Mechanical Stimulation and implications from microseismicity

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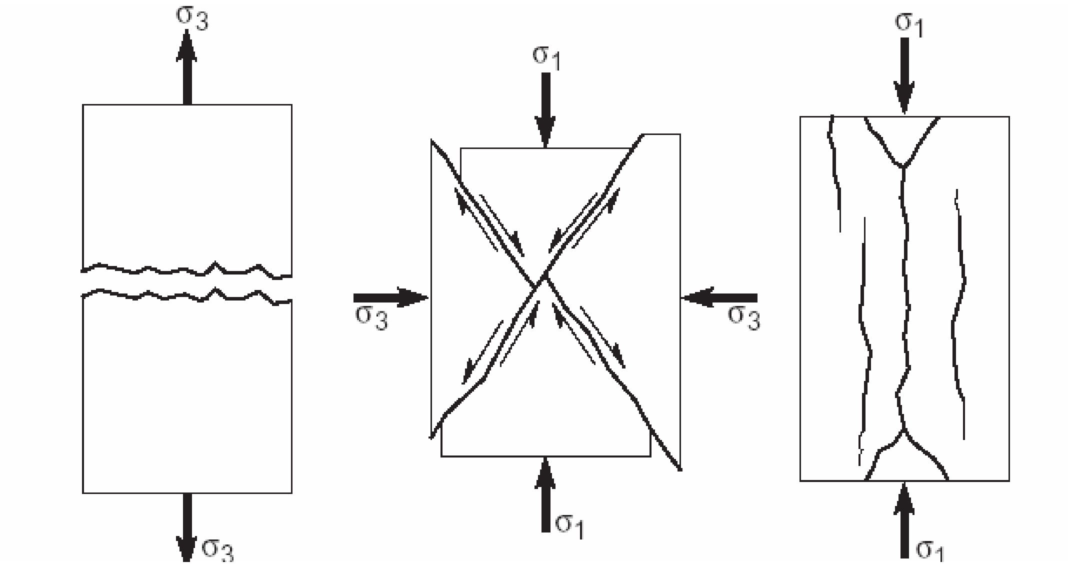
Mechanical (hydraulic) stimulation

- **Faulting** (= shear fracturing): shearing of pre-existing fractures, Soultz

  (mechanism is stress field dependant)

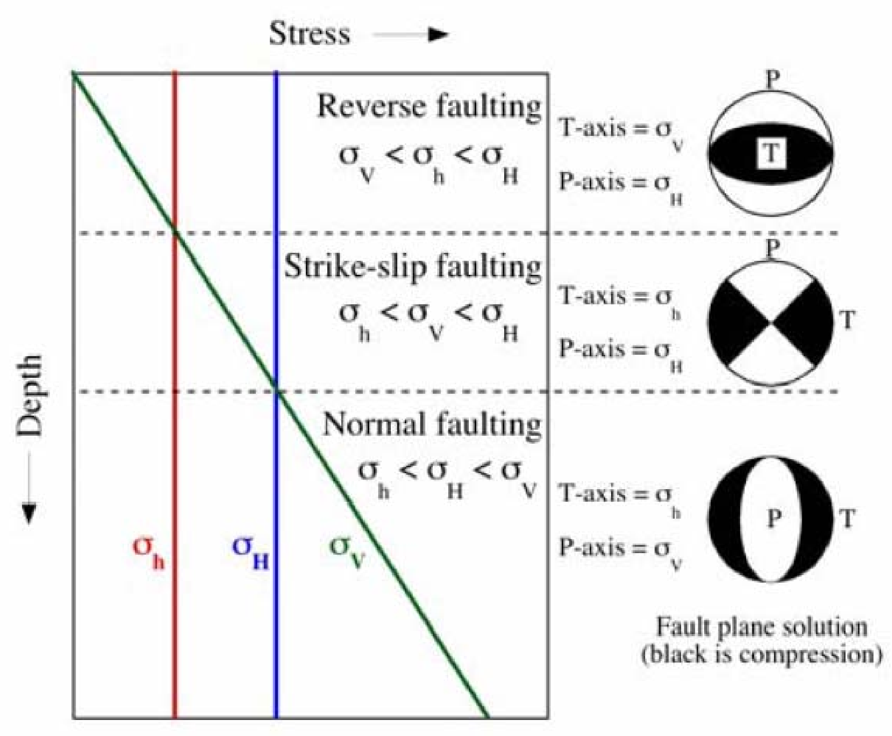
- **Jointing** (= hydrofrac, tensile fracturing, extensional fracturing): creation of new fractures, common in petroleum industry

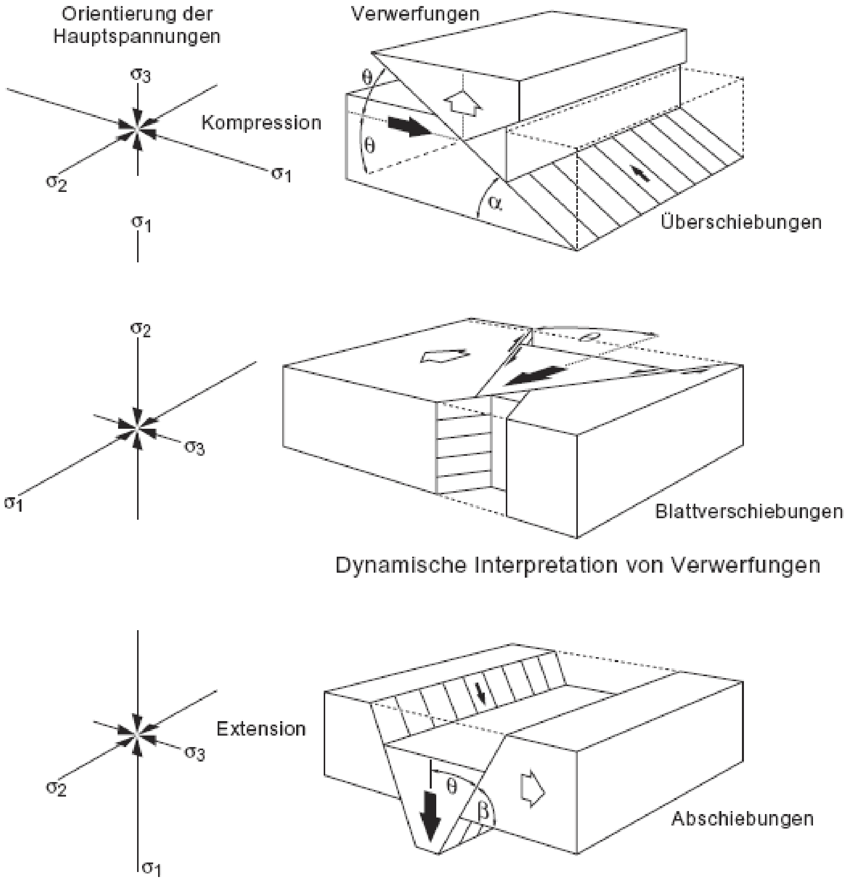
- **Jacking**: aperture enlargement of pre-existing fractures, Rosemanowes and Le Mayet-de-Montagne with proppant and gel injections



