Seismic and aseismic motions generated by fluid percolation in rock masses

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1. A bit of history: induced versus triggered seismicity
2. Seismicity and water reservoirs: a problem of long-term hydromechanics
3. Seismicity and deep fluid injections (Shale Gas, Geothermal, CO^2 sequestration, etc…)
    - Hydraulic stimulations
    - Long term percolation effects

A bit of history: Induced versus triggered seismicity

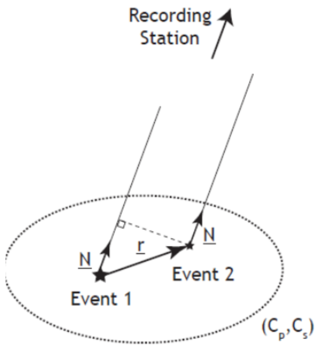
- The Hoover dam, Arizona (Garder, BSSA, 1945)
- The Denver earthquakes (Healy et al., Science, 1968)
- The Koyna dam (India) M6.4 earthquake (Gupta et al., 1969)
- The 2007 Basel M3.7 earthquakes (Deichmann and Giardini, 2009)
- The 2OO8 M7.9 Wenchuan earthquake (Lei, 2011) (hypocenter, 13 km deep)
- The 2011 Oklahoma city M5.6 earthquake (Holland, 2011)

What can be learned from the seismic signals ?

P and S waves Arrival times

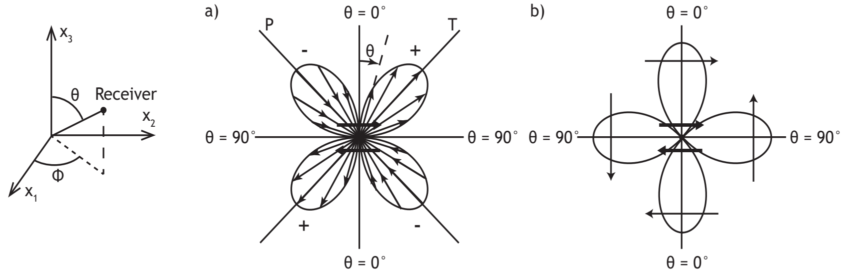
- When P and S wave velocities are known, first arrival times of P and S waves observed on at least four stations yield event locations.
- When many 3D stations are available, arrival times may be used to conduct seismic velocity tomography.
- When data are well distributed in time, repeated seismic tomographies provide means to detect variations with time of seismic velocity.

- Double difference technique for multiplets relocation helps better understand motion on asperities



Polarity diagrams; frequency spectrum

- Polarity diagrams yield source focal mechanisms
  - Double couple or complete seismic moment

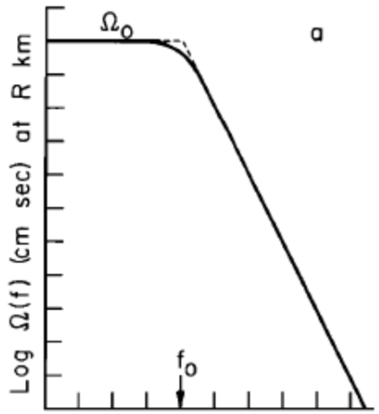


- Log-log plot of frequency spectrum of shear displacement yields source size and seismic moment $M_0=f(\Omega_0)=GDS$

G : shear modulus

$D = D(f_0)$: dislocation area

S : mean dislocation amplitude



Log of frequency

Seismicity and water reservoirs : A problem of fluid-solid interactions

Observations

- Short term and long term induced seismicity at Hoover dam (Simpson et al., 1988)

  Instantaneous elastic response to load versus delayed deep variations in pore pressure.

  How deep can induced seismicity get ?

- Variations in long term seismicity at Hoover dam (Roelloffs, 1988)

  high seismic activity initially associated with high water levels in dam gets progressively associated with low water levels in dam as time passes;

  Is there aseismic slip ?

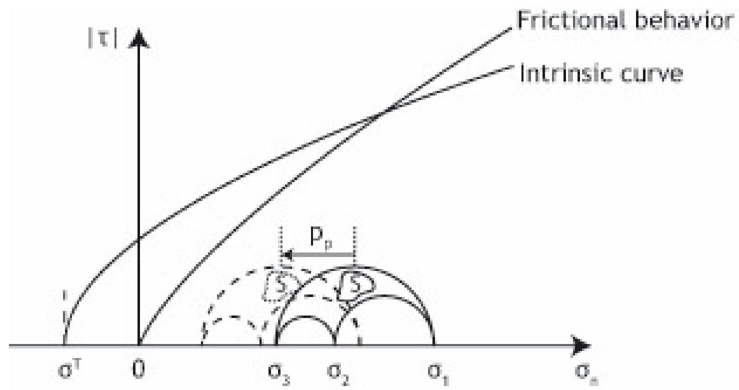
- The M 7.9 Wenchuan earthquake (Lei, 2011).

  An example of triggered seismicity and of critically loaded crust ?

  The problem of deep fluid migration and the coupling between shear motion and pore pressure variation.

Failure mechanisms and rheology

- Classical theory: Seismicity occurs when pore pressure increases (effective stress concept+ Mohr-Coulomb)



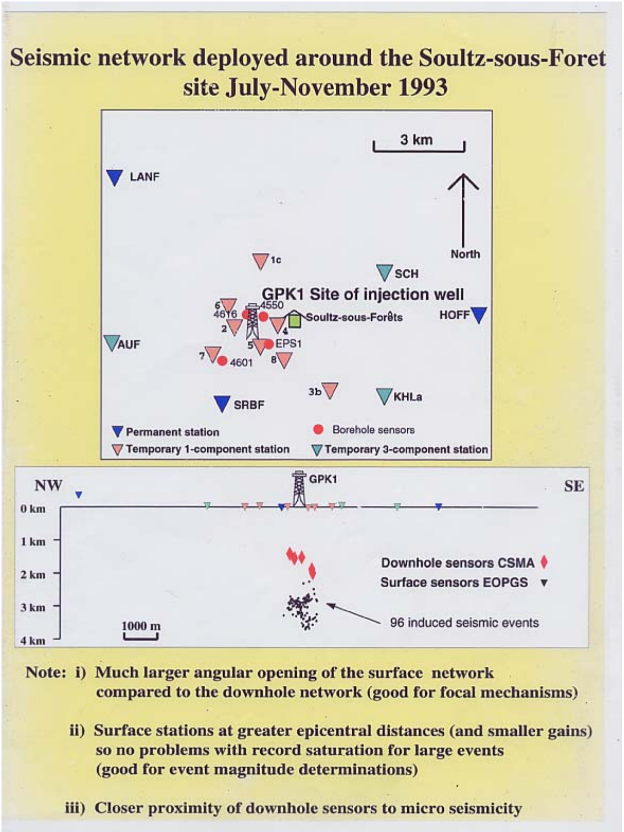
- Seismicity occurs when pore pressure decreases because of stress redistribution associated with mass balance (Segall, 1989)
- Role of rheology and of failure criteria, for geomaterials and for faults, for the identification of "critical loading conditions".

