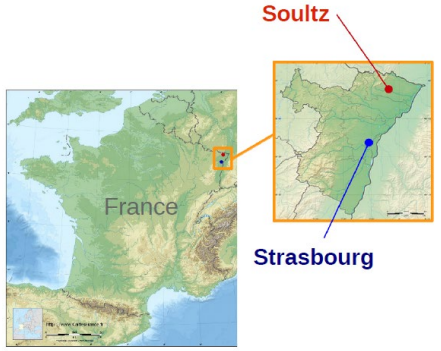




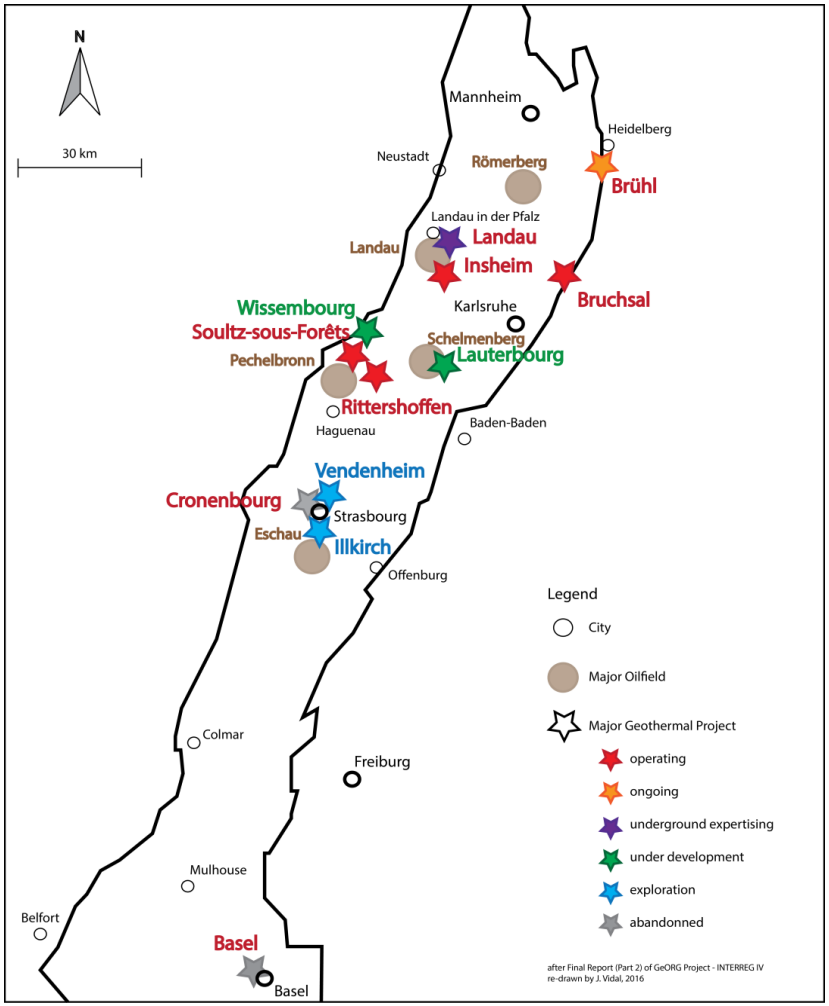
Outline

Induced seismic and aseismic events in deep EGS reservoirs –case studies from the Rhine Graben (2500m-5000m)

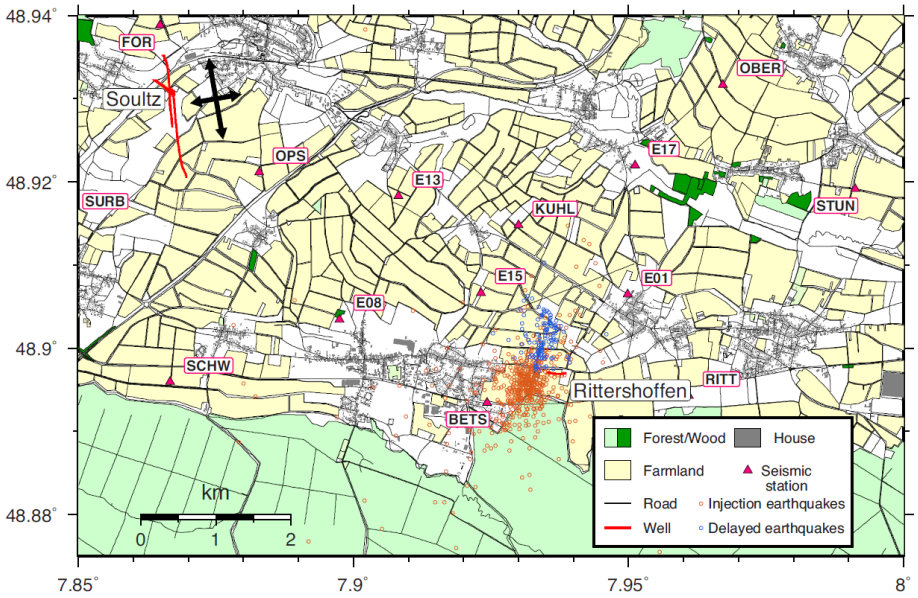
- Induced seimsicity at the recent **Rittershoffen** site, France (close by Soultz)
  - Development of the 2500m deep geothermal well GRT1 in 2013
- Induced seismicity at the **Soultz-sous-Forêts** site, France
  - Stimulation of the 3500m deep geothermal well GPK1 in 1993 – *importance of high quality data (deep boreholes)*
  - A focus on induced repeating events, tracers for induced aseismic slip

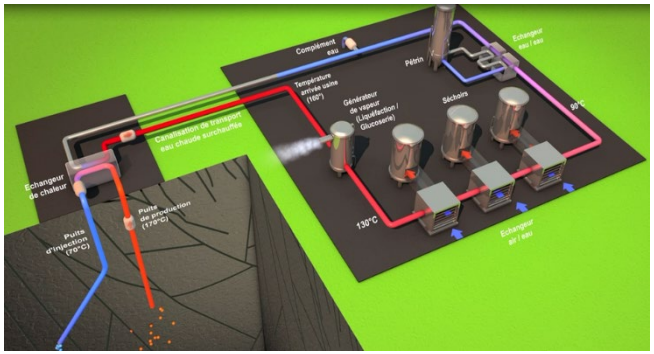
EGS projects in the Rhine Graben

- Soultz-sous-Forêts (quadriplet)
- Bruchsal (doublet)
- Landau/Insheim (doublet)
- Bâle (1 well)
- Brühl (1 well)
- Rittershoffen (doublet)
- Eurométropole: Illkirch/ Eckbolsheim/Vendenheim
- Wissembourg/Lauterbourg



The case of Rittershoffen GRT1 stimulation



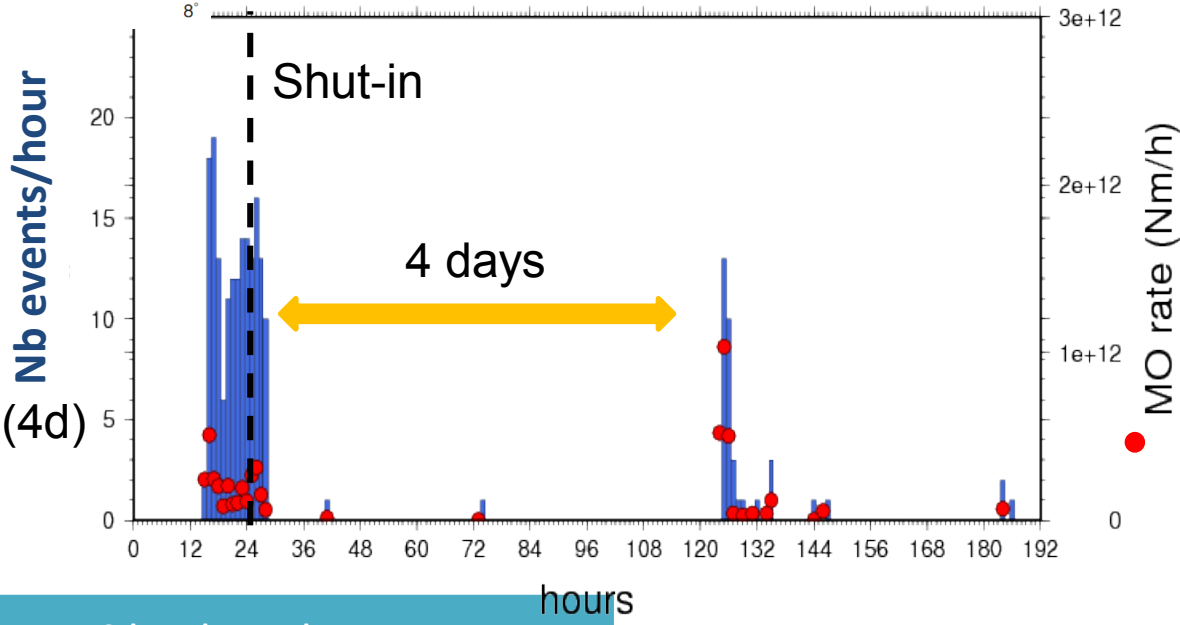


Rittershoffen (< 8 km Soultz)
Doublet GRT1/2 – 2500m

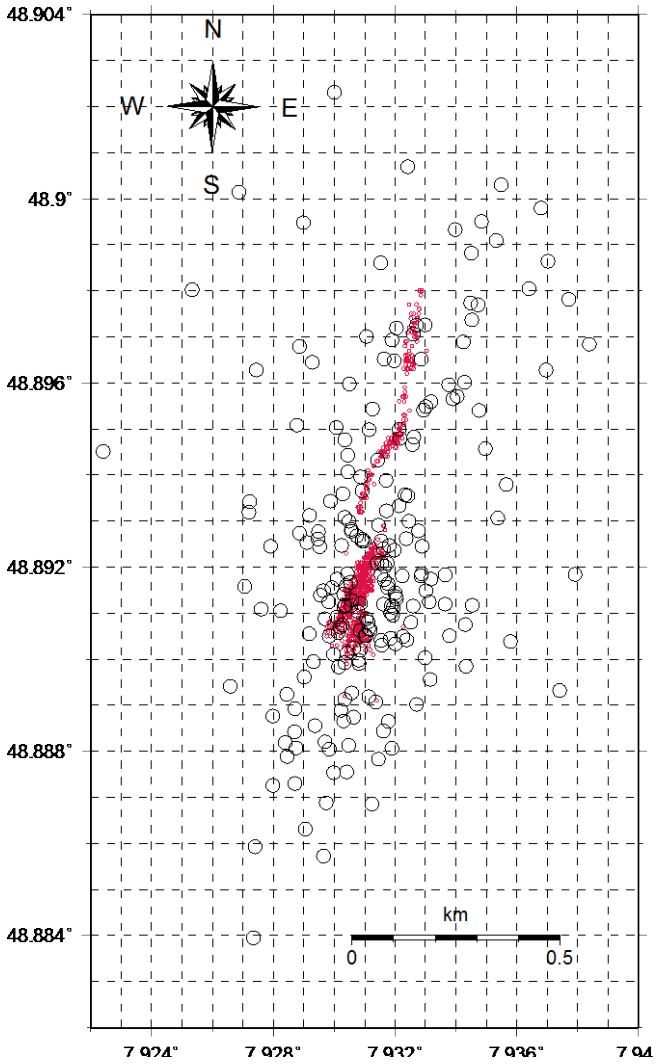
Stimulation of GRT1
(June/July 2013)

