

Activité microsismique et mouvements asismiques induits par des injections forcées d'eau

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Objectifs du suivi microsismique et conséquences pour le système
d'observation

Trois exemples de suivi microsismique

- Le Mayet de Montagne
- Résultats d'une expérience de fracturation hydraulique à Cotton Valley (Texas)
- Résultats obtenus sur le site expérimental de soultz-sous Forêts

Du problème de l'estimation de la magnitude maximum susceptible
d'être engendrée par des injections forcées.

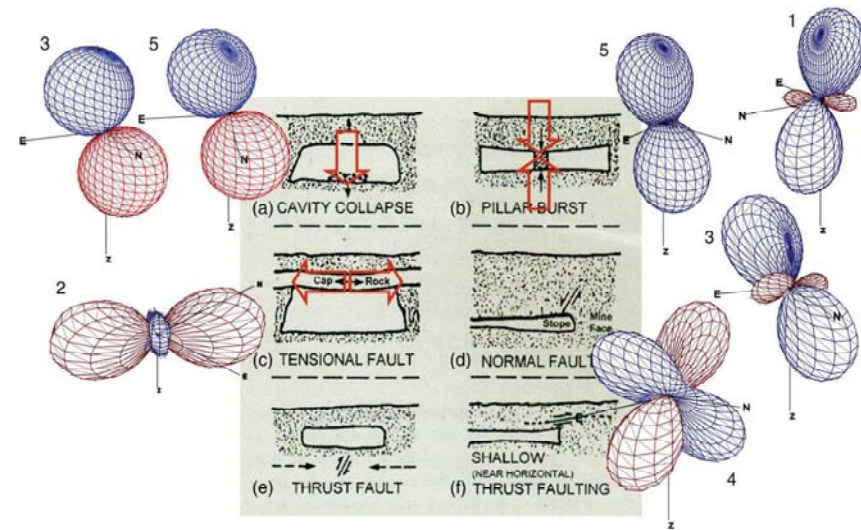
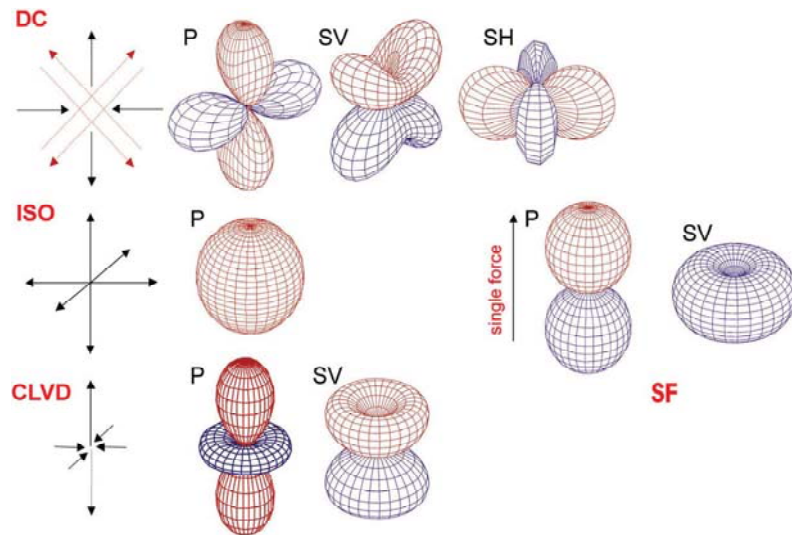
De la définition des caractéristiques d'un réseau d'observation

- Objectifs :
 - cartographie du domaine des perturbations induites par l'injection
 - Événements microsismiques liées aux variations de pression interstitielles instantanées
 - Ce que l'on apprend des localisations des événements
 - Ce que l'on peut apprendre des mécanismes à la source
 - Autres perturbations liées à une redistribution des contraintes effectives à diverses échelles : de l'existence de mouvements asismiques
 - Détermination des zones d'écoulement à fort débit?
- Caractéristiques du système d'observation
 - Localisation (de la nécessité de bien connaître le champ de vitesse)
 - Mécanisme à la source
 - Quel domaine de fréquences doit être couvert ?
 - De l'intérêt d'un système d'écoute profond et d'un système d'observation de surface

Détermination des processus de rupture à partir du diagramme de radiation

d'après Sileny et Milev, Tectonophys. 2008

- Diagramme de radiation et système de forces équivalent
- Equivalence entre ruptures « minières » et diagrammes de radiation



Cartographie des fractures hydrauliques à partir de la sismicité induite

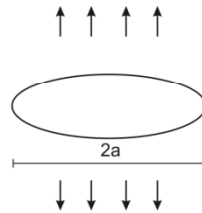
Sur la stabilité du processus de rupture

1. Pression appliquée jusqu'au fond de fracture

$$KI \propto (\sigma_3 - P)(2\pi a)^{1/2};$$

KI augmente avec a,

La fracture est instable

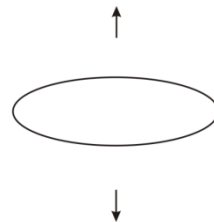


2. Pas de pénétration de fluide : la pression n'est appliquée que dans le forage

$$KI \propto (1/a)^{1/2}$$

KI diminue avec a ;
la fracture est stable.

Il faut augmenter la pression pour que la fracture se propage.



Source des signaux de sismicité induite

- Signaux hautes fréquences liés (KHz) au front de propagation
- Signaux courtes-périodes (de qq Hz à qq centaines de Hz): cisaillements le long de fractures préexistantes, dans les épontes de la fracture hydraulique

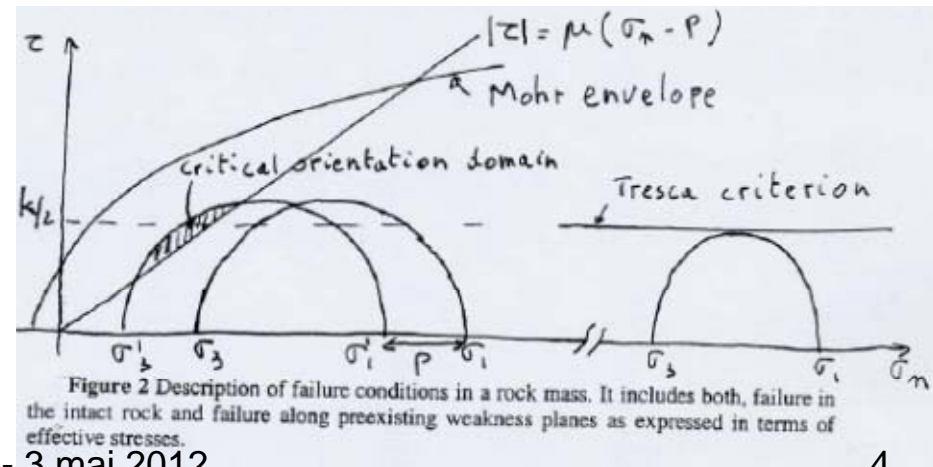


Figure 2 Description of failure conditions in a rock mass. It includes both, failure in the intact rock and failure along preexisting weakness planes as expressed in terms of effective stresses.

Results from the Le Mayet de Montagne Geothermal Laboratory (1985-1987)