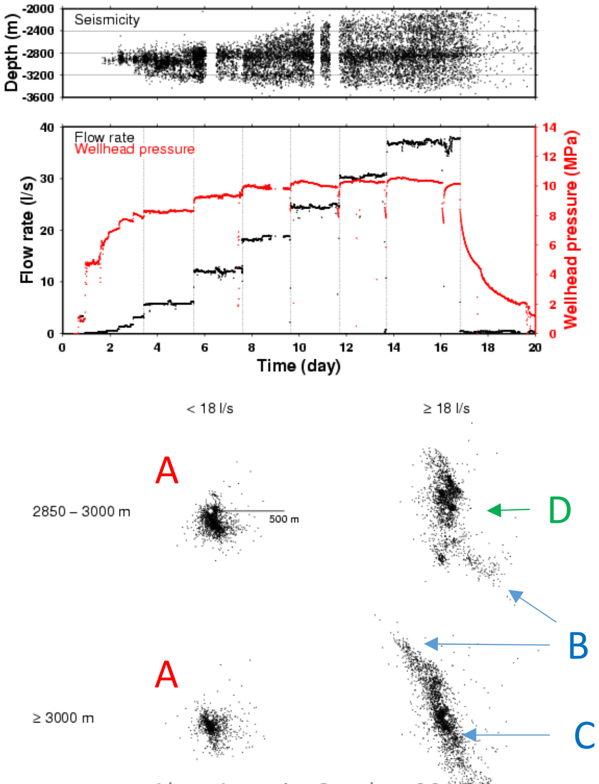
Fluid induced versus fluid triggered seismicity

- Fluid induced seismicity :
  The seismicity appears after some local conditions have been perturbed;
  The seismicity stops when the perturbation stops (Denver earthquakes).
- Fluid triggered seismicity :
  Seismicity starts because of some perturbation;
  Returning to initial conditions would not stop observed seismicity.
- Changing pore pressure in a critically(?) loaded crust
  What rheology for geomaterials ?
  What Hydromechanical behavior for fractures and faults ?
  What failure criteria for geomaterials , for fractures and and for faults?
  What far-field loading conditions for solids and for liquids?
  What makes slip seismic or aseismic ?

The four hydromechanical coupling levels observed during forced fluid injections

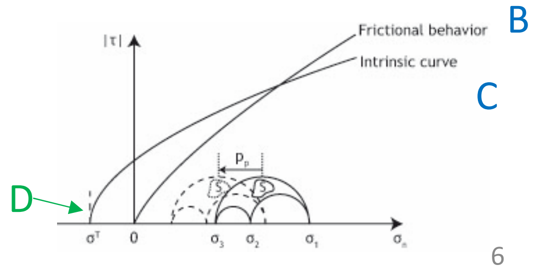
The 1993 stimulation for the Soultz Geothermal EGS project





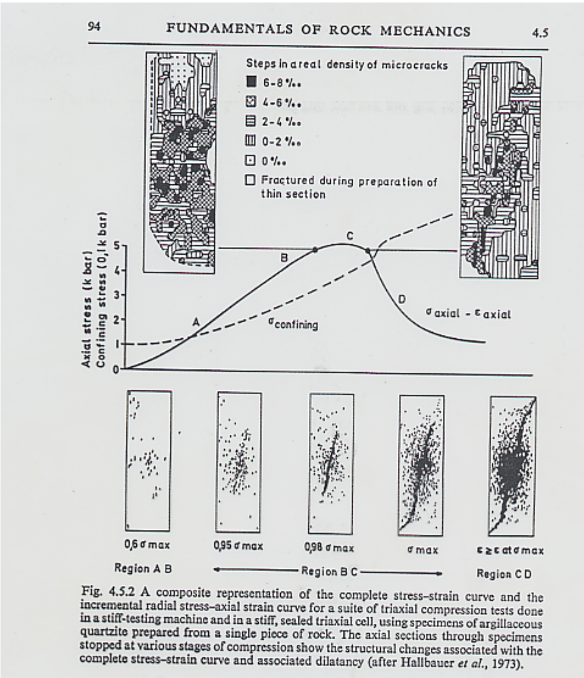
Modeling

- A : Poroelasticity
- B : slip on preexisting fractures
- C : Development of a fresh shear zone
- D : Hydraulic fracturing

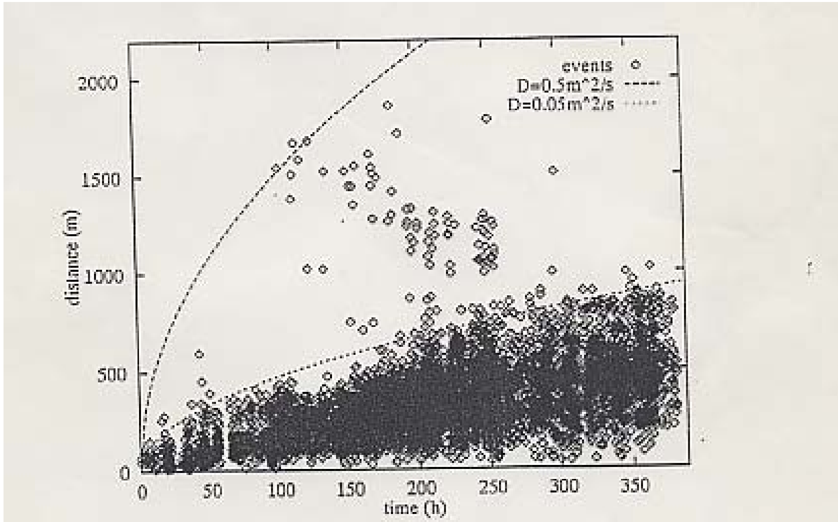


The level A of hydromechanical coupling :
Kaiser effect and Poroelasticity

Laboratory observations



Field observations (Shapiro et al., 1999)

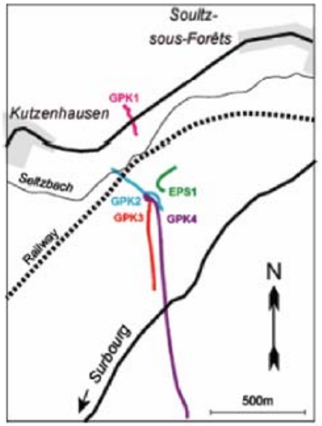


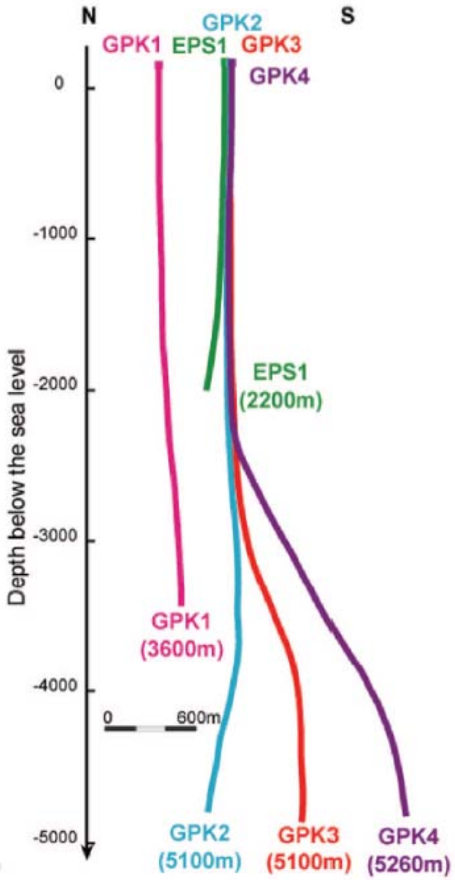
Modeling : fluid diffusion according to Darcy Law; Point source : $R = \sqrt{4\pi\, Dt}$; D= rock mass diffusivity; R= distance of furthest away events at time t; $\sigma_3' = (P_c - P_0)$;