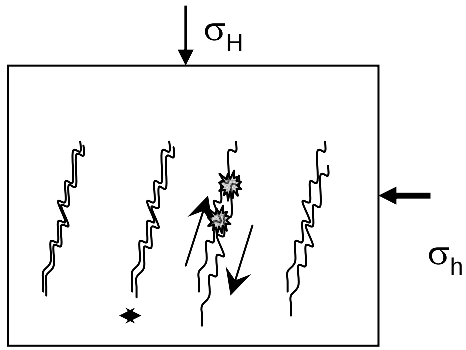
Hydraulic Stimulation

major parameter for failure in an EGS reservoir is the stress regime, i.e. relative vertical / horizontal stress





Mechanical (hydraulic) Stimulation

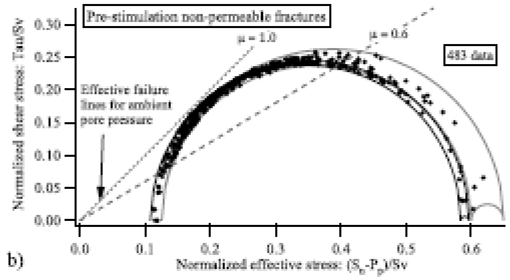


Faulting (shear fracturing)

- Increase of pore pressure
- Slip of pre-existing mechanical discontinuities
- Generation of larger apertures / or new faults

Mohr (-Coulomb) - Criterion

$$\tau = c + \tan(\Phi) \bullet \sigma_n$$



Evans

Microseismicity

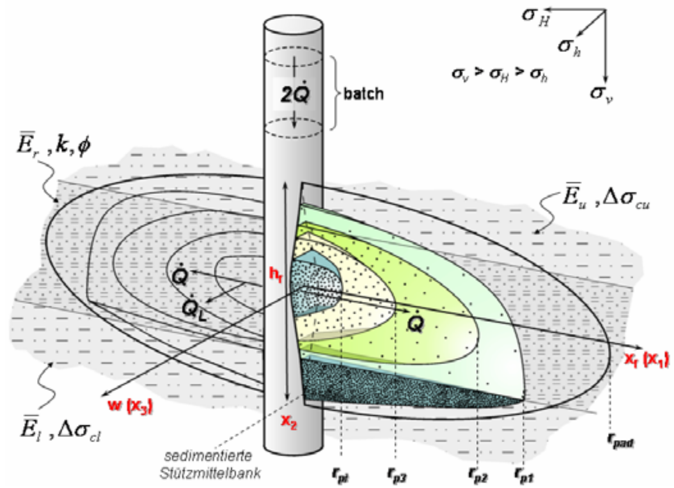
- Prediction of Magnitudes (Gutenberg-Richter)
- Identification of large structures (e.g. multiplet analysis)
- Identification of hydraulic diffusivity

Stimulation of multiple fracture sets, mostly in crystalline rock

Mechanical (hydraulic) Stimulation

Jointing (tensile fracture)

- Develops perpendicular to least principal stress



Criterion

$$P_f > S + \sigma_{\min}$$

$$P_f > S + \sigma_{\min} + \alpha \cdot P_p$$

Applied mostly in sedimentary rocks

Creation of single, far extending fractures

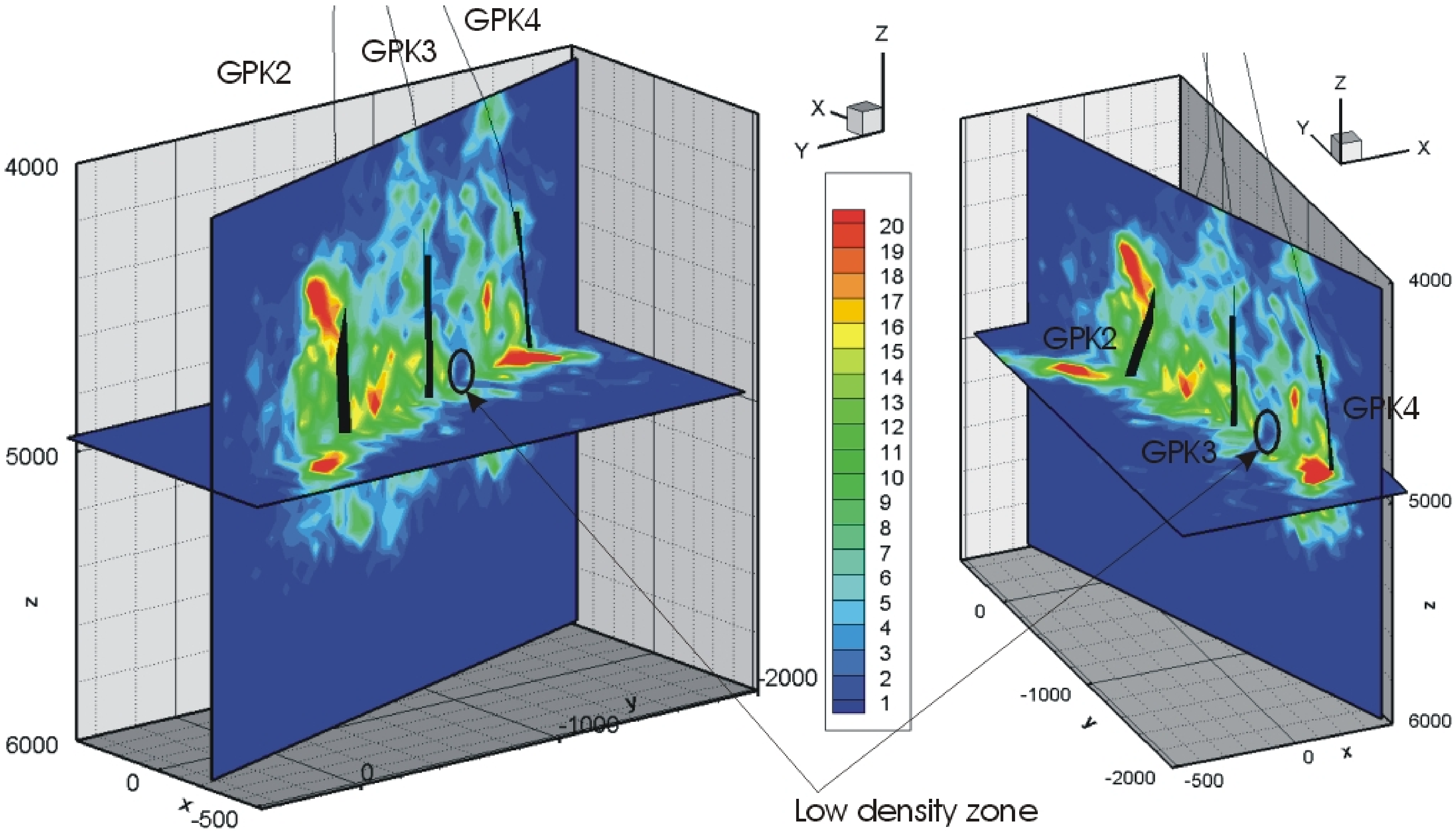
Analysis of Microseismic Density from Stimulations in Soultz

