G.E.I.E.

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Aspects for Re-Stimulating GPK4

Technical Note
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1 DENSITY ANALYSIS OF THE MICROSEISMICITY RECORDED AT SOULTZ-SOUS-FORÊTS DURING WELL STIMULATIONS

1.1 DATA BASIS

This section provides an analysis of the density of microseismic events recorded in Soultz since year 2002. The purpose is to locate an eventual structure between wells GPK3 and GPK4.

The microseismic events considered in this analysis are the following ones:

- 2002 (stimulation GPK2) events, recorded in July 2000: 14080 events
- 2003 (stimulation GPK3) events, recorded in july 2003: 21600 events
- 2004 (stimulation GPK4) events:
    - Stimulation September 2004: 5753 events
    - Stimulation February 2005: 2966 events
    - Step 1 February 2005: 183 events
    - Acidization Mars 2005: 304 events
    - Step 2 Mars 2005: 256 events

A total of 45142 located microseismic events are taken in account in this study.

One should note here that seismic events recorded during circulation tests are not taken in account in this study, by lack of data. By the way, complex pressure distributions in the reservoir during these phases make the interpretation of the location of these events very hazardous.

1.2 RESULTS

Figure 1-1 shows the computed density of located microseismic events during the last 4 years in Soultz. Calculations are maid on a 50 m mesh; on each point of this mesh, the number of events recorded in a cube of volume $50x50x50m^3$ is calculated. Results are shown on this figure on two planes; the first one goes through the open sections of the three wells and the second one is located at the bottom of the wells, i.e. z=4975 m.

One can clearly observe on this figure an "aseismic" zone located between wells GPK3 and GPK4. At the intersection of the two planes drawn on Figure 1-1, the coordinates of this low-density seismic zone can be estimated to:

- x = 165 m
- y = -1175 m
- z = 4975 m

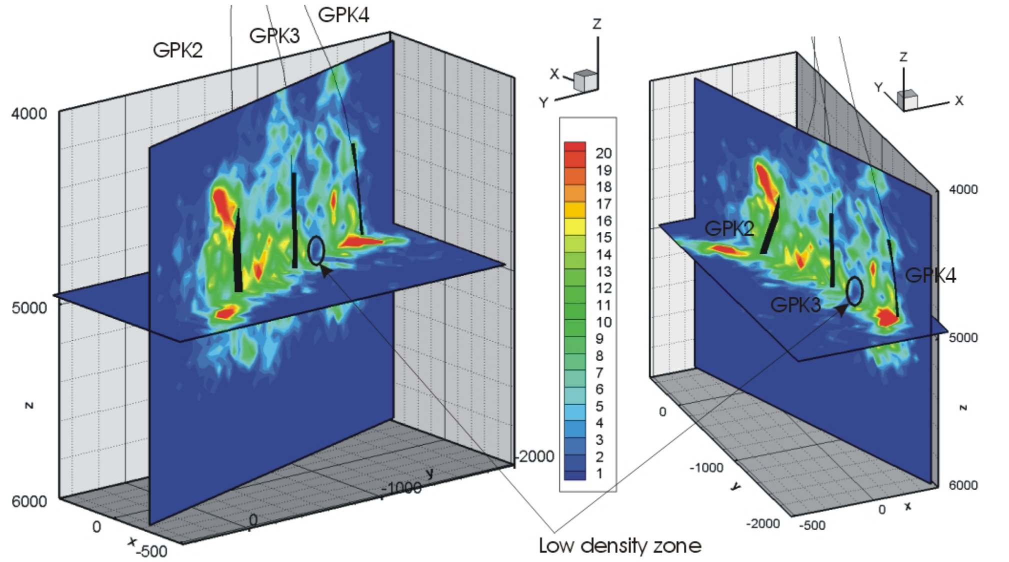


Figure 1-1: Density of microseismic events recorded during 4 last years in Soultz. Results are given in number of located events per 50 m side length cube.

Starting from an area between GPK3 and GPK4 with low seismic density, a plane was determined that has the lowest density of events. The calculation is based on a simple search for a plane orientation that minimizes the number of microseismic events located closer than a distance *d = 25 m* of this plane. For a given point, 90x360=32400 planes are tested (every degree of dipping and azimuth). The calculation resulted in a subvertical plane of orientation N96p64W. A number of 643 microseismic events over a total of 45142 were found to be at a distance of less than *25 m* of this plane. As seen on Figure 1-2, the density of events on that particular plane is noticeably low. The maximum seismic events density over that plane is 13 events / 50 m side length cube.

If the existence of such a structure can be clearly established, the question is to know what kind of boundary it represents for the system. A no-flow boundary and a drain would both appear as an aseismic zone.