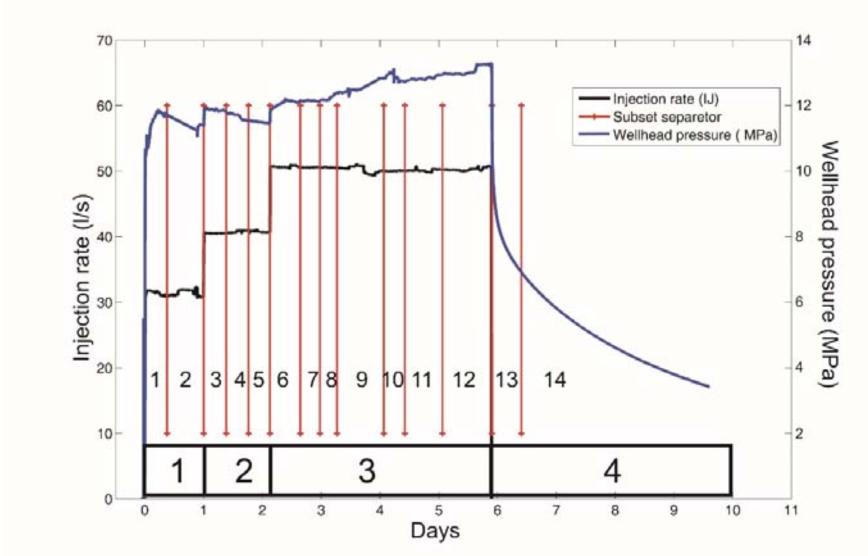
as t increases, $(\sigma_a' - \sigma_3')/\sigma_3'$ increases;

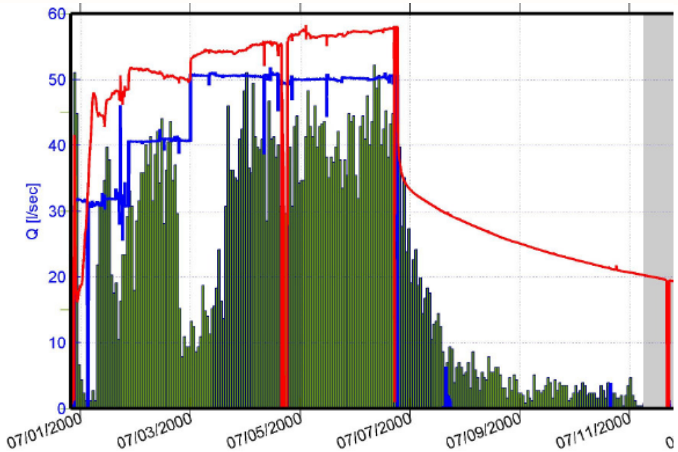
Induced seismicity = Kaiser effect. Poroelasticity prevails, loading-unloading is sub-reversible.

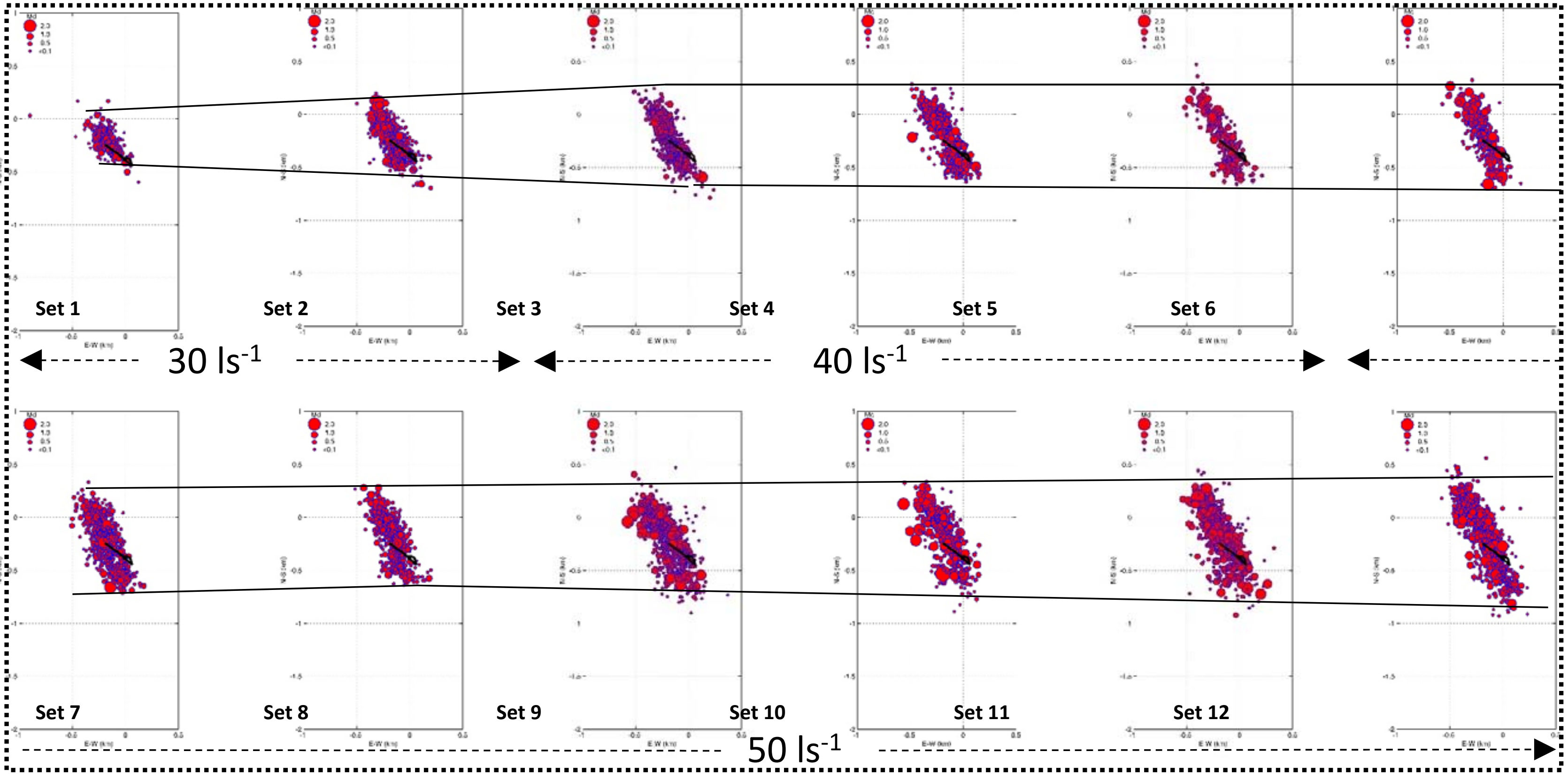
The levels B and C of hydro-mechanical coupling:
Slip on preexisting or on fresh fractures (The 2000 Soultz hydro-stimulation)