- GPK2 Stimulation (July 2000): 14'080 events
- GPK3 Stimulation (July 2003): 21'600 events
- GPK4 Stimulation (September 2004): 5'753 events
- GPK4 Stimulation (February 2005): 2'966 events
- GPK4 1st Step rate test (February 2005): 183 events
- GPK4 Acidization test (March 2005): 304 events
- GPK4 2nd Step rate test (March 2005): 256 events

Analysis of Microseismic Density from Stimulations

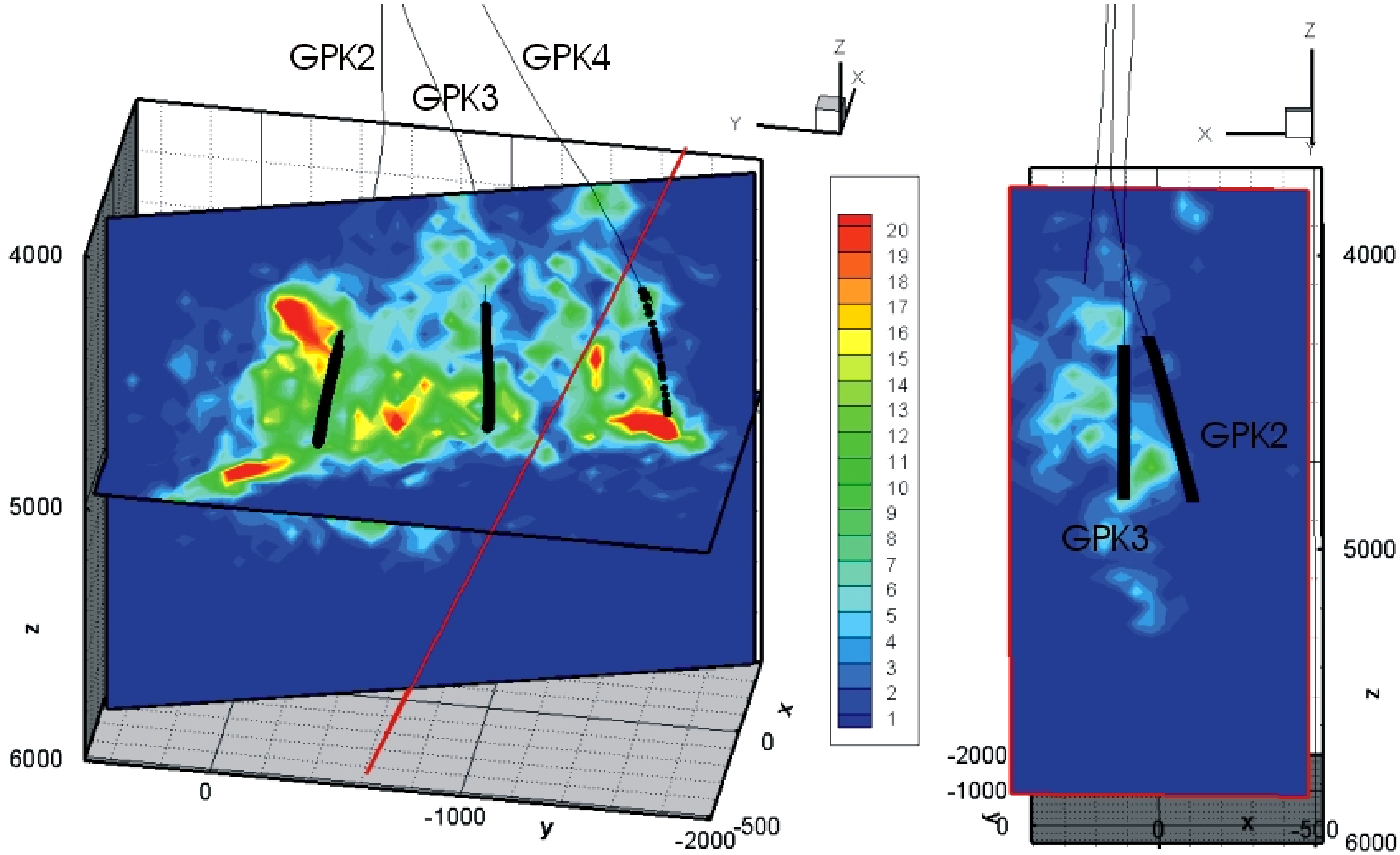
Total events

Calculated cube volumes: $50x50x50m^3$



Analysis of Microseismic Density from Stimulations

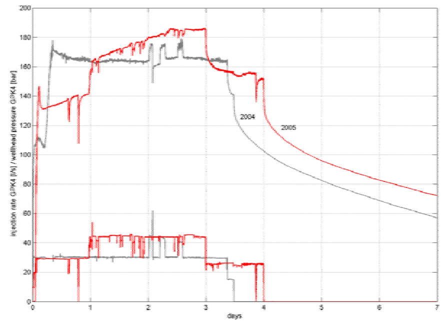
Calculated low-density structure N96p64W.

