Induced microseismic activity at the Soultz-sous-Forêts EGS site: Main scientific results obtained in different experimental conditions.

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ECGS Workshop on Induced Seismicity – Luxembourg – November 15-17, 2010

Outline:

- The EGS site of Soultz-sous-Forêts
- Seismological networks
- Seismicity during drilling
- Seismicity during hydraulic and chemical stimulations
- Seismicity during circulation tests
- Use of seismic data
- Conclusions

The Soultz EGS project – Project's partners

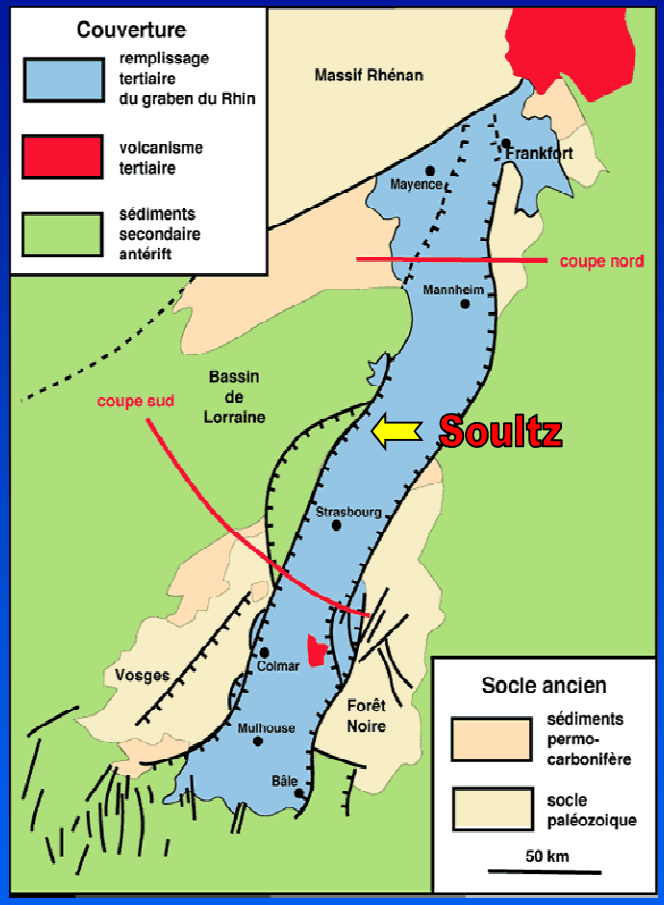
GEIE "Exploitation Minière de la Chaleur"
EEIG "Heat Mining

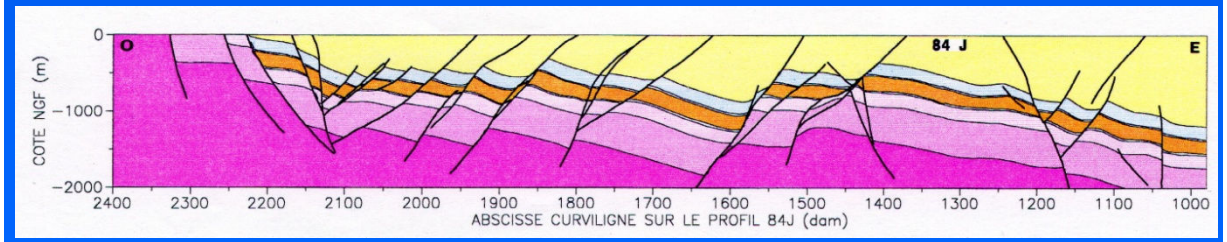
Industrial Partners

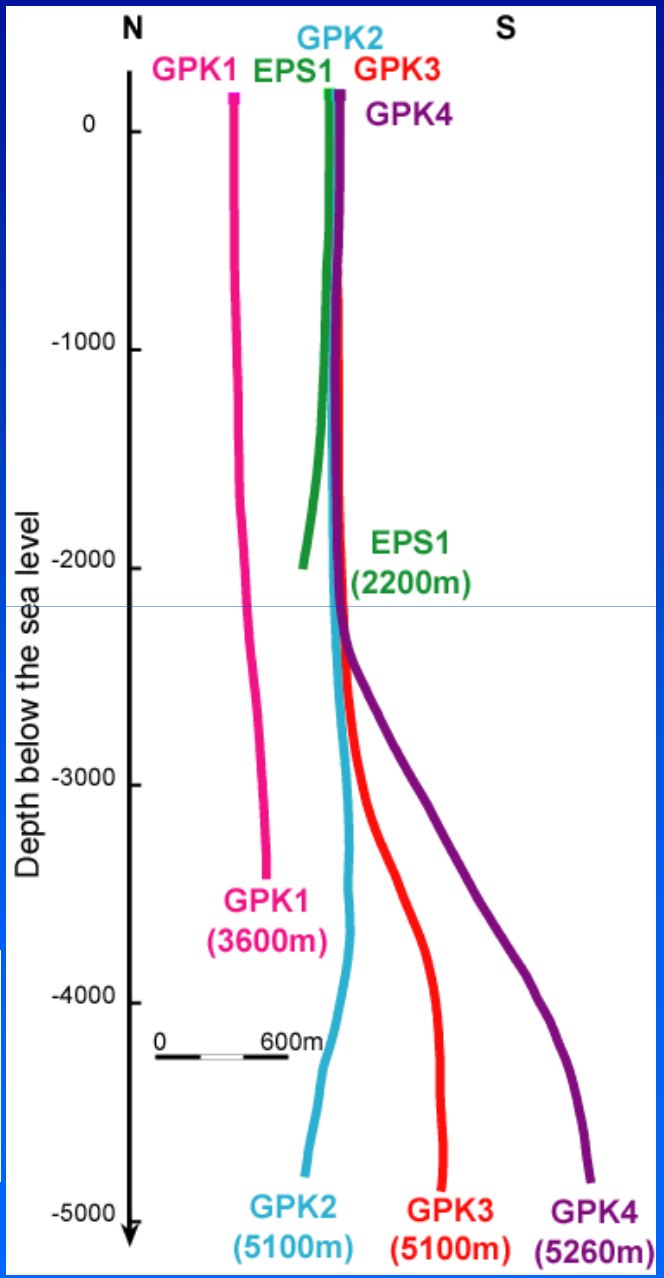
Public Funding

Scientific Partners

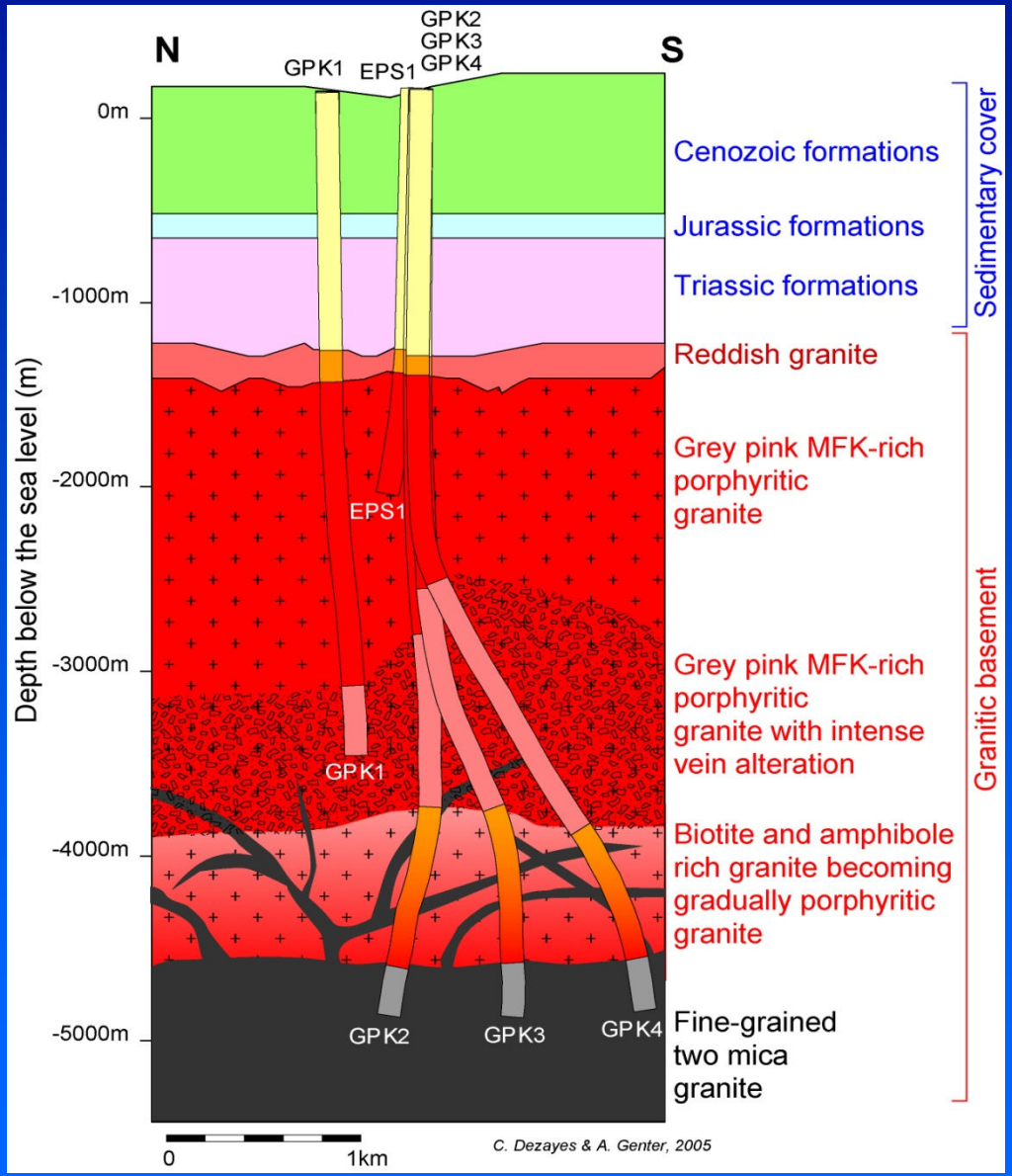
The Soultz EGS project – Location and boreholes