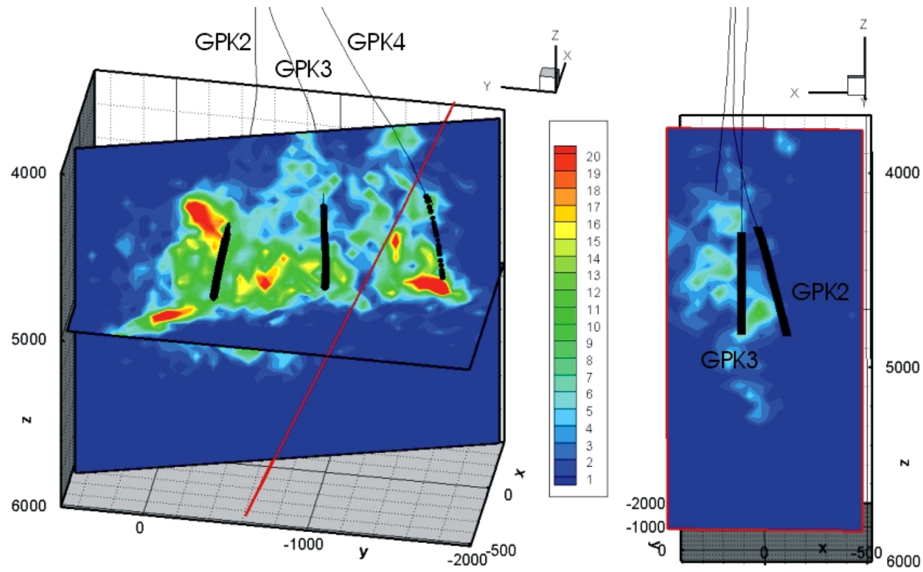


Figure 1-2: Representation of a low-density structure of orientation N96p64W.

1.3 TRANSIENT ANALYSIS OF GPK4 STIMULATION MICROSEISMICITY

Figure 1-3 shows injection scenario performed in GPK4 during stimulation campaigns.

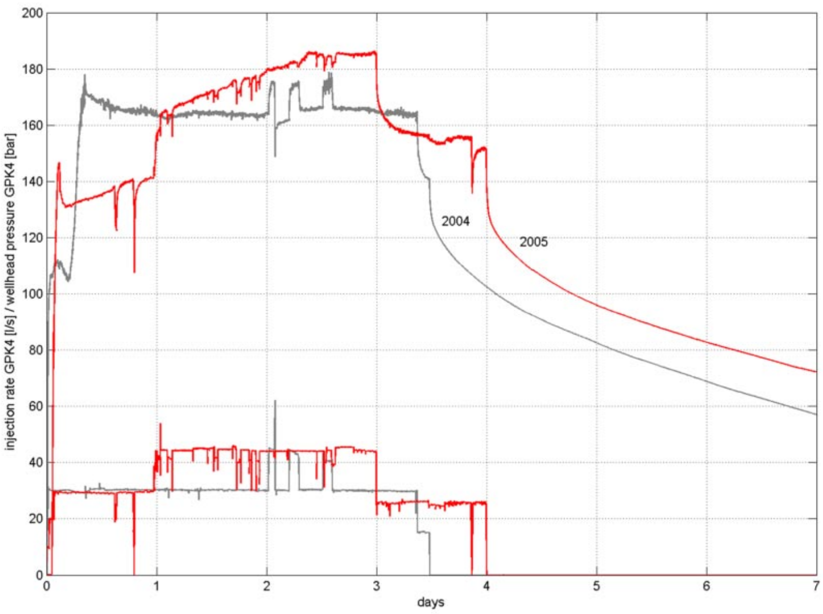


Figure 1-3: Imposed flowrate and measured pressure in well GPK4 during Sept. 2004 stimulation (in gray) and Feb. 2005 stimulation (in red)

<u>Microseismicity during September 2004 and February 2005 stimulation</u>

It has been underlined in the literature that the slow decrease of pressure in well GPK4 during shut in and very poor productivity of well GPK4 strongly indicate that the structure interfering between GPK3 and GPK4 was a no flow boundary.

The shape of the d = 15 events per 50 m side length cube envelope no longer changes between t=200000s and t=300000s, implying a constant well pressure during this phase of injection.