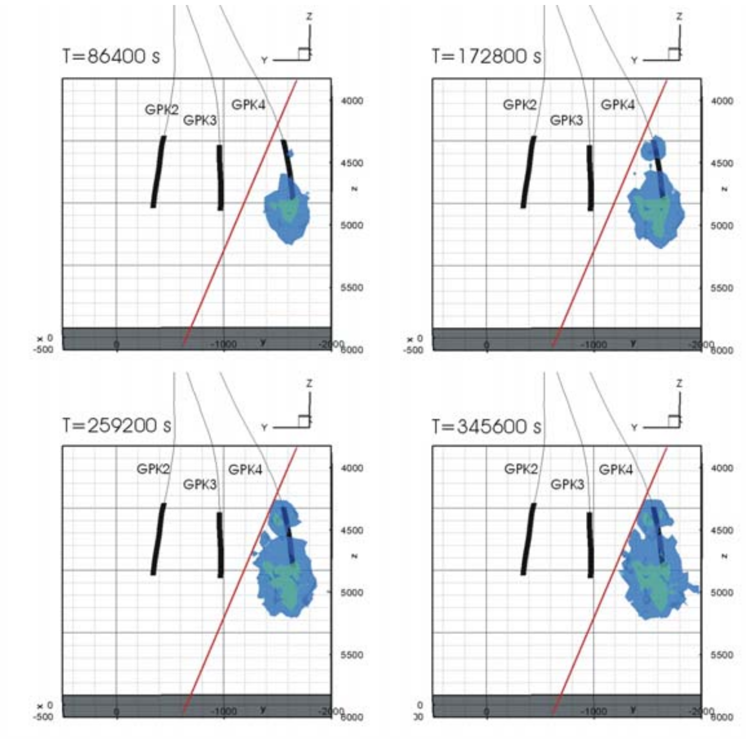


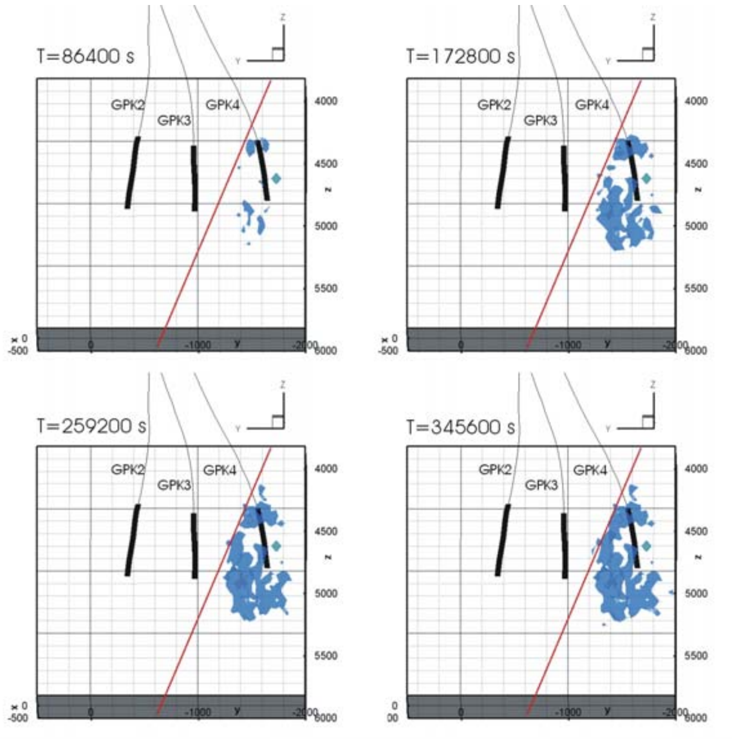
Analysis of Microseismic Density from Stimulations

Comparison of GPK4 Stimulations:

September 2004 February 2005

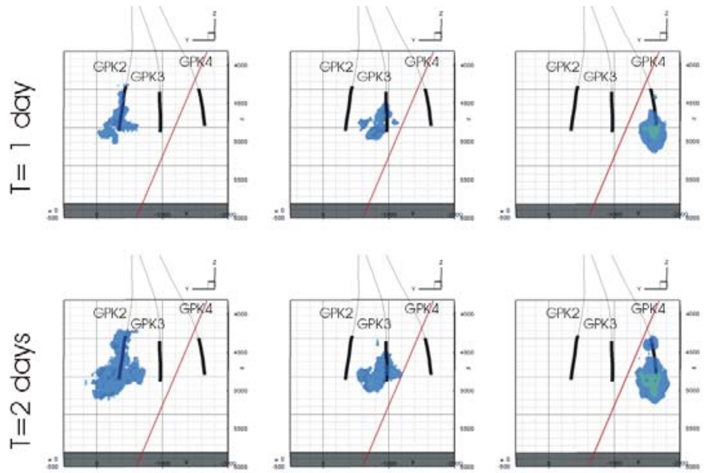


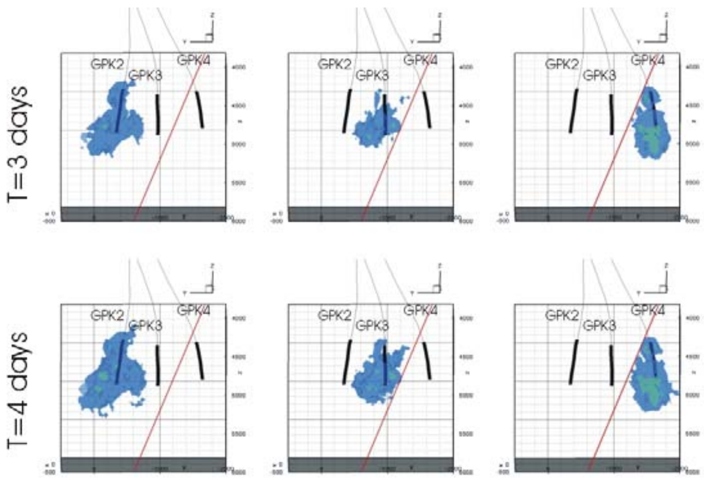


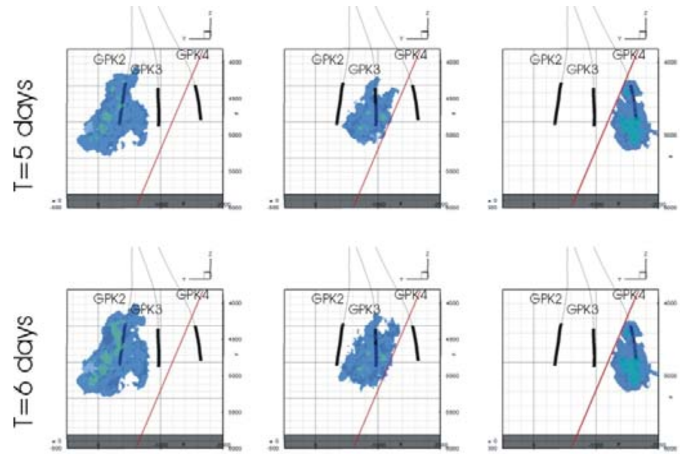


Analysis of Microseismic Density from Stimulations

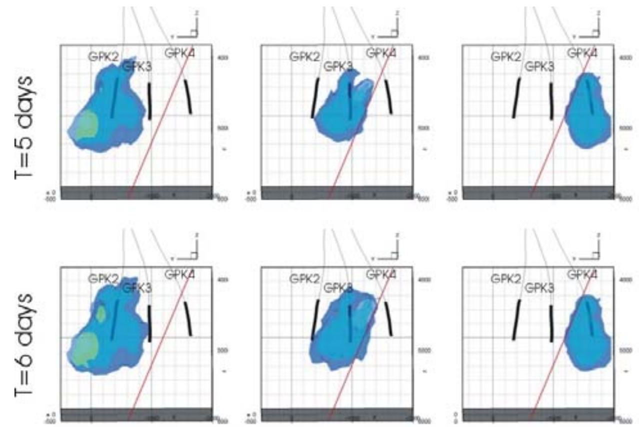
Comparison of GPK2/3/4 Stimulations







Compare at 100m cube:



Conclusion on possible hydraulic impact of low-seismic zone

High conductive zone (draining fluid into a far field fault zone and thus prevents any pressure increase)

- "Fingering" of microseismic density indicates flow into this zone
- No increase of the density of microseismic events once zone has reached and injection continues
- Weak hydraulic connection between GPK3 and GPK4
- Tracer diffusion into this "storage zone" can explain the small tracer recovery
- Next to the intersection with GPK4 depth, high fluid-losses were encountered during drilling

High impedance zone (extreme low natural fracturization = possible no-flow boundary)

- Orientation nearly perpendicular to S_H;
- Long transients during GPK4 shut-in
- Weak hydraulic connection between GPK3 and GPK4
- Hardly no tracer recovery between GPK3 and GPK4
- High seismic density between GPK4 and aseismic zone

Conclusion on possible hydraulic impact of low-seismic zone

individual observations are non-unique (I.e. tracer breakthrough)
$\Rightarrow$ ambivalent characterization.

Although orientation does not coincide with N-S pattern, such faults necessarily exist on Horst structures

High impedance needs extreme low fracturization that is hardly to imagine for the general permeability pattern

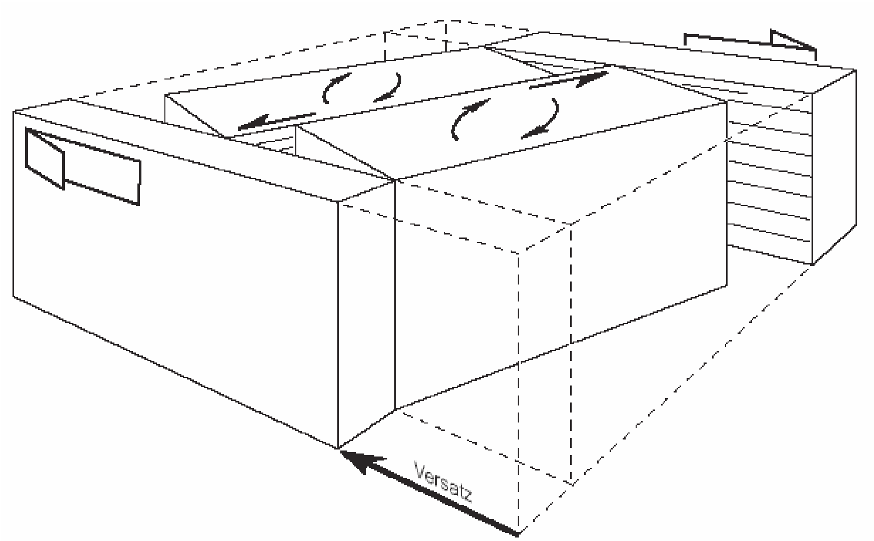
$\Rightarrow$ aseismic zone corresponds to a subvertical structure that is well linked to N-S striking drainage systems

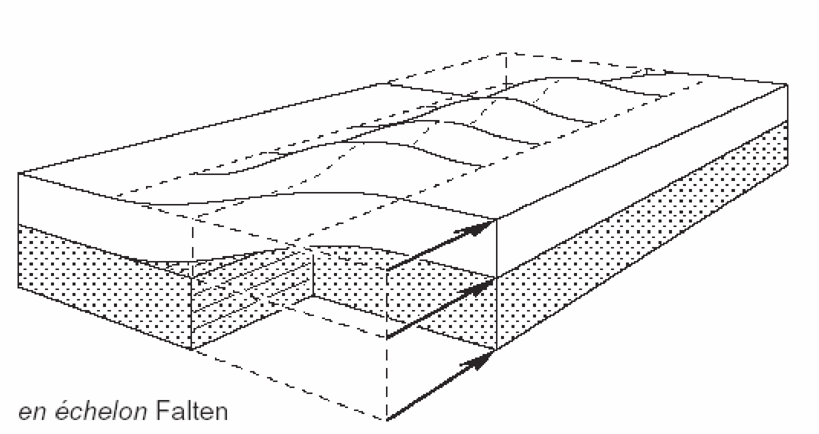
$\Rightarrow$ Due to its orientation, we can expect a low compliance for normal stress variations and especially little shearing.