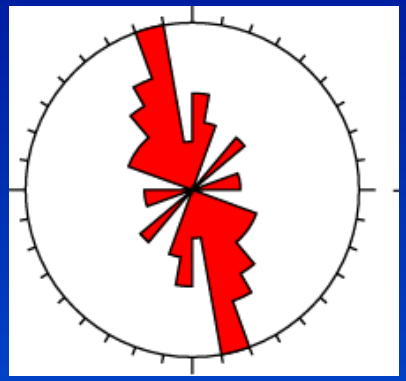


The Soultz EGS project – Synthetic geological profile

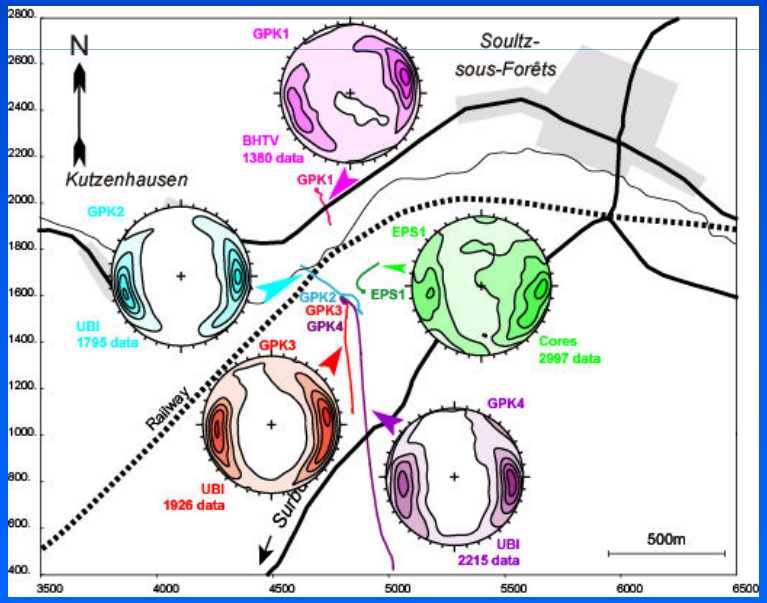


The Soultz EGS project – Fracture network

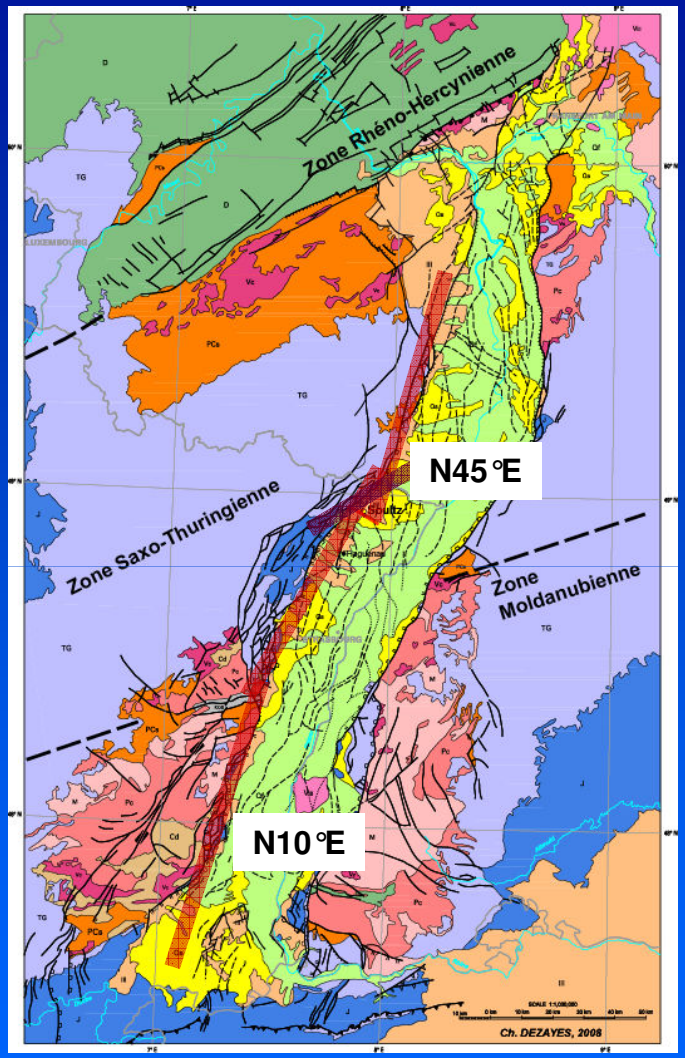
Fracture zones



N160°E±10°

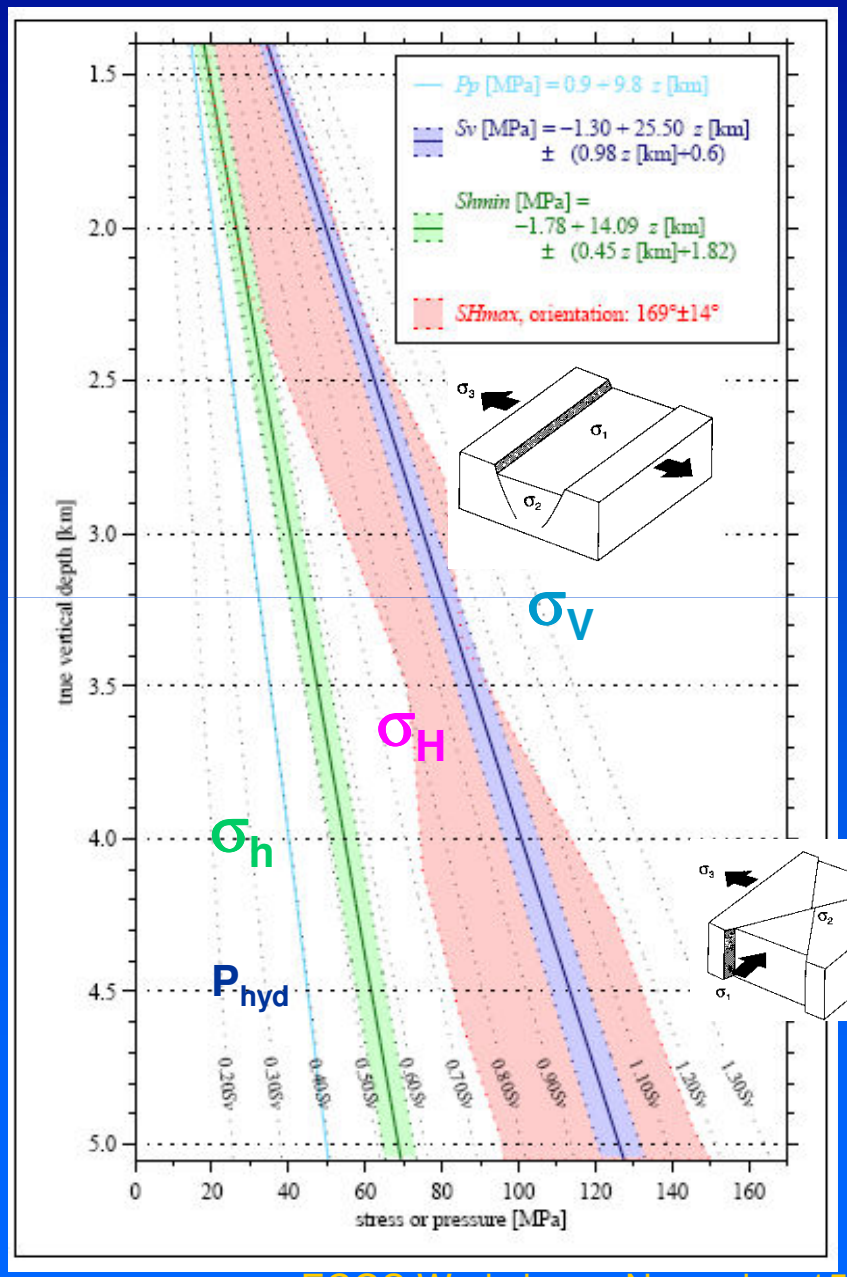


Dezayes *et al.*, 2005



The Soultz EGS project – Stress field

From Valley, 2007



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The Soultz EGS project – Main project steps

Géothermie Soultz

1987 – 1991

Exploration phase

- Drilling GPK1 at - 2000 m
- Coring EPS1 at - 2227 m

1991 – 1998

Creation of the 2 wells system GPK1/GPK2 at - 3600 m

- Deepening of GPK1 at - 3600 m and stimulation
- Drilling of GPK2 at - 3880 m and stimulation
- Circulation test between the 2 wells (4 months)

1999 – 2007

Creation of the 3 wells system GPK2/GPK3/GPK4 at - 5000 m

- Deepening of GPK2 at - 5080 m and stimulation
- Drilling of GPK3 at - 5100 m and stimulation
- Drilling of GPK4 at - 5270 m and stimulation
- Circulation test between the 3 wells (5 months)
- Complementary stimulations (chemical)