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

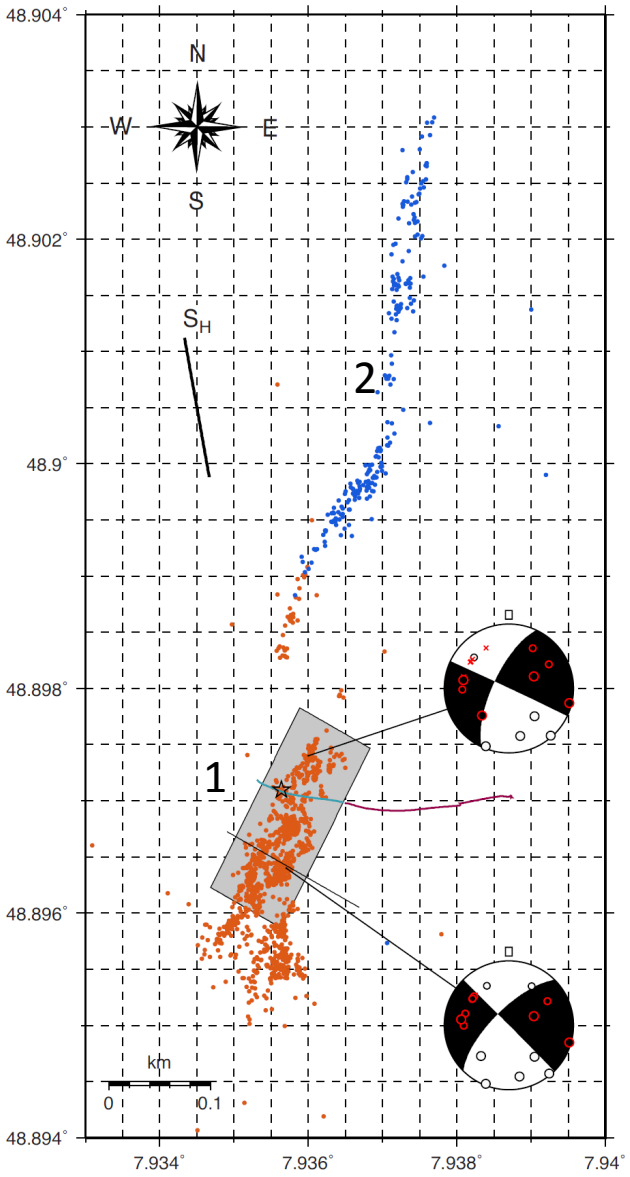
[Baujard et al, Geothermics, 2016]

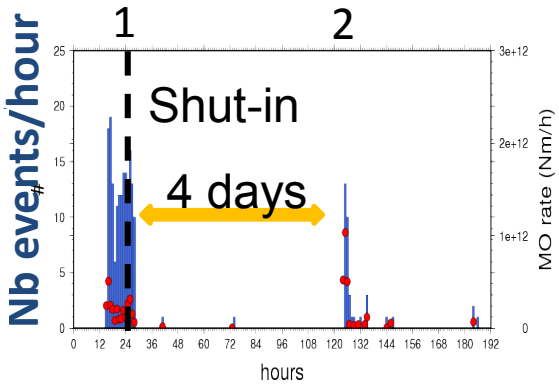


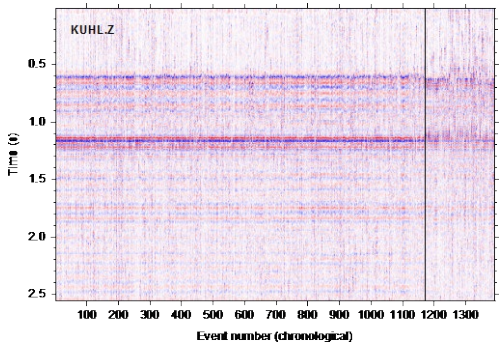
Template matching/Relocations

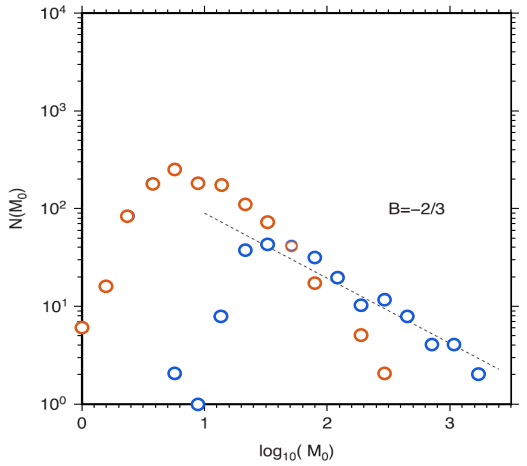


Seiscomp - realtime







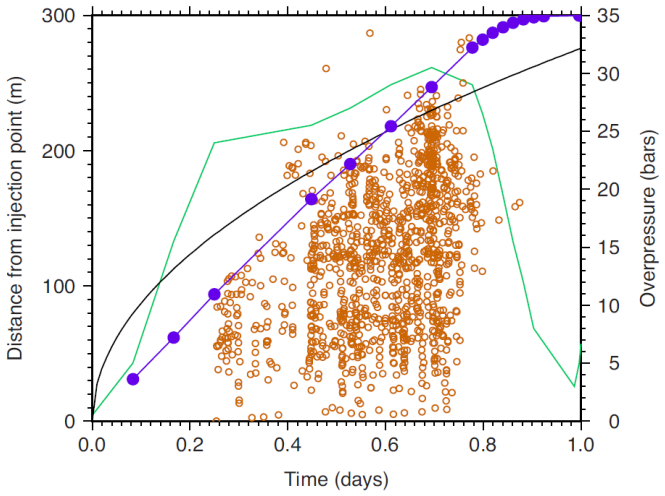


[Lengliné et al, GJI, 2017]

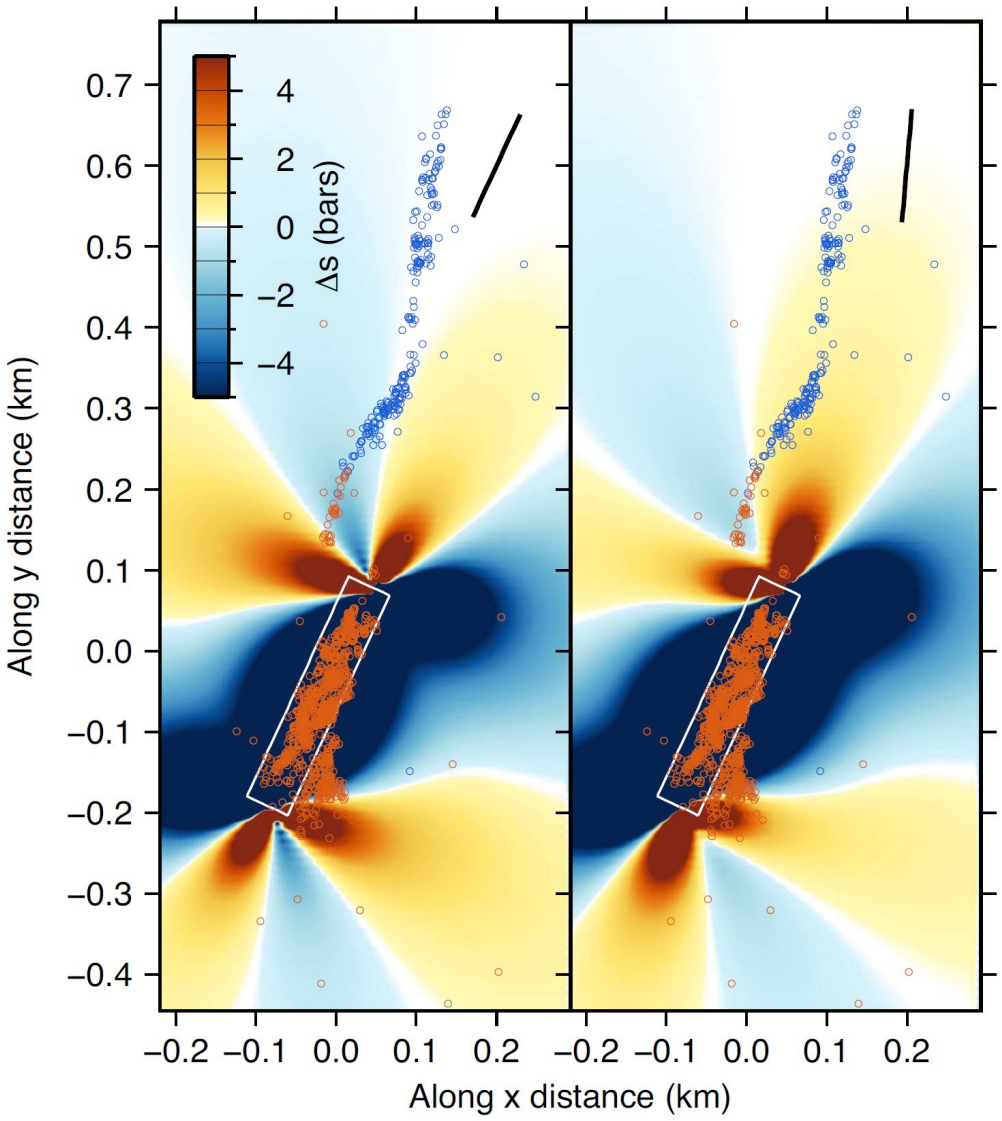
Stress transfer from aseismic slip (?)