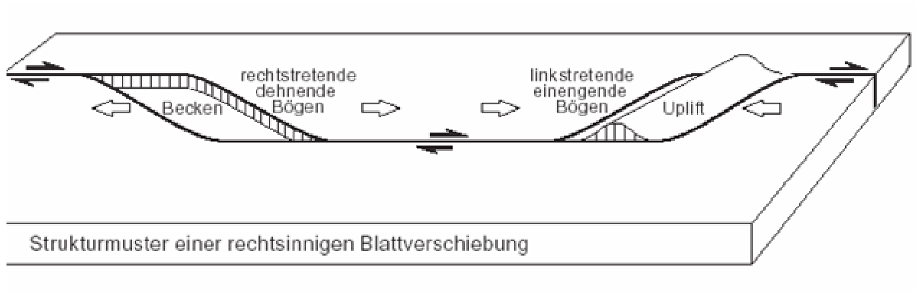
Complex tectonic regimes

Interplay of different tectonic mechanisms can lead to faulting ~parallel to S_h:

- rotational bulk strain
- Pull-apart
- en-echelon structures







Conclusion

The hydraulic re-stimulation of GPK4 includes the risk of low efficiency and of higher seismicity.

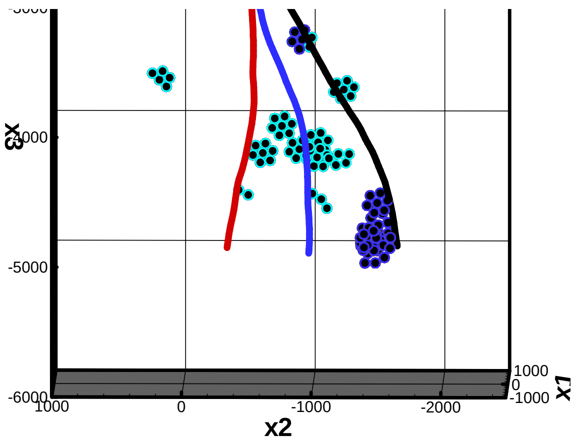
A proper hydraulic characterization of the aseismic zone between GPK3 / GPK4 is necessary for a successful GPK4 re-stimulation.

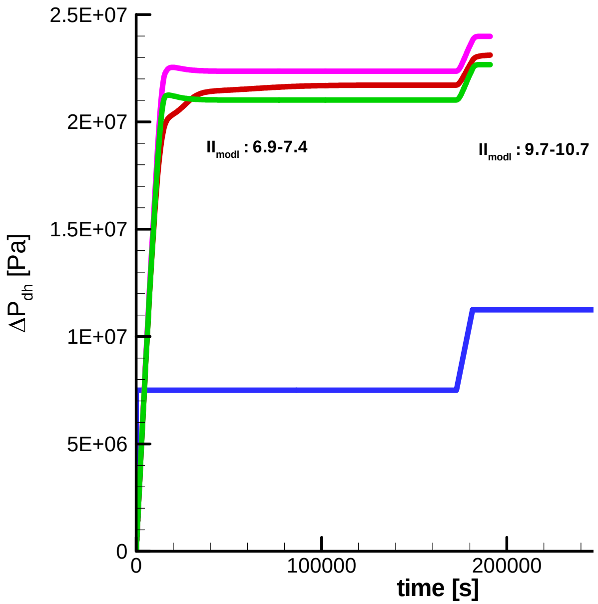
Microseismicity favours structures parallel to S_H

- However perpendicular structures may exist
- Visible only as low seismic activity

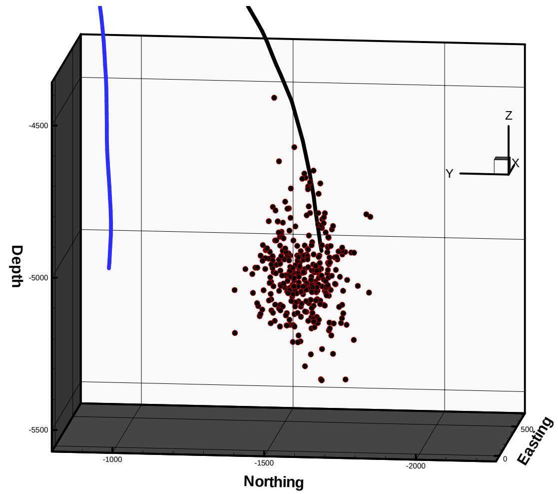
Modeling Tool HEX-S:
Prognosis GPK4 stimulation 04SEP13