2007 – 2009

Construction of the first production unit ORC - 1.5 MWe

- Installation of surface equipment (turbine and generator, heat exchangers, cooling systems …)
- Installation of the LSP in GPK2 at - 350 m
- Inauguration of the power plant 13.06.2008
- Installation of the ESP in GPK4 at - 500m
- Submersible pumps tests

The Soultz EGS project – The power plant

Seismological networks

2 seismological networks: 1 downhole & 1 on surface

- **From 1991 to 2002:**

Temporary downhole stations

(accelerometers + geophones + hydrophones)

Temporary surface stations

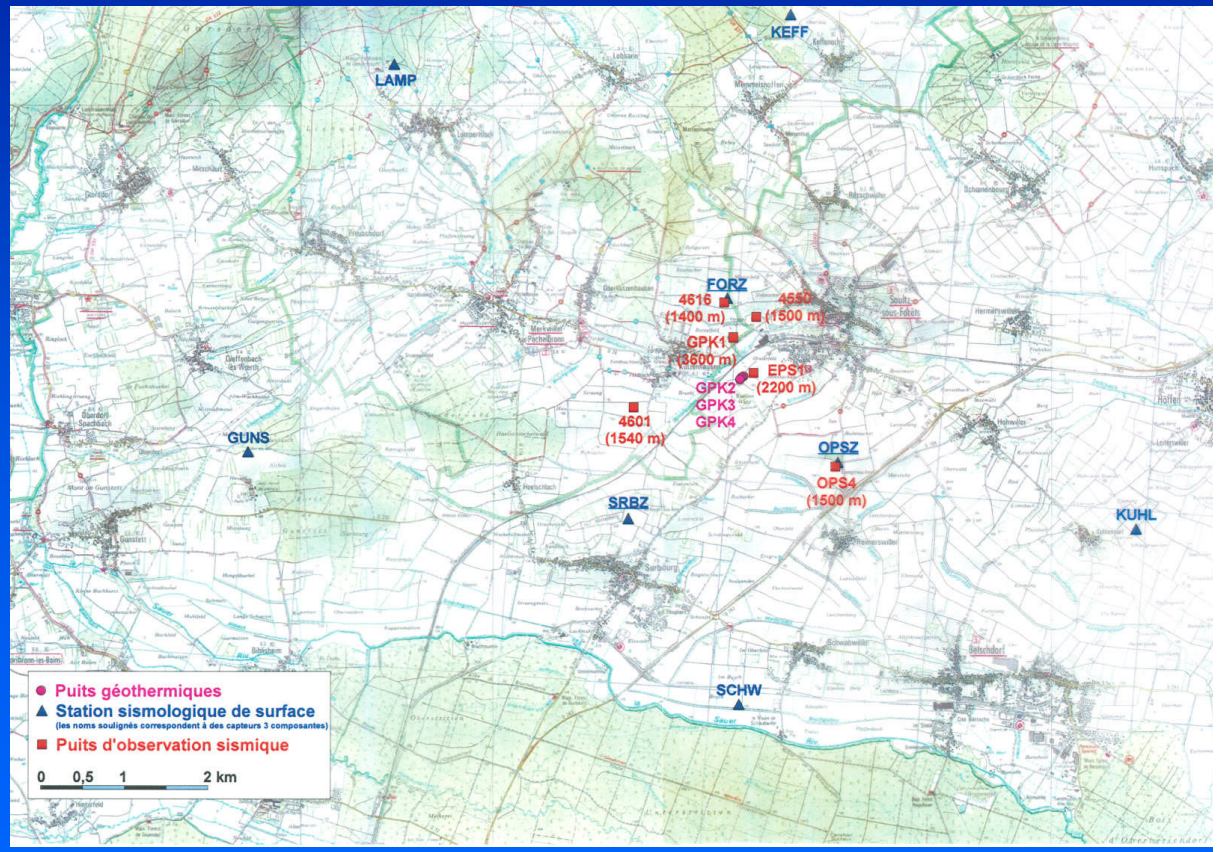
(seismometers)

- **From 2002**

Temporary downhole stations

Permanent surface stations

Temporary surface stations



Seismicity during drilling

- 2 exploration wells GPK1 & EPS1
- 3 seismic observation wells 4550, 4601 & OPS4
- 3 deep geothermal wells GPK2, GPK3 & GPK4
- around 25 km of wells drilled mostly in granite

NO EVIDENCE OF DRILLING-INDUCED SEISMICITY AT SOULTZ!!

Seismicity during hydraulic stimulations

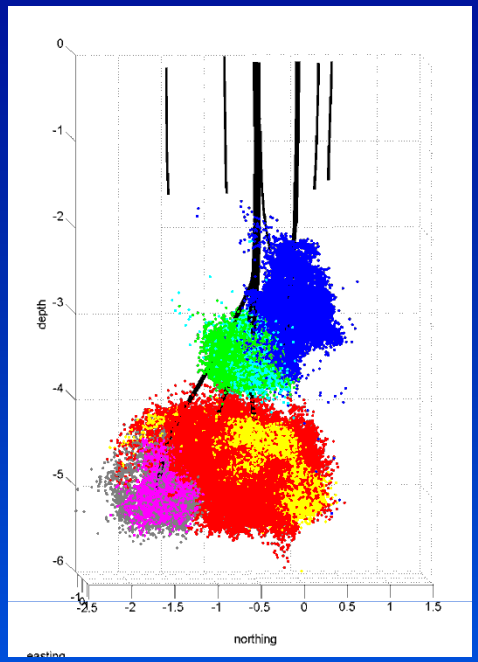
- "Upper" reservoir
  - GPK1 hydraulic stimulation 1993
  - GPK2 hydraulic stimulation 1994 & 1995
- "Lower" reservoir
  - GPK2 hydraulic stimulation 2000
  - GPK3 hydraulic stimulation 2003
  - GPK4 hydraulic stimulation 2004 & 2005

Seismicity during hydraulic stimulations

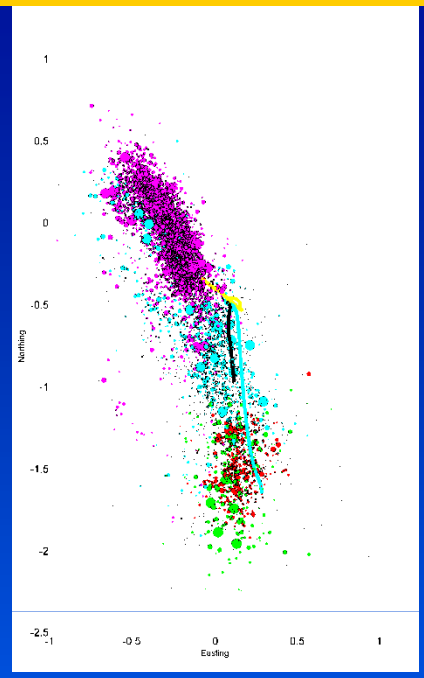
	Injected volume	Maximum flow rate	Maximum overpressure	Induced seismicity	Larger magnitude events
GPK2 (2000)	~23400 m^3	50 l/s	13 MPa	~14000 (located)	75 (M≥1.8) 1 x 2.6 2 x 2.4
GPK3 (2003)	~34000 m^3	50 l/s; 60 & 90 l/s "Focused stimulation"	18 MPa	~22000 (located)	43 (M≥1.8) 1 x 2.9 2 x 2.7
GPK4 (2004)	~9300 m^3	45 l/s	17 MPa	~5800 (located)	3 (M≥1.8) 1 x 2.0
GPK4 (2005)	~12300 m^3	45 l/s	19 MPa	~3000 (located)	17 (M≥1.8) 1 x 2.6 1 x 2.3

Seismicity during hydraulic stimulations

- Several thousands of earthquakes
- Magnitude range: -2 to 2.9
- change of hydraulic parameters → instantaneous variation of seismic activity
- Observation of large magnitude (M≥2) events occurred in the shut in phase
- From focal mechanisms: double-couple solution for all seismic events : shearing on pre-existing fracture planes. No evidence of tensile rupture (Horalek et al., 2008)