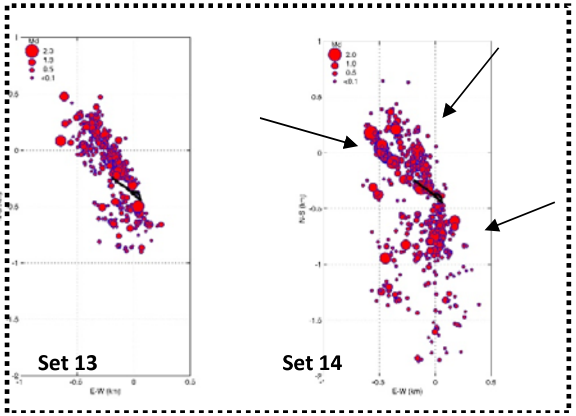












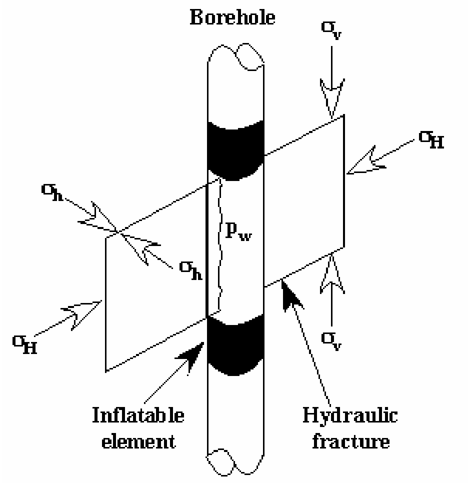
Seismicity re-located with the 3D velocity models derived from tomography.

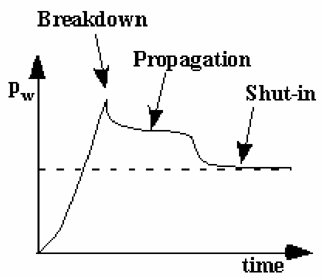
No pre-existing structure observed during the stimulation (sets 1-12). But the post-injection seismicity (sets 13 and 14) reveals pre-existing structures .

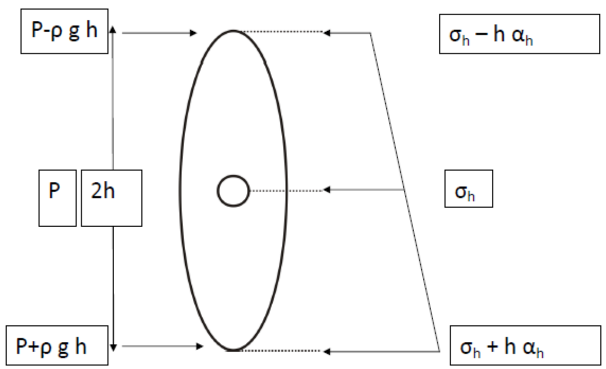
Calò et al., JGI, 2011

The level D of hydromechanical coupling : hydraulic fracturing

Fracture initiation and fracture propagation







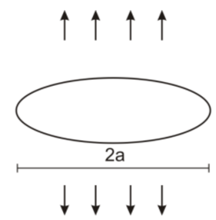
Stability of the fracturing process

1. Uniform pressure up to crack tip:

K_I proportional to $(\sigma 3\text{-}P)(2\pi\ a)^{½}$;

K_I increases with crack length,

fracture is unstable if pressure remains constant. Hydraulic fracturing with gas is unstable

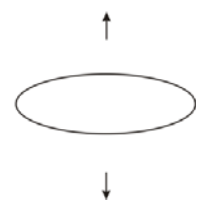


2. No fluid penetration:

Pressure is applied only within the borehole without penetration in the fracture (line load)

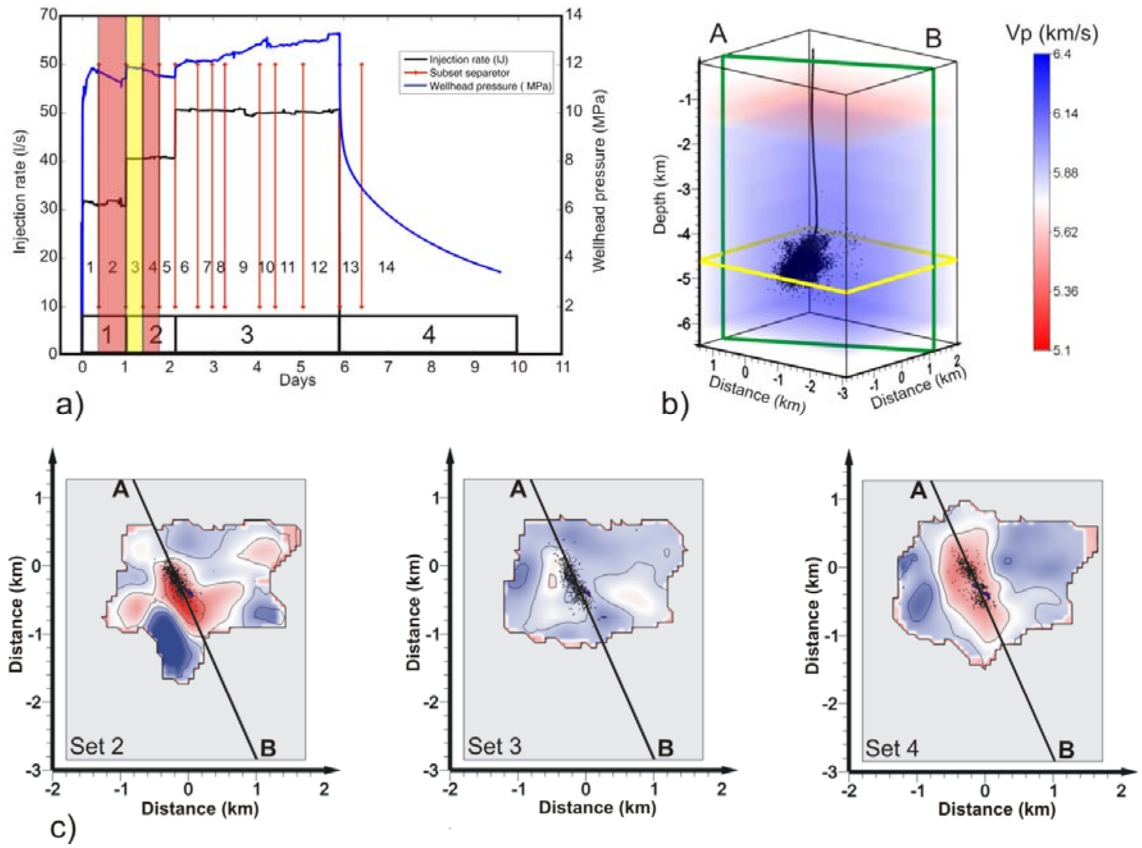
KI proportional to $(1/a)^{½}$

KI decreases as fracture extends and load must be increased for propagating the fracture. Hydraulic fracturing with a liquid is a quasistatic process