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

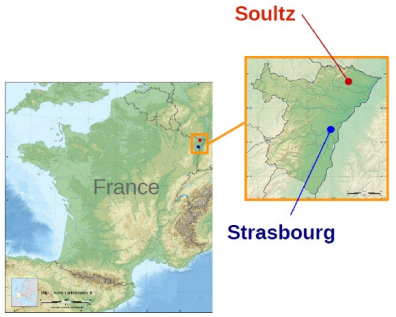
Different from a fluid pressure diffusion mechanism



[Lengliné et al, GJI, 2017]

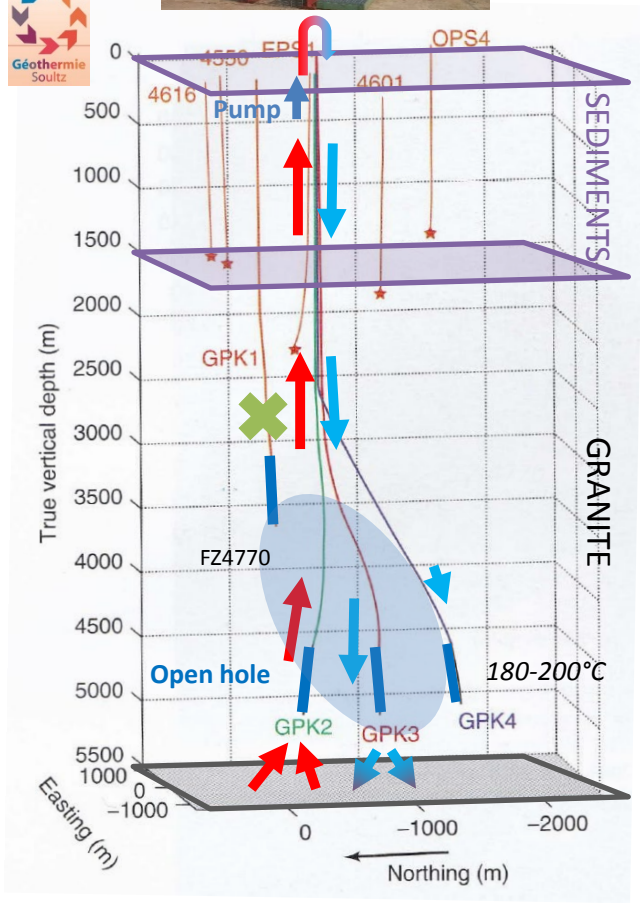


Soultz-sous-Forêts (GEIE EMC- Soultz I->II)



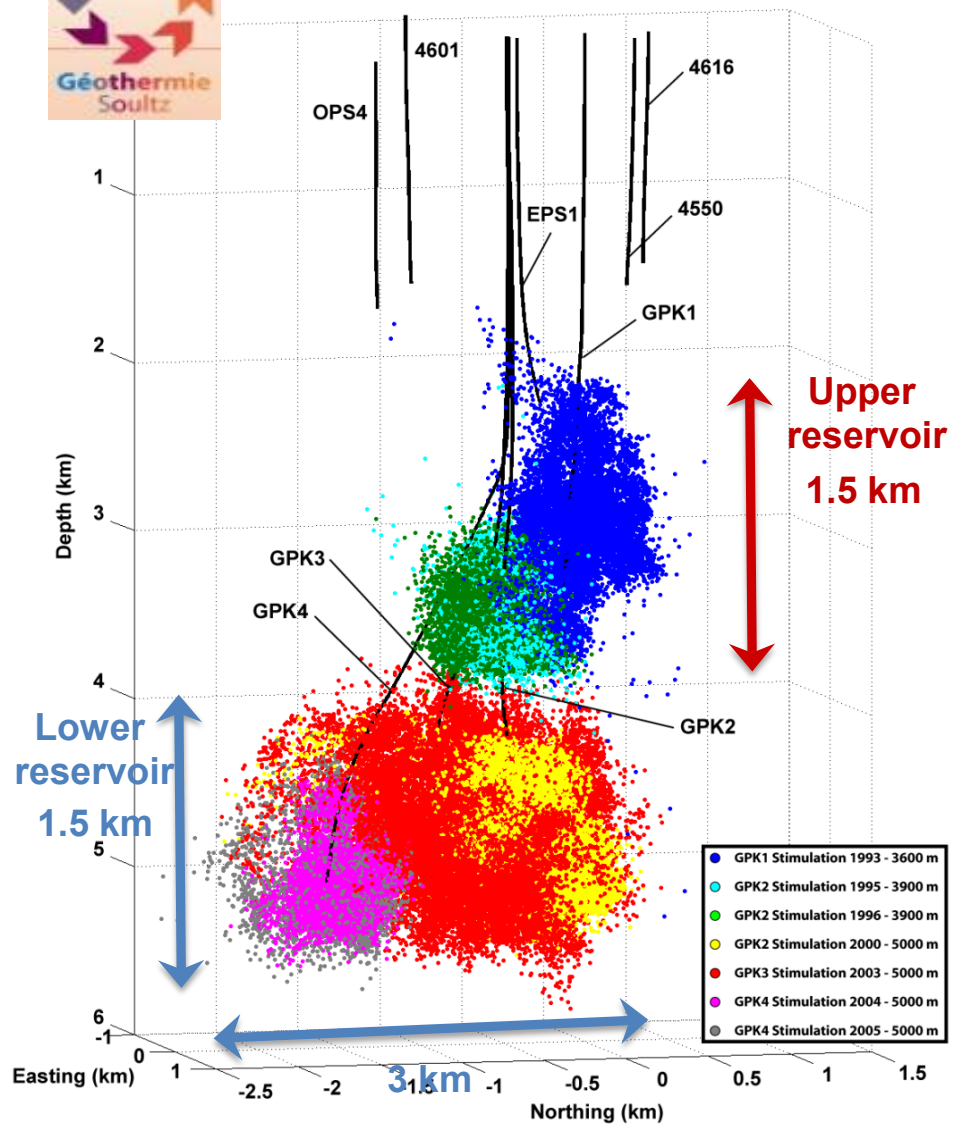
Soultz II (since 07/16)

- A triplet at 5000m: GPK2 (production) – GPK3 (injection) + GPK4
- Openholes (500m) in the fractured granite (a major fault FZ4770)
- A long shaft pump 300m (22 bars): 35 l/s
- T° production: 150-160°C – T° injection: 70-80°C
- Thermal power 11MWth



7 hydraulic stimulations (Soltz)

+ chemical stimulations



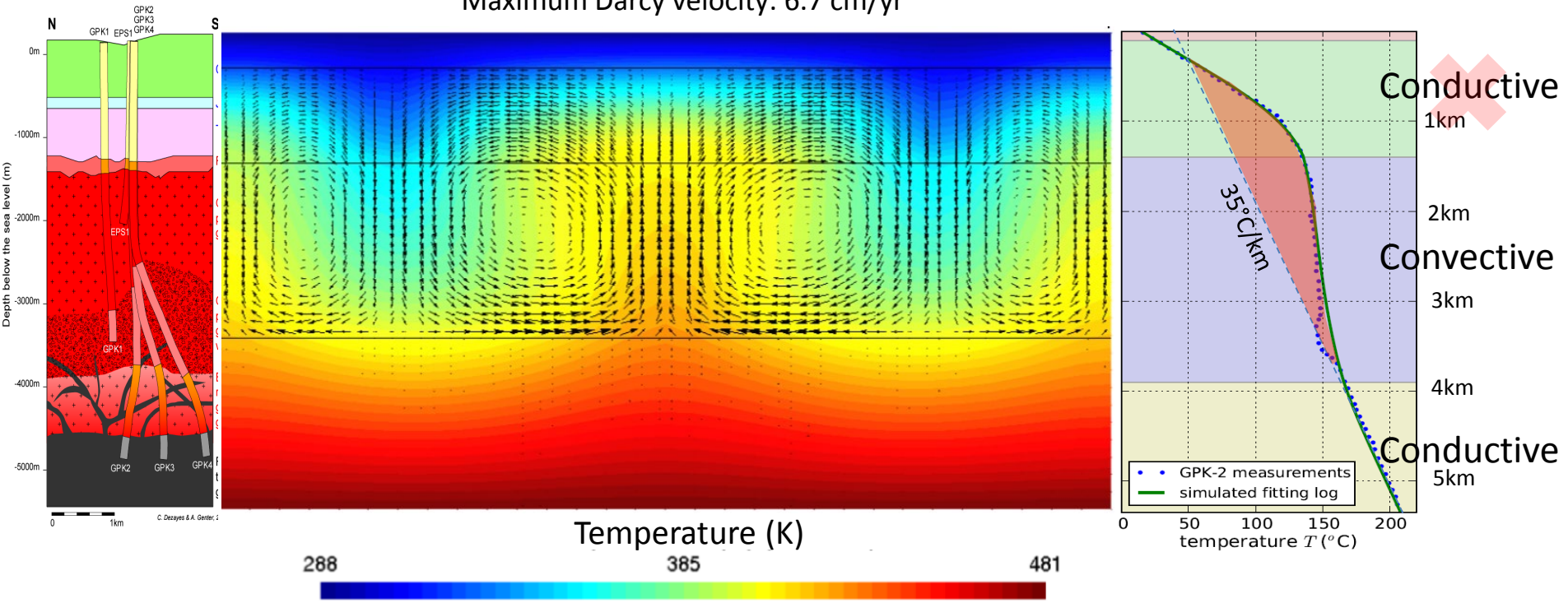
- 4 deep monitoring boreholes (1-1.5km) (from oil industry)
- 2 zones of stimulations:
  - Upper reservoir (~3000m)
  - Lower reservoir (~5000m)
- felt EQs (Ml > 2) **in the lower reservoir**
  - 2000 : Ml_{max}=2.6
  - 2003 : Ml_{max}=2.9, 2.7
  - 2004 : Ml_{max}=2.0
  - 2005 : Ml_{max}=2.6
- A data center: CDGP (https://cdgp.u-strasbg.fr/)

https://tcs.ah-epos.eu/

Deep temperature logs/THM modeling
large scale natural hydro-thermal fluid circulation

[Vallier et al, Geothermics, 2018]

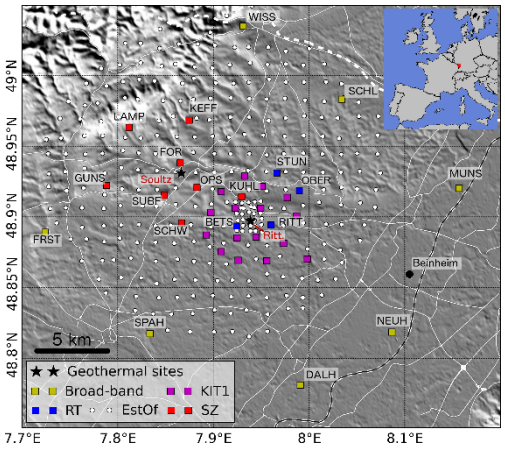
Maximum Darcy velocity: 6.7 cm/yr

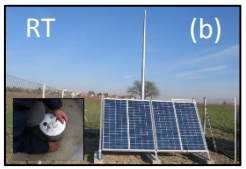


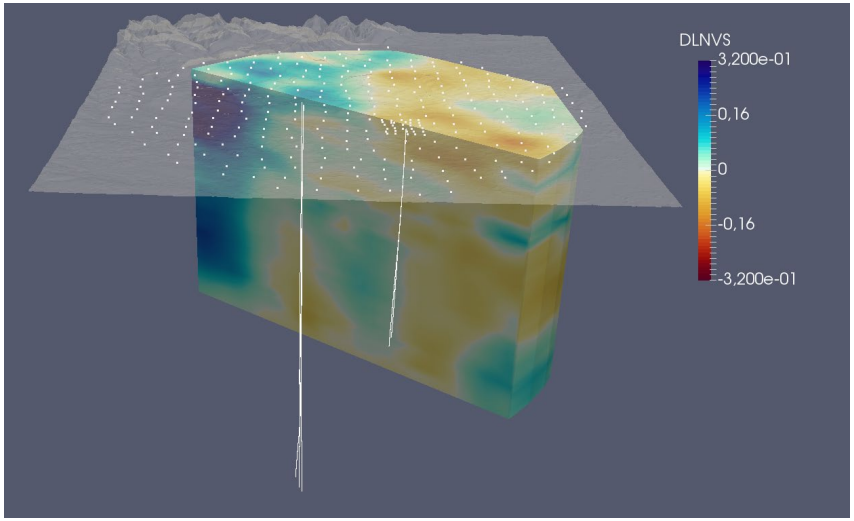
- *A weak hydraulic role of the sediment/basement transition (a boundary layer effect)*
- *A weak influence of the regional faults in the fluid circulation*
- *Significant lateral variations of the temperature (up to 50°C)*