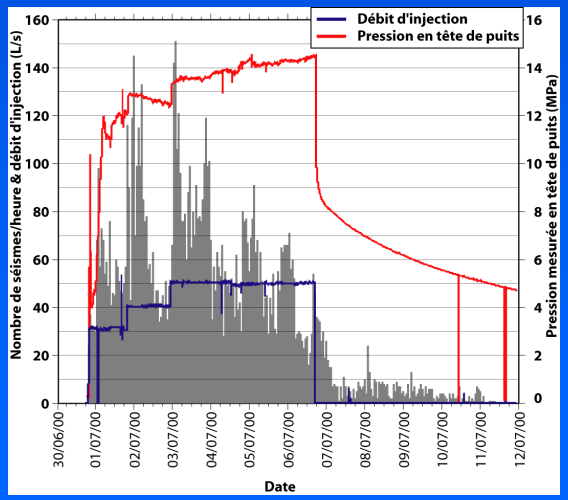


Downhole stations

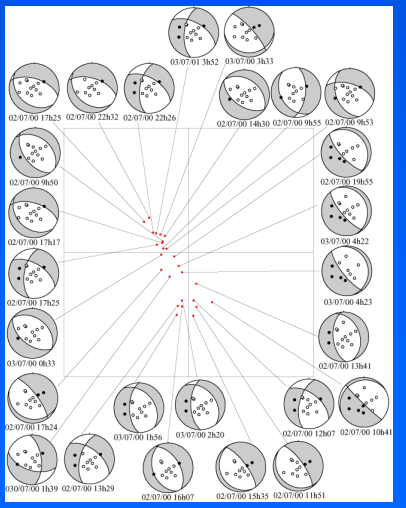


Surface stations

From Dorbath et al., 2005

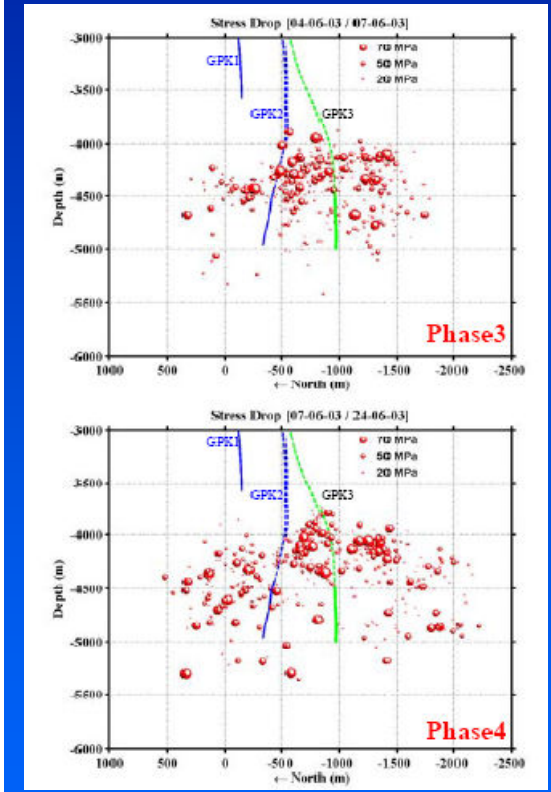


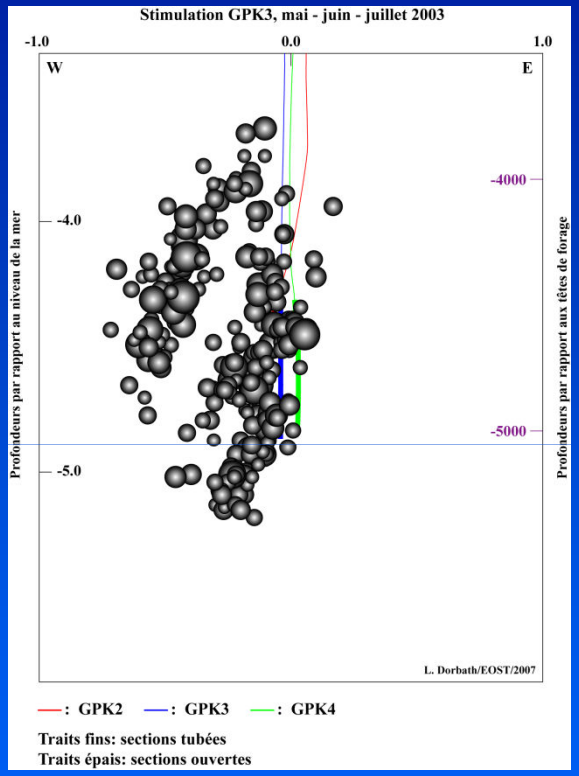
Cuenot et al., 2008

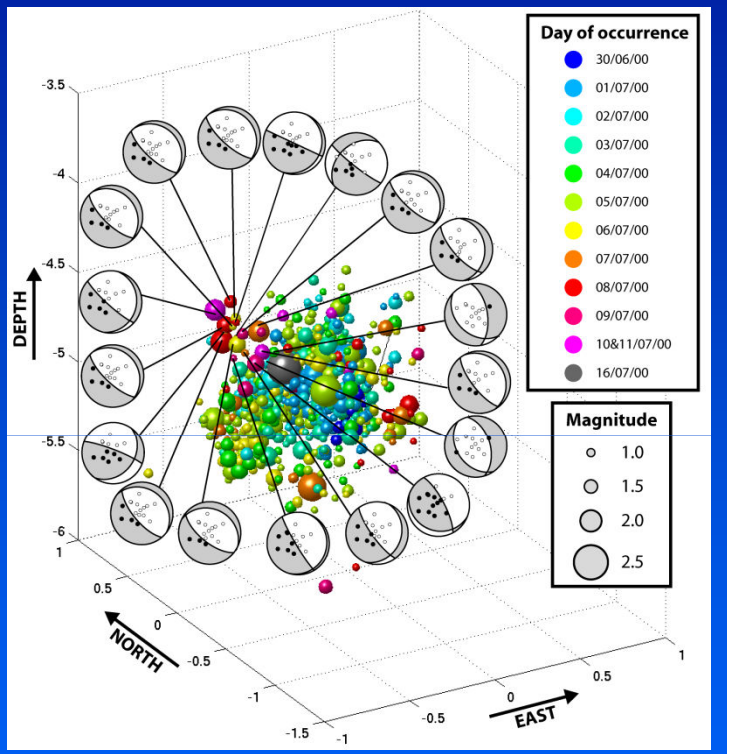


Seismicity during hydraulic stimulations

- **Stronger earthquakes : discussion between 2 explanations**





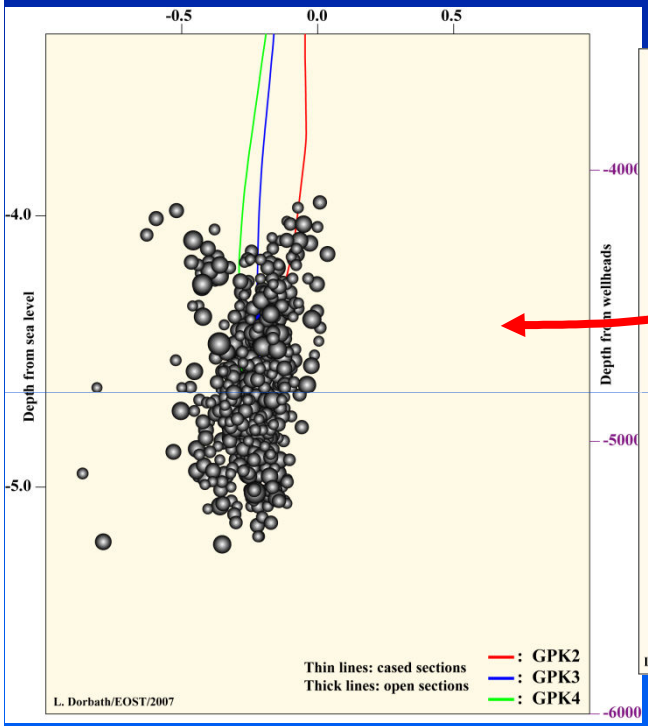


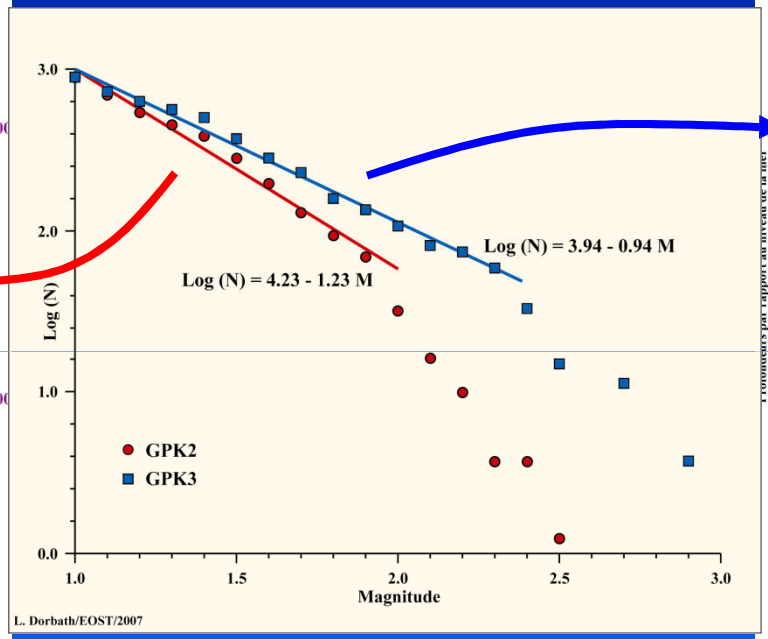
high stress drop: strong energy released on small fractures (Michelet et al, 2004)

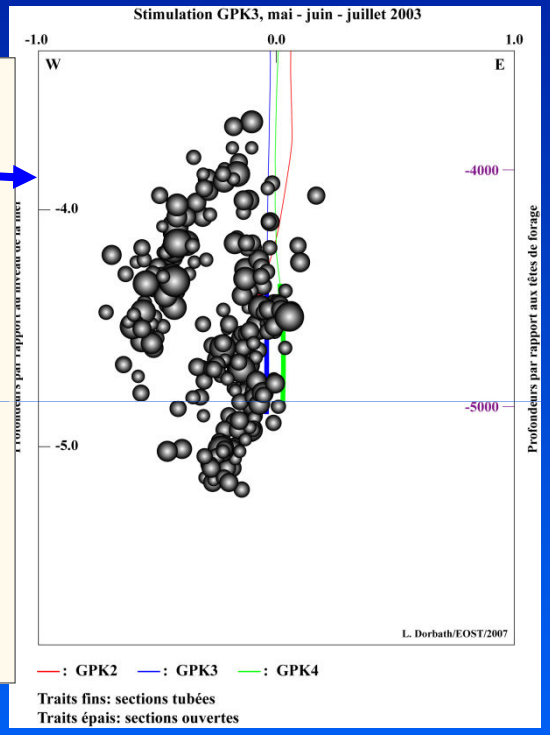
presence of large faults, able to produce seismic events of such magnitudes (Dorbath et al., 2009; Cuenot, 2009)

