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Agence de l'Environnement et de la Maîtrise de l'Énergie

Ecole et Observatoire des Sciences de la Terre

Enhanced Geothermal Innovative Network for Europe

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Microseismicity & Stimulation the case of Soultz-sous-Forêts

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Outlines

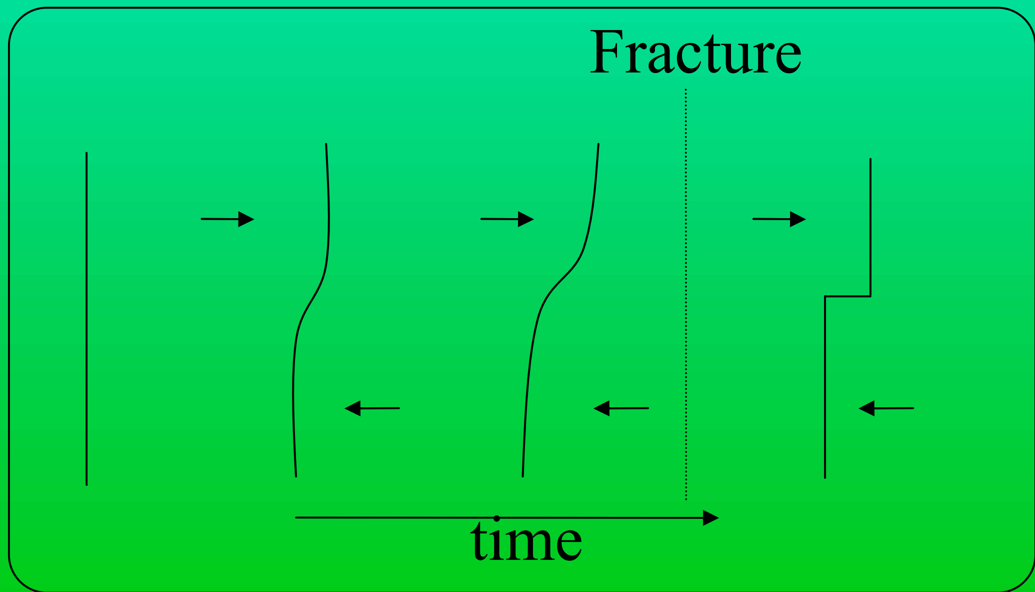
- Seismology: Theory and principles
- The induced seismicity during stimulation period

Seismology: theory and principles

Definition

An earthquake is the relative motion of two blocks, which is caused by the tangential traction that overcomes the frictional forces.

When slip occurs, the strain energy at that position is released, and the stress propagates to the near environment



Seismology: theory and principles

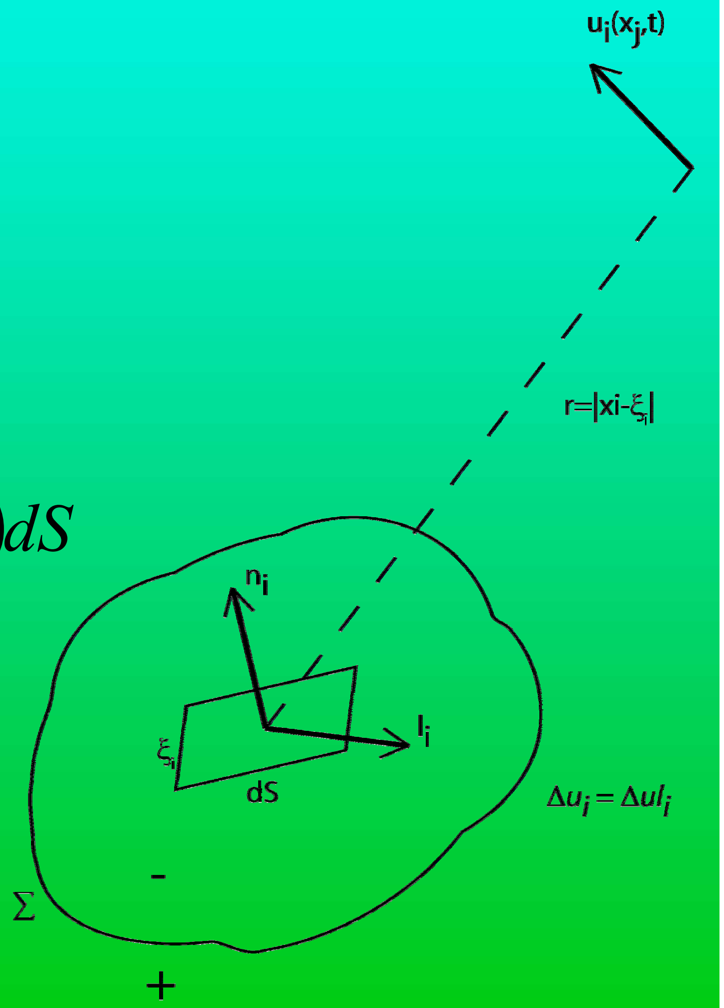
From the equation of motion and considering that there are no body forces, the displacement for a shear dislocation can be written:

displacement discontinuity

$$u_i^p(\xi_k,t) - u_i^n(\xi_k,t) = \Delta u_i(\xi_k,t)$$

displacement observed at the point **x**

$$u_n(x_s,t) = \int_{-\infty}^{\infty} d\tau \int_{\Sigma} \Delta u_i(\xi_s,\tau) C_{ijkl} n_j(\xi_s) G_{nk,l}(\xi_s,\tau;x_s,t)\, dS$$



Seismology: theory and principles

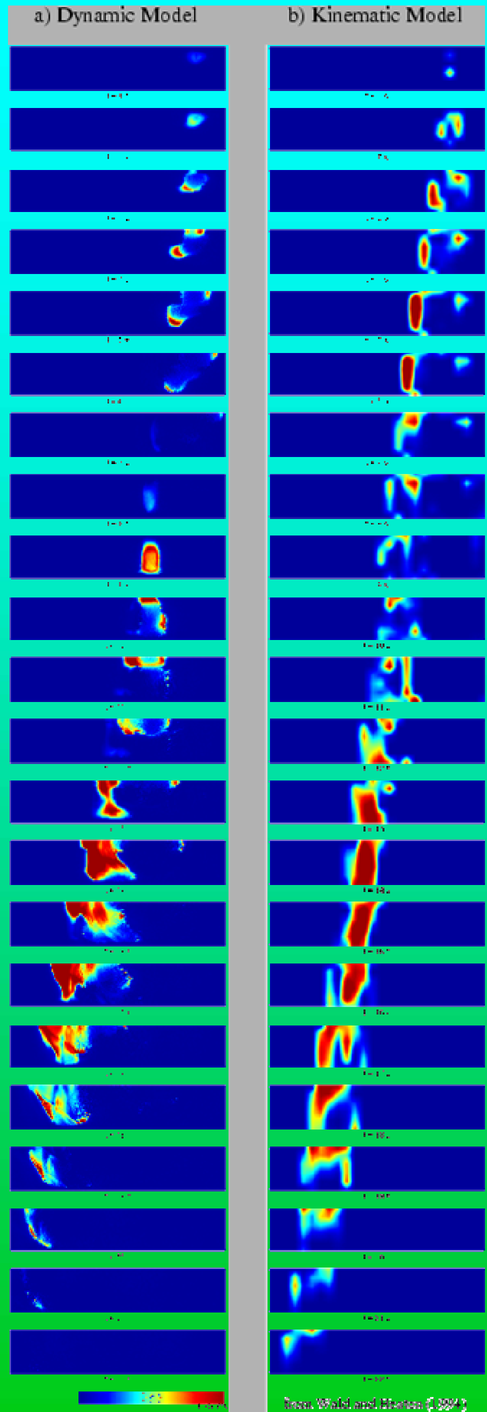
Landers earthquake:
28 june 1992, M_w=7.2

1) similar overall dislocation patterns and amplitudes with seismic moments of 7-8 x 10^{26} dyne-cm (seismic potency of 2.3-2.7 cubic km),

2) very heterogeneous, unilateral strike-slip distributed over a *fault length of 65 km* and over a *width of at least 15 km*, though slip is limited to shallower regions in some areas

3) a total rupture duration of 24 sec and an average rupture velocity of 2.7 km/sec

4) substantial variations of slip with depth relative to measured surface offsets.



Seismology: theory and principles

<u>Particular case</u>:

- isotropic medium
- plane surface
- constant slip $\Delta\mathbf{u}$ with the same direction defined by $\mathbf{l}$

$$u_n(x_s,t)=\int_{-\infty}^{\infty}d\tau\int_{\Sigma}\underbrace{\Delta u_i(\xi_s,\tau)C_{ijkl}n_j(\xi_s)G_{nk,l}(\xi_s,\tau;x_s,t)dS}_{\text{becomes}}$$

$$\Delta u_i(t)\lfloor\lambda l_k n_k\delta_{ij}+\mu(l_i n_j+l_j n_i)\rfloor G_{ni,j}$$

Seismology: theory and principles

The point source approximation

- isotropic medium
- plane surface of area S and normal **n**
- constant slip Δ**u** with the same direction defined by **l**
- **n.l** = 0 *i.e.* the slip vector is contained in the plane

$$u_k = \int_{-\infty}^{\infty} d\tau \int_{\Sigma} \Delta u \mu \left(l_i n_j + l_j n_i \right) G_{ki,j} dS$$

if the distance from the observation point to the source is large in comparison with the source dimension (r >>Σ) and the wave lengths are also large => point source approximation

$$u_k = \mu S \left(l_i n_j + l_j n_i \right) \int_{\Sigma} \Delta u (\tau) G_{ki,j} (t - \tau) d\tau$$

Seismology: theory and principles

Far field and radiation pattern
Focal mechanism

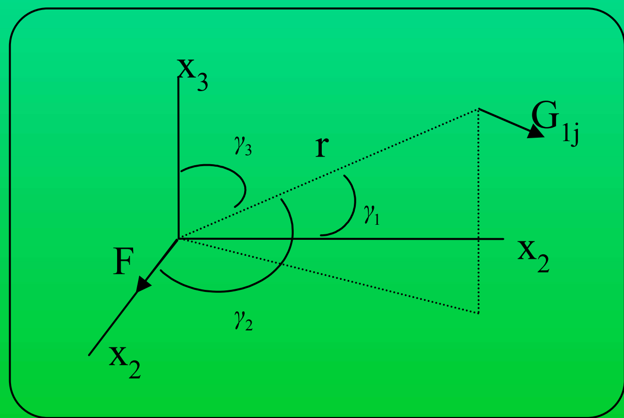
In the far field expression of the displacement (P-wave):

$$G^{P}_{ki,j} = \frac{1}{4\pi\rho\alpha^{2}}\frac{\partial}{\partial\xi_j}\left[\frac{1}{r}\underbrace{\gamma_i\gamma_k}_{\text{director cosine}}\delta\left(t-\frac{r}{\alpha}\right)\right]$$