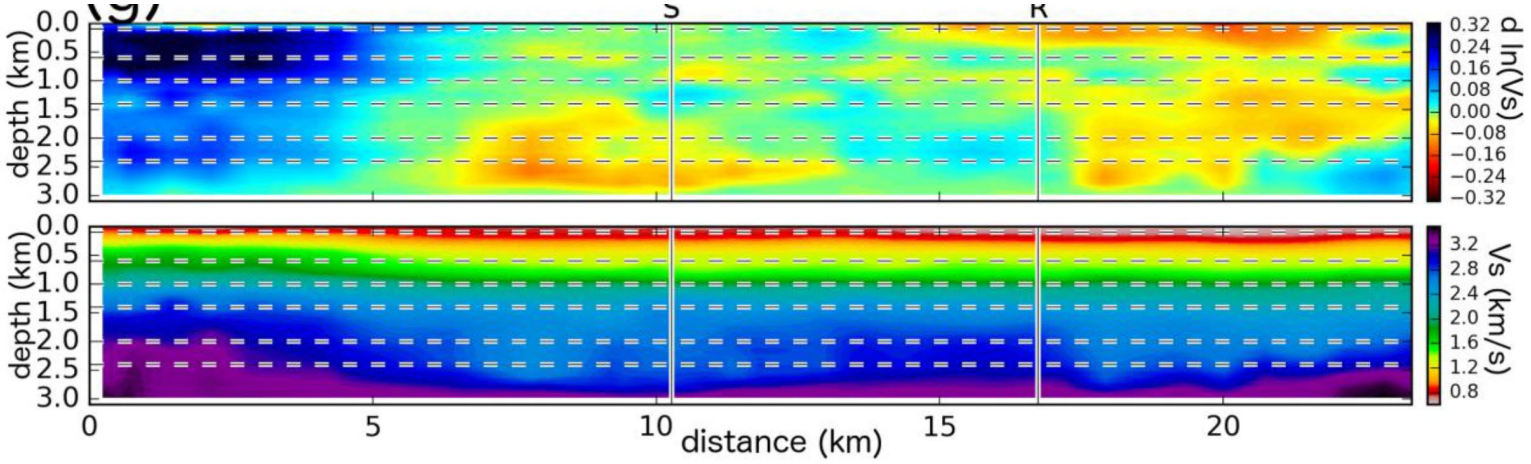
Ambient noise tomography using dense array

EstOf (Sept 2014) 288 nodes



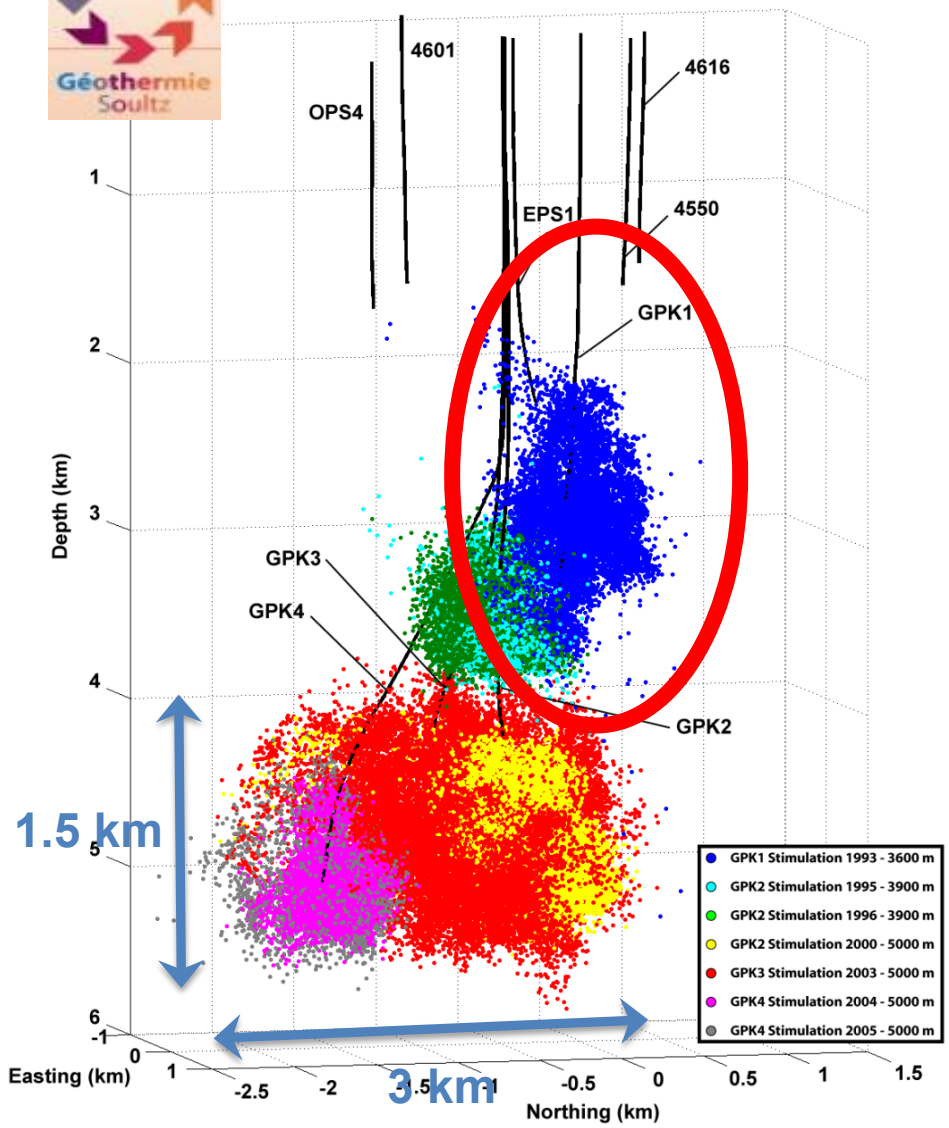






[Lehujeur et al, 2017, 2018]

GPK1 stimulation at Soultz-sous-Forêts (1993)

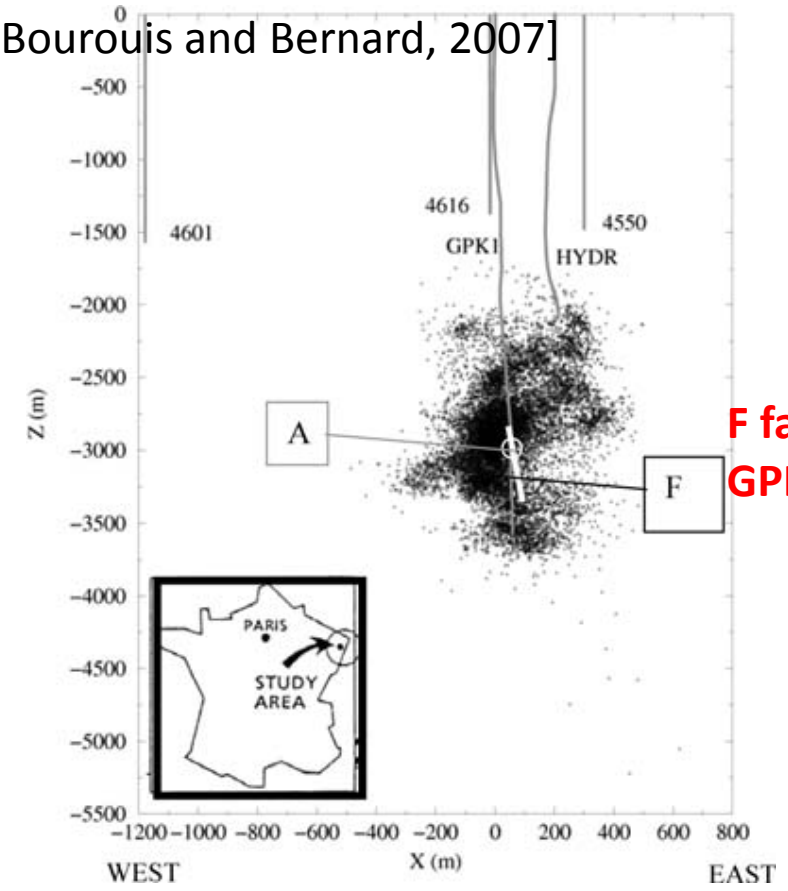


- Target: Enhanced Geothermal System (EGS) – increase permeability of the reservoir from fluid stimulation
- A large number of induced seismicity (~10000 EQ/stimulation)
- A possible risk of felt EQ (if Ml > 2)
  - 2000 : Ml_{max}=2.6
  - 2003 : Ml_{max}=2.9, 2.7
  - 2004 : Ml_{max}=2.0
  - 2005 : Ml_{max}=2.6
- A tool for reservoir imaging

GPK1 stimulation at Soultz-sous-Forêts (1993)

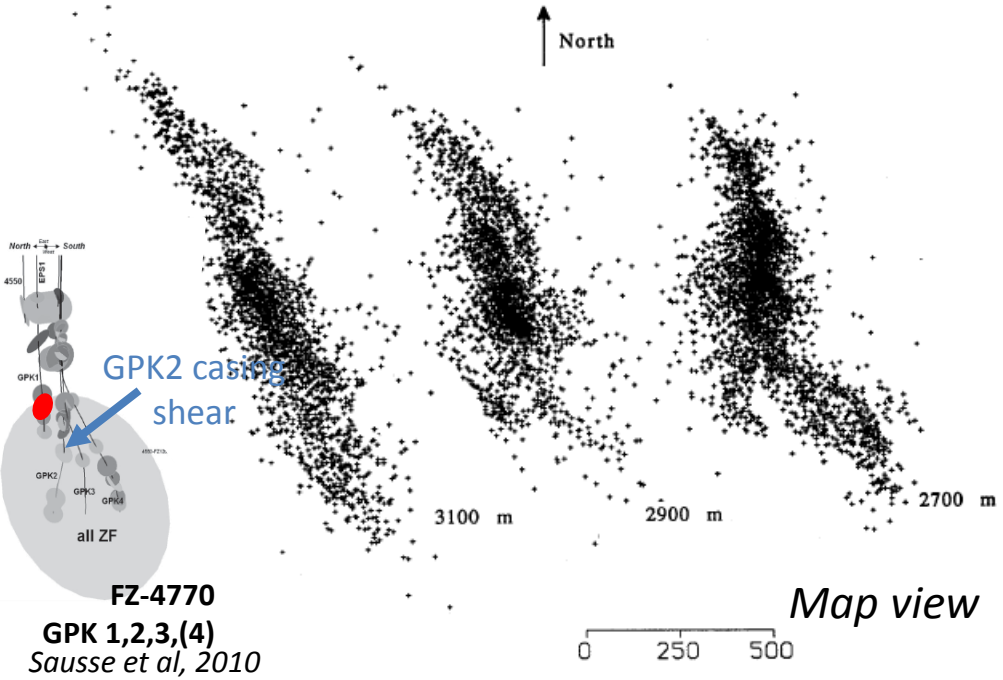
injection of 25 000 m^3 during 16 days ~10000 located events

[Bourouis and Bernard, 2007]