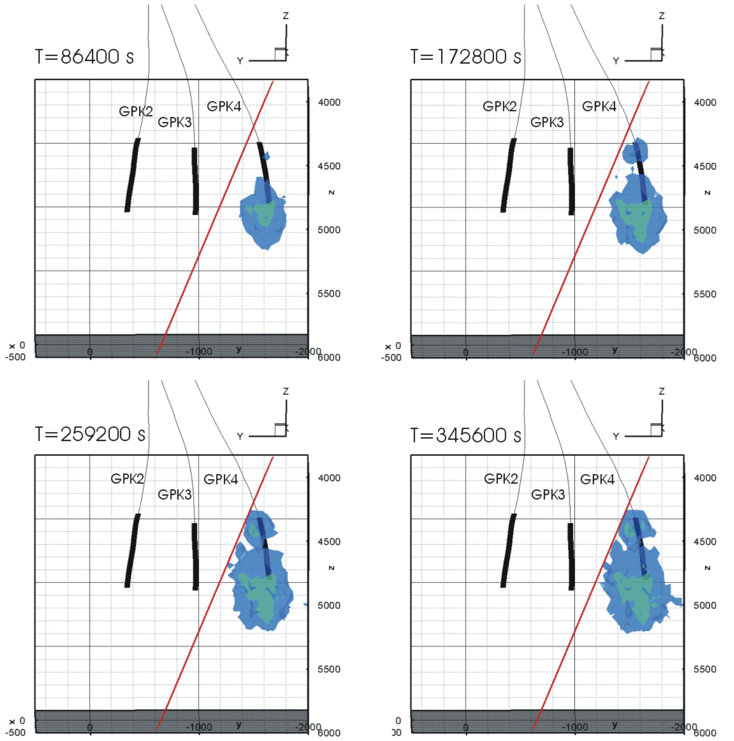


Figure 1-4: Evolution of the density of microseismic events during GPK4 September 2004 stimulation. Blue envelope: d = 3 events per 50 m side length cube; green envelope: d = 15 events per 50 m side length cube. Times are given from beginning of injection.

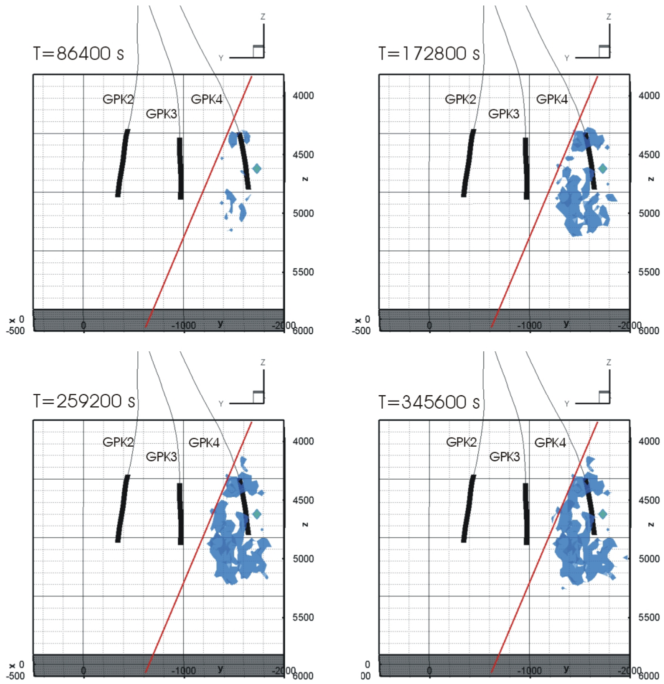
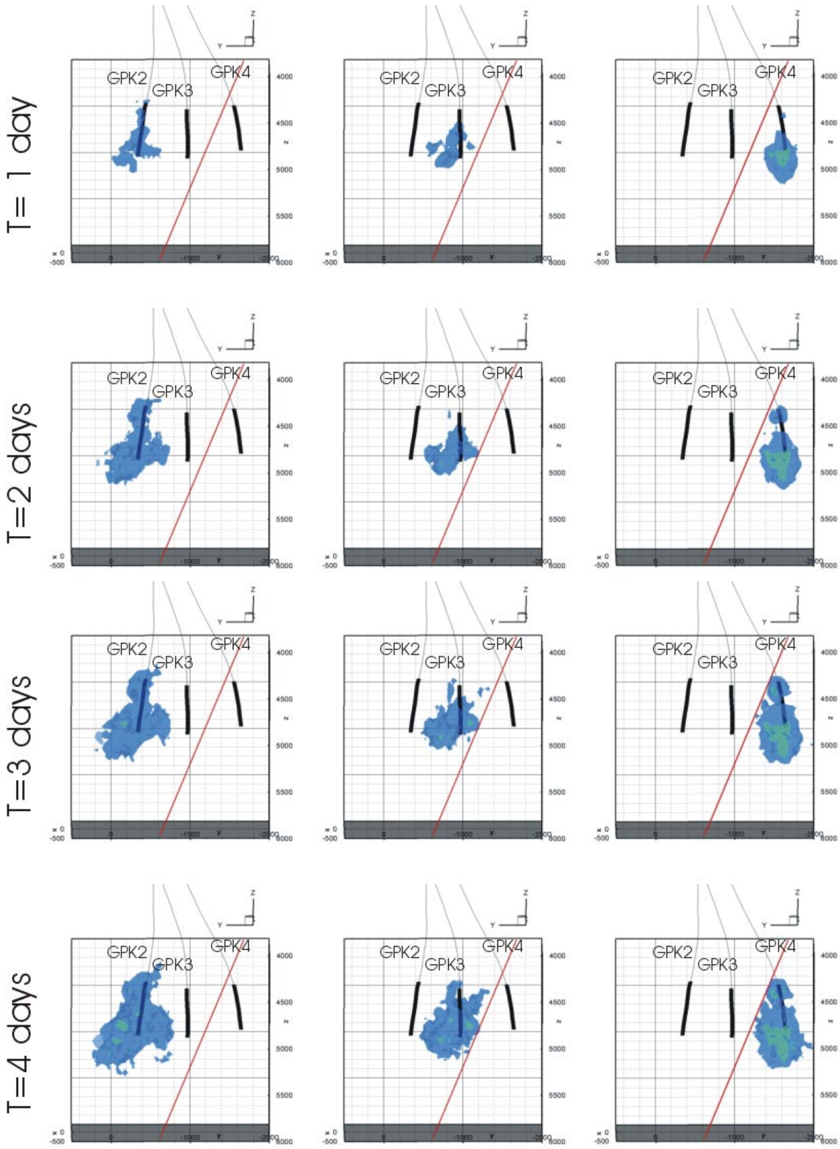