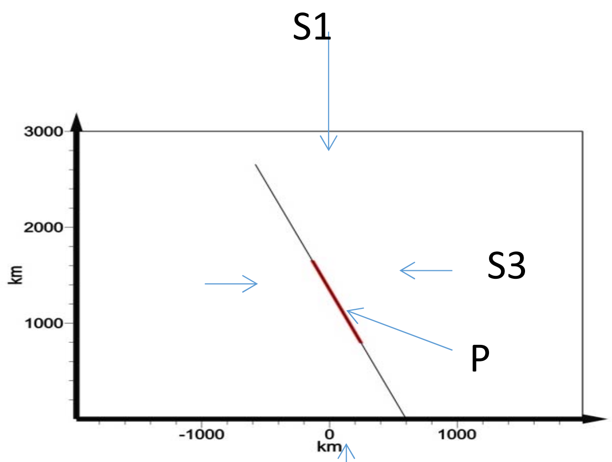


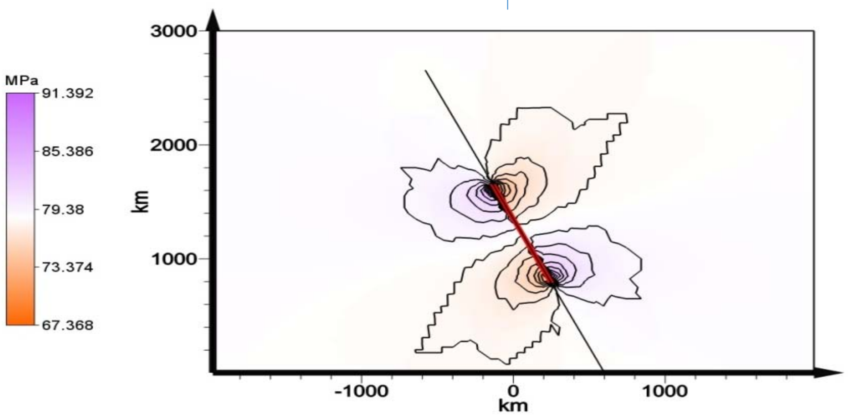
The GPK2 stimulation – Soultz,2 000 (Calò et al., JGI, 2011) :

Repeated P wave velocity tomography outlines a very rapid change in velocity at the km scale

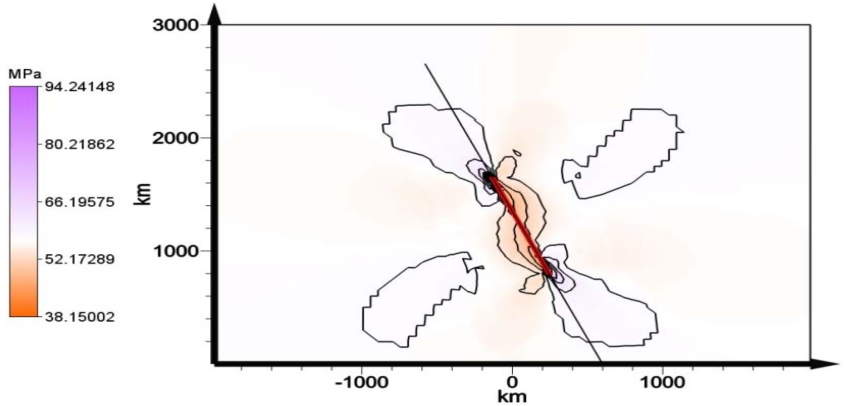


On the effect of shear relaxation on local stress field





(S1+S2+S3)/3

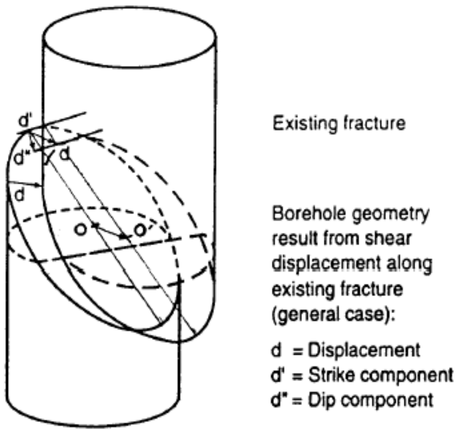


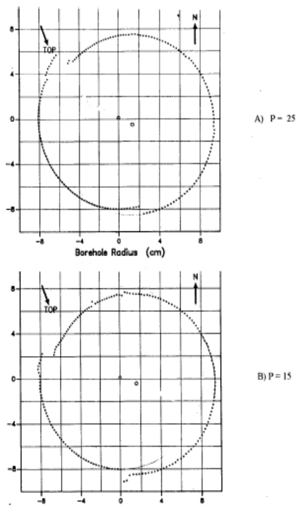
(S1-S3)

- The variation in P wave velocity may be interpreted either as a change in effective spherical stress component [(S1+S2+S3-3dP)/3] or as a change in relative maximum differential stress [(S1-S3)/(S3-dP)] (from boundary elements modeling, Crouch and Starfield, 1976; Cornet, 1979).
- Result suggests that the change in V_P velocity is caused by aseismic slip along the fresh shear zone, but what is the physics for observed velocity variation ?
- This is confirmed by identification of stress variations as determined with focal mechanisms inversions (Schoenball et al. 2014).
- Consequence for "seismic pumping".

Direct evidence of aseismic slip after the 1993 GPK1 stimulation at Soultz

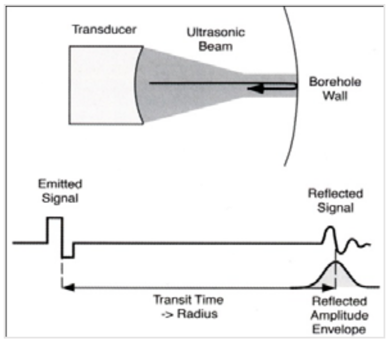
(Cornet et al., Pageoph, 1997)



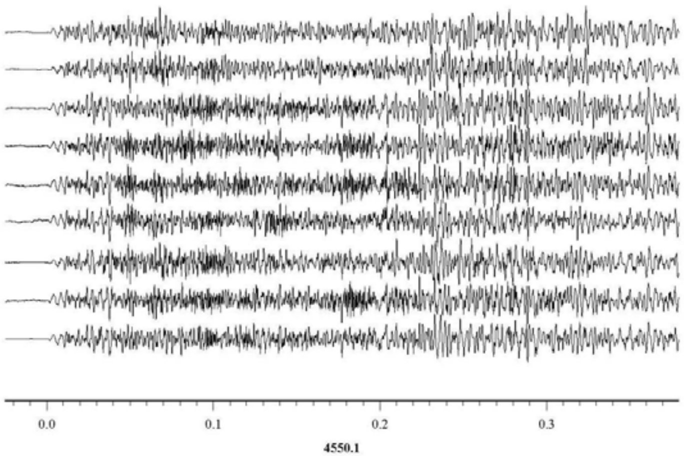


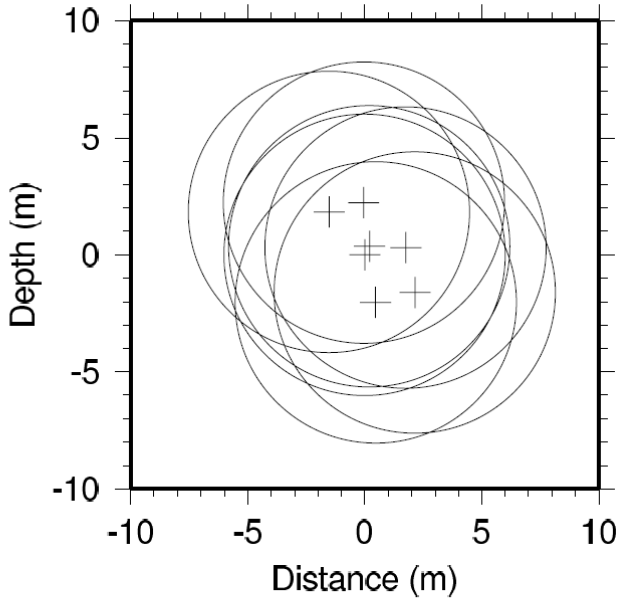
Amplitude of aseismic slip : Z is depth and A is slip module