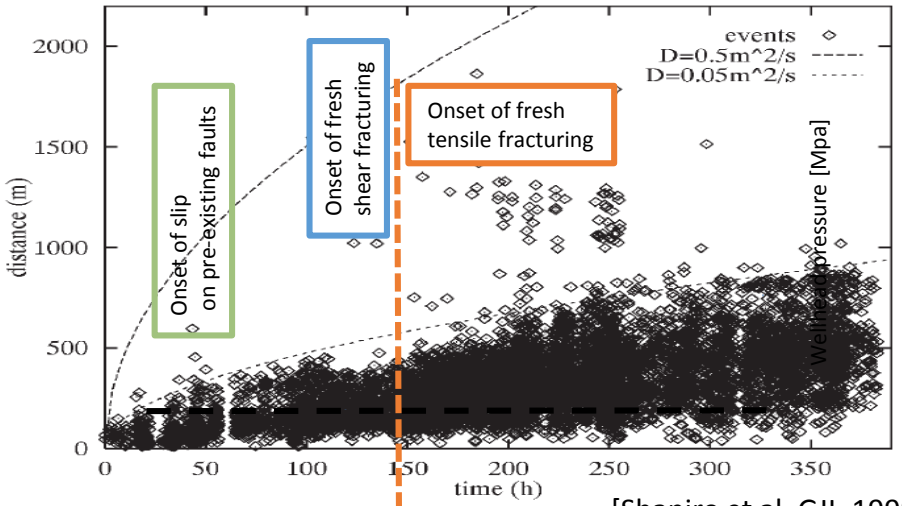
Fault F: depth *Z* = 2925 m; strike=138°; dip 86◦

[Cornet et al, 2007]

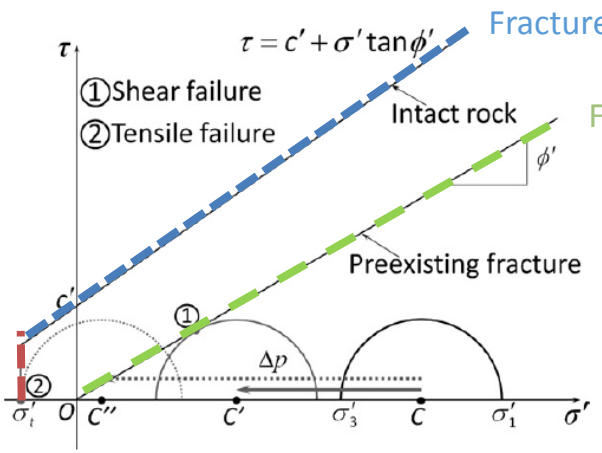


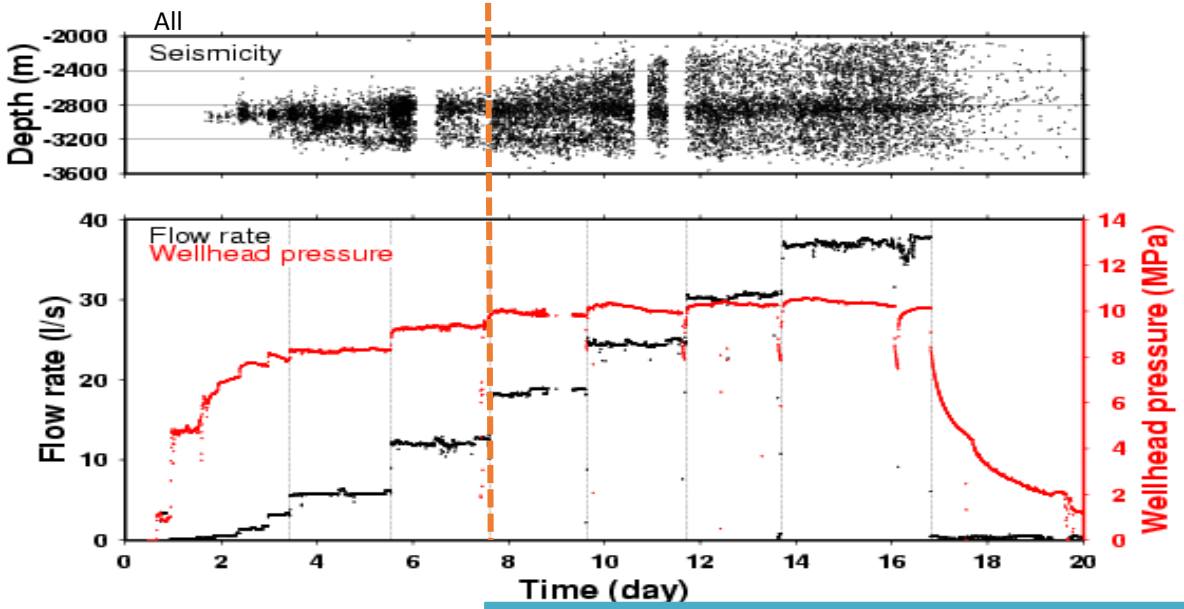
Depth interval (m)l	Mean azimuth	Mean dip (deg)	Number of events
2800–2900	N179°E	87	329
2900–3000	N165°E	67	402
3000–3200	N146°E	86	416

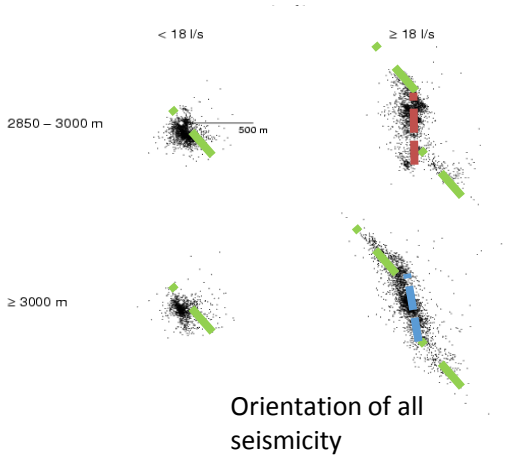
1993 GPK1 hydraulic stimulation at Soltz



[Shapiro et al, GJI, 1999]





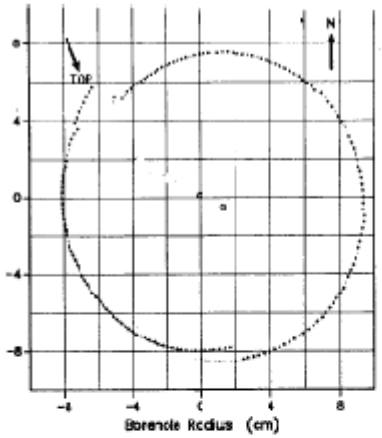


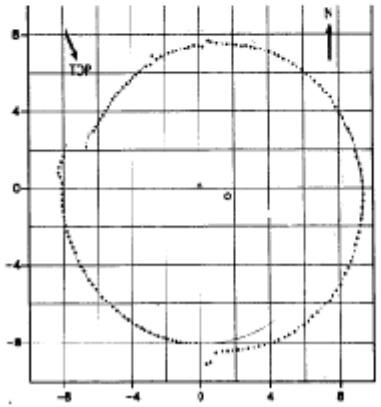
Orientation of all seismicity

[Cornet et al, 2007]

GPK1 stimulation: first direct evidence of aseismic slip

Cornet et al., 1997



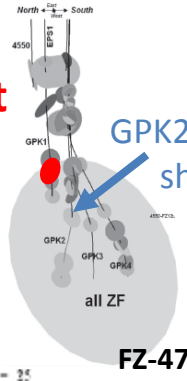


B) P = 15

F fault

GPK1

GPK2 casing shear

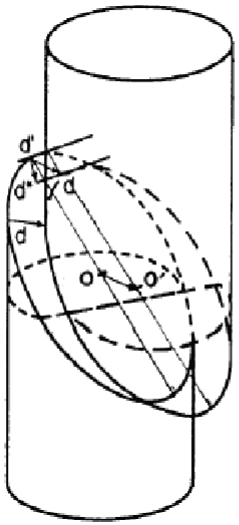


A) P = 25

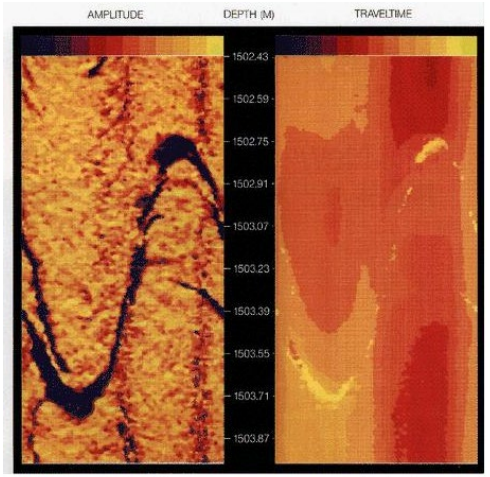
FZ-4770

GPK 1,2,3,(4)

Sausse et al, 2010



UBI



Existing fracture

Borehole geometry result from shear displacement along existing fracture (general case):

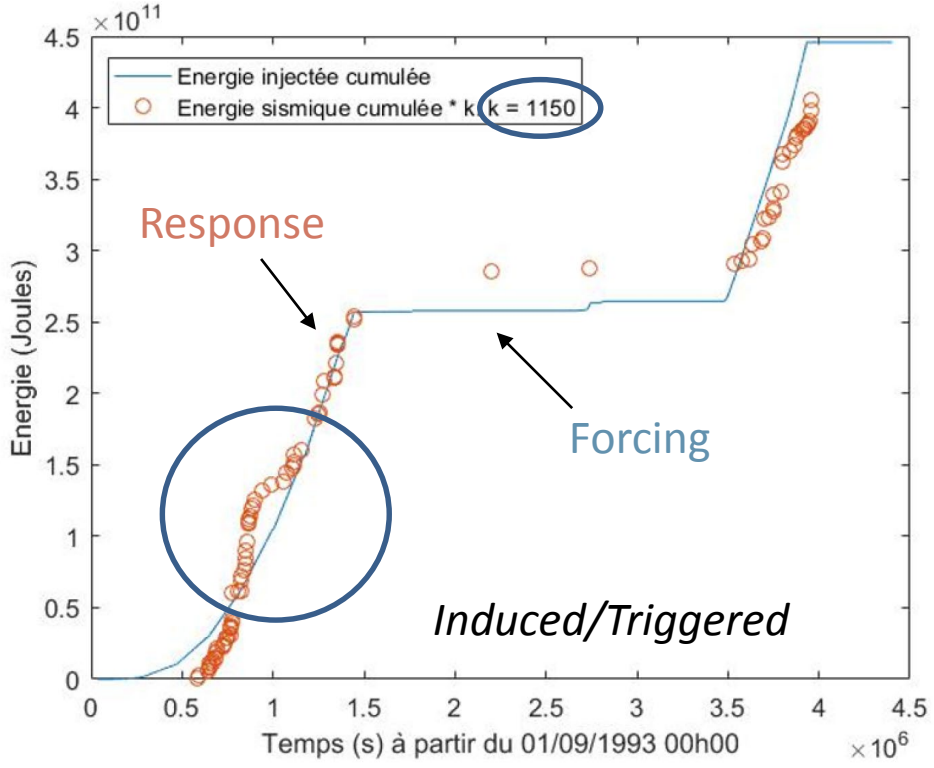
d = Displacement
d' = Strike component
d'' = Dip component