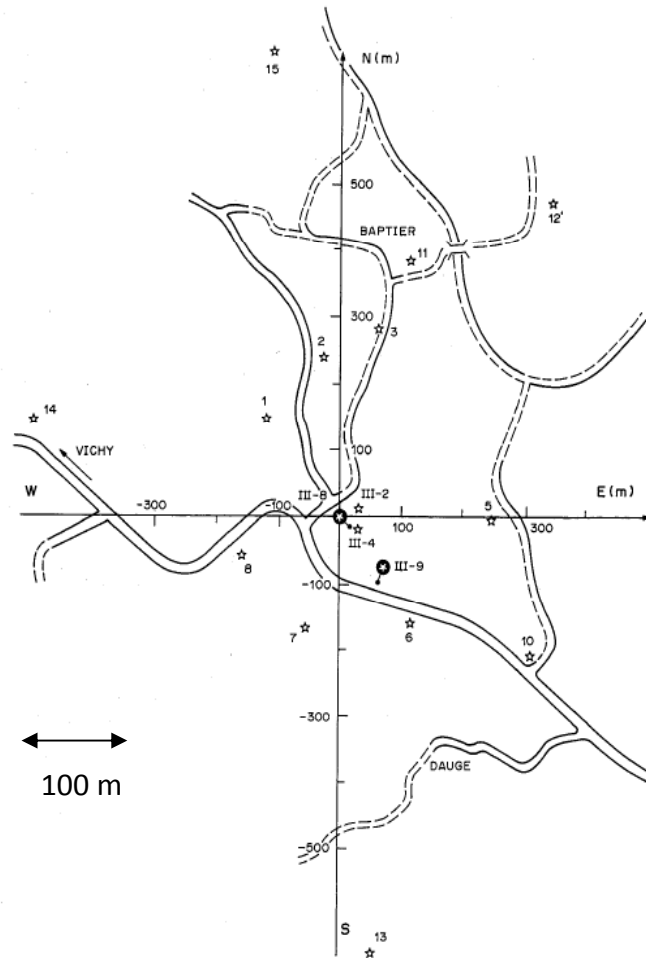
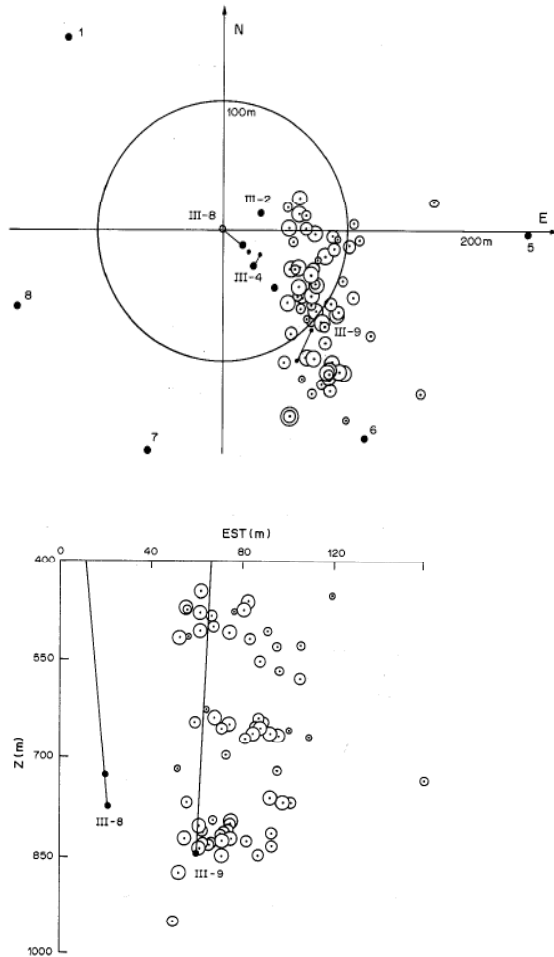


Fig. 1. Location of seismic stations (☆) and of boreholes used for the hydraulic injections (●). Scale is in m.

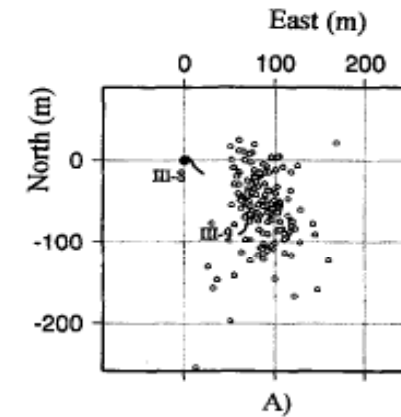
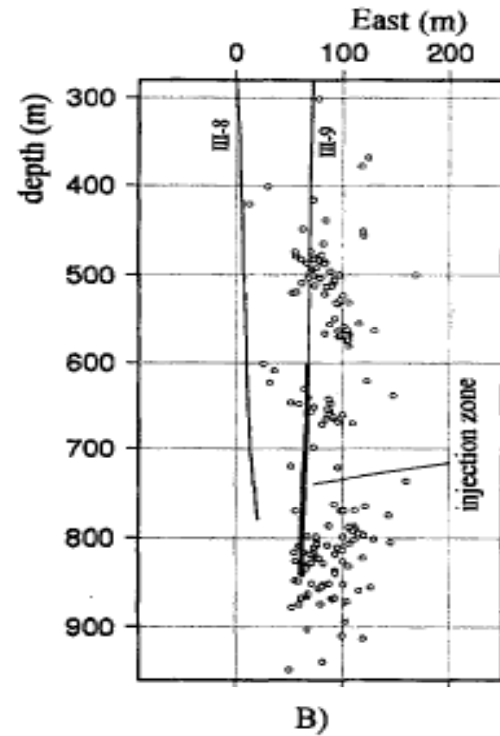
- An in situ 800 m deep laboratory on fluid percolation in fractured rock masses (granite) has been developed during the eighties, under French and European funding, for investigating the possibility of exploiting heat from deep hot rock formations.
- The main objective was to test the possibility of stimulating a granitic rock mass in order to develop an efficient heat exchanger out of the natural fractures network.
- The idea was to build up progressively pore pressure so as to induce shear along optimally oriented fractures. This required preliminary understanding of both the regional stress field and the natural fracture system. Monitoring of induced seismicity was conducted for all stimulation experiments with a 14 3C-station network.

Observed microseismic activity

- The 1985 stimulation (about 2200 m³)



- The 1986 stimulation (over 42 800 m³)



Stress measurements conducted after the long term circulation experiment imply aseismic slip

(Scotti and cornet, Int J Rock Mech Min Sc., 1994)

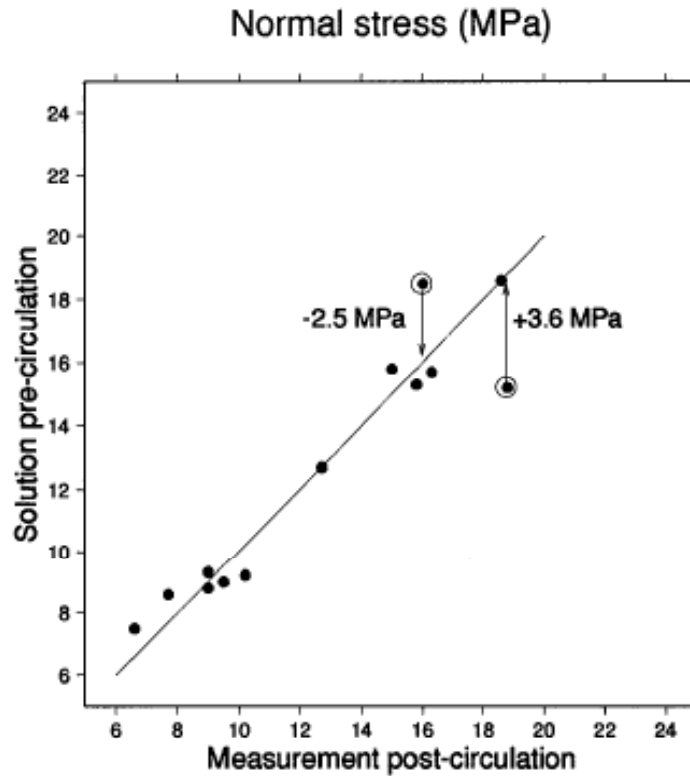


Fig. 2. By comparing the 13 post-circulation measurements to the pre-circulation solution it was possible to identify two extremely heterogeneous HTPF measurements. Notice that one perturbation is positive and the other is negative. Exact values are given in Table I.

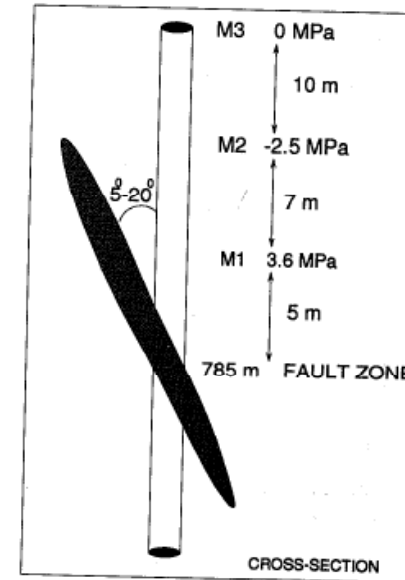
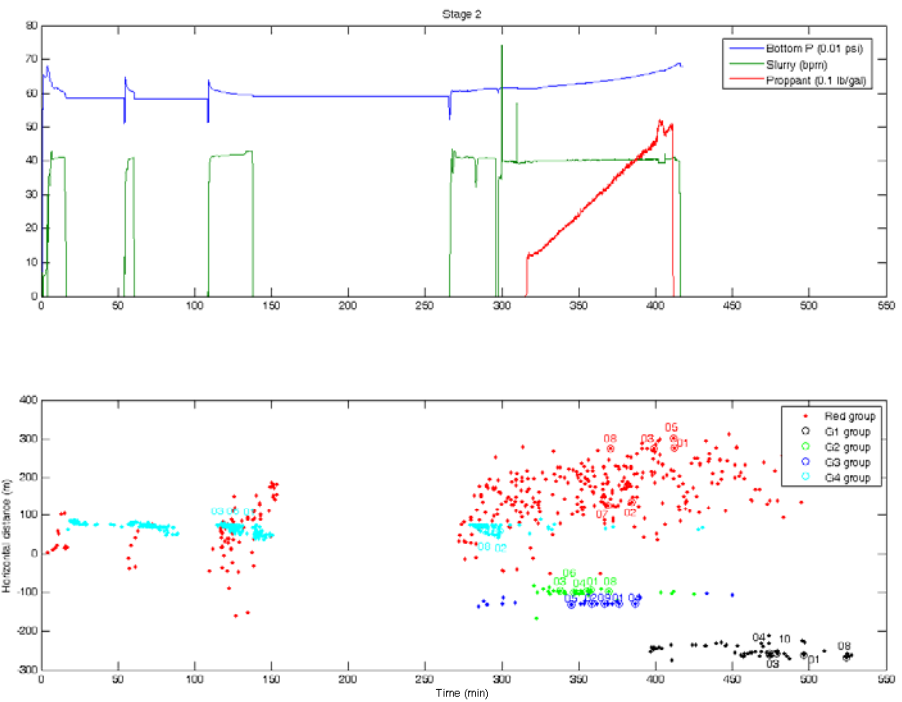
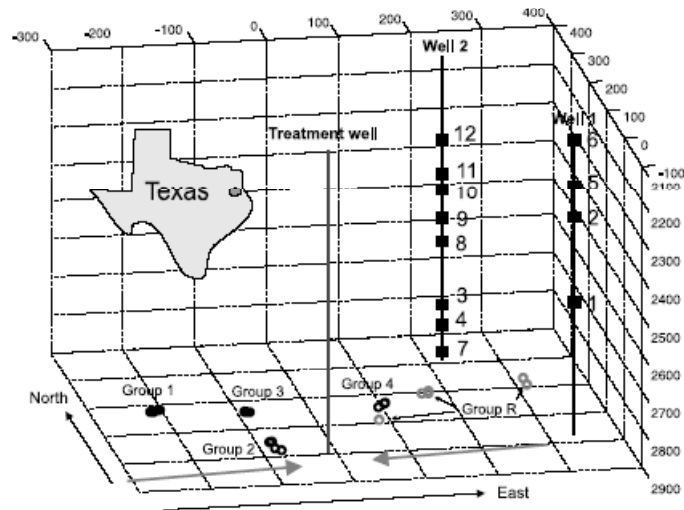