Seismicity during hydraulic stimulations

Efficiency of stimulation related to fracture pattern defined by seismicity







From Dorbath et al., 2009

GPK2: dense network of small to medium scale fractures

→Successful stimulation

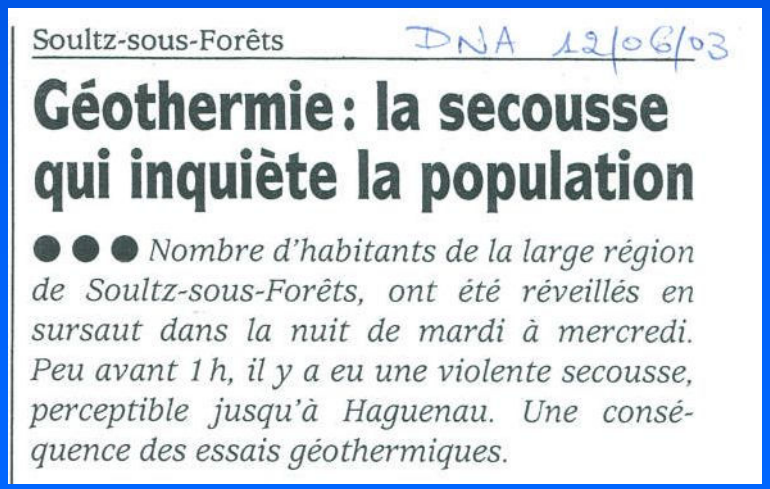
(improvement of injectivity index)

GPK3 : fault-driven seismicity

→ No significant improvement of injectivity index)

Seismicity during hydraulic stimulations

- growing fear due to:
  - the largest earthquakes (vibration, sound, moving objects)
  - repetition of felt earthquakes (within a short period and from one stimulation test to another)
- lots of phone calls (complain or ask for information)
- complaints to local authorities from individuals or associations
- articles in local newspapers
- around 30 complaints for presumed damages, which were evaluated by experts from insurance companies
- long-term risk of strong opposition to the project



Soultz-sous-Forêts DNA 12/06/03

Géothermie: la secousse qui inquiète la population

●●● *Nombre d'habitants de la large région de Soultz-sous-Forêts, ont été réveillés en sursaut dans la nuit de mardi à mercredi. Peu avant 1 h, il y a eu une violente secousse, perceptible jusqu'à Haguenau. Une conséquence des essais géothermiques.*

SOULTZ-SOUS-FORETS

La géothermie préoccupe les maires

●●● *Suite aux secousses qui se sont succédé récemment dans les environs du site géothermique de Soultz-Kutzenhausen (voir en pages régionales des DNA du 12 juin), les maires du canton de Soultz ont bousculé leur programme pour mettre à l'ordre du jour de leur réunion ce thème d'actualité qui préoccupe une partie de la population depuis quelques jours.*

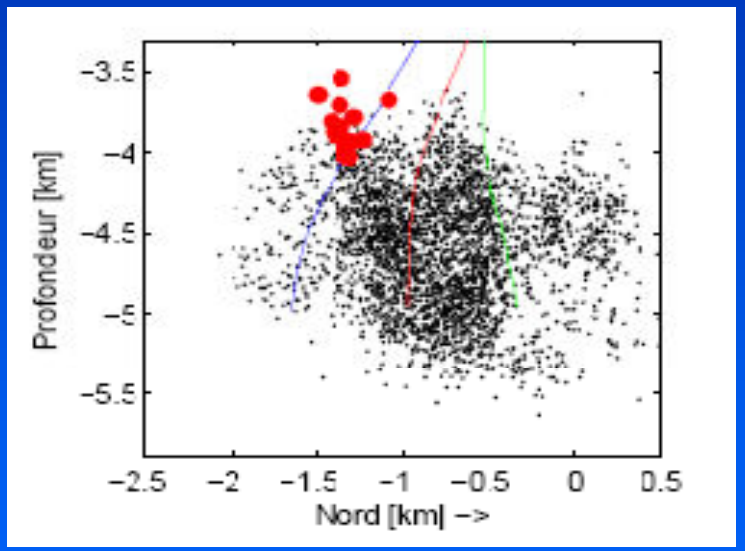
Pour répondre aux questions des élus et dissiper leurs inquiétudes, André Gérard et Pascal Vix, deux des responsables du Groupement d'Intérêt économique «Exploitation minière de la chaleur» présents dans la salle étaient accompagnés de deux experts en sismologie, en l'occurrence Catherine et Louis Dorbath, du Bureau central sismologique français situé à Strasbourg.

Après les explications d'André Gérard, quant à la nature des opérations pratiquées pour élargir les fractures contenues dans le granit à 5000 mètres de profondeur et de leurs conséquences, à savoir des déplacements de roches à peine de l'ordre du millimètre, mais aux effets pour le moins impressionnants, les sismologues ont réitéré leurs propos qui se voulaient rassurants à propos de dégâts éventuels provoqués par ces phénomènes: *«Pour des secousses inférieures à une magnitude de 3,5 sur l'échelle de Richter, nous ne faisons même pas d'enquête, elles n'ont aucune incidence sur les bâtiments».* Or la secousse enregistrée l'autre nuit n'était que de 2,9.

Toutefois, pour les gens qui estiment avoir subi un préjudice causé par ces tremblements répétés, M. Gérard ajoute: *«Ces derniers sont invités à signaler les dégâts. Des experts envoyés par l'assurance se rendront sur place pour constater les faits.»* Une visite prochaine sur le site de la géothermie a été demandée par certains élus; elle leur permettra d'en savoir davantage sur le sujet.

Seismicity during chemical stimulations

- RMA (Regular Mud Acid) in May 2006; max flow rate: 28 l/s, aiming at dissolving minerals like clay, feldspars and mica.
- Chelatants (NTA) in October 2006; max flow rate: 40 l/s, aiming at acting on calcite
- OCA (Organic Clay Acid) in February 2007; max flow rate: 55 l/s, used in high temperature medium with high clay content.



Left figure: seismicity during the RMA test

Right figure: seismicity during the OCA test

both from EOST (J. Charléty & L. Dorbath)

RMA: ~20 seismic events, highest magnitude: 1.9 (earthquake not felt)
NTA: no seismicity
OCA: ~80 seismic events, highest magnitude: 1.5

Seismicity during hydraulic circulations

1997 : circulation between GPK2 (pump-assisted production) and GPK1 (re-injection) for 4 months → NO seismicity

2005: artesian circulation between GPK2/GPK4 (production) and GPK3 (re-injection) for 6 months

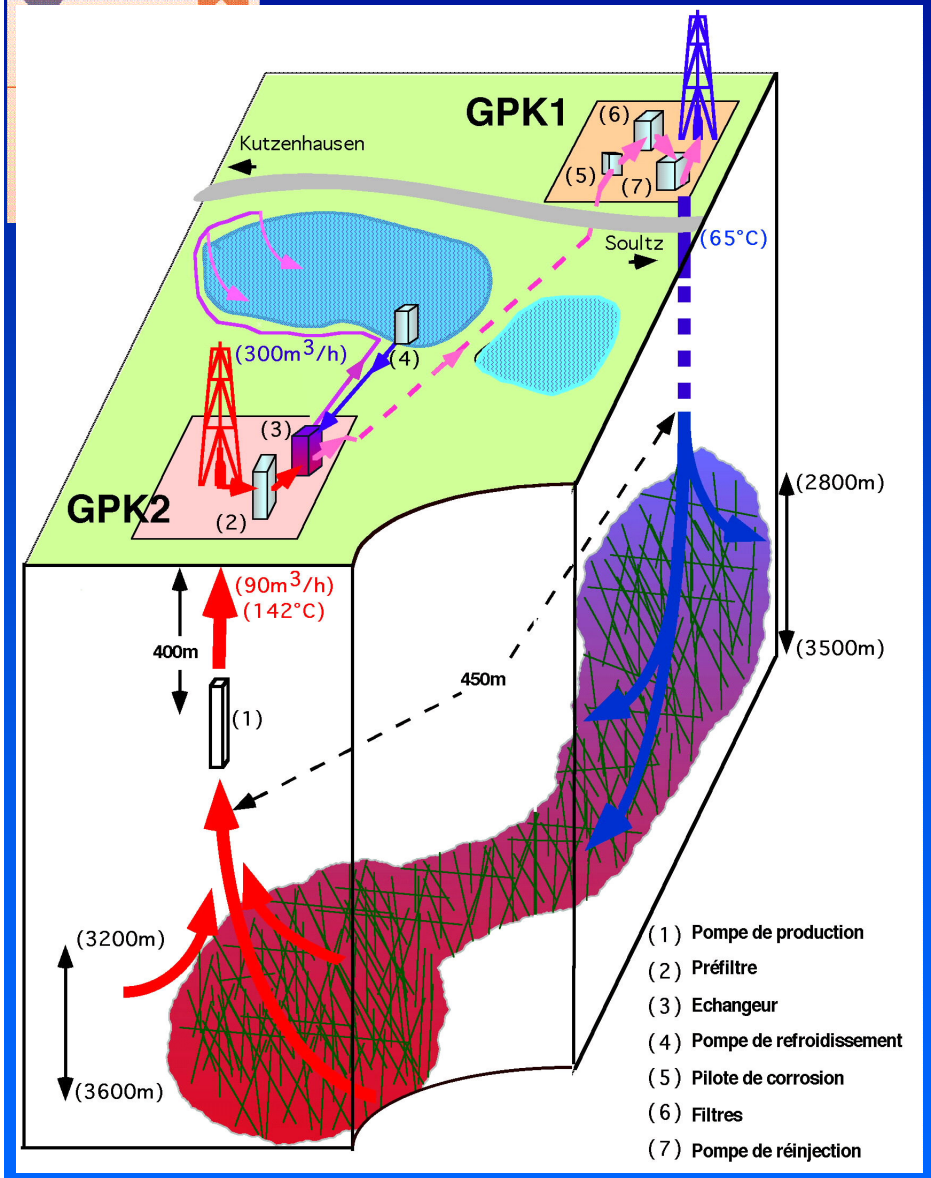
2008: circulation between GPK2 (pump-assisted production) and GPK3 (re-injection) for 2 months (July-August 2008)