The displacement of the P-wave in the far-field is

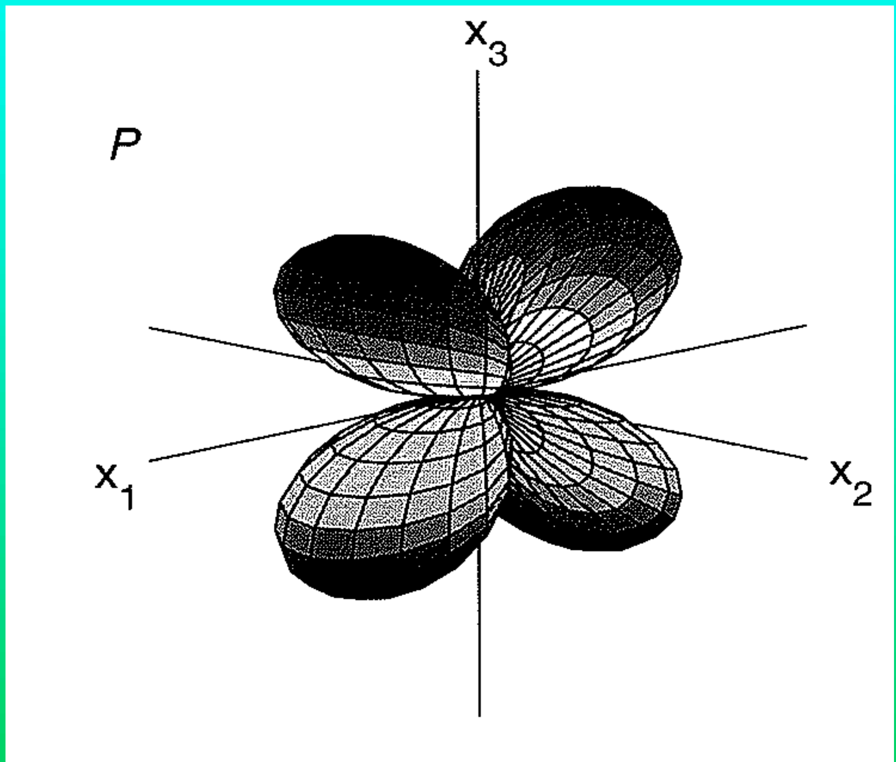
$$u_j^{P} = \frac{\mu S}{4\pi\rho\alpha^{3} r}\overbrace{\left(n_k l_i + n_i l_k\right)\gamma_i\gamma_k\gamma_j}^{\text{Radiation pattern}}\overbrace{\Delta\dot{u}\left(t-\frac{r}{\alpha}\right)}^{\text{becomes}}$$

$$\Delta u\,\dot{f}\left(t-\frac{r}{\alpha}\right)$$

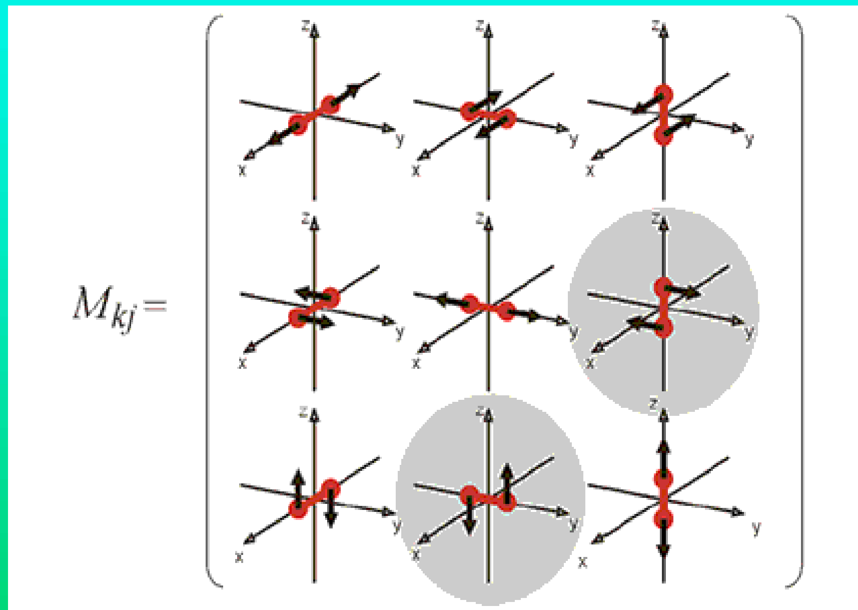


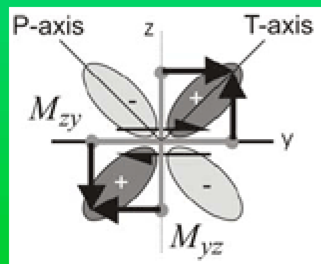
Seismology: theory and principles

- scalar seismic moment: $$M_0 = \mu \Delta u S$$
- moment tensor for a shear dislocation: $$M_{ij} = M_0 \left(l_i n_j + l_j n_i \right)$$



Radiation pattern generated by the double couple $M_{31} + M_{13}$





Seismology: theory and principles

Focal mechanism: interpretation

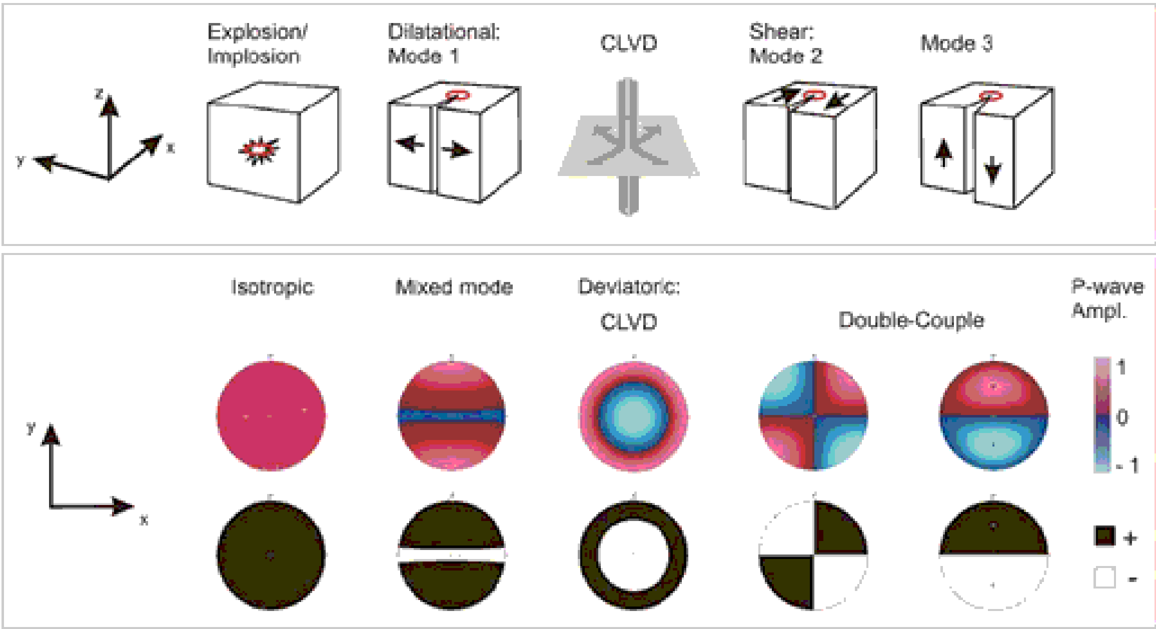
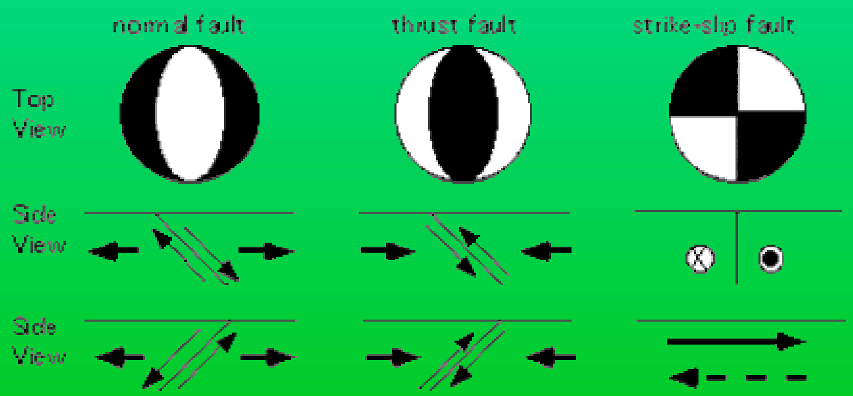


Figure 3: Correlation between models of failure mechanisms (top) and the estimated radiation patterns of these events in a spatial projection with view from above (same column, respectively).



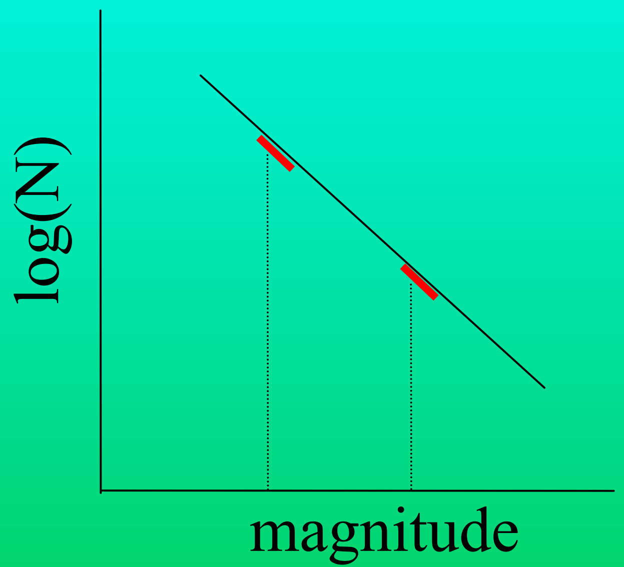
Summary

- An earthquake is a 2D object defined by an orientation (plane and slip vector) and an area S.
- The geometry of the rupture can be assessed by the mean of the focal mechanism.
- The scalar seismic moment allows to appreciate the area of the ruptured zone.