Fig. 5. Cross-sectional view of the modeled fault geometry at 785 m depth in the INAG III-9 well.

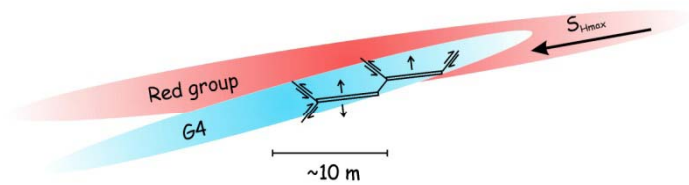
The stress anomalies are reproduced if the shear stress along the plane is completely released over a 20 m fracture length. No seismic event with such a magnitude has been detected by the monitoring system

Un exemple de fracturation hydraulique: l'expérience de Cotton Valley au Texas

(Sileny et al., JGR, 2009)

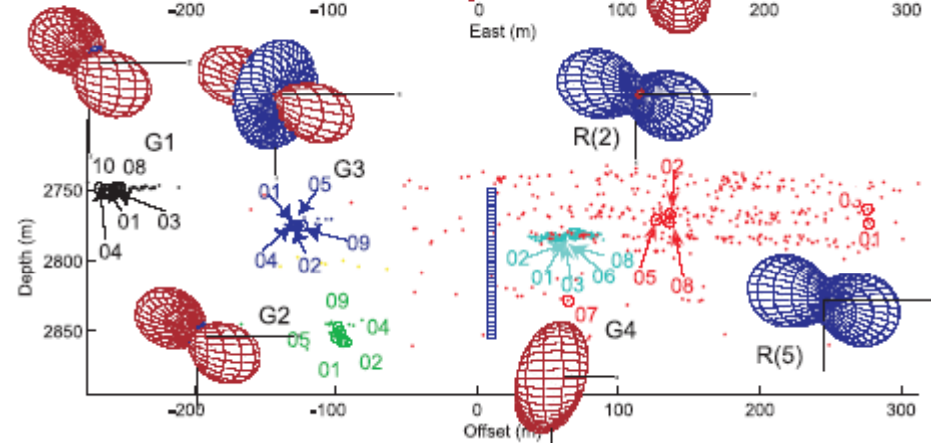
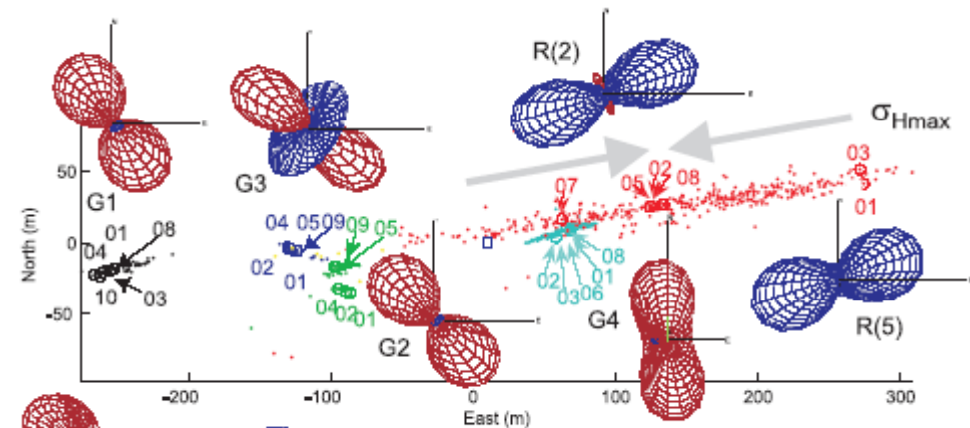


Diagrammes de radiation observés et model proposé



Model de rupture satisfaisant les diagrammes de radiation des diverses sources

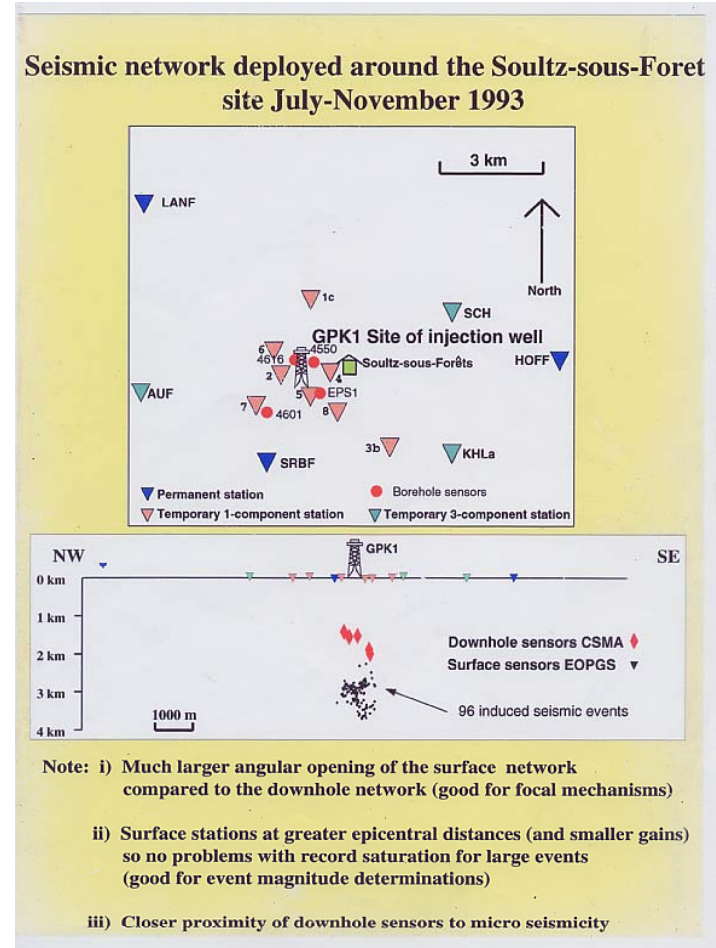
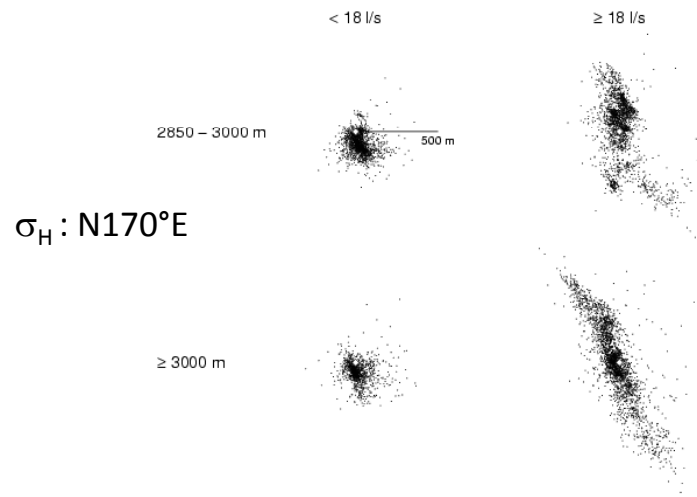
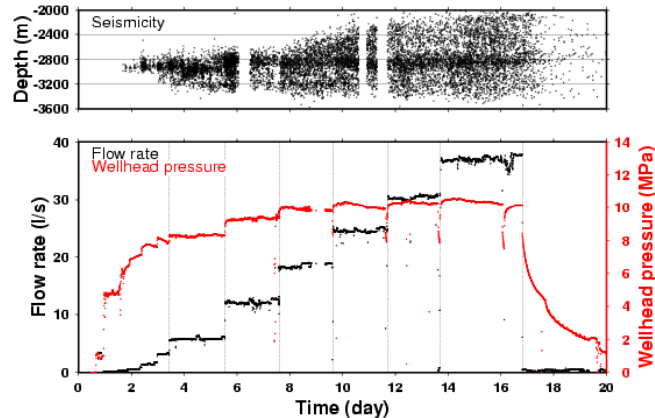
Vue de dessus