Figure 1-5: Evolution of the density of microseismic events during GPK4 February 2005 stimulation. Blue envelope: d = 3 events per 50 m side length cube. Times are given from beginning of injection

1.4 COMPARISON OF THE THREE SIMULATION RESULTS IN TERMS OF DENSITY OF MICROSEISMIC EVENTS



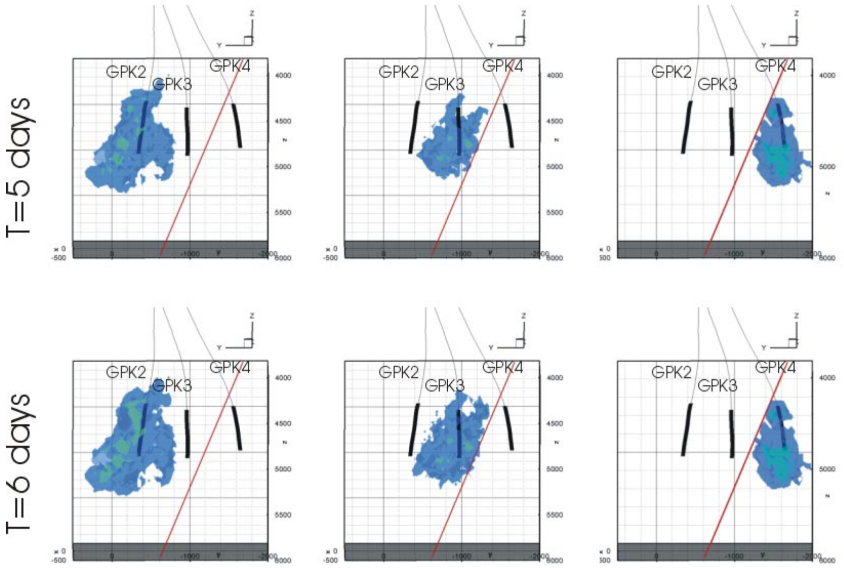
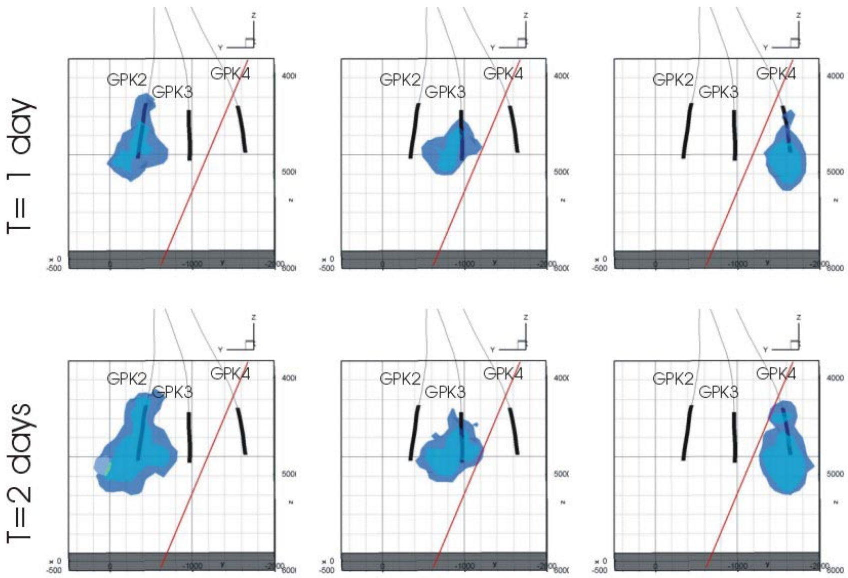