2008: circulation between GPK2/GPK4 (pump-assisted production) and GPK3 (re-injection) for 2 months (November-December 2008)

2009: circulation between GPK2/GPK4 (pump-assisted production) and GPK3 (re-injection) for ~7 months (mid-March to October 2009)

2009-2010: circulation between GPK2 (pump-assisted production) and GPK3/GPK1 (re-injection) (November 2009 – October 2010)

Seismicity during hydraulic circulations



1997 GPK1-GPK2 circulation test

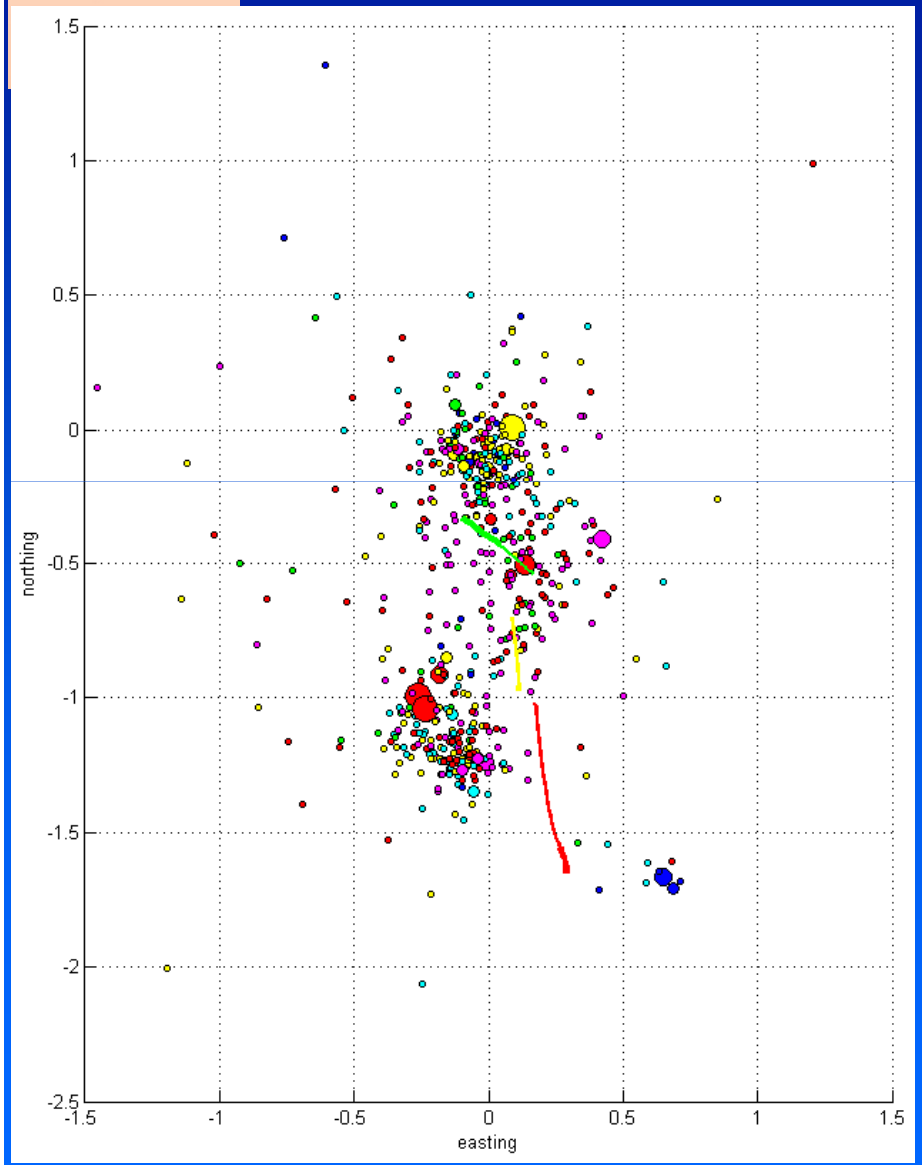
NO OBSERVED SEISMICITY!!

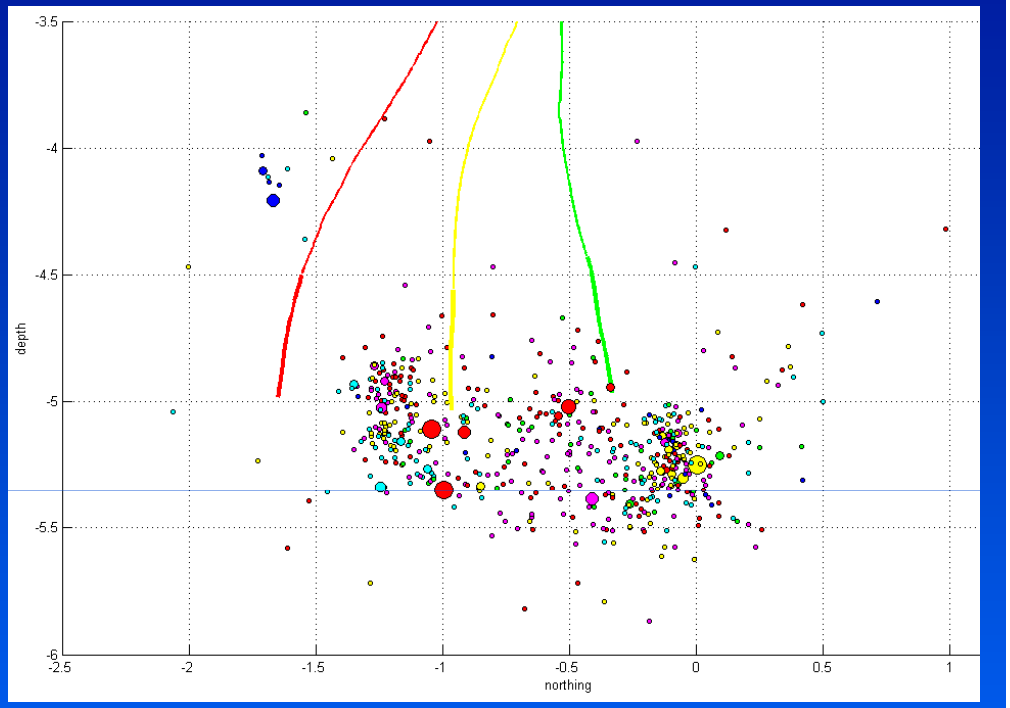
Seismicity during hydraulic circulations

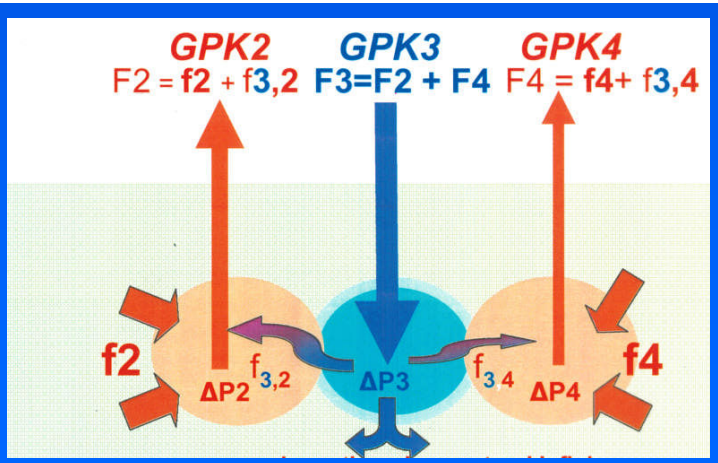
	Jul.-Dec. 2005	Jul.-Aug. 2008	Nov.-Dec. 2008	Mar.-Oct. 2009	Nov. 09-Oct. 10
GPK2 prod. flowrate	~12 $l.s^{-1}$	~25 $l.s^{-1}$	~17 $l.s^{-1}$	~20 $l.s^{-1}$ then ~22 $l.s^{-1}$	~18 $l.s^{-1}$
GPK4 prod. flowrate	~3 $l.s^{-1}$	-	~12 $l.s^{-1}$	~12 $l.s^{-1}$ then 9 $l.s^{-1}$	-
GPK3 inj. flowrate	~15 $l.s^{-1}$ then ~20 $l.s^{-1}$	~23 $l.s^{-1}$	~12 $l.s^{-1}$ then ~27 $l.s^{-1}$	~20 $l.s^{-1}$, 10 $l.s^{-1}$ then 11 $l.s^{-1}$	~15 $l.s^{-1}$
GPK3 max. pressure	4 MPa then 7 MPa	7.3 MPa	2.8 MPa then 8.6 MPa	~6 MPa	~6 MPa
GPK1 inj. flowrate	-	-	-	18 $l.s^{-1}$	~3 $l.s^{-1}$
GPK1 max. pressure	-	-	-	~0.7 MPa	~0.5 MPa
Number of earthquakes	~600	~190	53	205	~400
Highest magnitude	2.3	1.4	1.7	1.7	2.1