Vue en coupe verticale

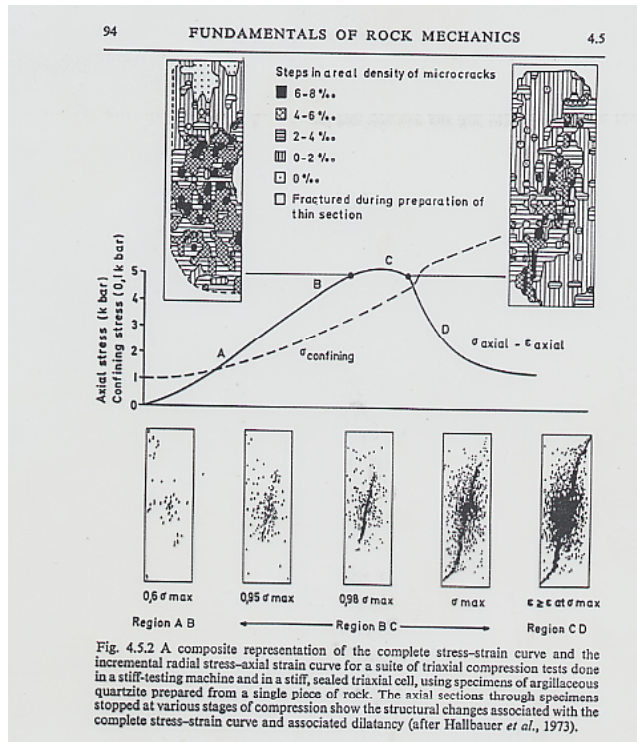
The European Experimental Enhanced Geothermal site at Soultz; the 1993 stimulation.

Cornet et al., IJRMMSc, 2007



From laboratory experiments to field data : models for fluid induced seismicity

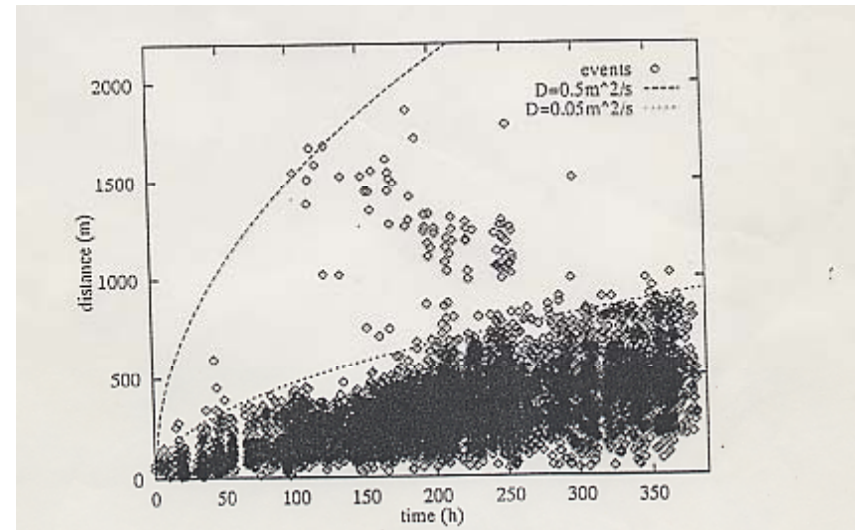
- Acoustic emission during Laboratory triaxial testing of intact rock specimen



After Jaeger and Cook, 1979

- Kaiser effect and fluid diffusion in rock masses may help understand the rate of growth of the seismic cloud (Shapiro *et al.*, 1997)

$$\sigma' = \sigma - P I$$

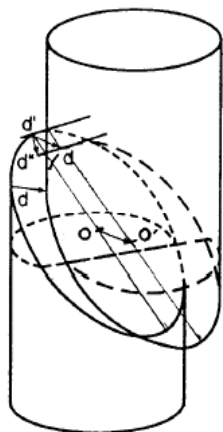


$$r = \sqrt{4\pi Dt}$$

- D: diffusivity; r distance of event to injection point

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

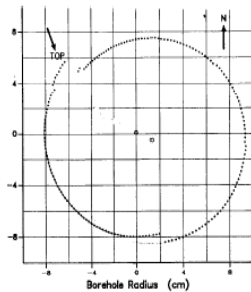
(Cornet et al., Pageoph, 1997)



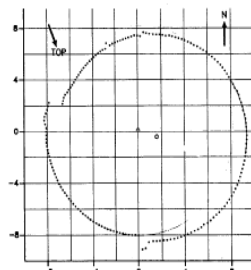
Existing fracture

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

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



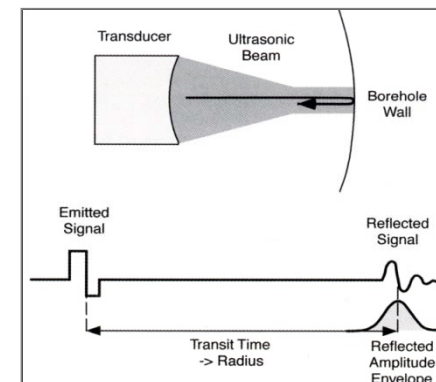
A) P = 25



B) P = 15

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).

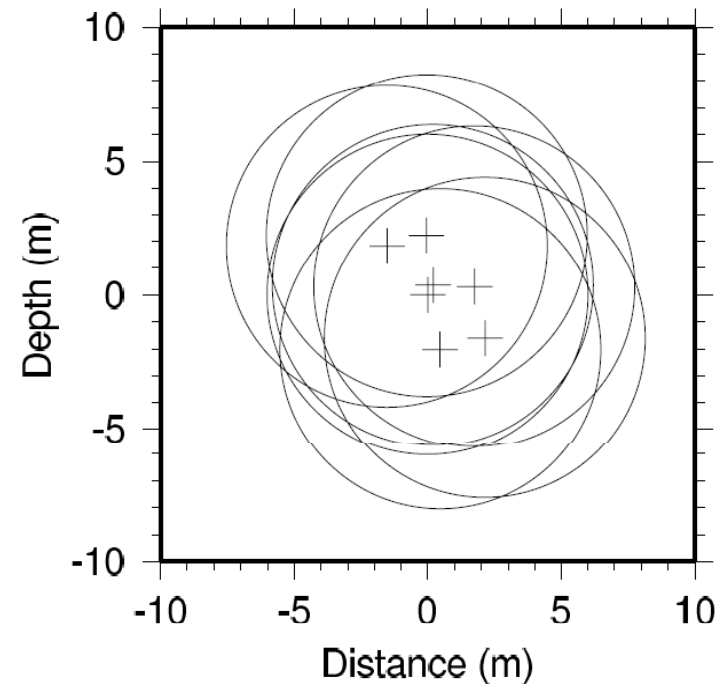
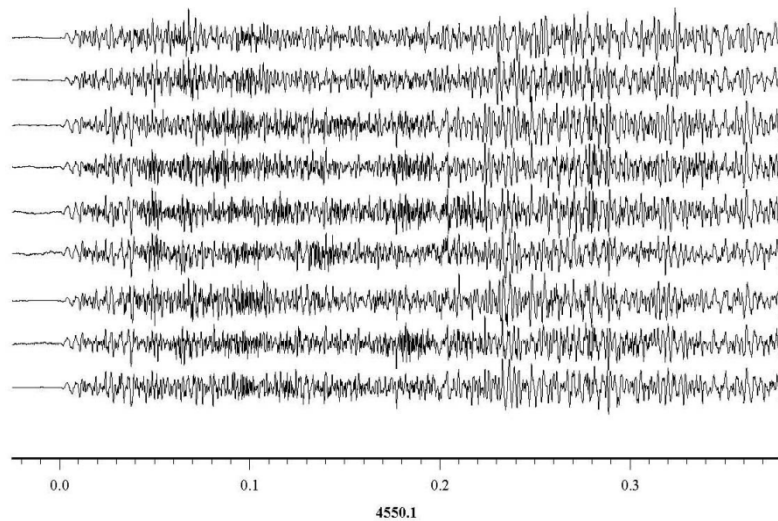
Z (m)	β	α	λ	A (cm)	ϵ_λ	ϵ_A (cm)	SX (cm)	ϵ_{SX} (cm)
2966	105	84	110	4.7	5	0.7	0.5	0.1
2867	259	62	304	2.2	3	0.1	1.45	0.07
2976	269	61	218	0.8	15	0.2	0.5	0.05
2887	298	75	271	0.85	8	0.3	0.28	0.1
2973	273	78	198	0.4	10	0.06	0.22	0.04
2925	48	86	99	4.3	13	1.3	0.5	0.14