Z (m)	β	α	λ	A (cm)	ε_A	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

M~4.2 >> M~1.9 (observed)

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

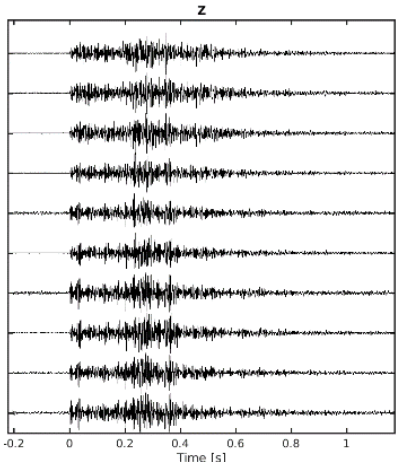
15000 recorded seismic events

Repeating earthquakes of the whole **1993 stimulation** (and not only on fault F)

[Cauchie et al, 2018]

Multiplets Activity

4500 seismic events clustered in **663 multiplets**



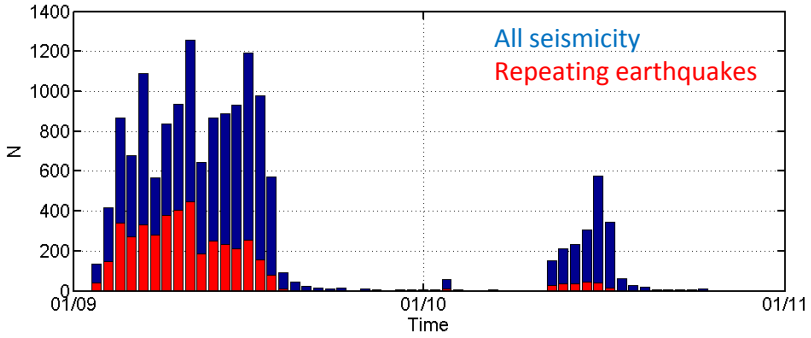
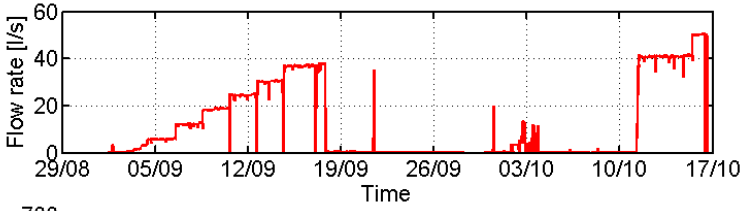
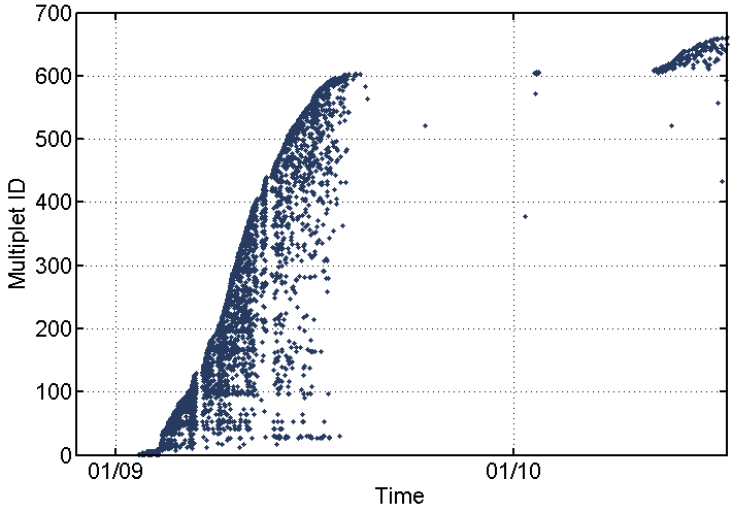


Fig.:Blue:daily number of events, Red: daily numbers of events belonging to multiplets





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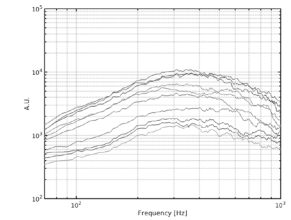
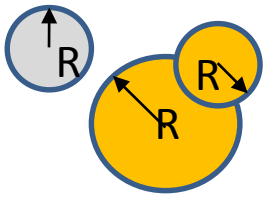
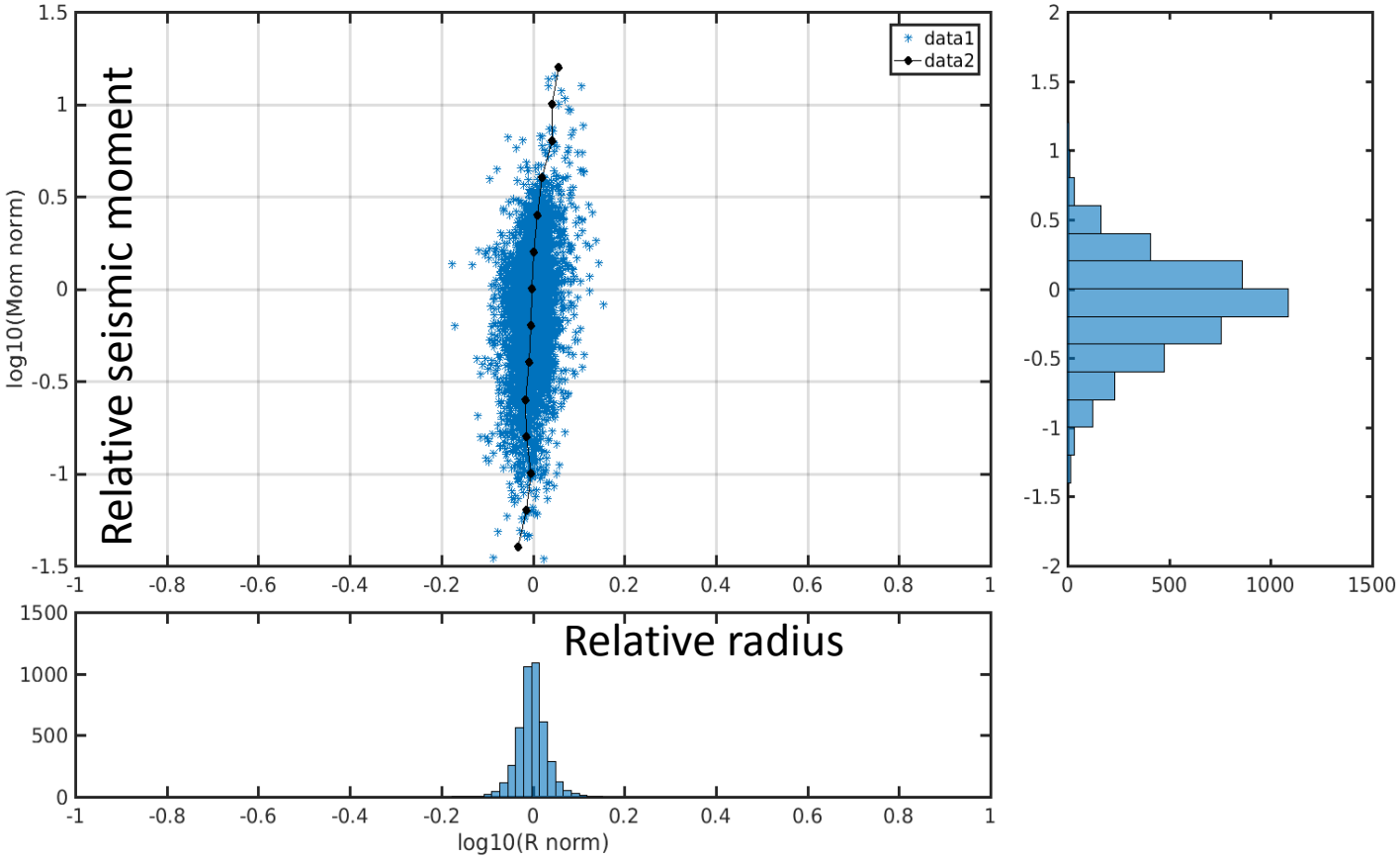
Moment / size relationship ?