Seismicity during hydraulic circulations

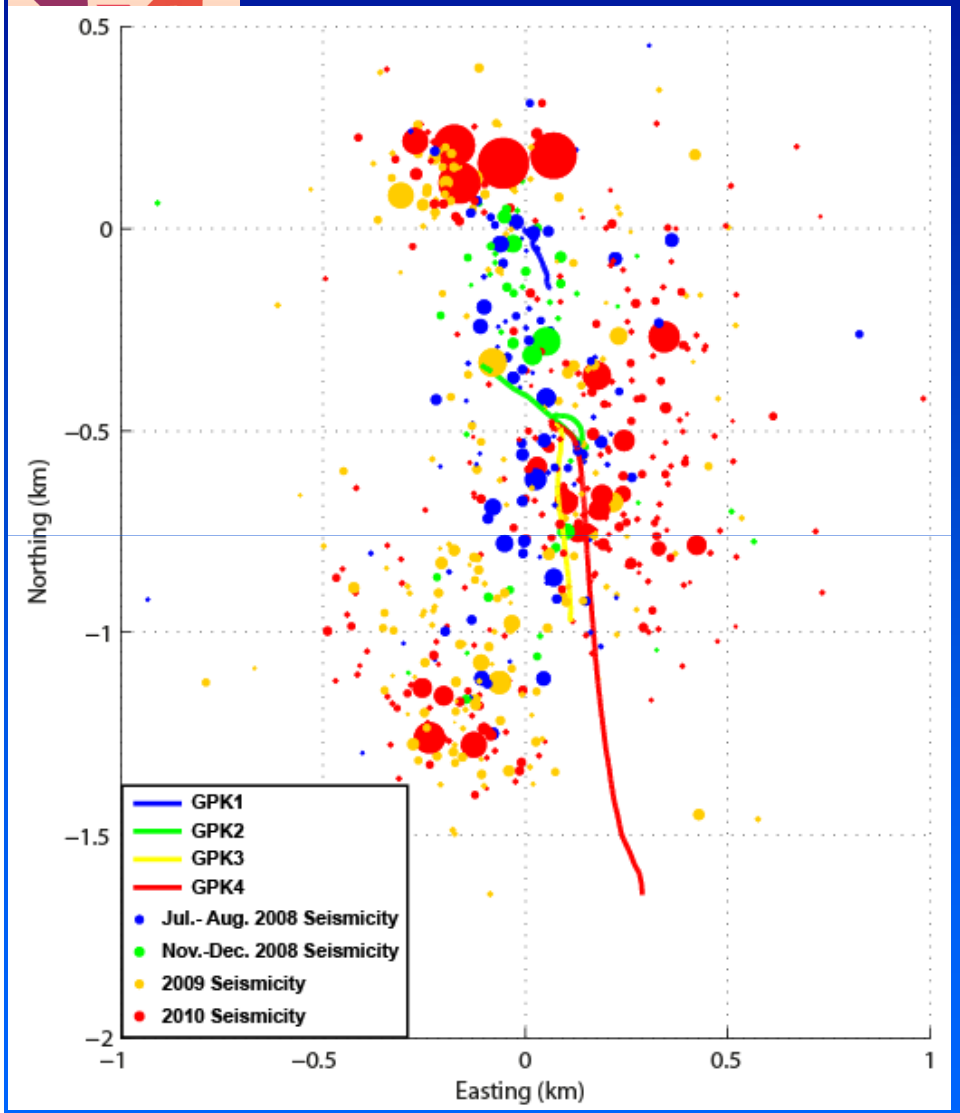
2005 circulation - 3 wells - artesian

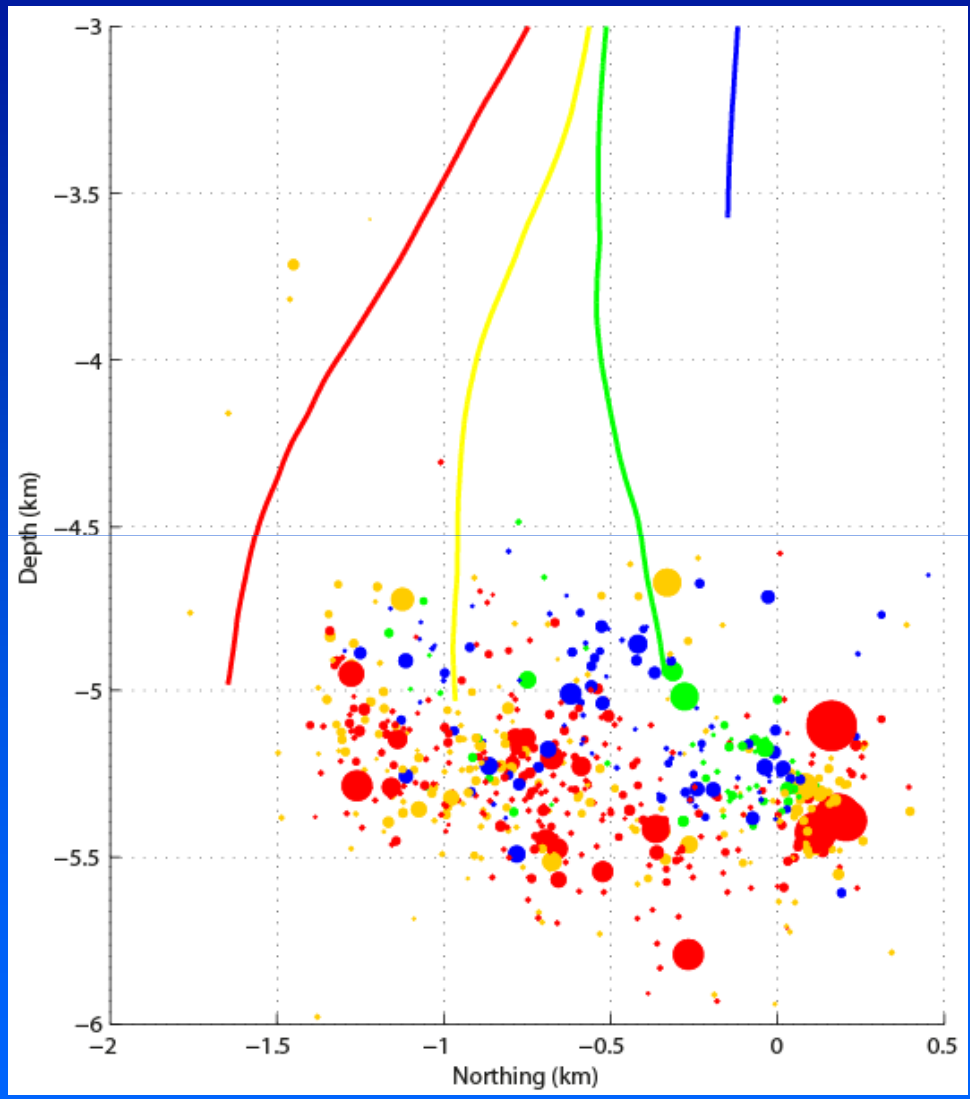






Seismicity during hydraulic circulations

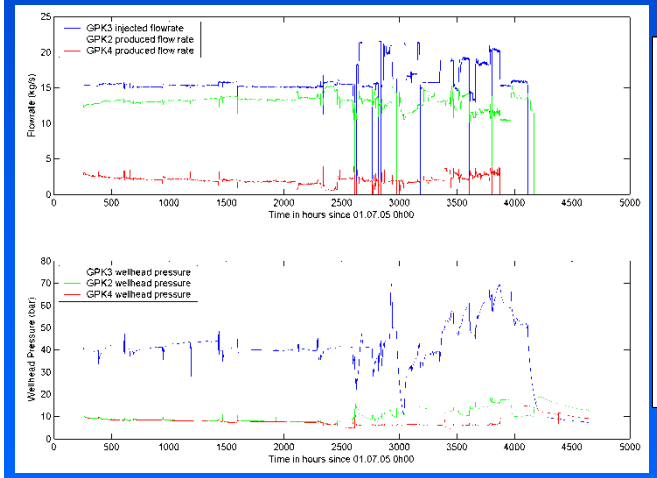


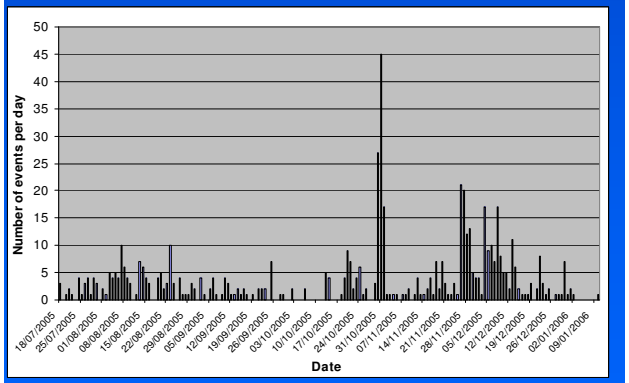


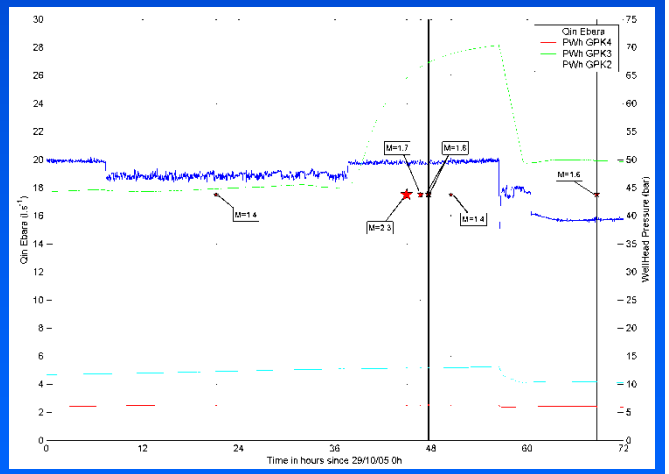
Jul.-Aug. 2008, Nov.-Dec. 2008, 2009, 2010 circulation

Seismicity during hydraulic circulations

- Moderate microseismic activity, but possible occurrence of larger earthquakes (M≥2)
- Stable hydraulic regime : low seismic activity, but change of hydraulic parameters followed by increase of seismic activity and sometimes by larger events
- Recently, observation of 3 earthquakes of magnitude ≥ 2, occurred under stable hydraulic conditions:
- Same areas activated during all circulation tests.