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Analysis of microseismic “multiplets” associated with these aseismic shear motions

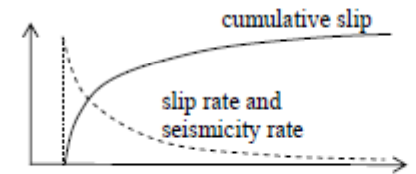
(Bourouis & Bernard, GJI, 2006)



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

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Comparison between seismic and aseismic motion for one of the faults



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

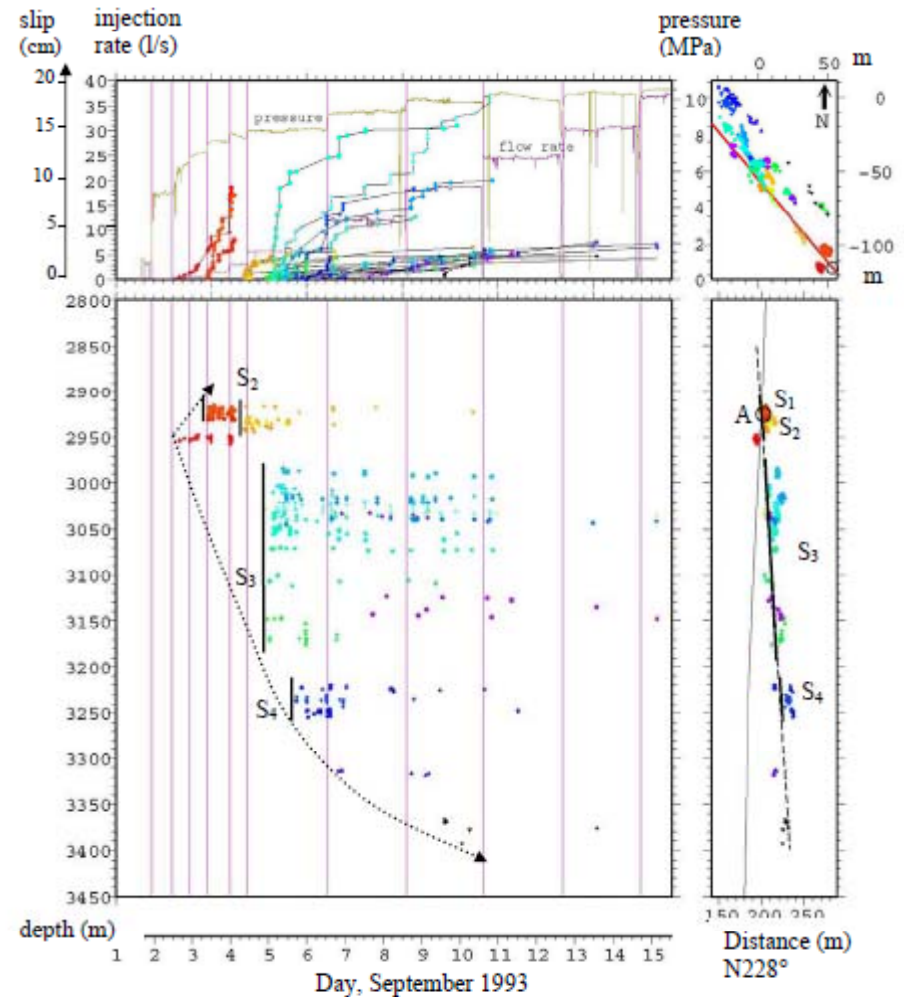
An important missing parameter is the fluid pressure magnitude at the location of each asperity.

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 ?

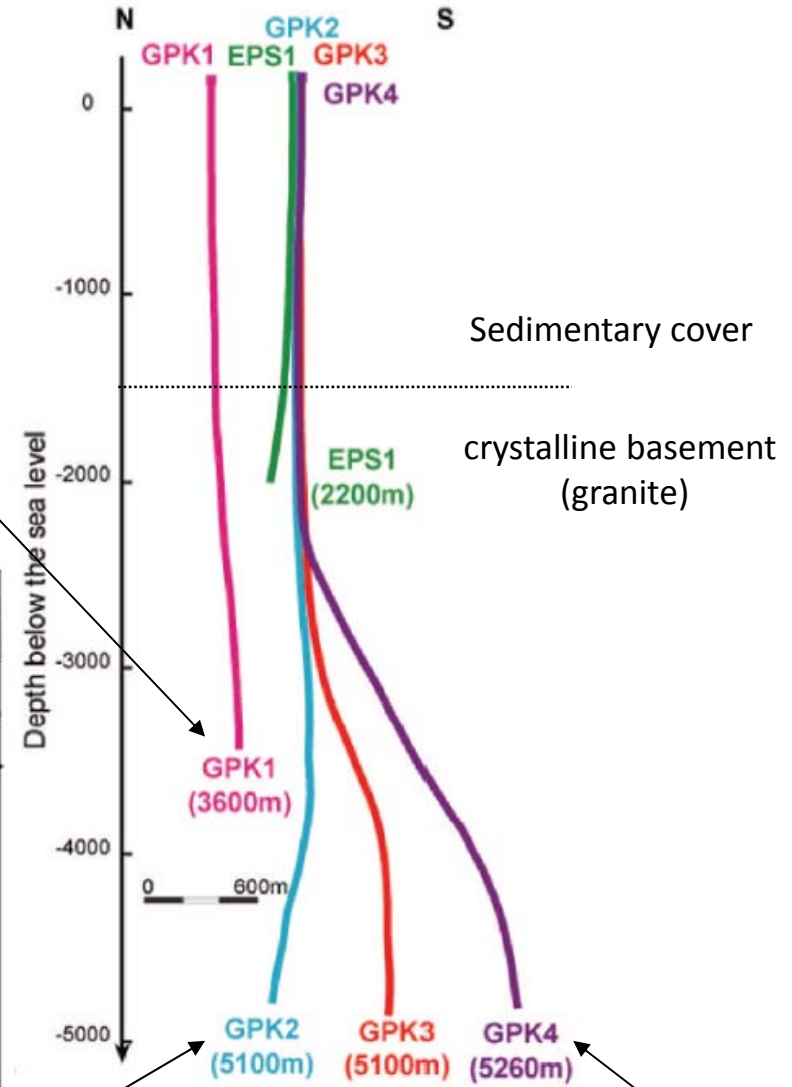
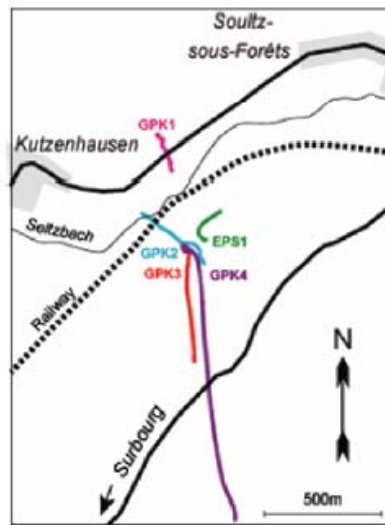


The Soultz Site today

Present situation: four wells have been drilled.

All the wells have been stimulated by large progressive hydraulic injections at different depths and different periods to increase their connectivity.