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



Analysis of microseismic "multiplets" associated with these aseismic shear motions (Bourouis & Bernard, GJI, 2006)





Brune's model (Brune, JGR,1970) is used to evaluate stress drop, slip magnitude, sources dimensions (around 5 m)

Comparison between seismic and aseismic motion for one of the faults , from multiplets analysis, Soultz, 1993 experiment, Bourouis and Bernard, GJI, 2006

The displacement measured at point A, at the end of the injection, is 4.3 cm.

Rate of growth of zone of aseismic slip estimated at 8m/h between day 4 and day 6.

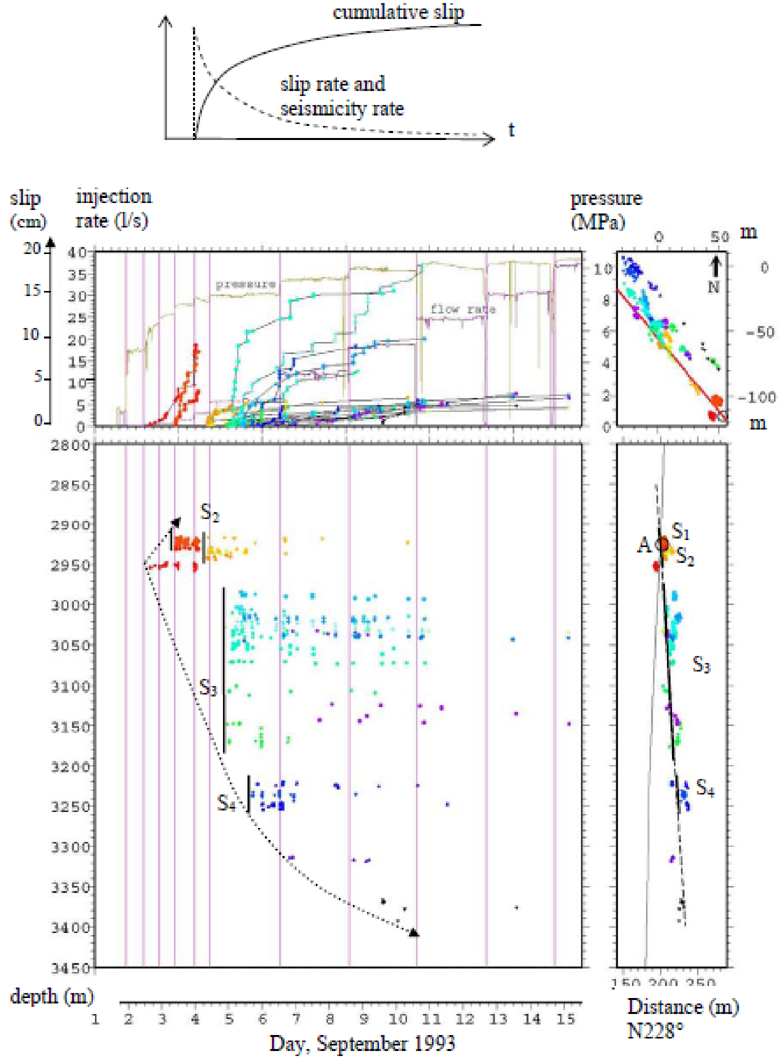
An important missing parameter is the fluid pressure magnitude at the location of each asperity.

Displacements on the various asperities are not uniform. Are the differences significant ?

How significant is the non seismic motion between asperities ?

Is it meaningful to evaluate elastic stress redistribution associated with each asperity slip?

How do we simulate the role of heterogeneity ?



Inversion of focal mechanisms for stress field estimates

(Gephart and Forsyth, 1984; Maury et al., 2013)

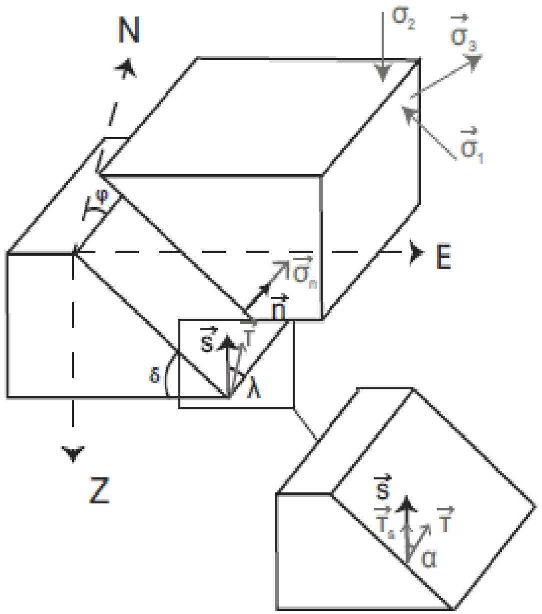


FIG. 1. – Diagram of a fault showing the variables used in the paper. The parameters defining the fault are in black whilst the parameters linked to the stress field are in grey. The angles defining the fault plane of normal $\vec{n}$ are φ the strike of the fault, δ the dip. λ is the rake, which defines the slip $\vec{s}$. The local coordinates system R' is defined by $(\vec{n}, \vec{s} \wedge \vec{n}, \vec{s})$. The principal stresses $(\vec{\sigma}_1, \vec{\sigma}_2, \vec{\sigma}_3)$ define the stress tensor $\underline{T}$. $\vec{\tau}$ is the projection of the stress vector on the fault plane and $\vec{\sigma}_n$ the normal stress. The SSSC, $\vec{\tau}_n$ is the projection of the shear stress onto the slip vector.