Seismicity properties

Seismology: theory and principles

- Observation of Gutenberg-Richter (1956)



$$\log(N) = a - bm$$

N = cumulated number of events with a magnitude larger than or equal to m

Self-similar process because same slope regardless of the magnitude

Seismology: theory and principles

- Other observations

It can be shown that $\bar{u} = c \dfrac{\Delta\sigma}{\mu} S^{1/2}$

so that the scalar seismic moment can be written

$$M_0 = c \Delta \sigma S^{3/2}$$

the slope indicates that $\Delta\sigma$ is constant

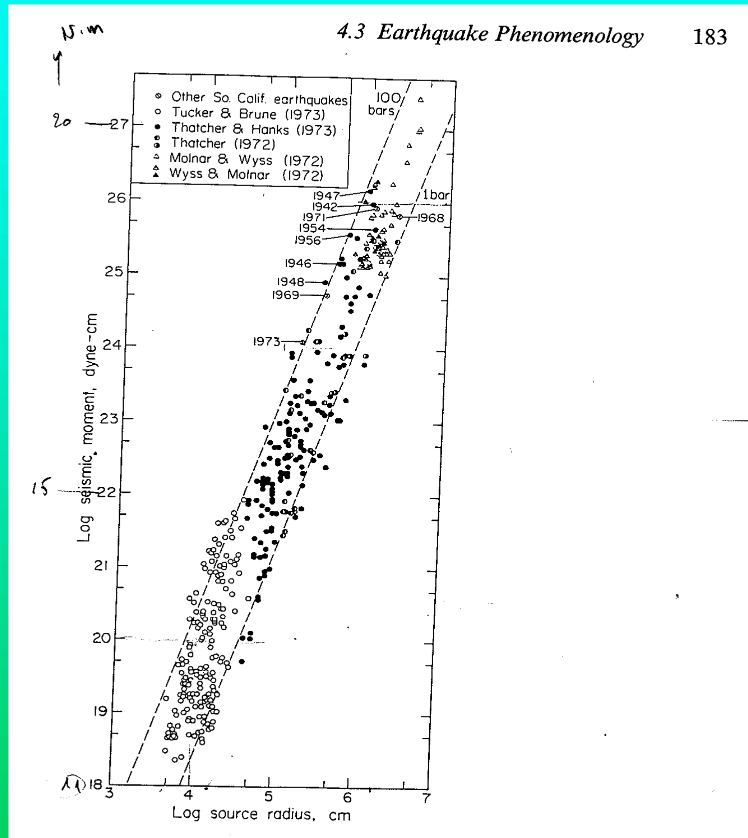


Fig. 4.10 A collection of data for small earthquakes showing the relationship between M_0 and source radius. Dashed lines are of constant stress drop. (From Hanks, 1977.)

Seismology: theory and principles

- Self organized criticality (SOC)

spontaneous organization of a system driven from outside in a dynamical statistical stationary state, which is characterized by self-similar distributions of event sizes and fractal geometrical properties.

- Properties:

1) highly non-linear behavior (essentially a threshold response)

2) very slow driving rate

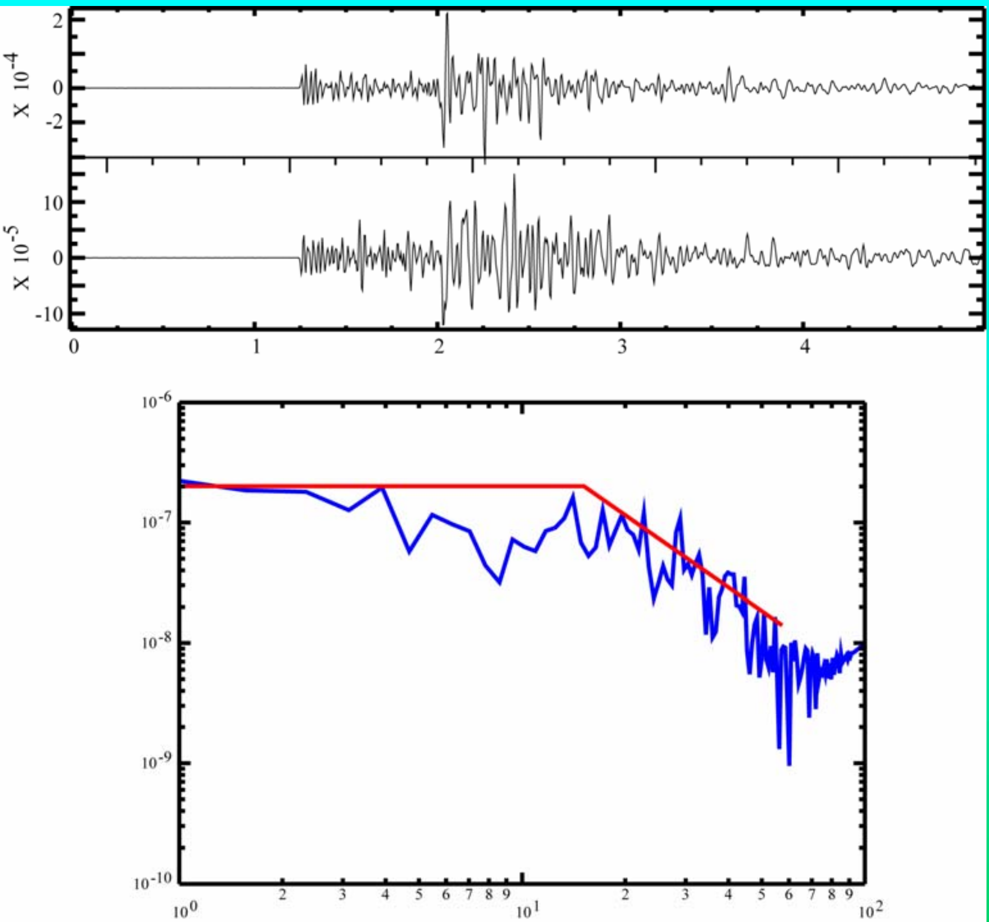
3) globally stationary regime, characterized by stationary statistical properties

4) power distributions of event sizes and fractal geometrical properties

The case of Soultz-sous-Forêts

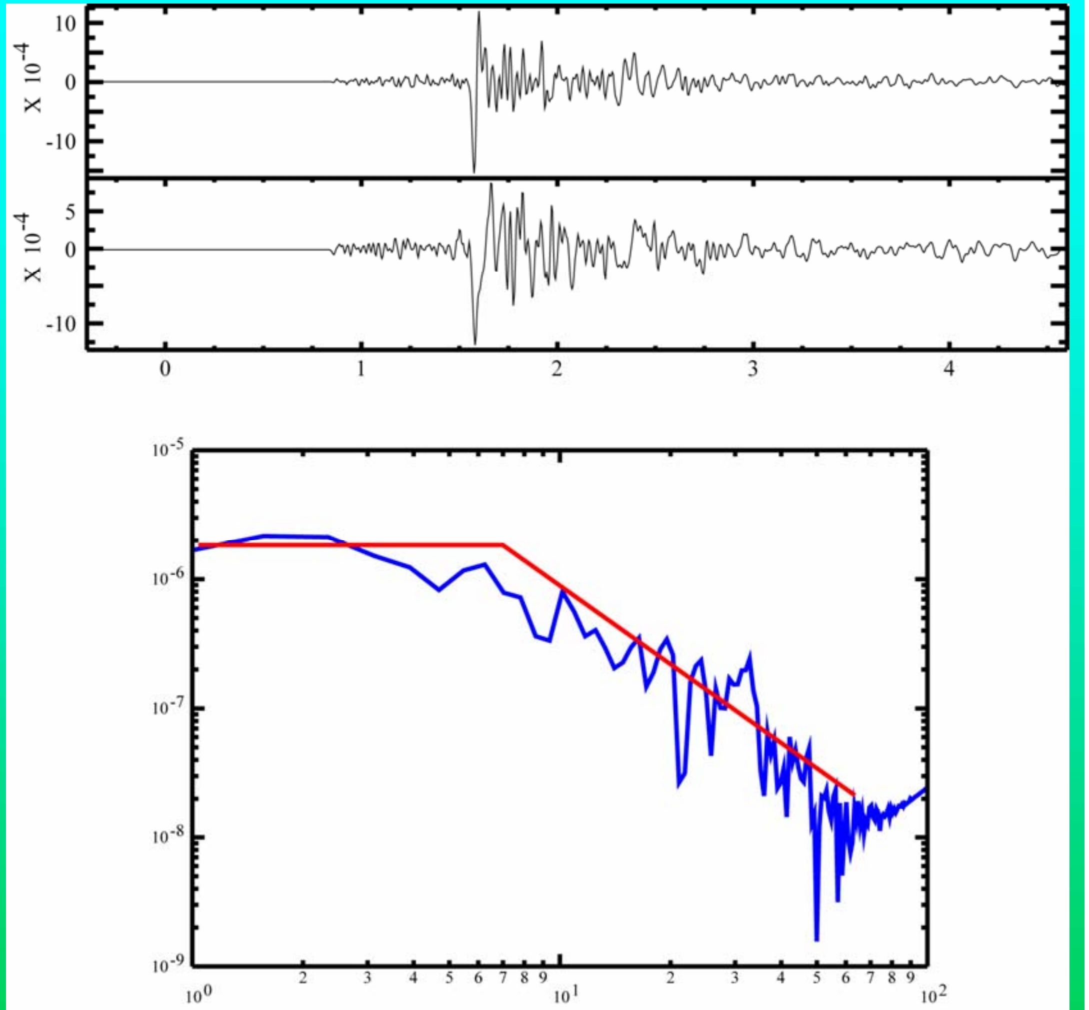
Is the induced seismicity ruled by the same laws?

Size of the earthquakes



02 Juin 2003 21h29

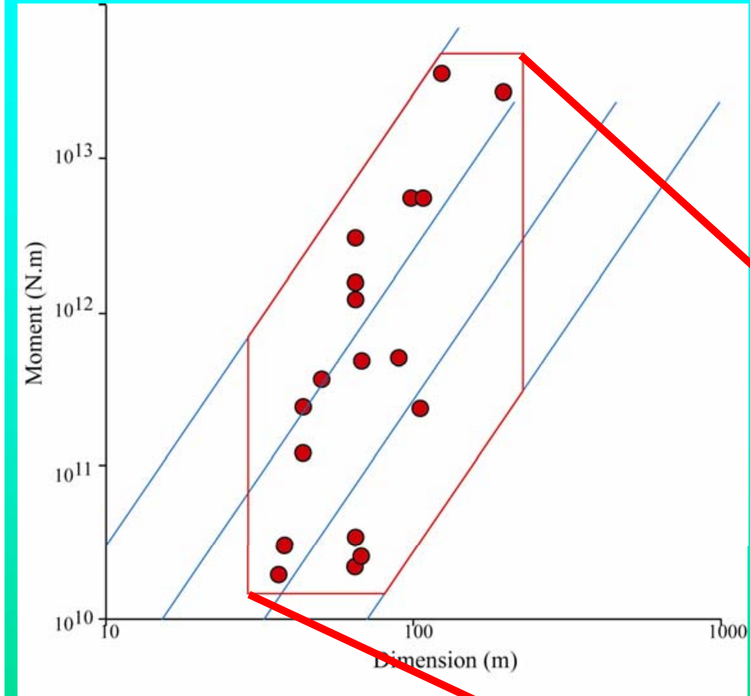
$M_0 = 2.53\ 10^{12}$ N.m
$M_w = 2.17$
fc = 15 hz, r0 = 49 m
$\Delta\sigma$ = 9.70 MPa