Brune's models + Spectral Ratios method + P-S time

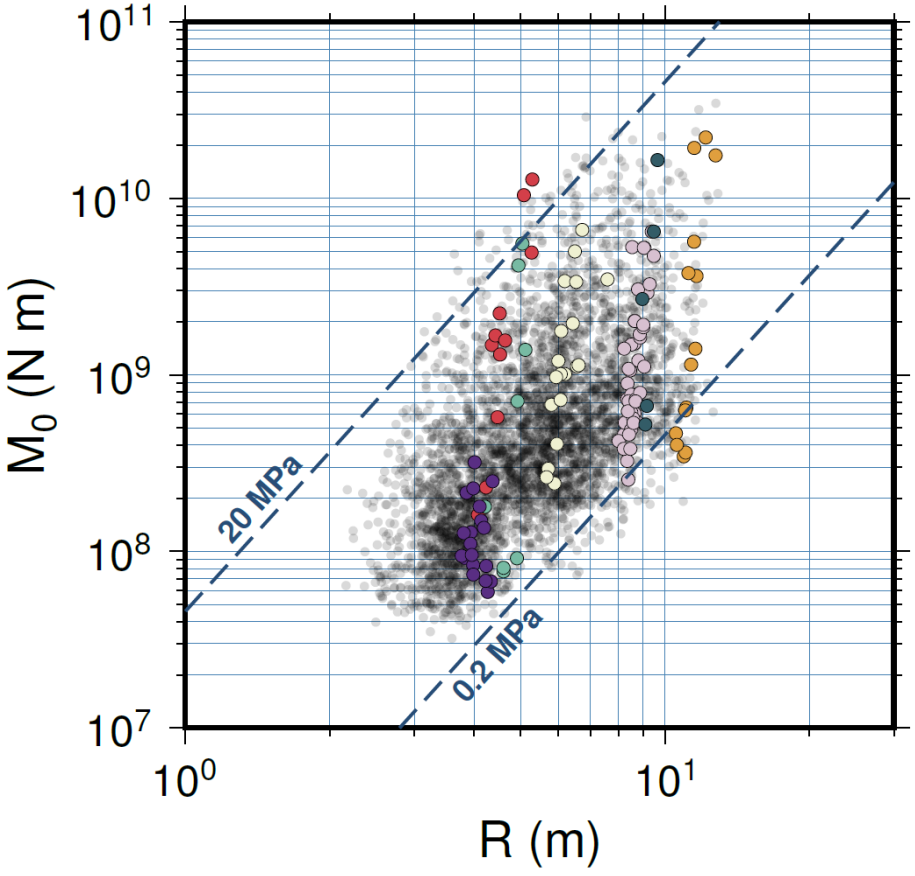
Multiplets/repeating events







Stress drop and multiplets

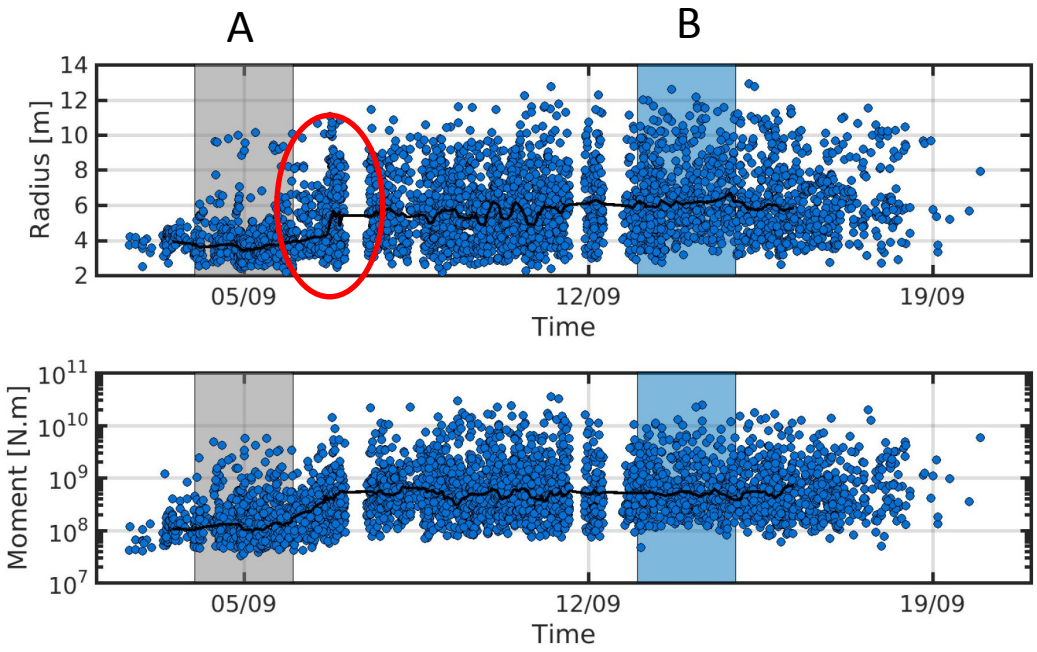


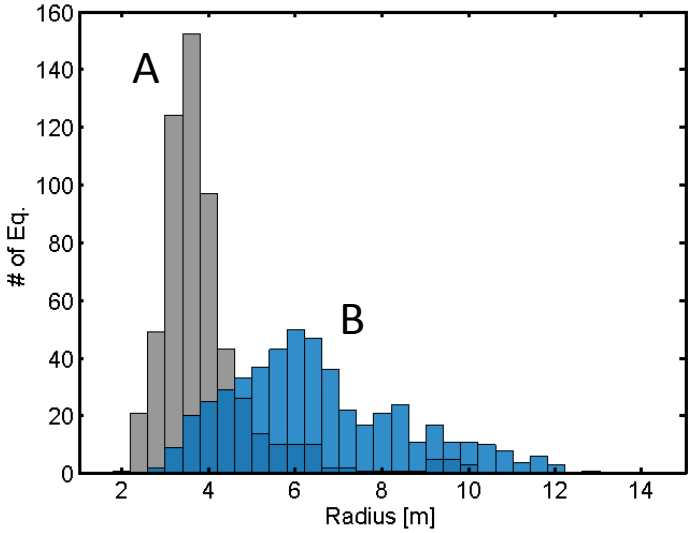
- Seismic moments as a function of source radii.
- The dashed lines represent constant stress drop values. The colored dots are attributed to individual sequences of repeating earthquakes.

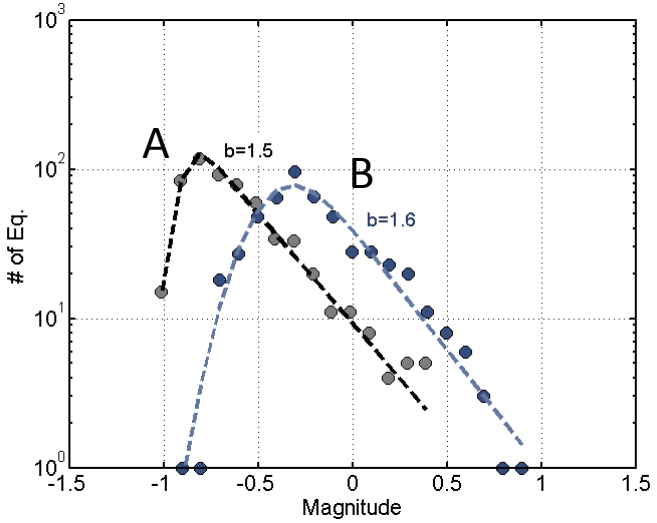
$$M_0 = \frac{16}{7}\Delta\sigma\, R^3$$

[Cauchie et al, 2018]

Two populations of events



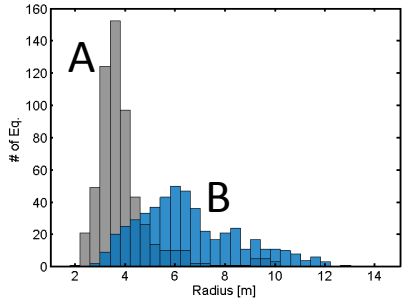




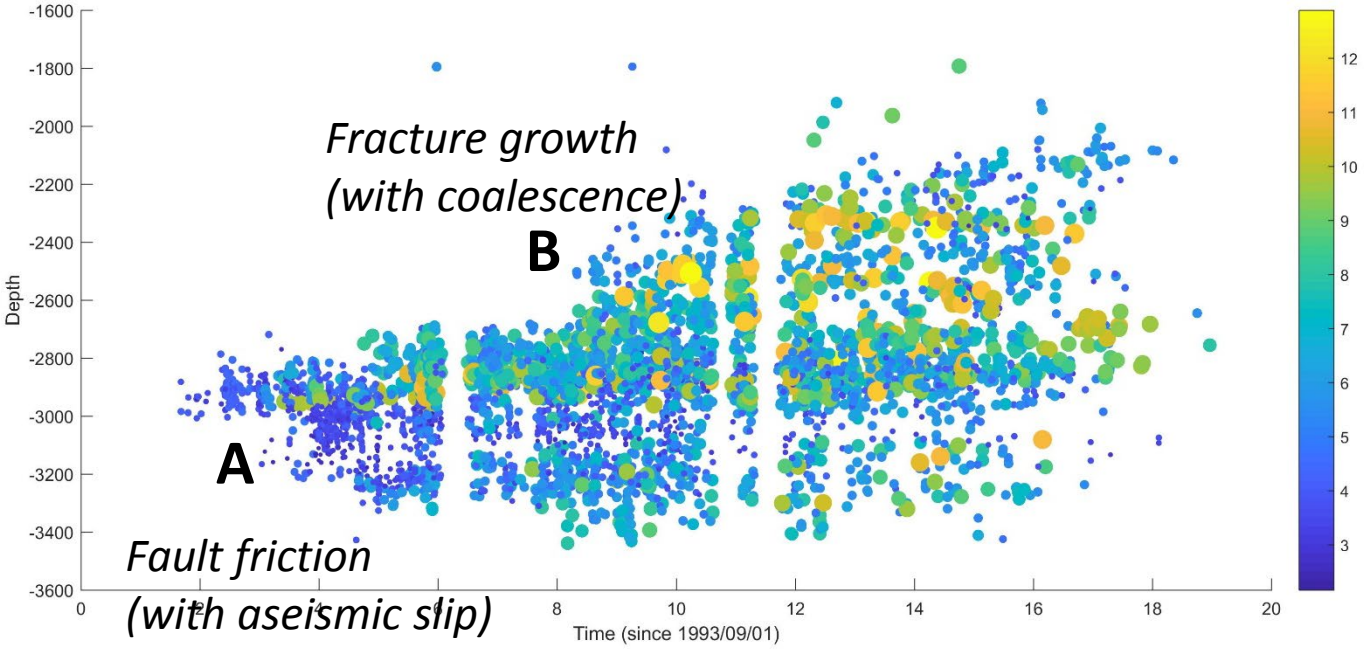
[Cauchie et al, 2018]

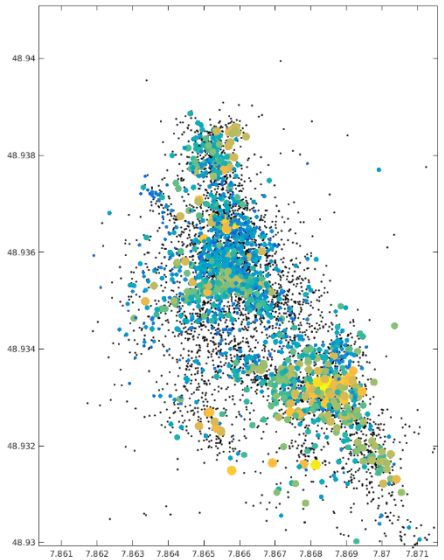
[Cauchie et al, 2019]

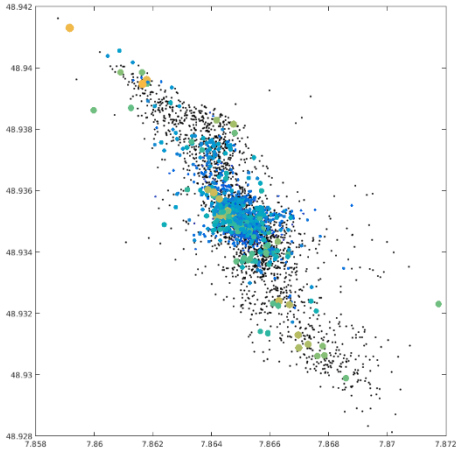
Asperity size changes



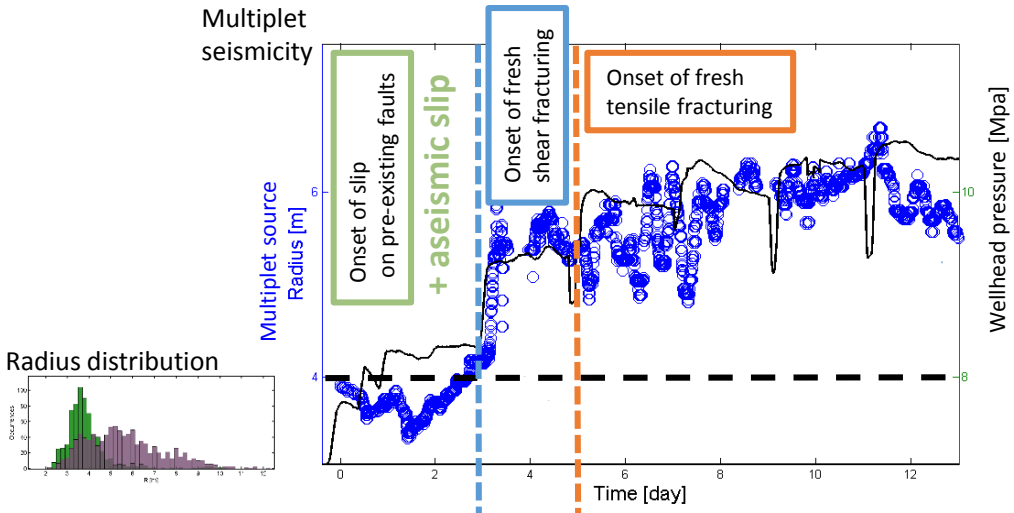
Radius (m)