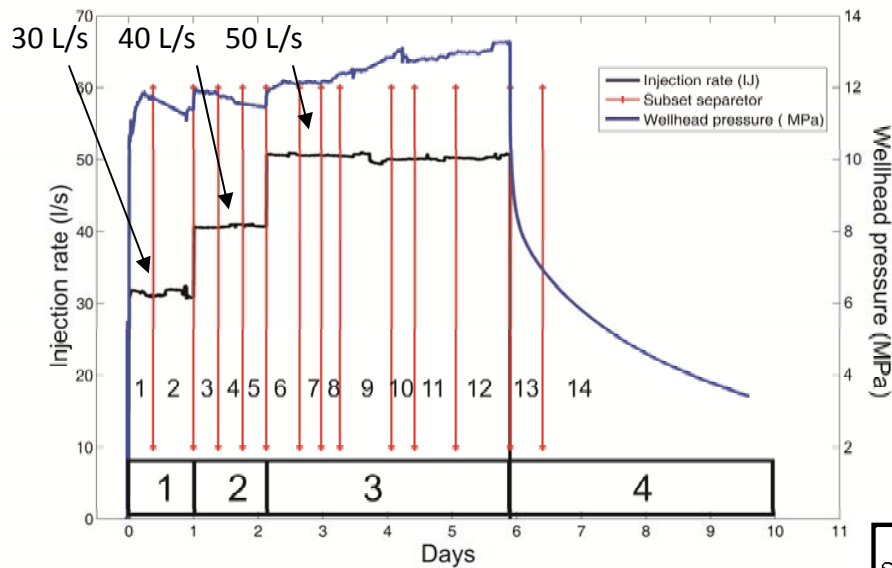
Stimulated in 1993 at 2850-3600m



Stimulated in 1995 and 1996 at 3200-3800 m and in 2000 at 4400-5000 m

Stimulated in 2003 at 4487-5100 m

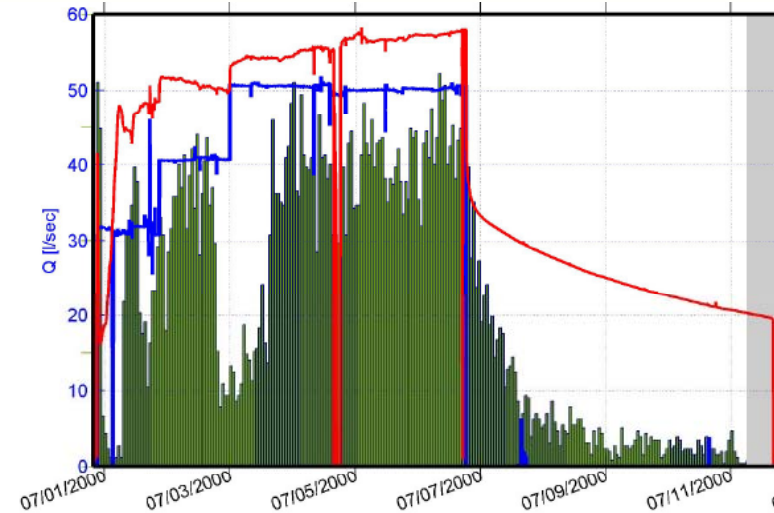
Stimulated in 2004 and 2005 at 4479-5000m



Time domains seismic tomography with data sets adapted to the injection parameters. (Calo' et al., JGI, 2011)

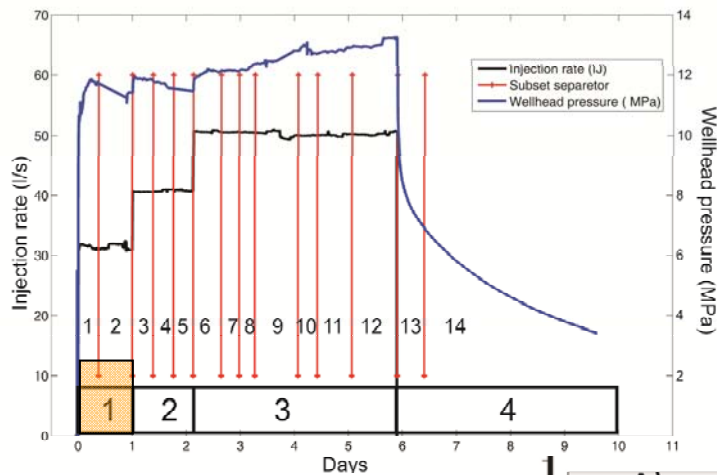
We decided to apply the tomographic method to fourteen not-equally populated sets to better fit the sub set separation with the hydraulic parameters of the injected fluids (injection rate and wellhead pressure).

Data and subset selection



Subset	Time period range	N. events	abs. P phases	abs. S phases	diff. P data	diff. S data
1	06/30 h 19:15	300	3131	1162	32839	9167
	07/01 h 03:40					
2	07/01 h 03:41	600	6443	1874	65316	15351
	07/01 h 18:39					
3	07/01 h 18:39	630	5807	2105	59163	17907
	07/02 h 03:50					
4	07/02 h 03:50	490	6807	1782	43582	14809
	07/02 h 12:57					
5	07/02 h 12:58	240	2246	674	23429	6324
	07/02 h 21:39					
6	07/02 h 21:46	490	4382	900	44049	6402
	07/03 h 10:04					
7	07/03 h 10:04	550	5836	2040	59341	17470
	07/03 h 18:06					
8	07/03 h 18:07	540	5745	2068	58460	17391
	07/04 h 10:25					
9	07/04 h 10:32	780	7192	2545	71515	22830
	07/04 h 20:11					
10	07/04 h 20:12	480	4493	1344	47121	12977
	07/05 h 04:45					
11	07/05 h 04:47	600	6701	2469	63488	20140
	07/05 h 20:06					
12	07/05 h 20:07	780	8659	3440	81361	20140
	07/06 h 16:10					
13	07/06 h 16:10	285	3213	1328	28826	11296
	07/07 h 04:18					
14	07/07 h 04:32	450	5098	1951	43835	13977
	07/11 h 00:55					

The whole period of the injection test has been divided into four main phases; 3 during the stimulation and 1 post-stimulation



PHASE 1

Set 1 and 2

injection rate: 30 L/s

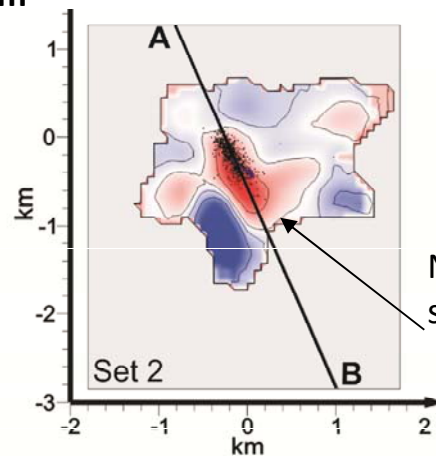
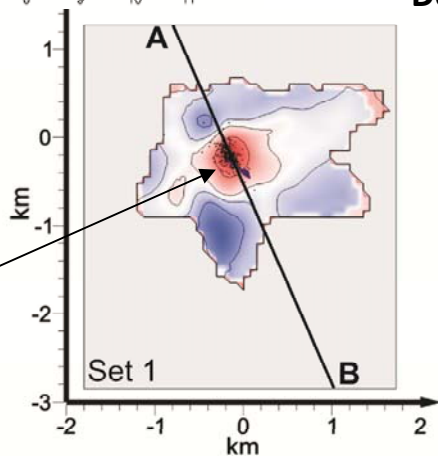
Total Nb of events : 900

Duration: 24 h.

Volume of fluids injected: 2592 m³

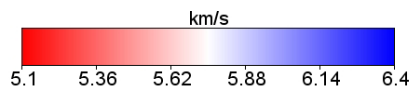
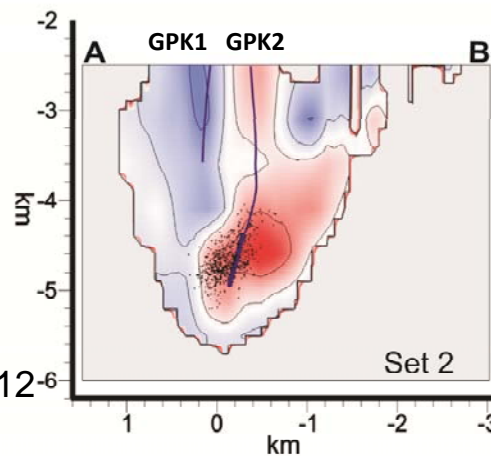
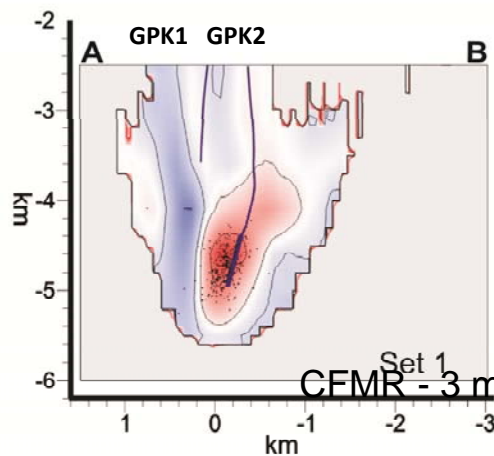
Results from the seismic tomography; GPK2, 2000 at Soultz. Calò et al., JGI, 2011