10 Juin 2003 22h54

$M_0 = 2.73\ 10^{13}$ N.m
$M_w = 2.85$
fc = 7.5 hz, r0 = 97 m
$\Delta\sigma$ = 11.60 MPa

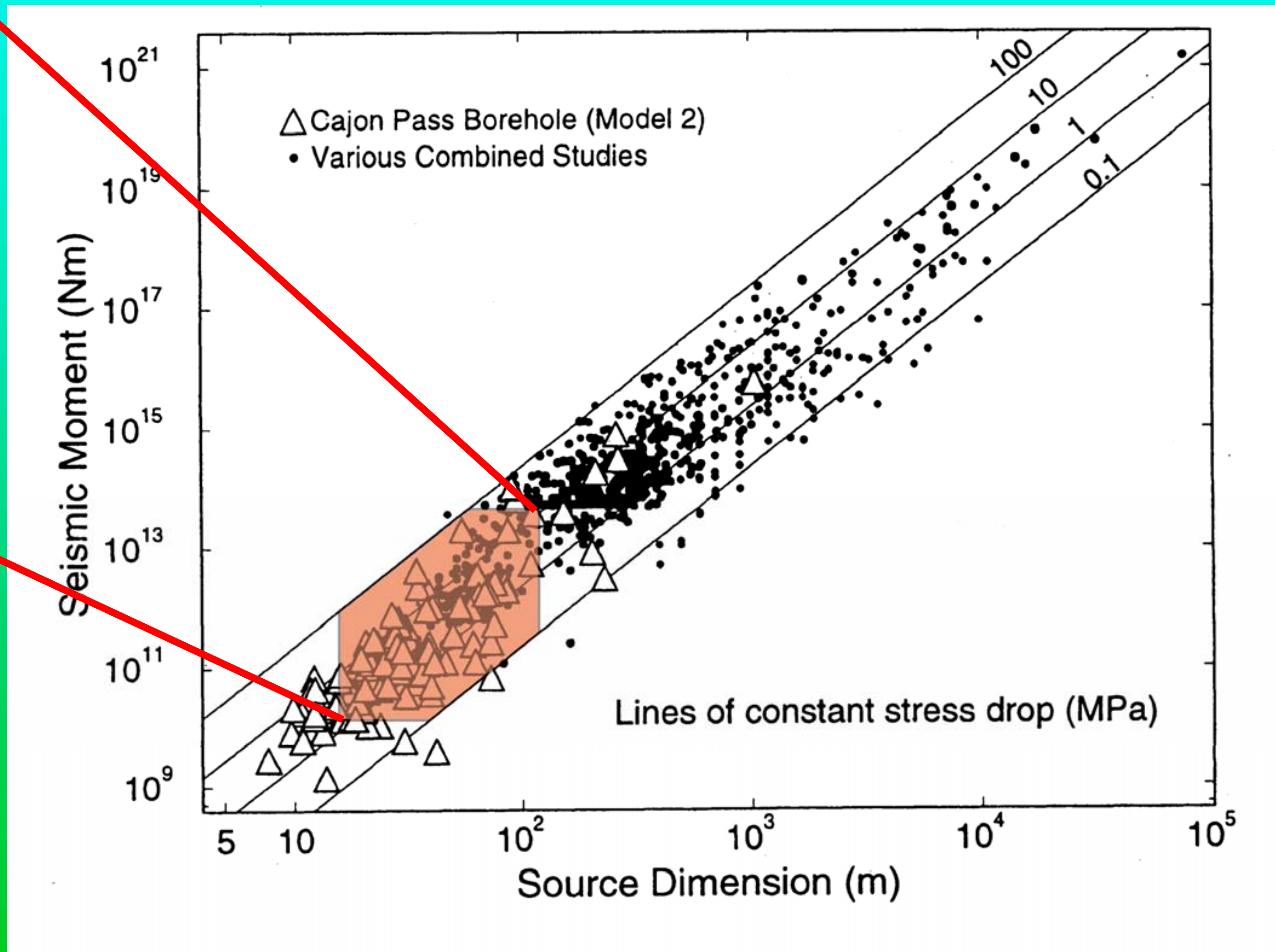
Size of the earthquakes



In blue, lines of constant stress drop, 0.1, 1 10 and 10 MPa

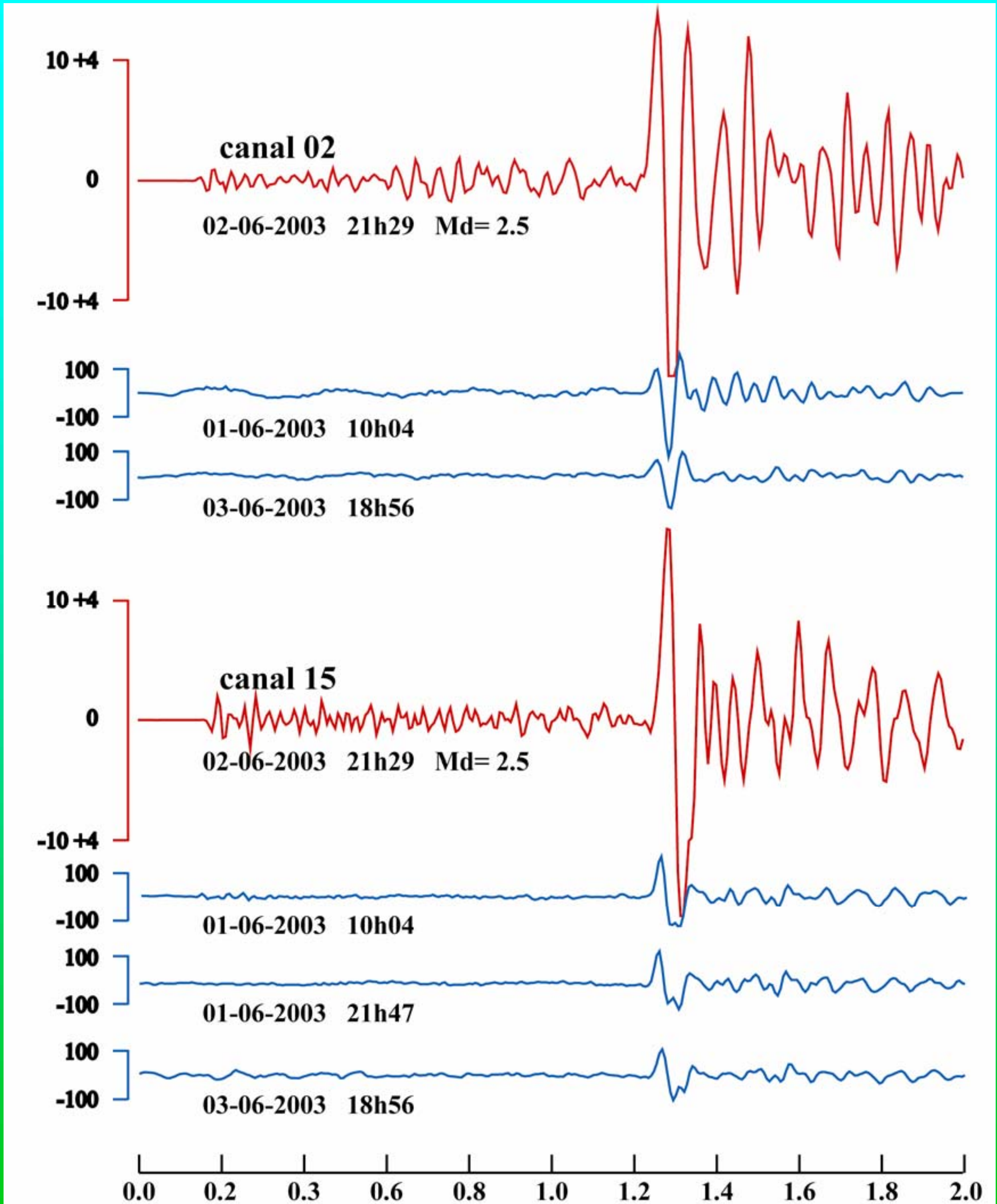
Soultz-sous-Forêts

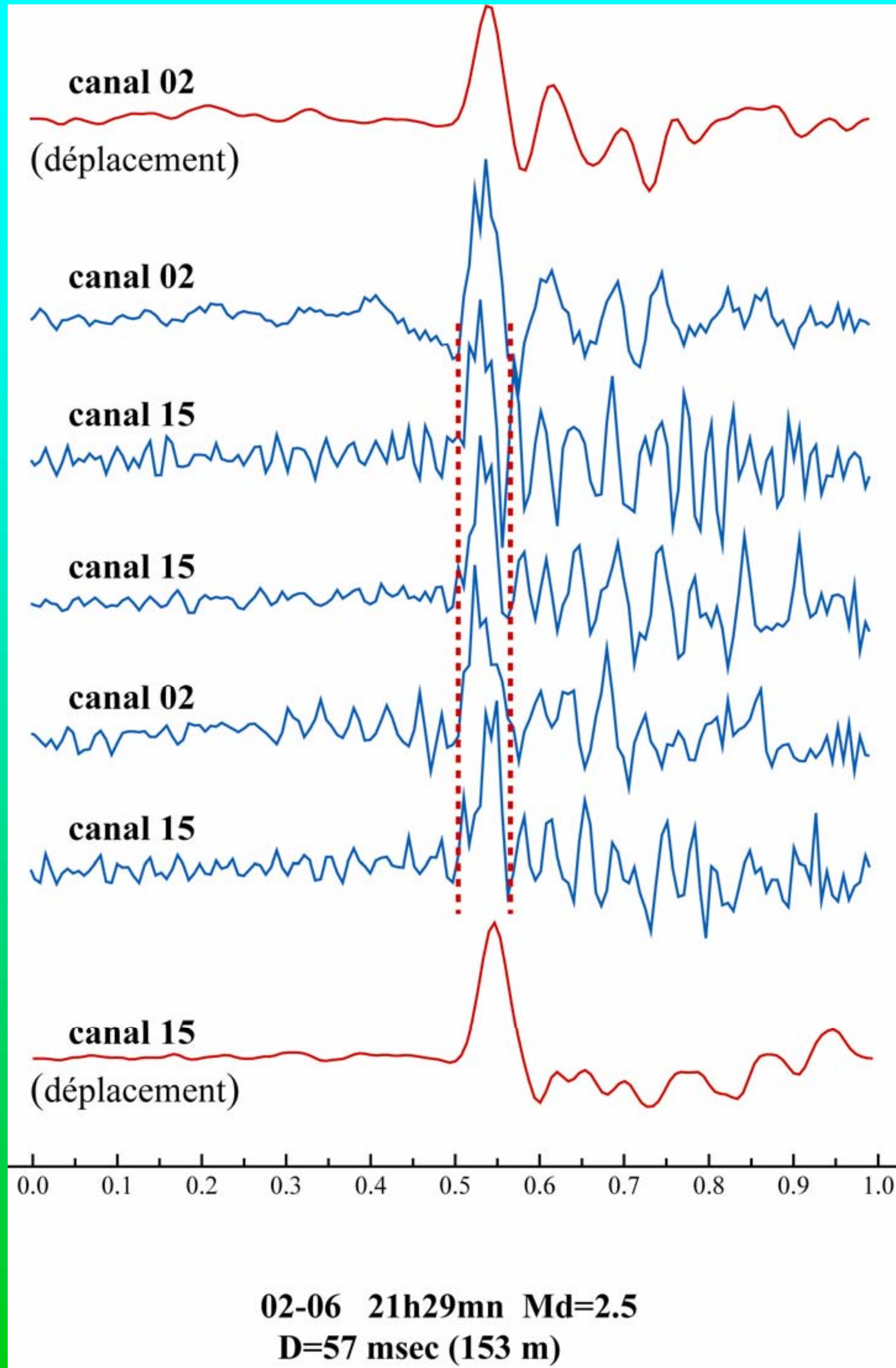
other studies

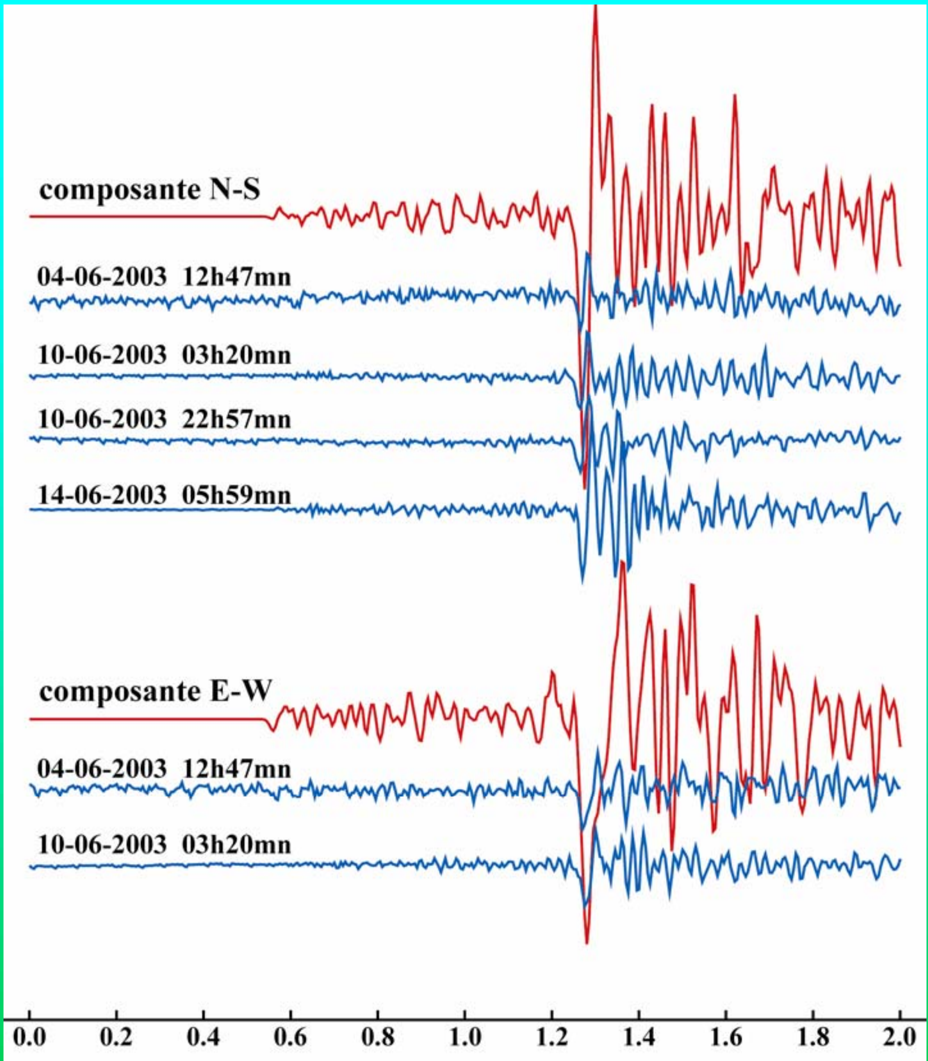


Soultz data (pink) together with Abercrombie (1995) results (black symbols)