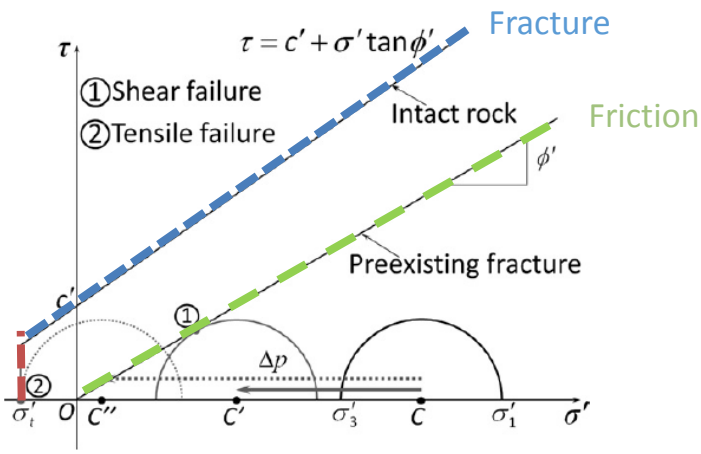


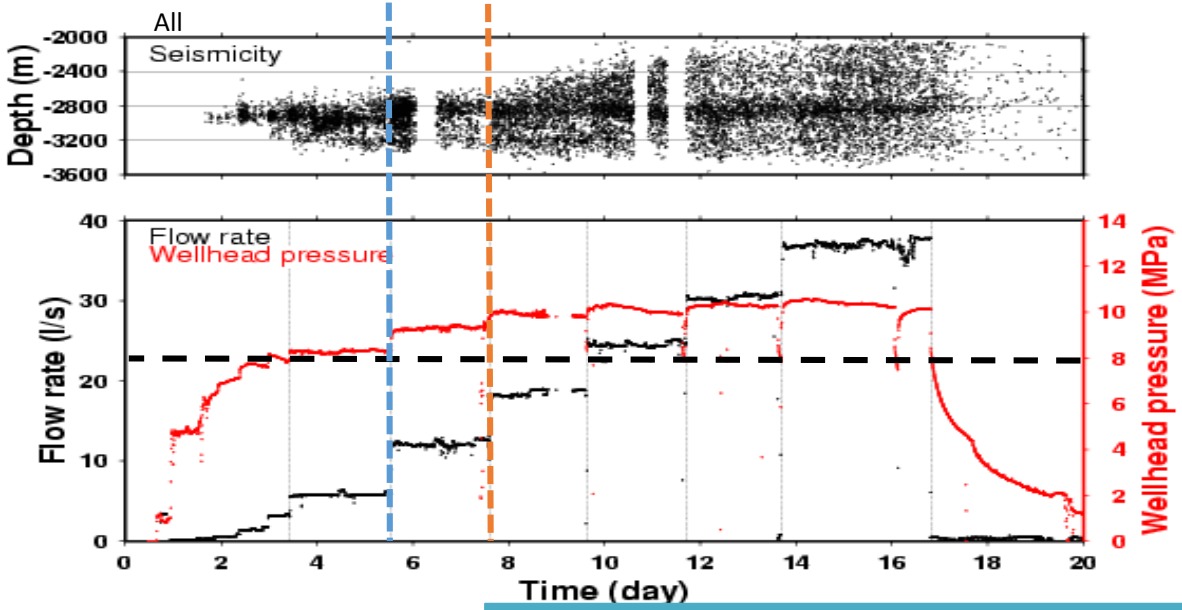


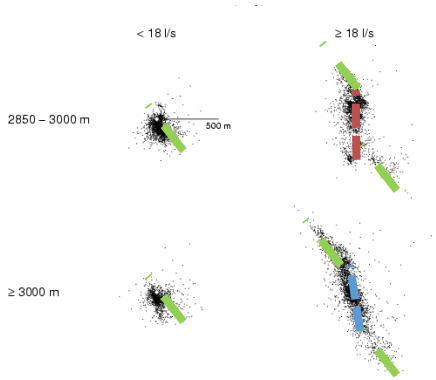


1993 GPK1 hydraulic stimulation at Soltz









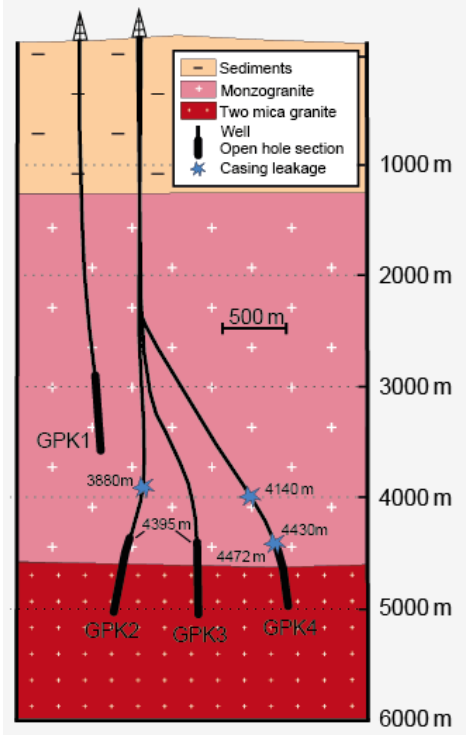
Orientation of all seismicity

Conclusions

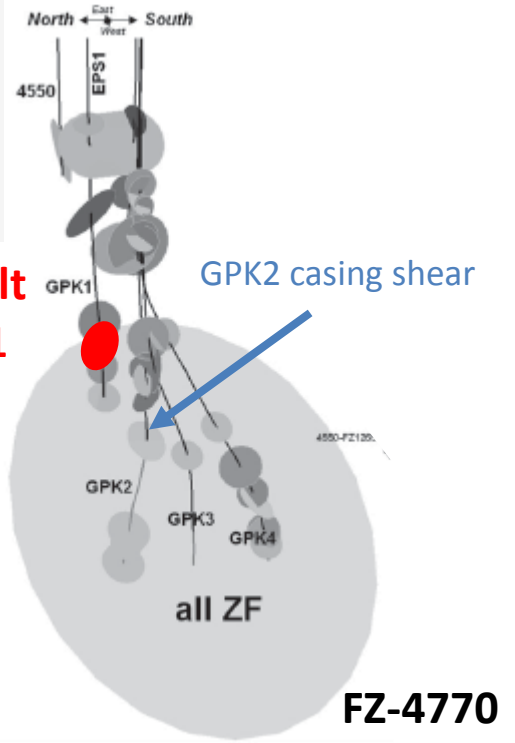
- Evidences of aseismic induced events
  - At Rittershoffen (4 days – Coulomb stress transfer from an aseismic event)
  - At Soultz: direct evidences (well) – indirect evidences from repeating seismic events (common rupture areas)

- From high resolution seismicity analysis
  - Decoupling between asperity radius and seismic moment
  - Strong stress drop variability along repeating sequences
  - two populations of repeating events /two processes
    - Fault friction along existing structures with aseismic slip
    - Large scale fracture development
  - Asperity radius monitoring: a new tool to detect induced seismicity changes

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



Held et al, 2013



F fault
GPK1

Cornet et al, 1997

GPK2 casing shear

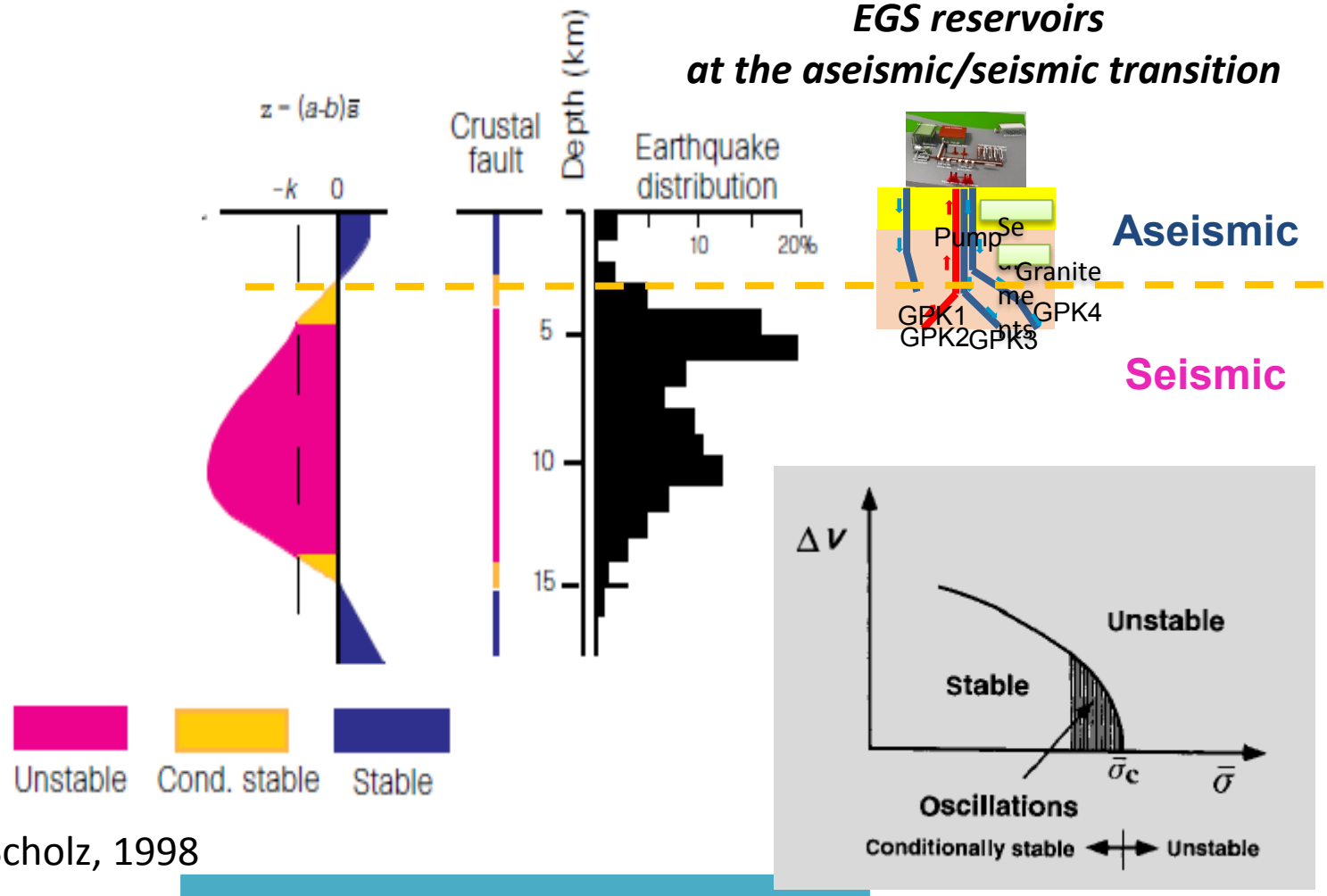
FZ-4770
GPK 1,2,3,(4)

Sausse et al, 2010

Lessons from Soultz:

- A complex pre-existing 3D network (granite)
- A major fault zone (most of the seismicity) GPK1 FZ- 3492; **GPK3 FZ-4770 N144°/71°**
- Shear and hydraulic fractures
- Evidenses of aseismic slip in **GPK1 F-2925 N138/86°**
- from GPK2 casing deformation along FZ-4770 (Jung et al, 2010)
- From casing deformation in GPK4

Seismic/aseismic behavior: the upper transition



Scholz, 1998