Figure 1-6: Transient development of GPK2, GPK3 and GPK4 microseiosmic distribution (Δx=50m)

Given the relative resolution of events localization, i.e. the accuracy of one event relative to a nearby event, which varies from 50m to 80m to the least well constrained events (according to Soultz 2005 report, by B. Dyer), it could be useful to extend the size of the cube used to compute the density of located seismic events during the stimulation of the three wells.

Therefore, a second analysis of the density of located seismic events was realized, using this time a 100m side length cube. Results are presented Figure 1-7.



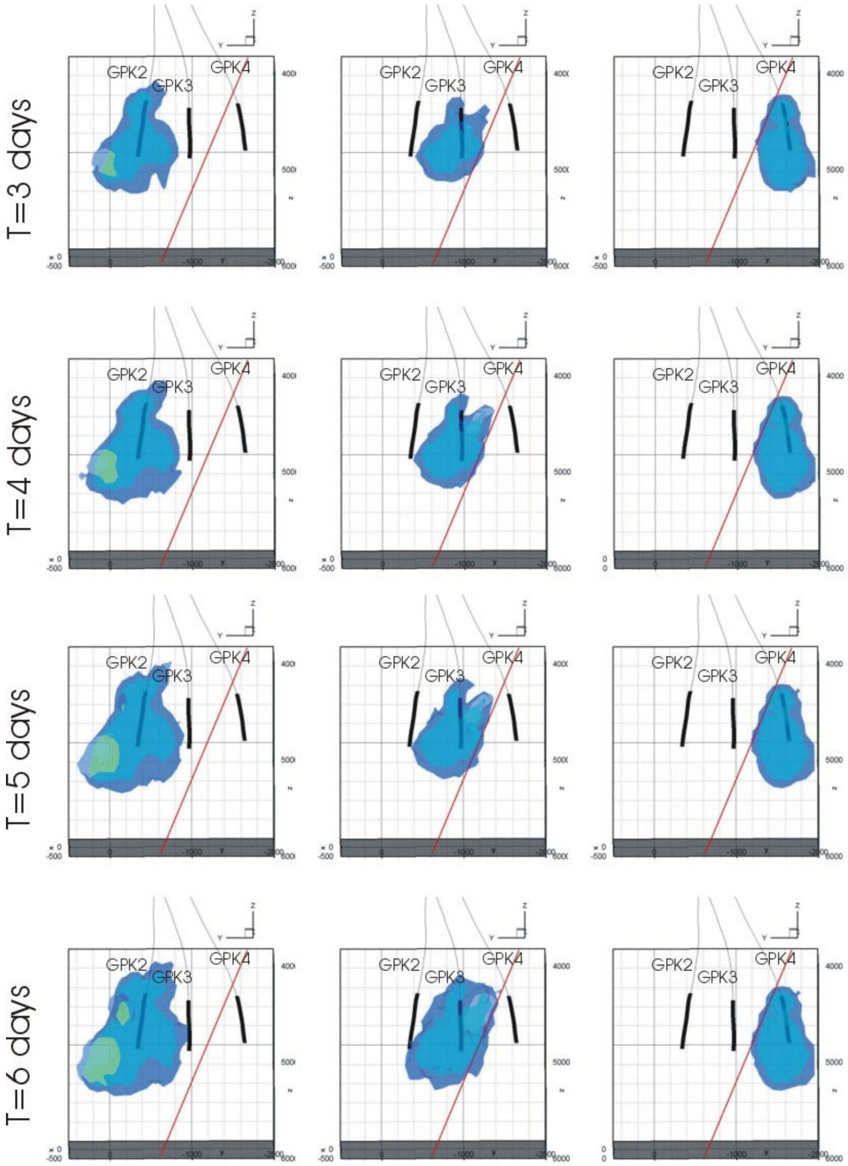


Figure 1-7: Transient development of GPK2, GPK3 and GPK4 microseiosmic distribution (Δx=100m)

1.5 CONCLUSION FROM ANALYSIS OF MICROSEISMIC DISTRIBUTION

After 3 days of injection the microseismicity does not strongly develop any more

A subvertical plane can be determined that has a minimum density of seismic events

This zone has certainly a different hydraulic characteristic and will play a key role during the stimulation. The following arguments may support a characterization as highly conductive zone:

- Fingering of microseismic density
- No increase of the density of microseismic events once zone reached and injection continues

- Weak hydraulic connection between GPK3 and GPK4
- Tracer diffusion into this "storage zone" can explain the small tracer recovery
- At the intersection with GPK4, high fluid-losses have been encountered during drilling

The following arguments may support a characterization as high impedance zone (possible No flow boundary?)