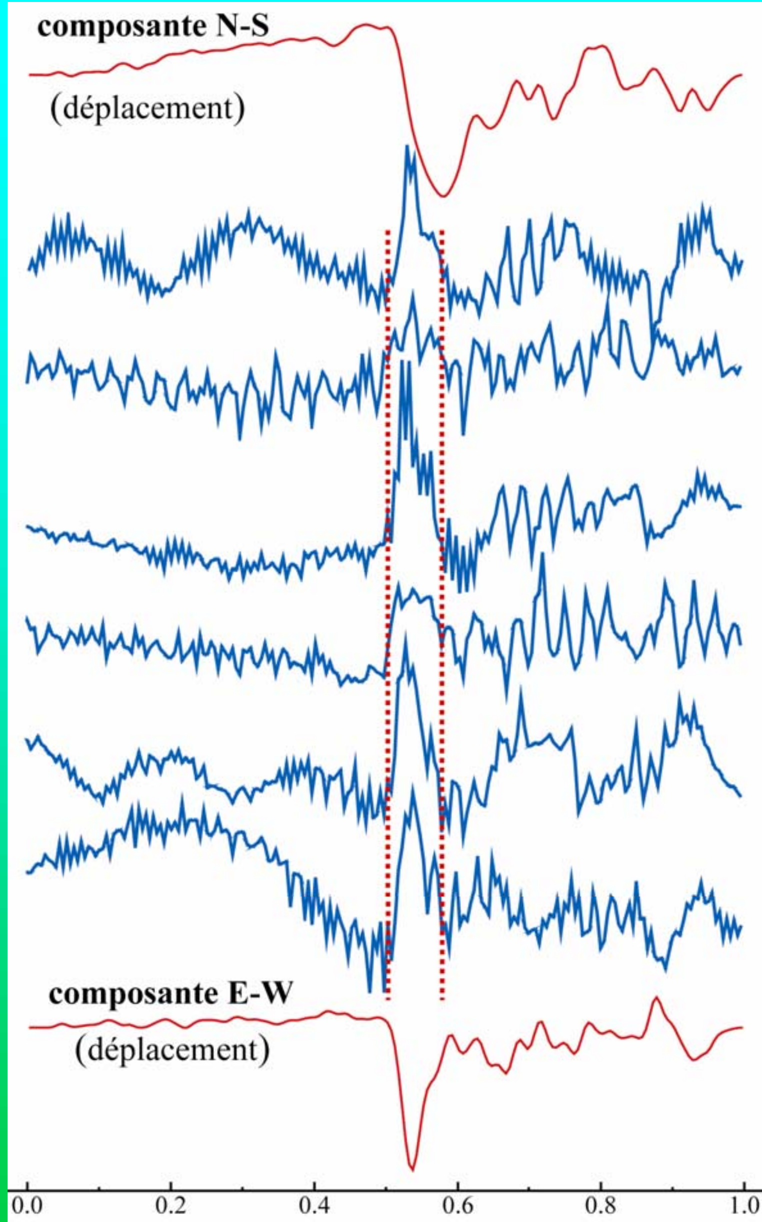
Empirical Green's functions





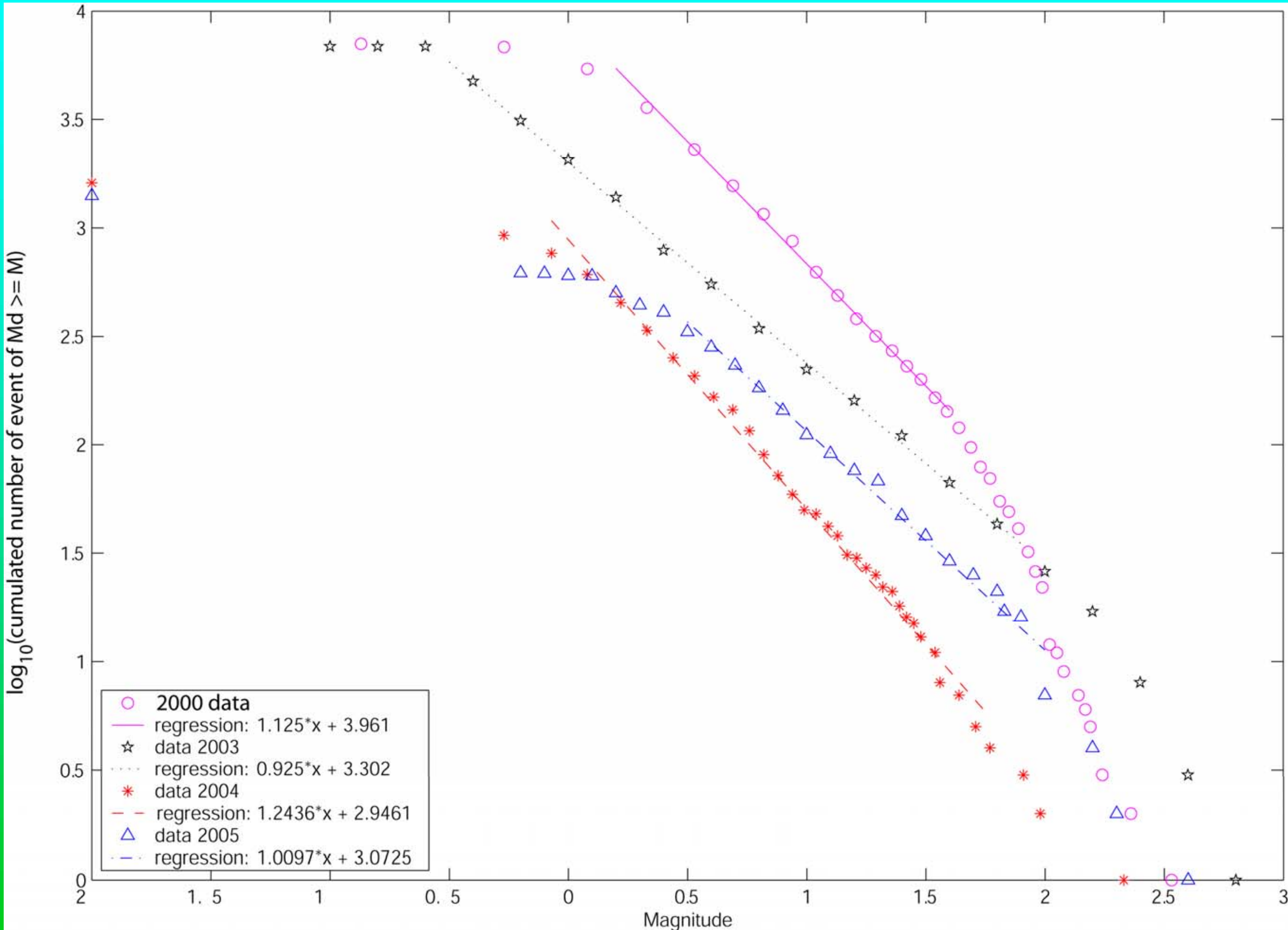


10-06-2003 22h54mn Mw = 2.8



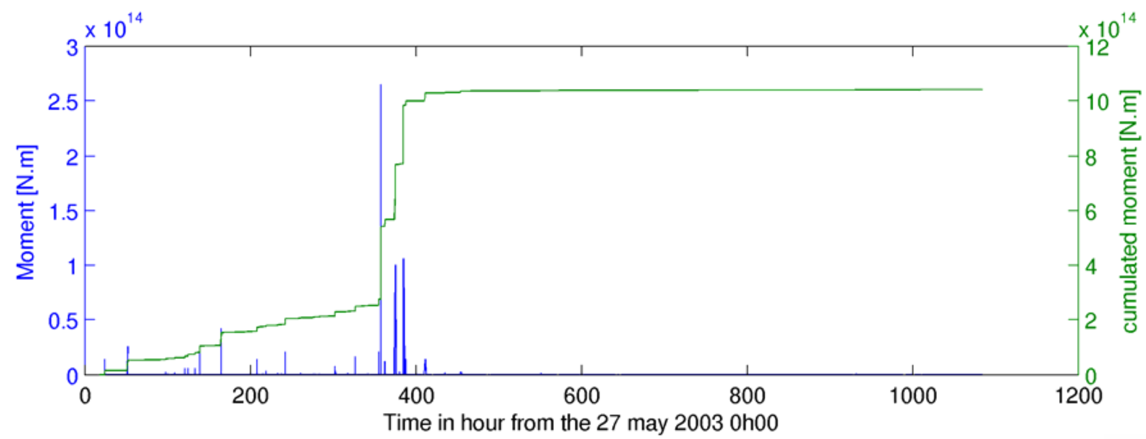
10-06 22h54mn Mw=2.8
D=75 msec (203 m)

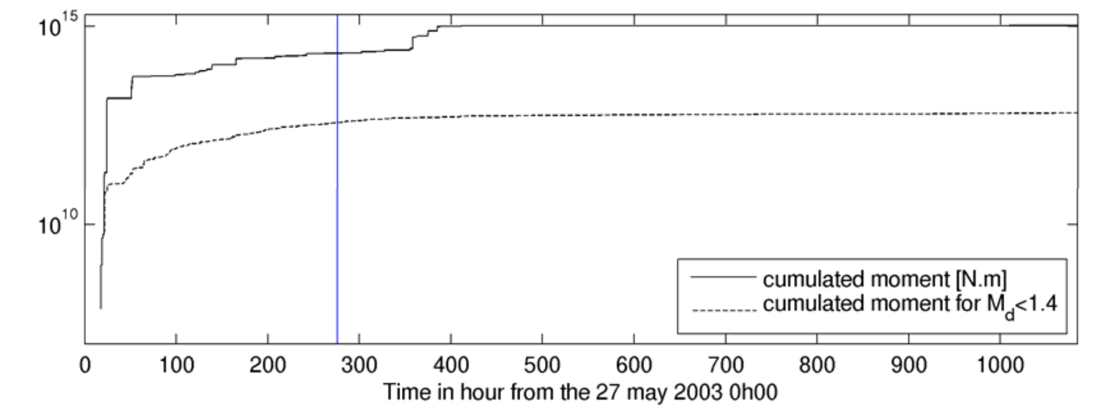
Power distribution