Depth 4.6 km

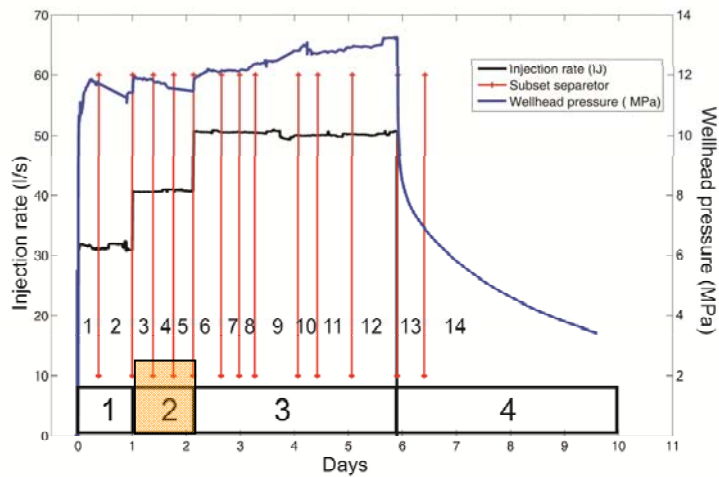


NNW-SSE elongated shape of Low Vp

8 hours after the stimulation began. Low Vp with circular shape



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PHASE 2

Set 3, 4 and 5

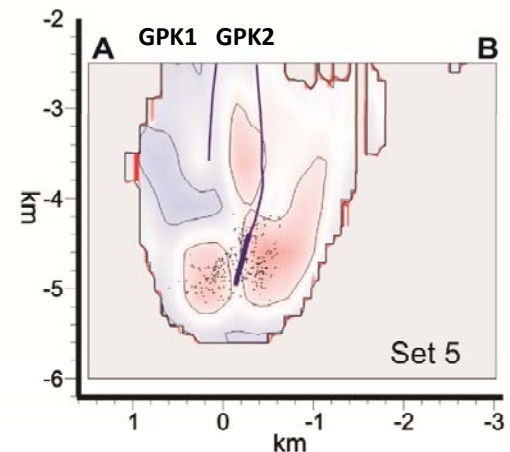
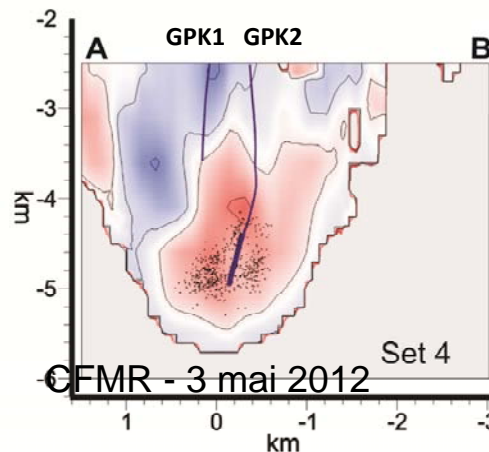
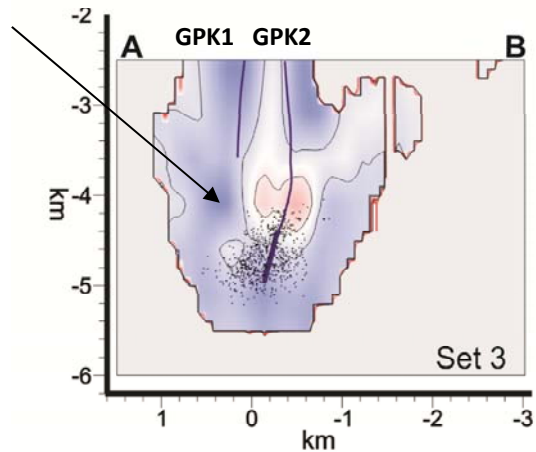
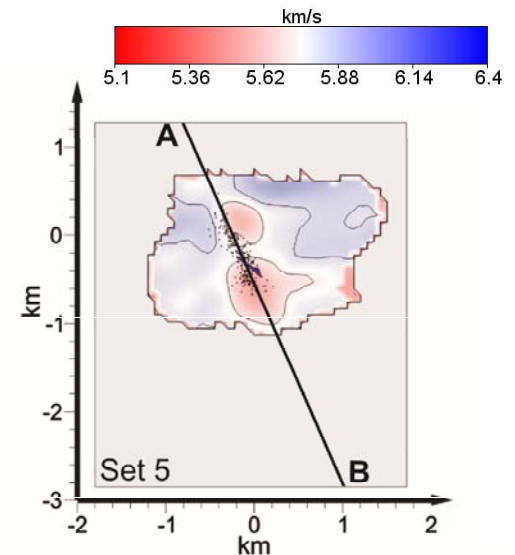
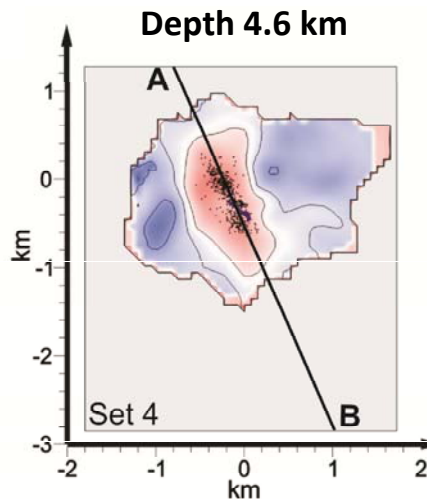
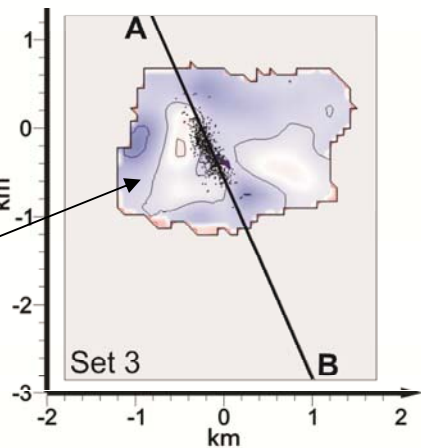
injection rate: 40 L/s

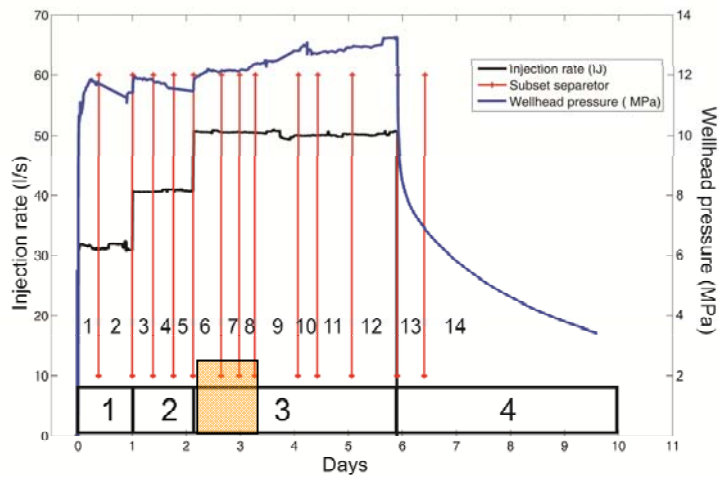
Total Nb of events : 1360

Duration: 27 h.

Volume of fluids injected: $2592 + 3888 = 6480 \text{ m}^3$

9 hours after injected flow rate changed, Low Vp almost absent at depth of the stimulation. Consistent with non seismic shear stress drop.





PHASE 3 (1)

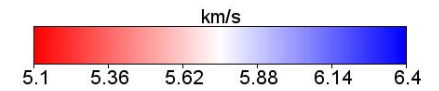
Set 6-8

injection rate: 50 L/s

Total Nb of events : 4220

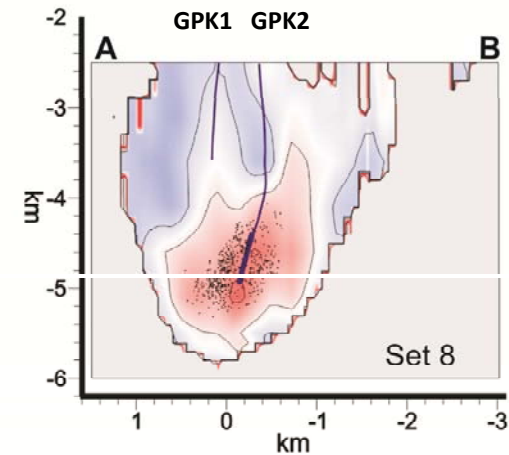
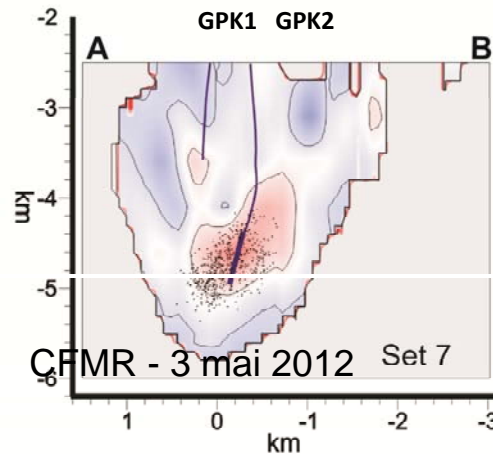
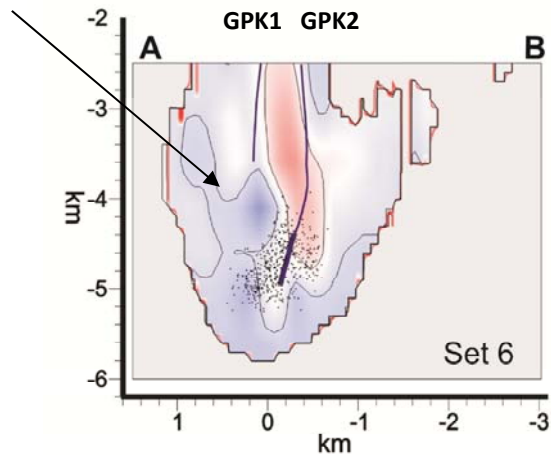
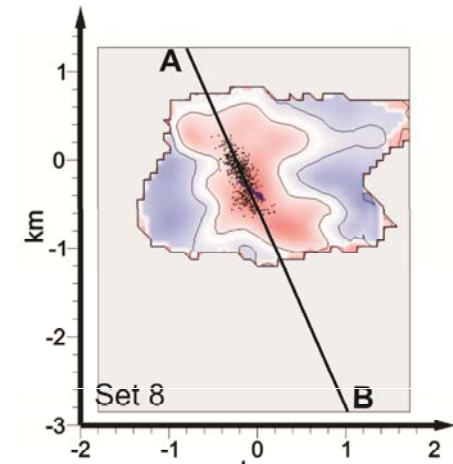
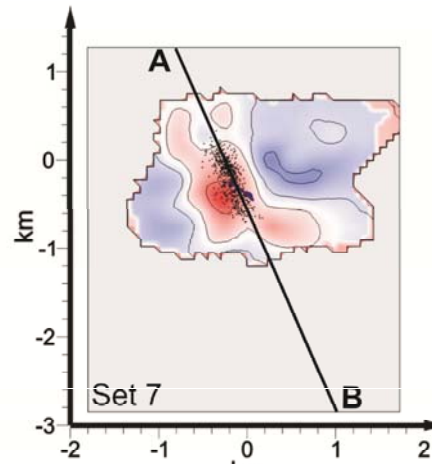
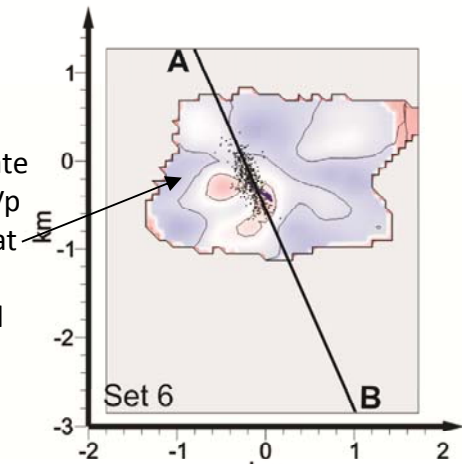
Duration: 90 h.