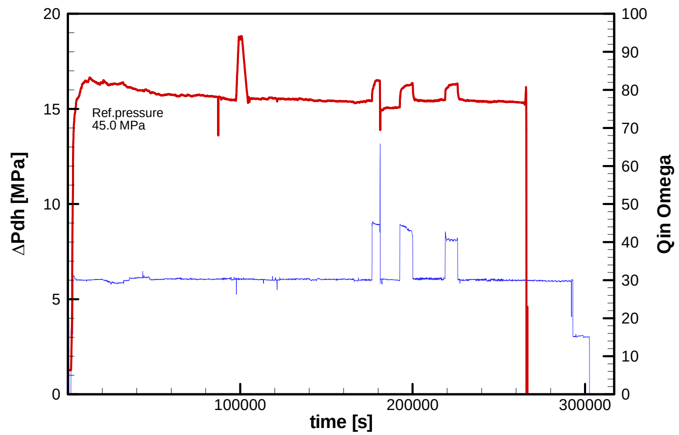
Forecast





Measurement





Modeling Tool HEX-S: Stimulation Model

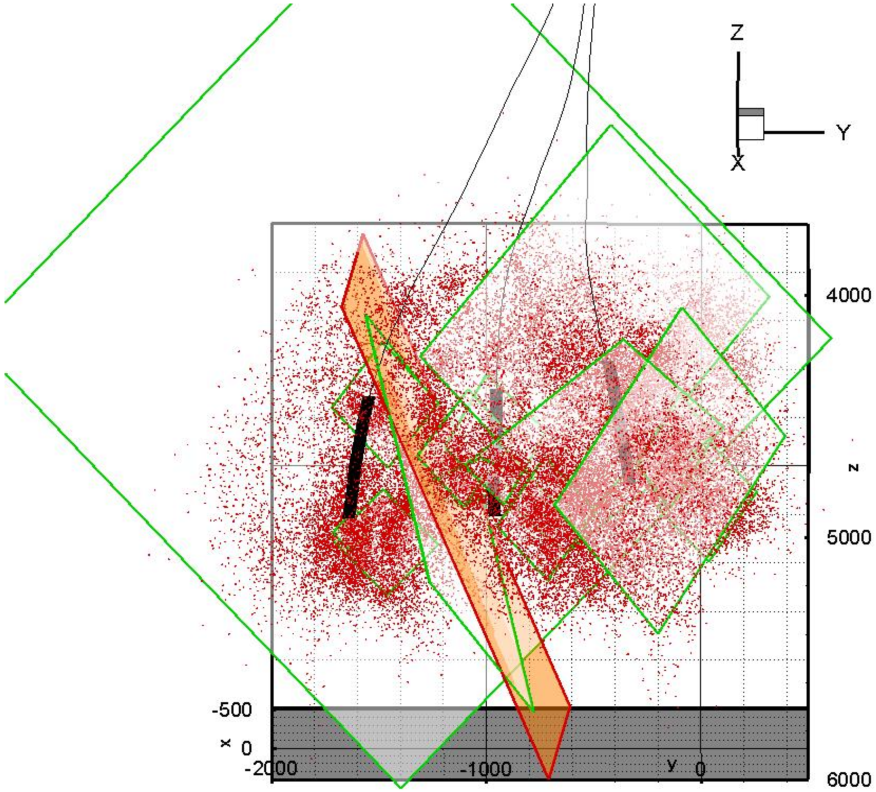
Forecast model did not include aseismic zone

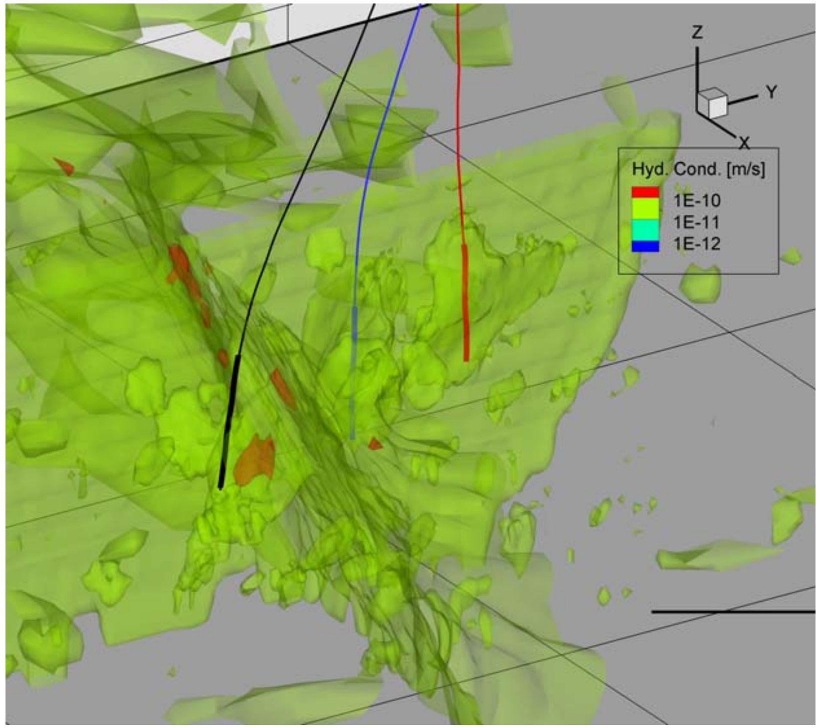
New fault model of the 5km reservoir at Soultz

- deterministic fractures intersecting the GPK3 and GPK4 borehole
- faults derived from the seismic distribution using the density analysis
- aseismic zone with high hydraulic conductivity, i.e. flow injected to GPK4 will be drained through this zone into a nearby N-S extending Soultz fault.

Modeling Tool HEX-S: New Stimulation Model

Determination of fault planes from microseismic distribution





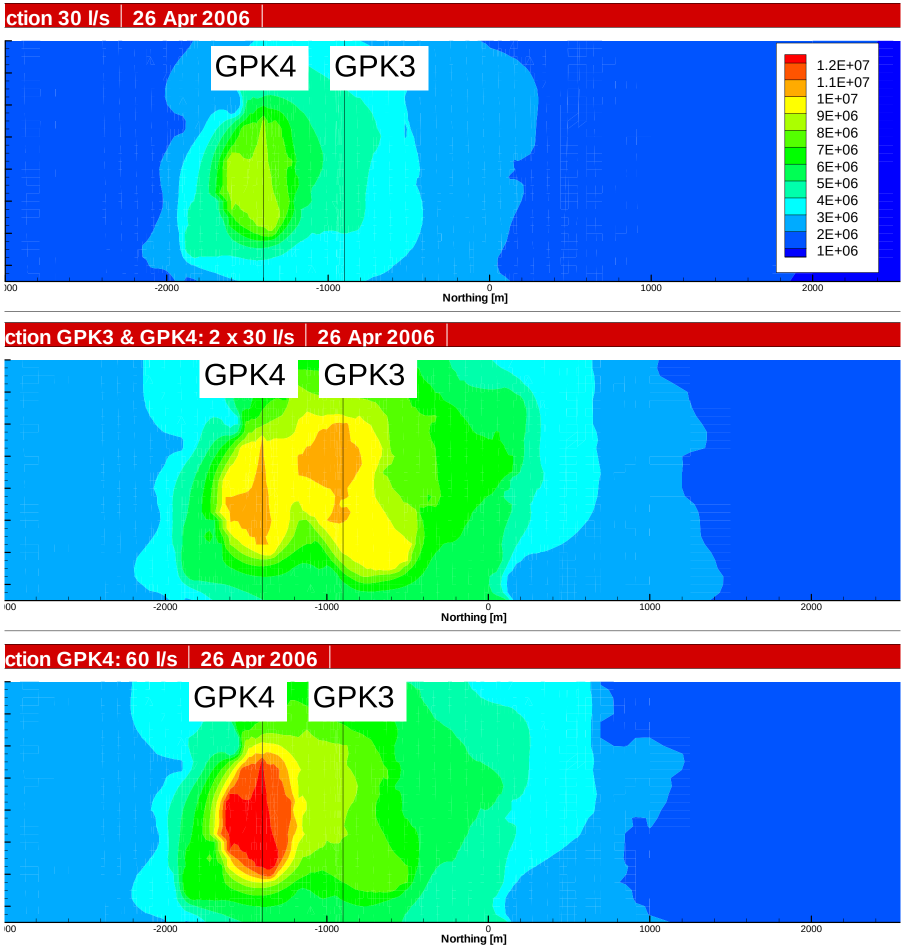
Modeling Tool HEX-S: New Stimulation Model