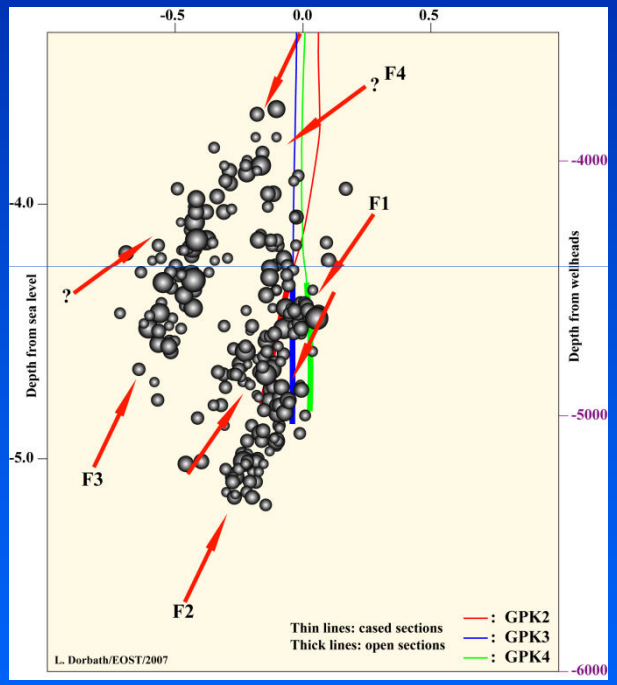




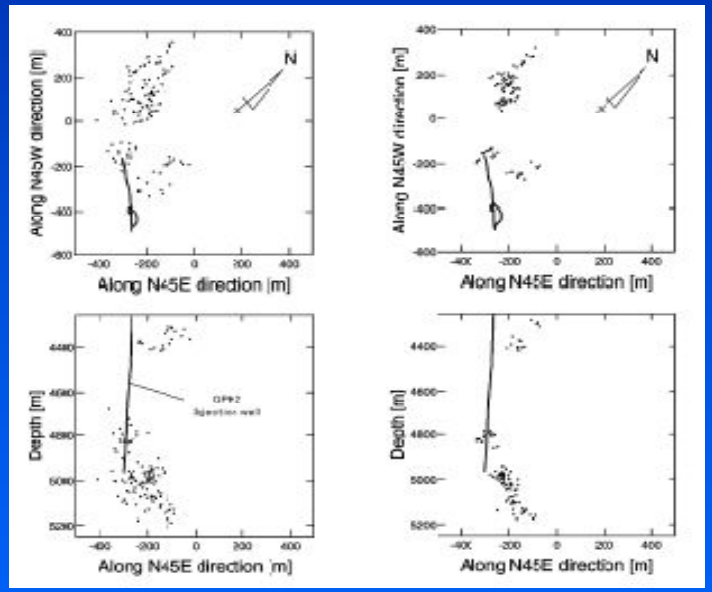


Use of seismic data

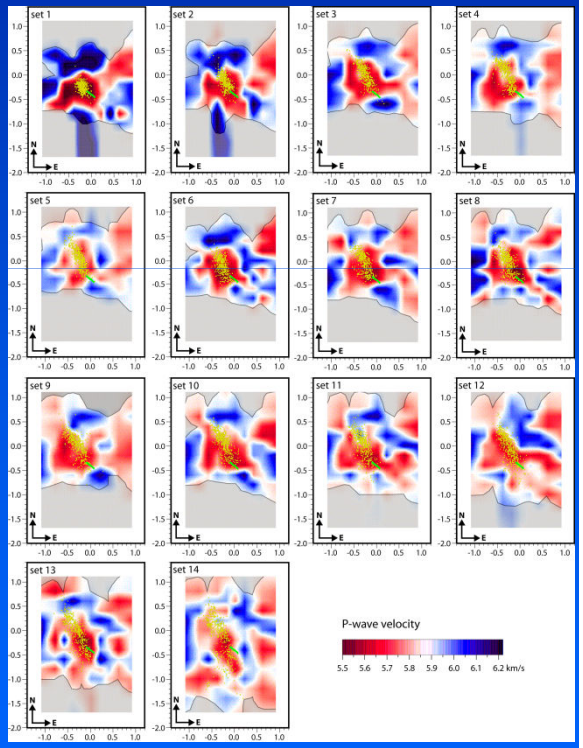
- **Characterisation of the geothermal reservoir properties**
  - **structural information**
  - **physical and mechanical processes**



Dorbath et al., 2009



Moriya et al., 2004

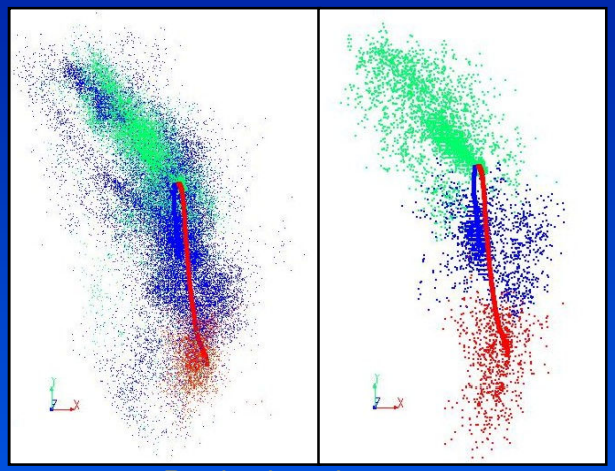


Cuenot et al., 2008

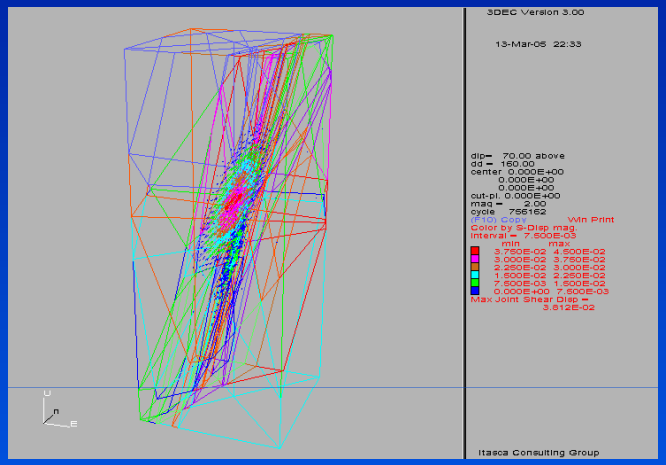
Results revised and improved by Calo' (next talk)

Use of seismic data

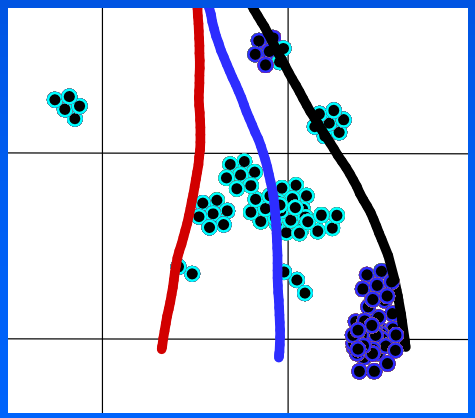
- **Constraint for thermo-hydro-mechanical models**



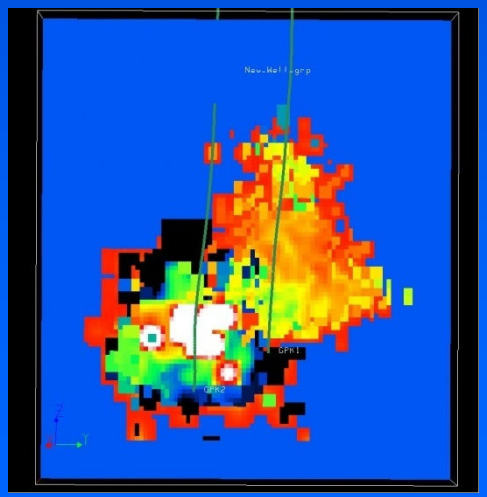
Baujard et al., 2005



Gentier et al., 2005



Kohl & Mégel, 2005



Royer & Voillemont, 2005

Conclusions

- Observation of microseismic activity during hydraulic & chemical stimulations and during circulation tests, but no evidence of drilling-induced earthquakes
- High activity during stimulation tests, moderate level during circulation tests at stable flow regime
- Observation of several larger magnitude earthquakes during shut in phase (both for stimulation & circulation tests)
- Variation of hydraulic parameters → variation of the behaviour of the seismic activity
- Recent observation of $M \geq 2$ earthquakes despite stable hydraulic regime
- During recent circulation tests, seismicity developed always in the same areas