- 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
- Orientation nearly perpendicular to SHmax

In the following considerations, the possible effects of this zone to stimulation is considered.

2 POSSIBLE SCENARIOS OF HYDRAULIC STIMULATION OF GPK3 AND GPK4

The HEX-S model has been used to forecast the hydraulic stimulation of GPK4 in September 2004. The results are remarkable since the model was able to predict

- short hydraulic transients during injection
- microseismic distribution during first day of injection
- main shear events after 16'000 sec of injection, including impact on hydraulic field
- the relative downhole pressure change resulting from an increase in flow rate from 30 to 45 l/s. The absolute level of hydraulic pressure was estimated however to be 20% too high.

This model didn't consider this aseismic zone between GPK3 and GPK4. Therefore, it failed to forecast the limited areal distribution of microseismicity. Therefore, a new fault/fracture model had to be established.

2.1 NEW FAULT MODEL OF THE 5KM RESERVOIR AT SOULTZ

The basis of this model are

- deterministic fractures intersecting the GPK3 and GPK4 borehole
- faults derived from the seismic distribution using the density analysis from Chapter 1

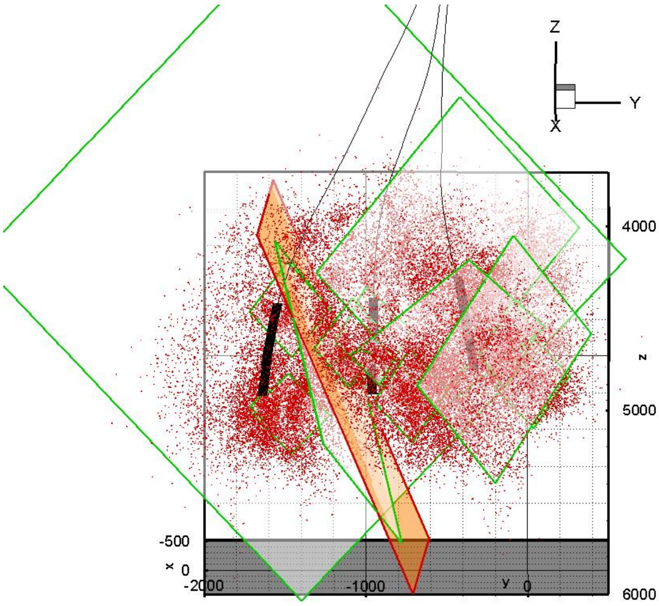


Figure 2-1: Determination of fault planes from microseismic distribution

In particular the model assumes that the aseismic zone has a high hydraulic conductivity, i.e. flow injected to GPK4 will be drained through this zone into a nearby N-S extending Soultz fault.

The off-borehole faults have been characterized in the following manner:

- Localization of 10 points of highest microseismic density
- Calculation of the higher density plane orientation and radius going through these points
- Selection of 8 planes of various orientation and radius
- Taking in account Soultz fault (West of the model), 6 other deterministic faults determined from an earlier analysis (R. Maurer, GEOWATT).
- Deterministic fractures at the well, based on UBI-log analysis (BRGM)

The calibration of this new fracture model is not yet finished. Therefore, the following calculations do not allow for a full quantitative interpretation, since the hydraulic pressure history of GPK4 and GPK3 do not yet match sufficiently well. However, already now, the effect of possible injection scenarios can be assessed.

2.2 HYDRAULIC STIMULATION SCENARIOS

Using the current stage of development of the HEX-S fault / fracture model the following scenarios have been calculated:

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 and GPK4 each with 30 l/s during 3 days and increase to 45 l/s
3. Single injection in GPK4 with 60 l/s during 3 days and increase to 90 l/s (i.e. doubled flow scenario 1)