- **Principle :** the shear stress **τ** is parallel to the shear displacement **S**:

$$\mathbf{S}.\frac{\tau}{|\tau|} = 1$$

- The six independent components of stress tensor ***σ*** are reduced to the four components of ***T***:

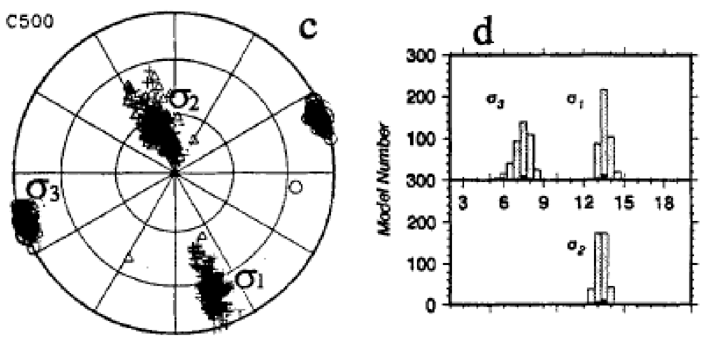
$$\boldsymbol{\sigma} = \sigma_1 \boldsymbol{I} + (\sigma_3 - \sigma_1)\boldsymbol{T}$$

where the principal directions of ***T*** are the same as those of ***σ*** whilst the principal values of ***T*** are respectively, 0, R, and 1, with

$$R = \frac{(\sigma_2 - \sigma_1)}{(\sigma_3 - \sigma_1)}$$

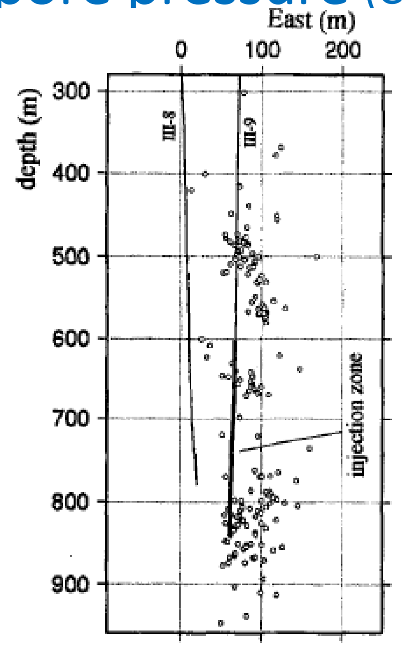
When the method is applied to data from induced seismicity, many events are found not to be consistent with a unique solution : existence of local stress heterogeneities

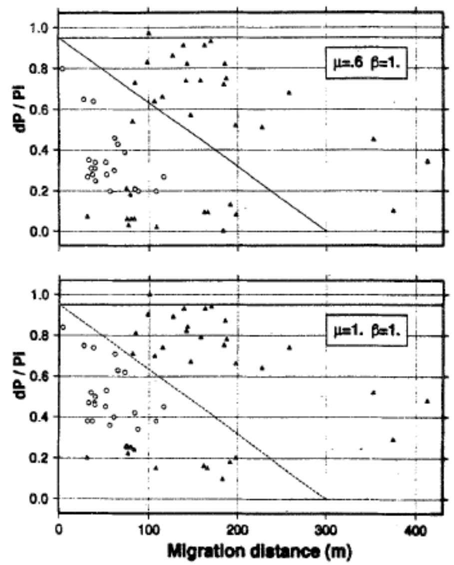
Combining focal mechanisms with results from hydraulic tests yields complete stress tensor and pore pressure (Cornet and Yin, 1995)



The solution (95% confidence interval) satisfies 75 % of focal mechanisms and 90 % of results from hydraulic tests.

Stress heterogeneity remains localized. The concept of critical loading does not apply to the whole rock mass.



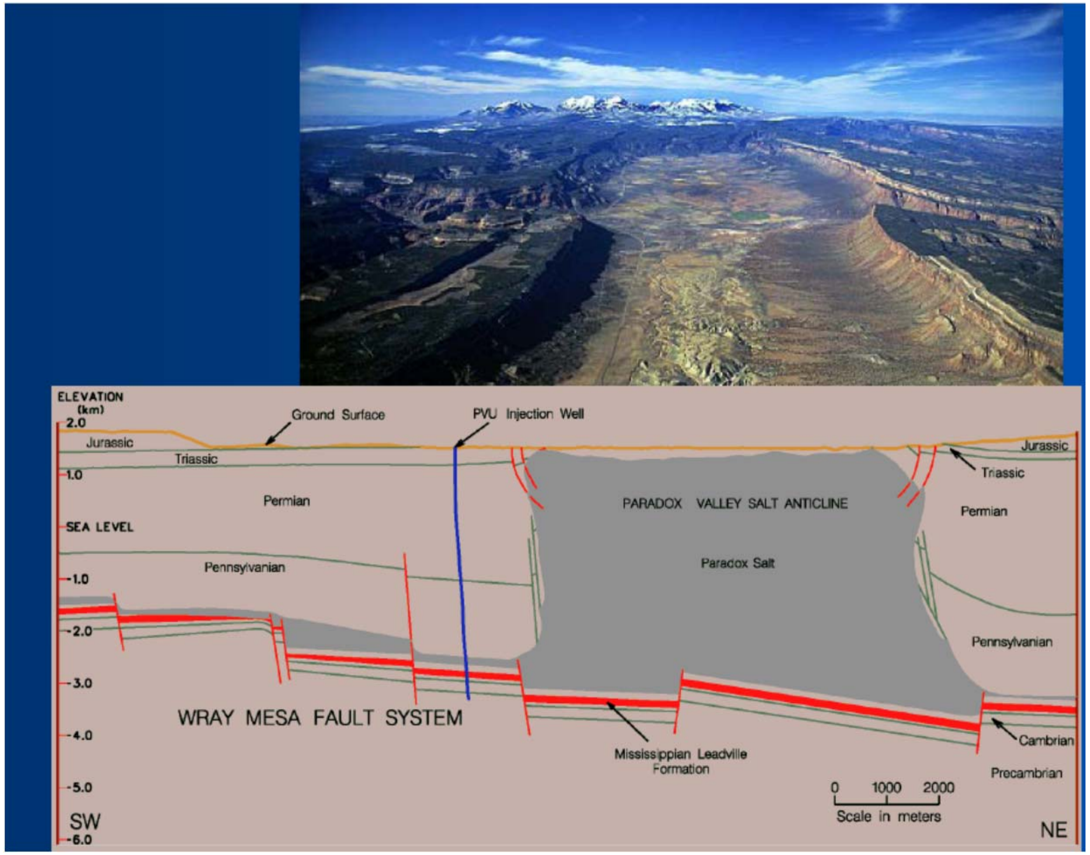


For some events far from the injection well, pore pressure is close to injection pressure : they correspond to zones with very little flow

$\tau = \mu\,[\sigma_n - \beta(P_i - dp)]$

Induced seismicity does not bring information on flow rate

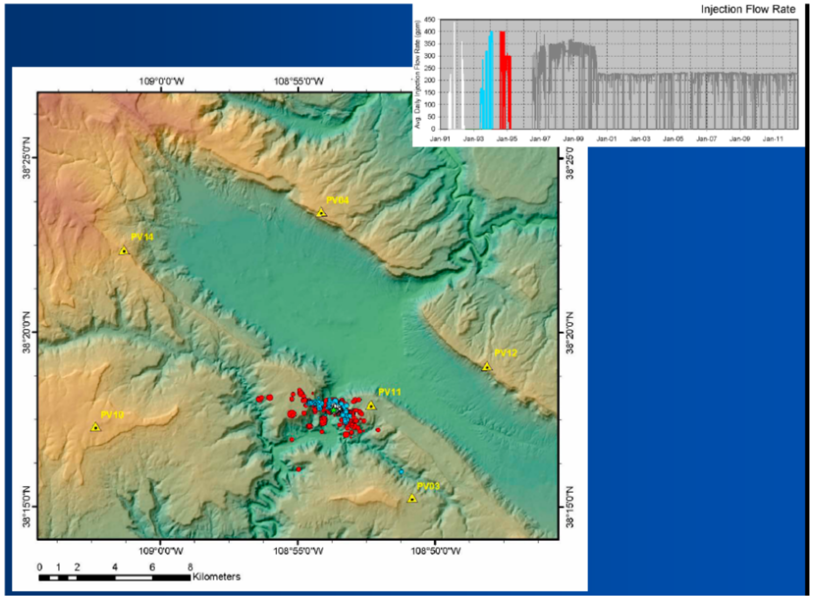
Growth of the seismic cloud during long term injections: The Paradox Valley project (Colorado, USA); L. Block, 2012