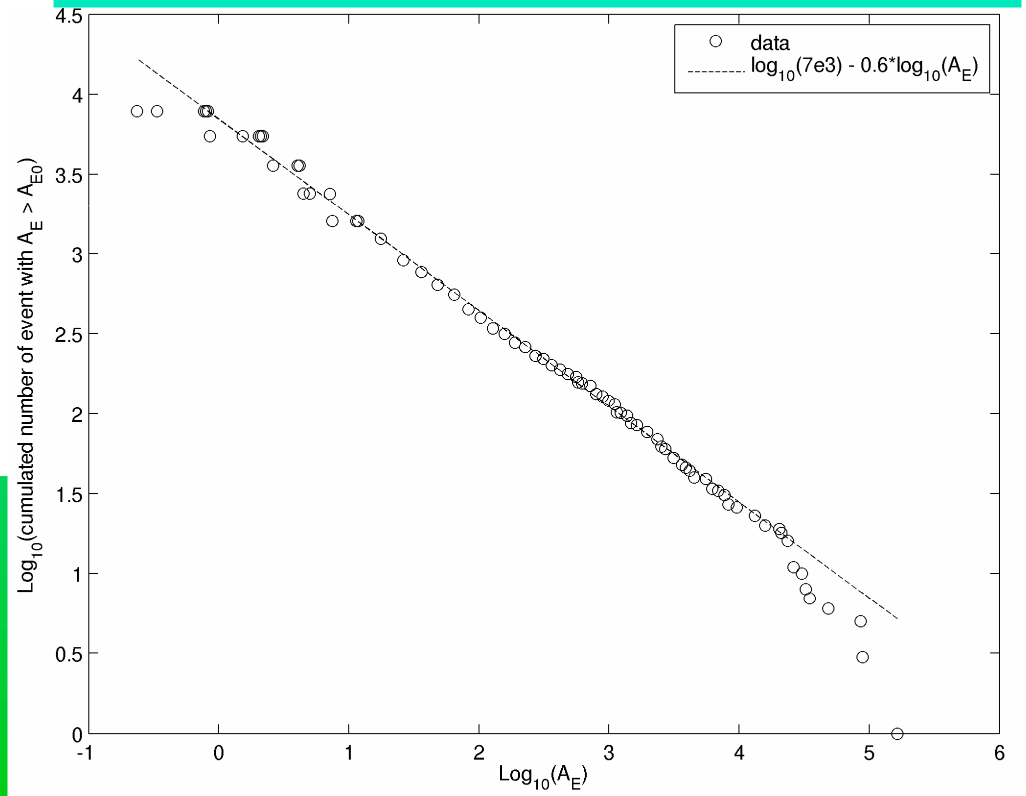
Stimulation of GPK3

Moment (N.m)



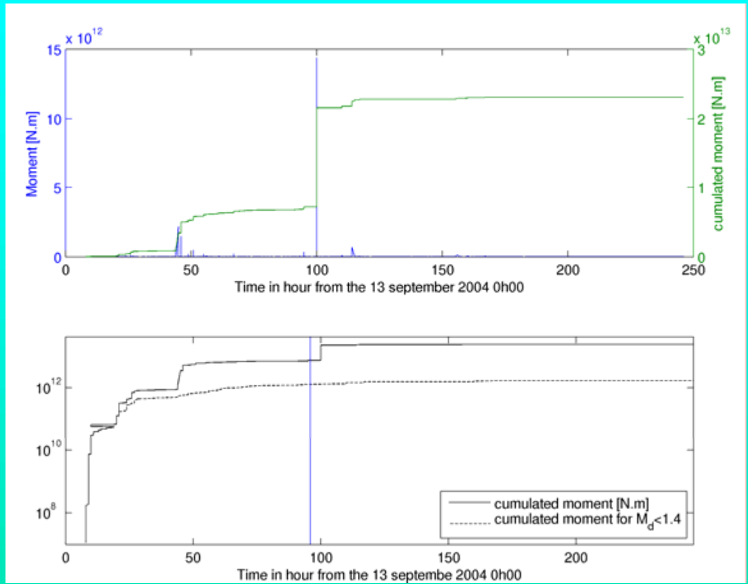


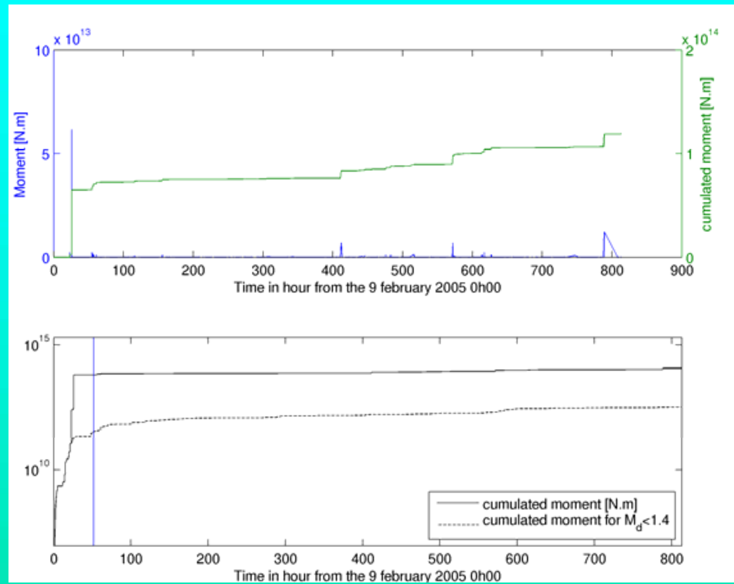
Surface (m^2)



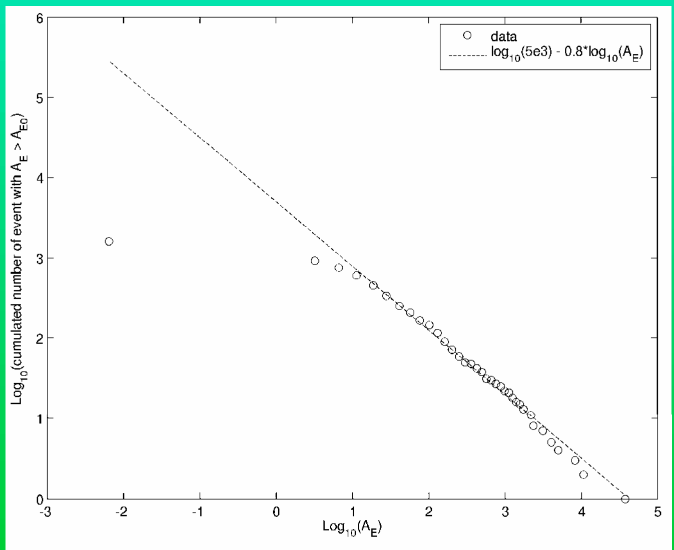
Stimulation of GPK4

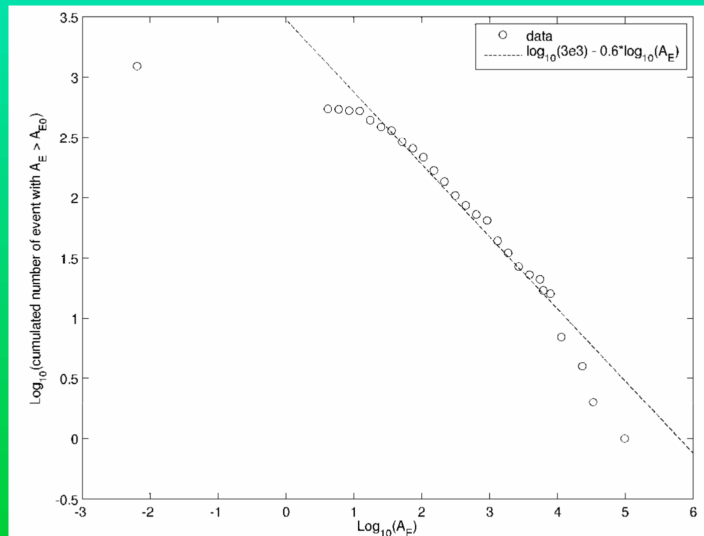
Moment (N.m)