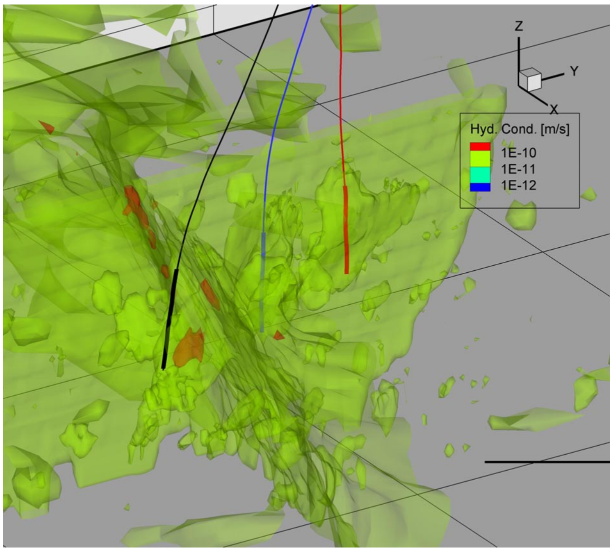


Figure 2-2: Calculated hydraulic conductivity distribution and GPK2 (red), GPK3 (blue) GPK4 (black) boreholes. The hydraulic conductivity is calculated for "scenario 1" after 1 day of injection in GPK4. The N-S trending Soultz fault and the E-W trending aseismic zone can be clearly identified. The red color next to GPK4 indicates deterministic fracture at in the open hole section.

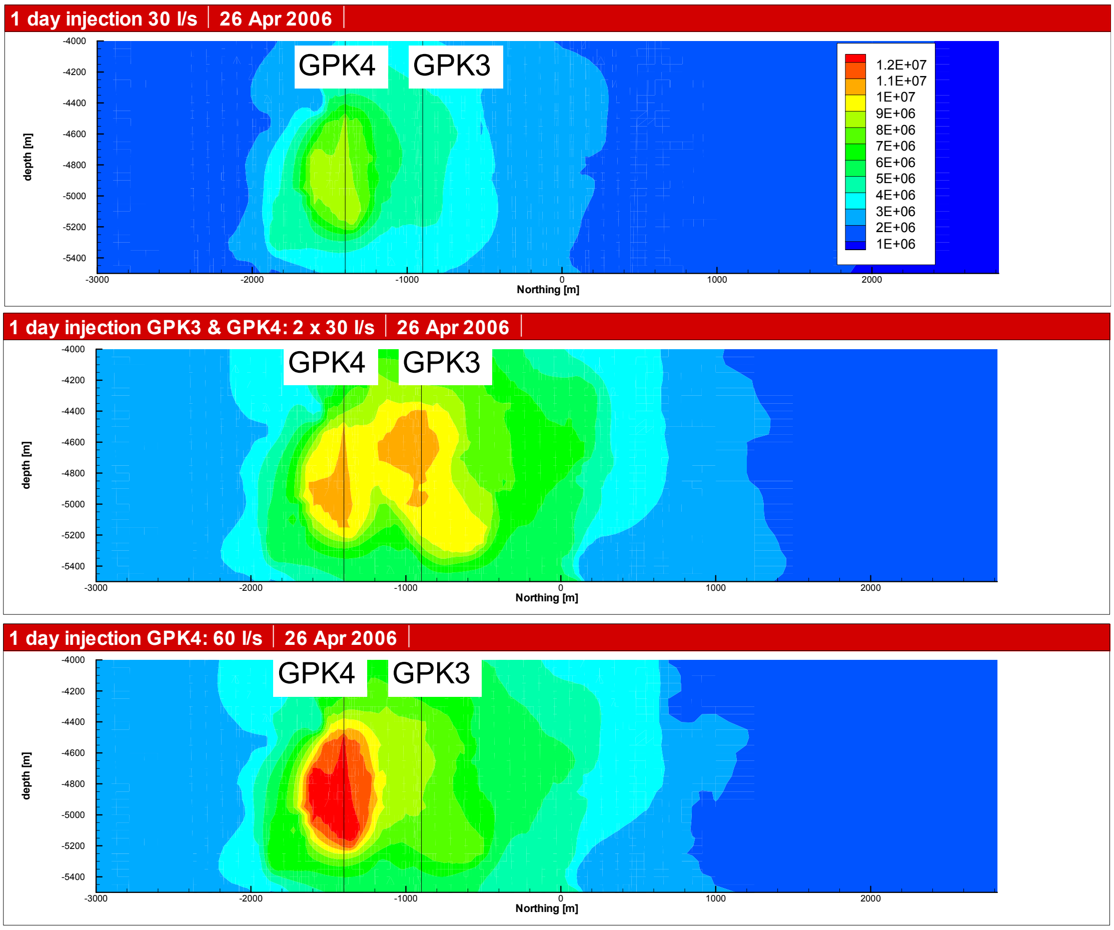


Figure 2-3: Calculated hydraulic pressure along a subvertical 2D section through GPK3 and GPK4 for each scenario ("1" top, "2" center" and "3" bottom). The pressure next to the boreholes are clearly identified.