Three Scenarios:

1. **Single injection in GPK4** with 30 l/s during 3 days and increase to 45 l/s (i.e. injection scenario from Sep. 2004)

2. **Dual injection in GPK3 / GPK4** each with 30 l/s during 3 days and increase to 45 l/s

3. **Doubling injection in GPK4** with 60 l/s during 3 days and increase to 90 l/s (i.e. doubled flow scenario 1)



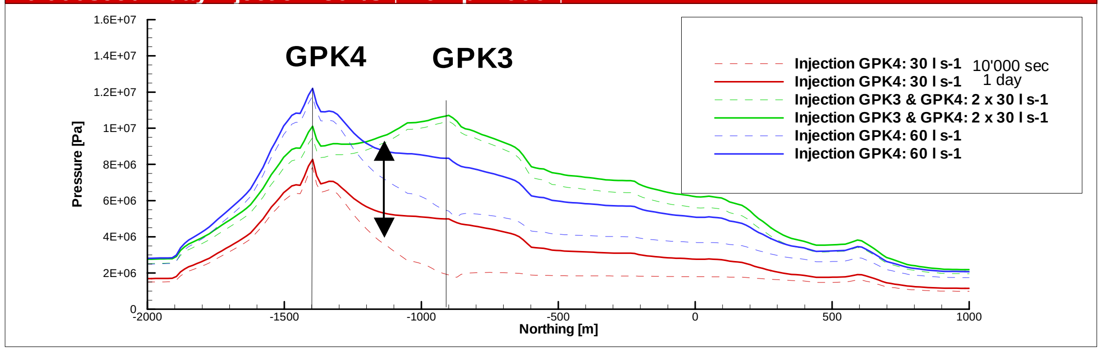
Not yet fully calibrated!

Modeling Tool HEX-S: New Stimulation Model

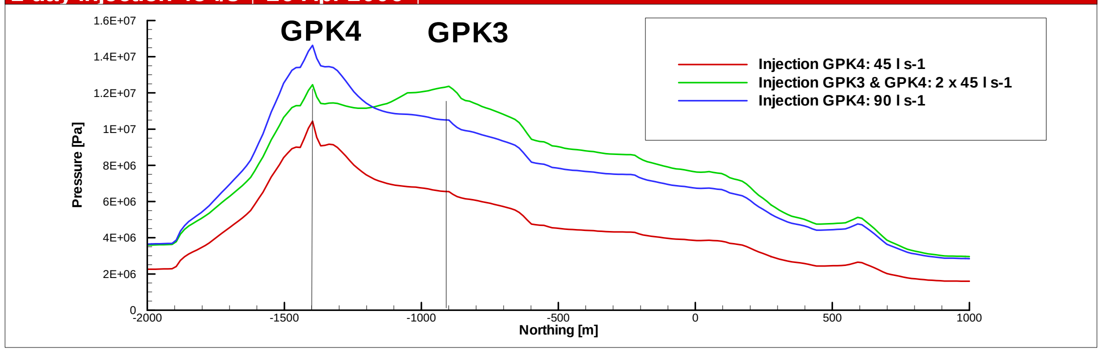
Three Scenarios:

- first injection step at t=10'000 s and 1 day
- second injection step at t=1 day after step change
- pressure history in GPK4

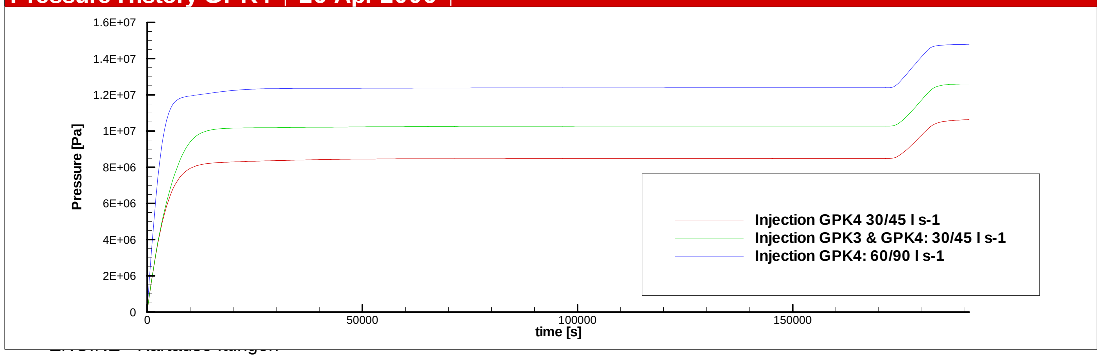
10'000sec / 1 day injection: 30 l/s | 26 Apr 2006



1 day injection 45 l/s | 26 Apr 2006



Pressure History GPK4 | 26 Apr 2006



Recommendations for Mechanical Stimulation

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Modeling indicates

- Transmissivities are created mostly in the vicinity of the boreholes
- Little success in far field stimulation

Short-term injections (1-2 days):

- prevents pressure build up in secondary flow zones (pore pressure)
- limits the size of the affected area.
- Successive short-term injections more efficient than long re-stimulations
- Dual injection would yield shorter transients in matrix / larger volumes.

When reaching maximum pressure:

- avoiding long-term shut-in.
- venting of boreholes as fast as possible

Chemical stimulation not considered.

- several successive chemical / mechanical stimulation
- they are complementary in nature:
  - acidization with HCl rather affects the nearest borehole vicinity
  - mechanical stimulation will influence the natural fracture network

Chemical stimulation

Acidization is used for

- removal of skin damage from drilling operations
- increase of formation permeability in undamaged wells.

The injection of acids is performed

- at modest flow rate (below pressures for mechanical stimulation)

1) preflush, usually with hydrochloric acid
2) mainflush usually with a hydrochloric – hydrofluoric acid mixture.
3) postflush/overflush usually with soft HCl acid solutions or with KCl, NH_4Cl solutions and freshwater.

Improvement of the well conditions can be generally observed (largely varying success).

André & Vuataz