Surface (m^2)

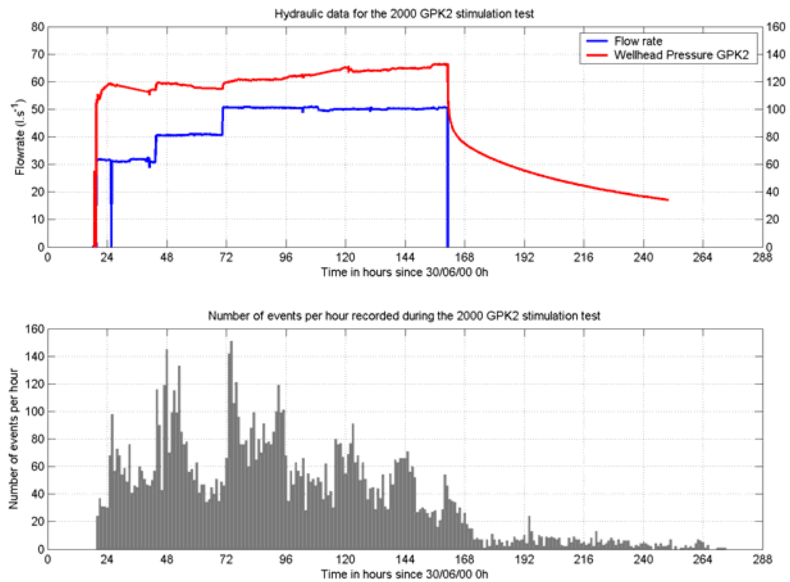


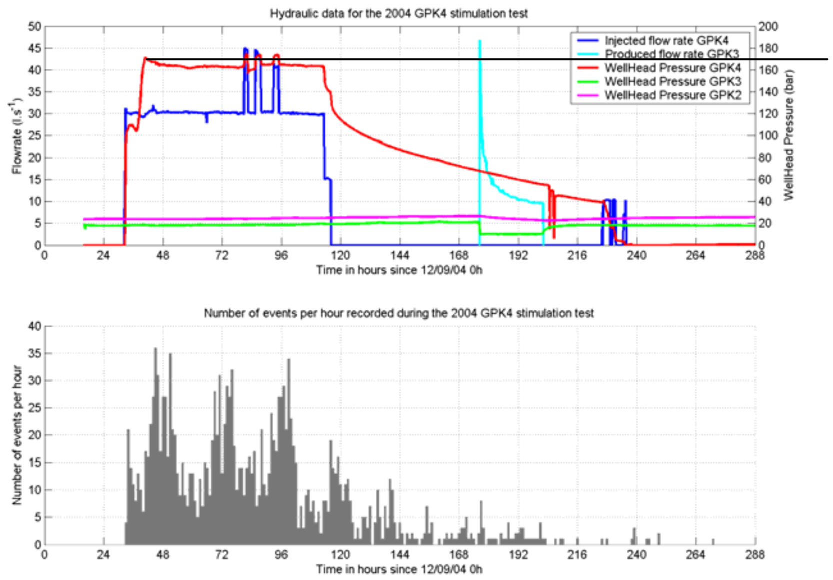


2004

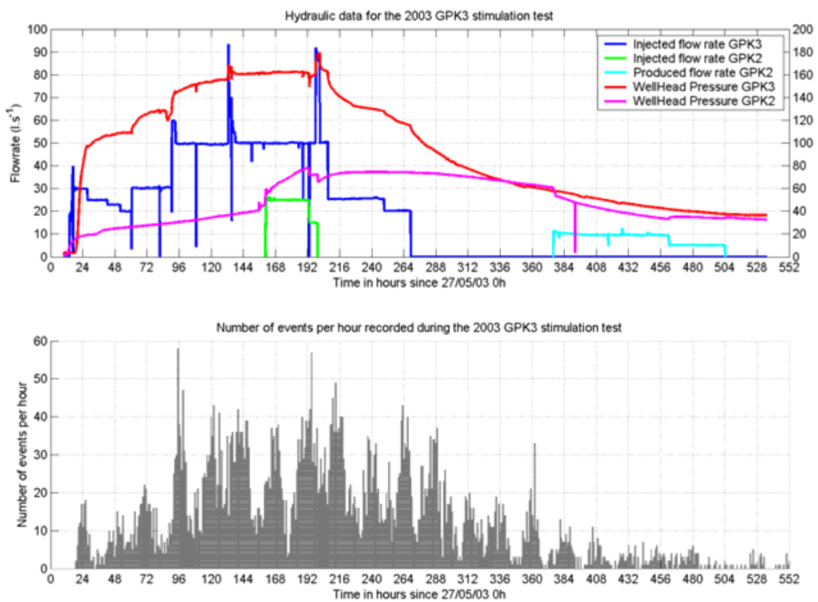
2005

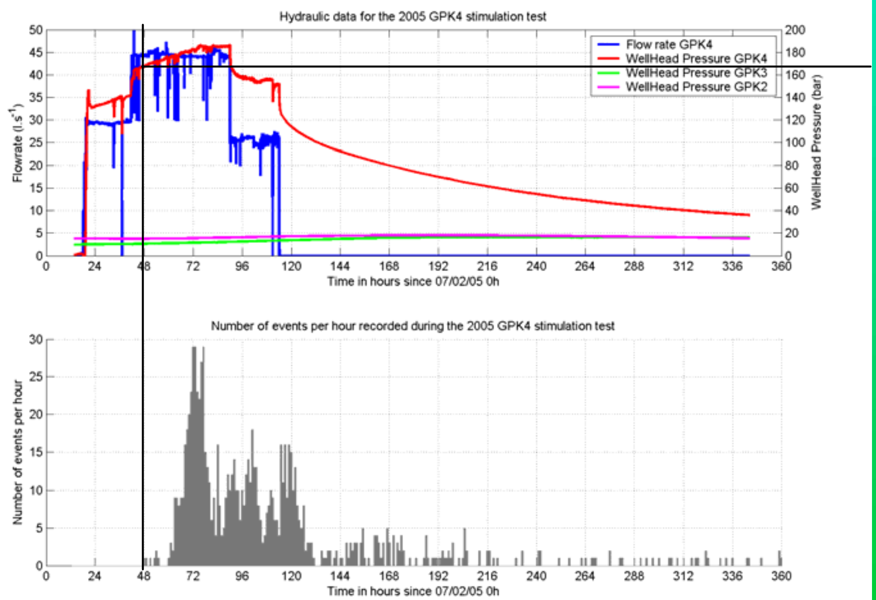
Microseismicity and stimulation





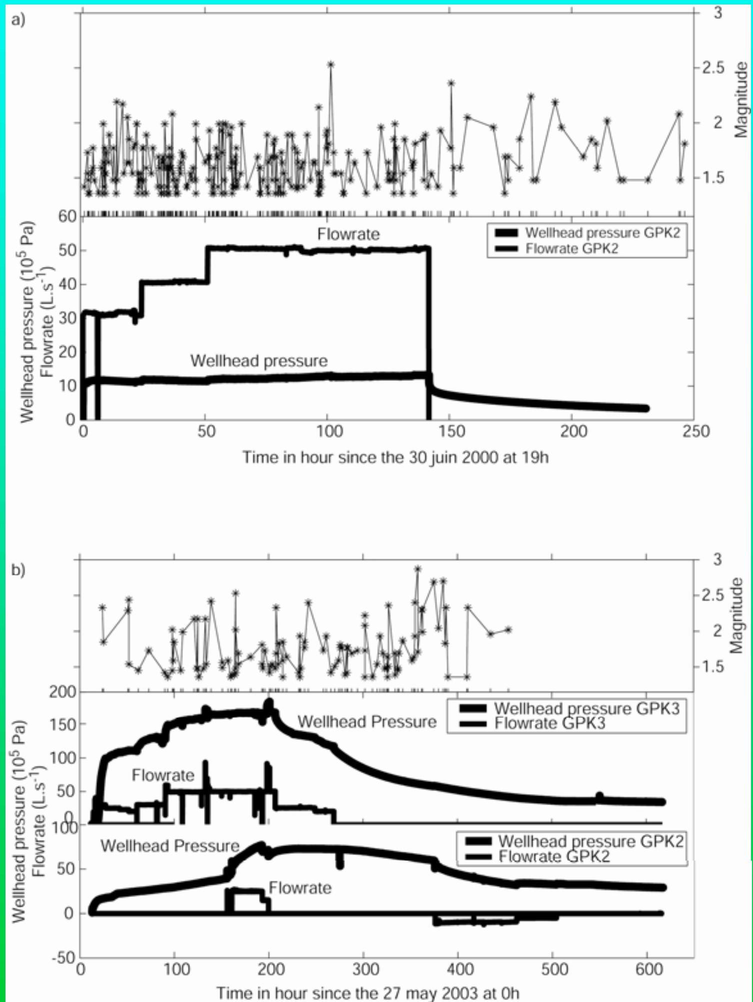
#170 bars

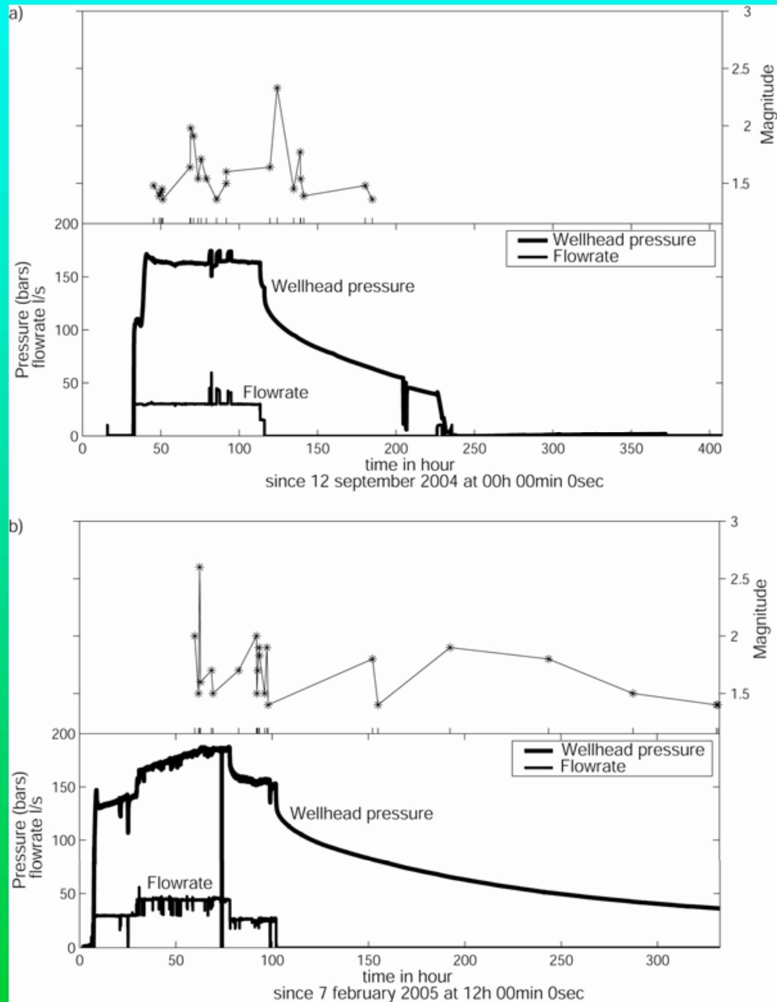




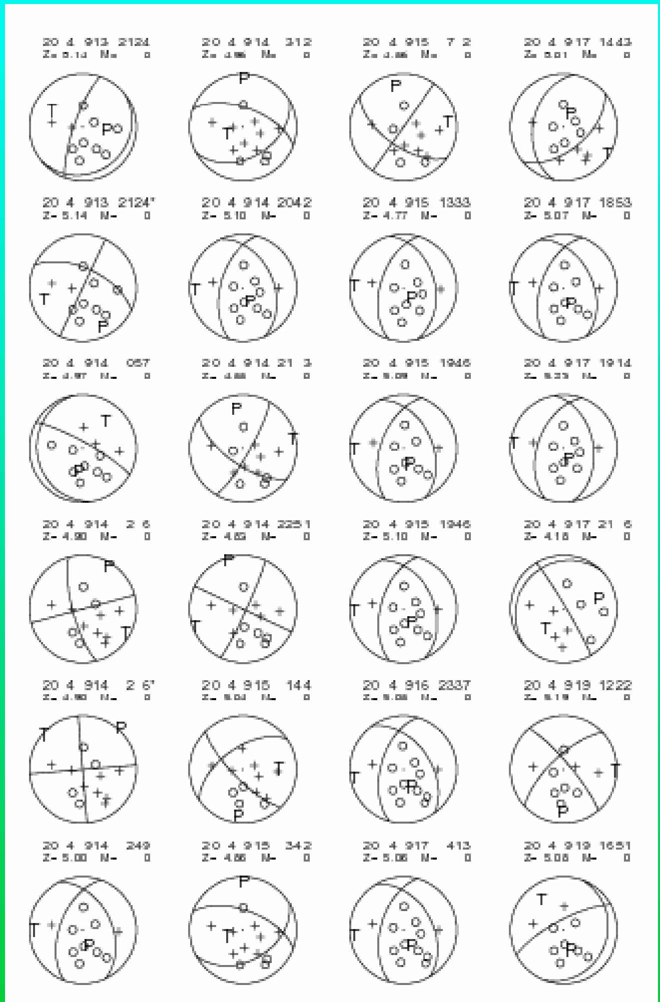
#170 bars

Seismicity (M≥1.4) and stimulation

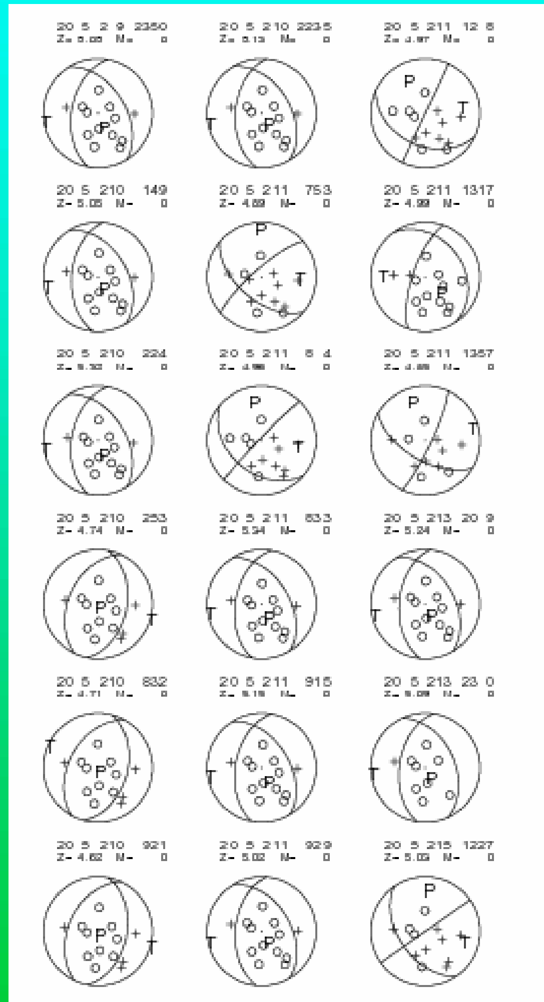