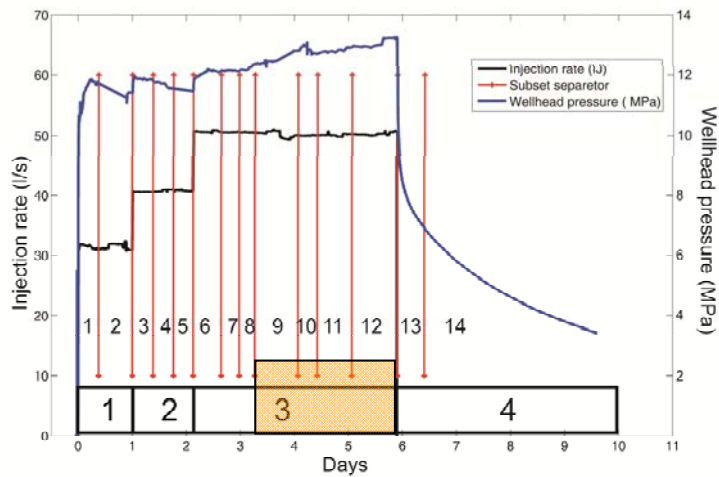
Volume of fluids injected: $2592 + 3888 + 16200 = 22680 \text{ m}^3$



Depth 4.6 km

12 hours after injected flow rate changed. Low Vp almost absent at depth of the stimulation and its migration toward shallow depths.





PHASE 3 (2)

Set 9-12

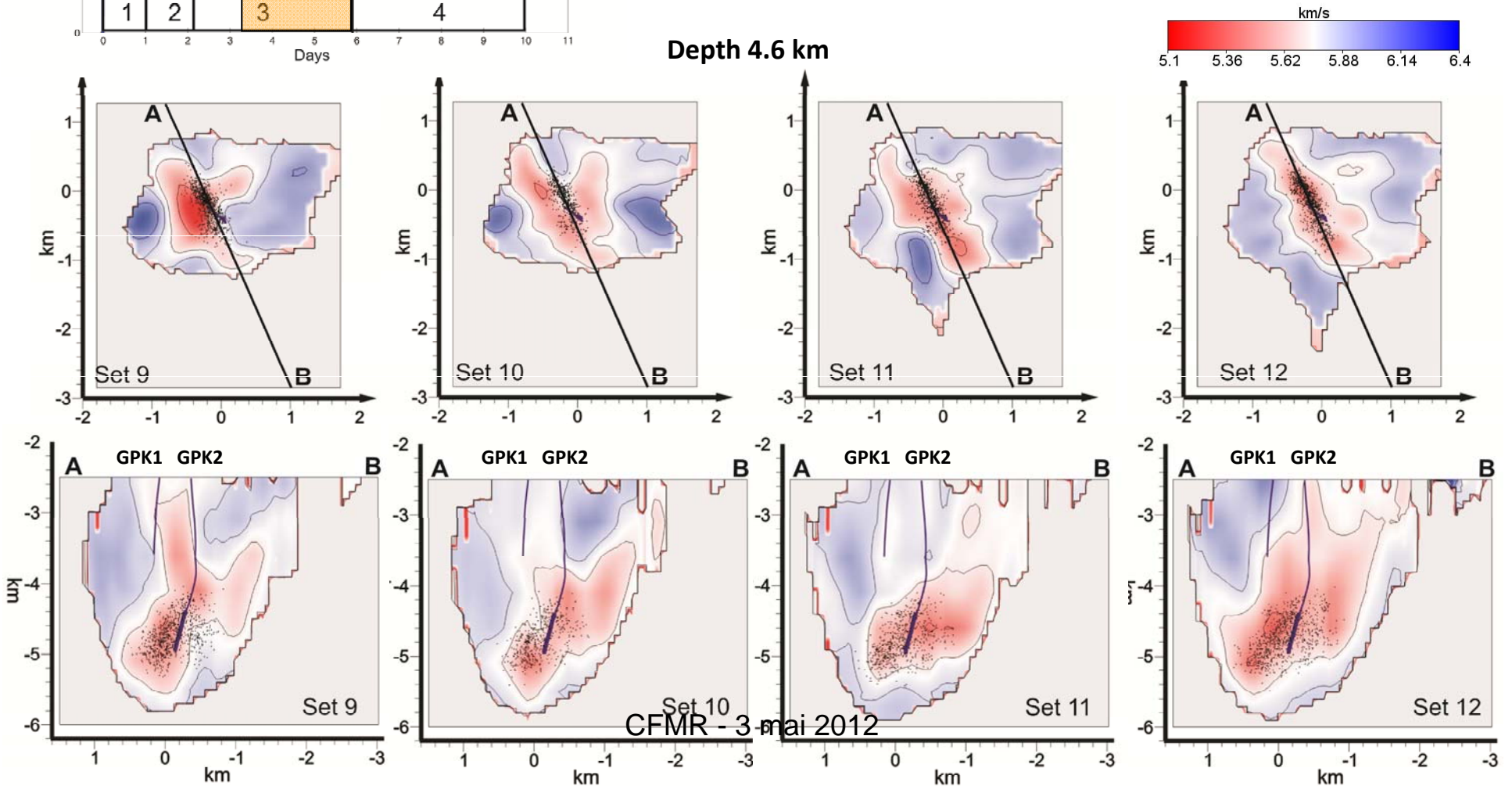
injection rate: 50 L/s

Total Nb of events : 4220

Duration: 90 h.

Volume of fluids injected: $2592 + 3888 + 16200 = 22680 \text{ m}^3$

Depth 4.6 km



Estimation de la magnitude maximum des événements susceptibles d'être induits

Sismicité induite et sismicité déclenchée (induced and triggered seismicity)

- Le cas de Soultz : magnitude 2.9 10 jours après la fin de l'injection.
- Le cas de Bäle : magnitude 3.2, un mois après que le système ait été drainé.
- Rappel de Koyna Dam (1964) magnitude 6.4
- Séisme de Wenchuan (2009) magnitude 7.2

Criticalité de l'état de chargement:

- A Soultz 3 Mpa (effet Kaiser), 8 Mpa : déclenchement de fractures fraîches
- A Aigion (golfe de Corinthe) qq kPa, à la bonne fréquence (de l'ordre de 20 secondes) déclenchent des glissements sur la faille.
- Modélisation des perturbations sismiques et asismiques induites par l'injection
- Suivi continu des injections dans un large spectre de fréquences

Conclusions

- Le suivi microsismique des injections de fluide poursuit plusieurs objectifs:
 - Détermination des volumes perturbés par l'injection et de leur croissance dans le temps. Le suivi temps réel dépend du système d'observation
 - Evaluation des caractéristiques hydrauliques à grande échelle du système fluide roche concerné; Nécessité de prendre en compte les couplages hydro-thermo-chimio-mécanique dans différents domaines de fréquence, y compris les très longues périodes (mois, voir années ?).
 - Détermination des instabilités maximum susceptibles d'être associées à ces perturbations. Nécessite une meilleure connaissance de la notion de « criticalité » et des lois de frottement dynamique.