Injection:

- Began in 1991
- Depth range: 14,100 to 15,800 ft (4.3 to 4.8 km)
- Initial injection rate: 345 gpm (~1300 l/min)
- Current injection rate: 230 gpm (~870 l/min)
- Maximum surface injection pressure: 5,100 psi (March, 2012)
- Volume injected to date: 1.92 billion gallons (7.25 billion liters)

- 6 years of pre-injection seismicity: 1 earthquake
- 21 years of induced seismicity: >5,800 earthquakes
- Magnitudes: ~M -0.5 to M 4.3
- Distance from injection well: 0 – 16 km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38°25'0"N
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PV04
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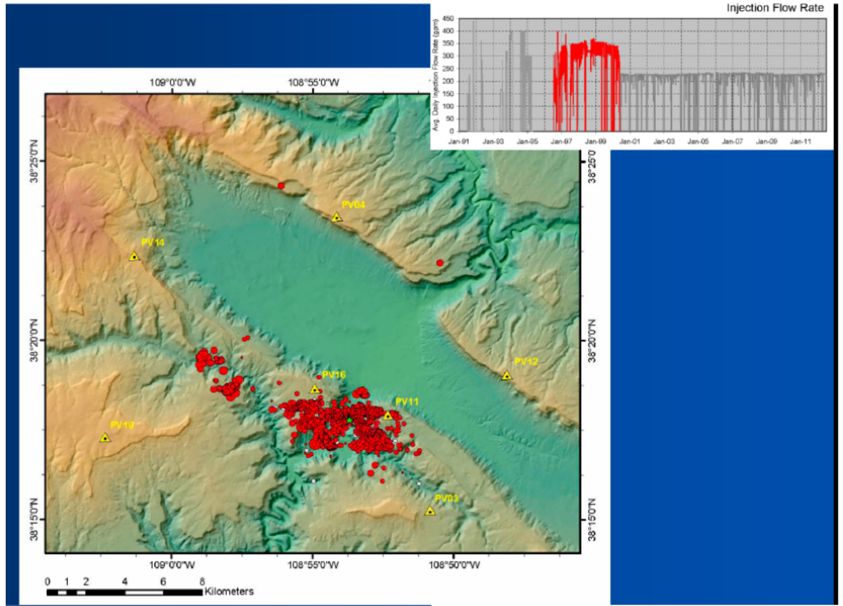
PV11
PV19
PV03
0 1 2 4 6 8
Kilometers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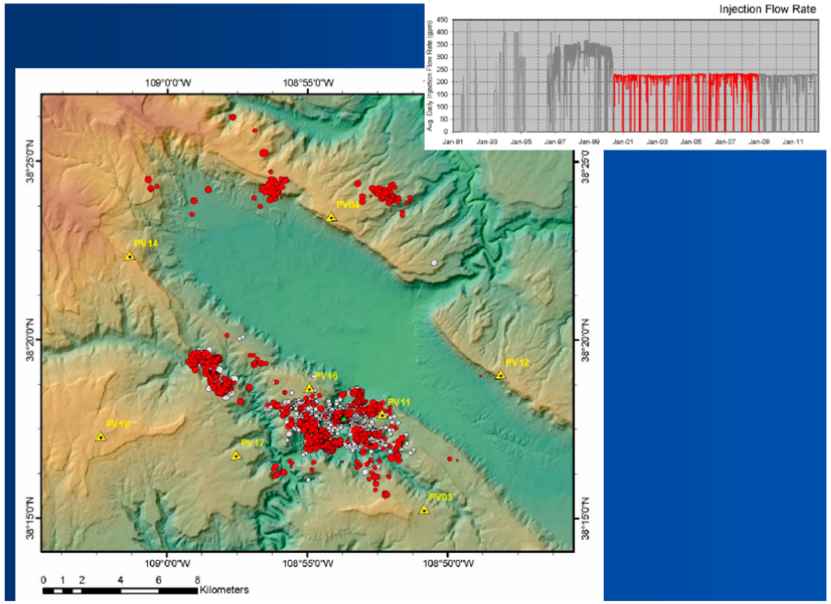
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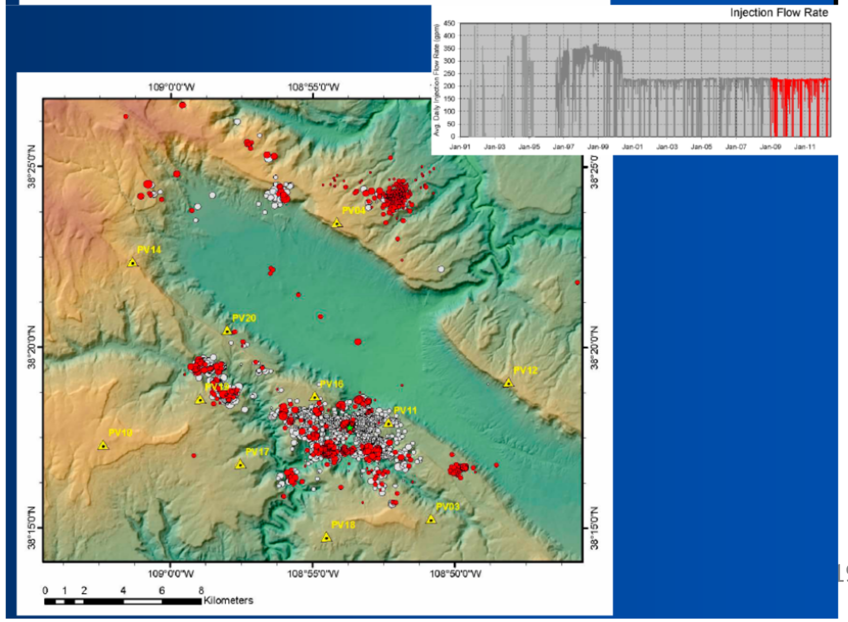
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PV14
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PV18
0 1 2 4 6 8
Kilometers

Summary and conclusions

- Seismicity and water reservoirs; the concepts of induced versus triggered seismicity
    - Hydromechanical coupling, critical loading conditions, rheology, failure criteria
- Four levels of hydromechanical coupling associated with forced fluid injections;
    - Kaiser effect, B and C levels of Shear Coupling, Hydraulic Fracturing
- Seismic-aseismic motion: identification and modelling
    - Rate and state friction laws, plastic yield criteria, pressure solution, time dependency, …
- Mitigating effects of induced seismicity
    - Monitor aseismic slip and adjust injection rate
- Necessity to know the regional stress field and its regional gradients for understanding the development of induced and triggered seismicity.
    - Concept of seismic pumping