Focal mechanisms

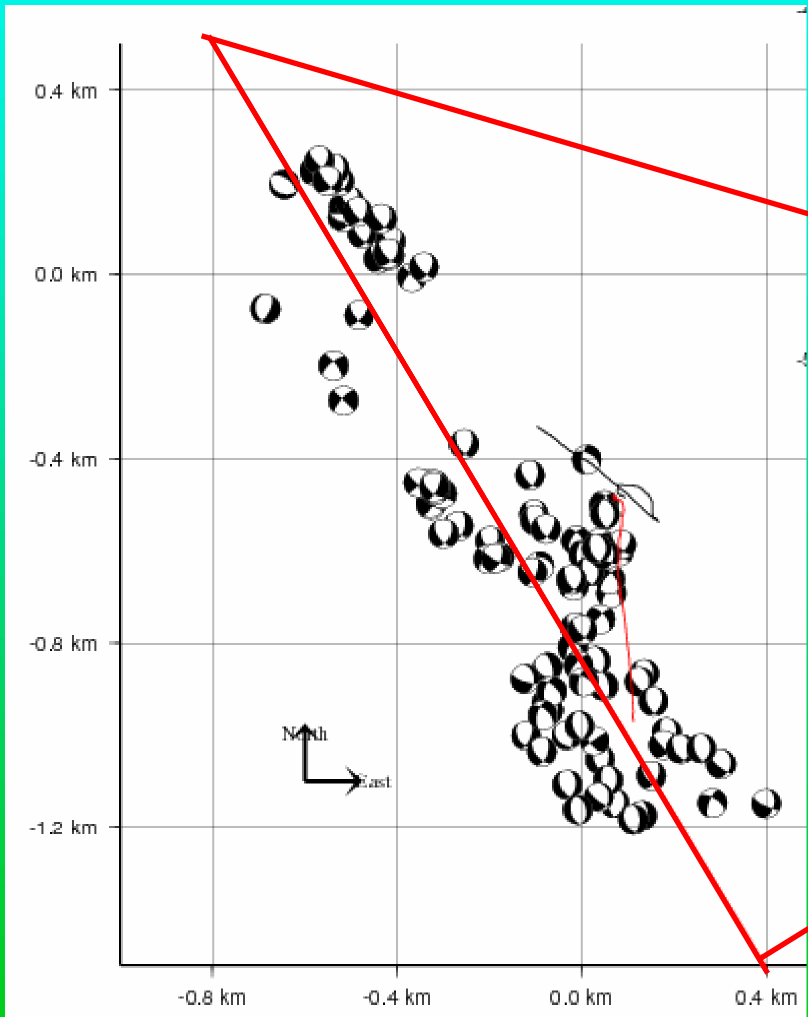


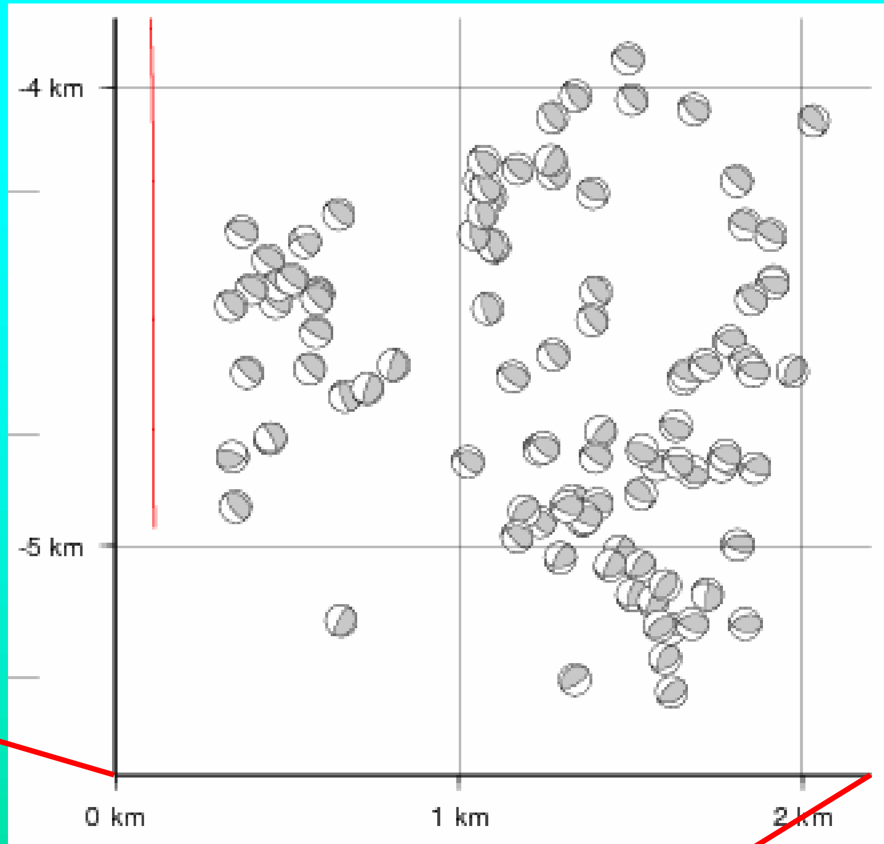
2004



2005

Plane view





Cross section

Conclusion

- The induced seismicity is ruled by the laws drawn for natural seismicity (power law distribution, self-similarity).
- There are no apparent evidence for tensile fracturing during the stimulation.
- It seems that a kind of Kaiser effect exists, concerning the behaviour of the reservoir.