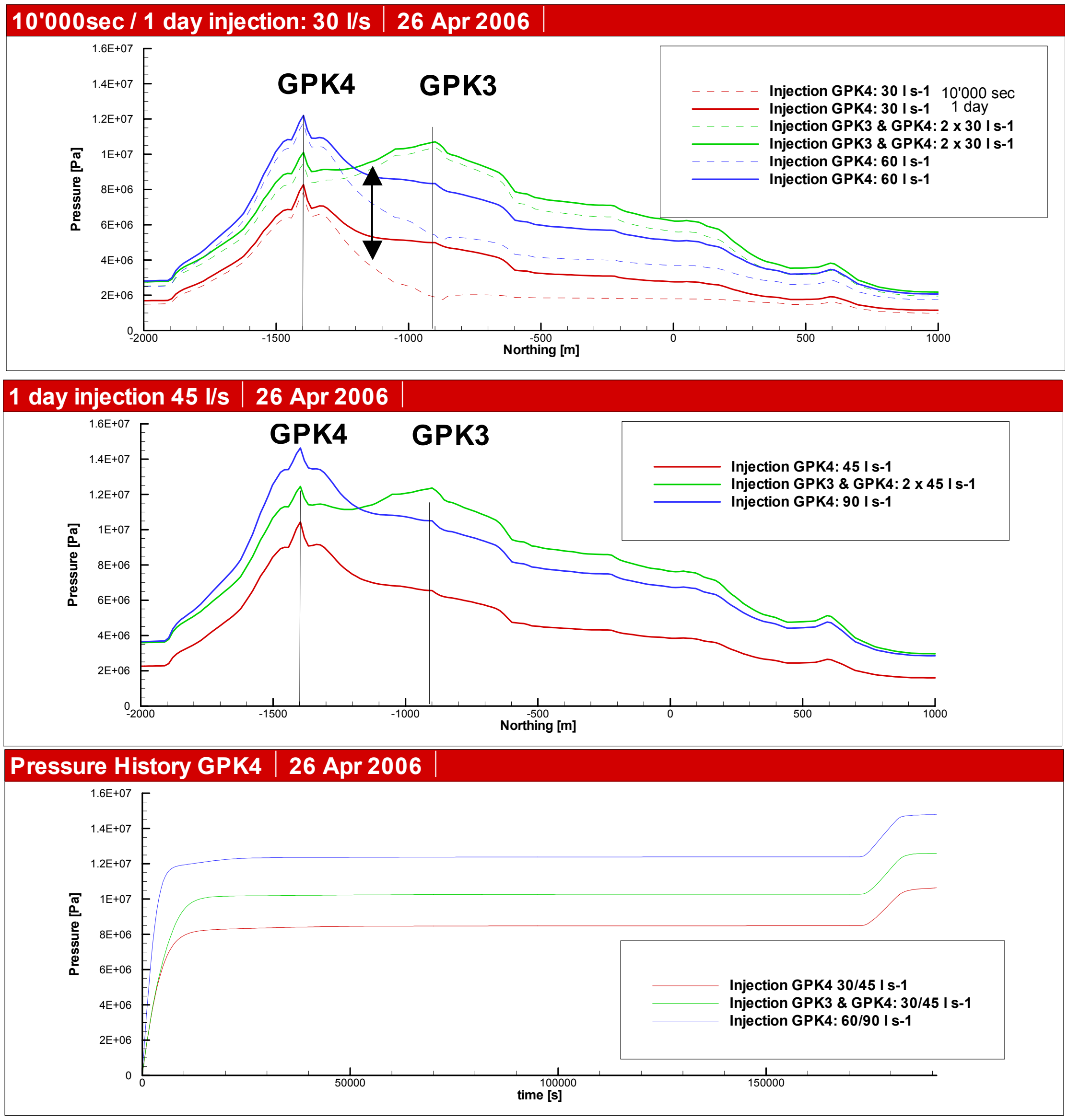


Figure 2-4: Hydraulic pressure distribution along a profile in 4750 m depth for the each scenarios (top 2 frames) and pressure history in GPK4 (bottom frame) for each scenario (red "scenario 1", green "scenario 2" and blue "scenario 3")

From Figure 2-4 the effect of transient evolution is clearly shown. Next to the borehole, steady state is reached within short time, however, at larger distance, the transient are more pronounced. A comparison of the different scenarios demonstrates that at dual injection a larger area is subject to **shorter transients**. In the central part around the aseismic zone pressure could increase nearly to steady-state within the first 12 hrs of injection (see the 6 MPa pressure difference [arrow] on top frame).

The effect of Non-Darcian flow is clearly demonstrated: a three times higher flow rate (from 30 to 90 l/s) would cause a pressure increase of only 75%. Different fault models would even suggest lower pressure increase!

2.3 CONCLUSION

A proper hydraulic characterization of the aseismic zone is definitely necessary for the success of the GPK4 re-stimulation. The monitoring and localization of microseismicity is therefore important.

The pressure field for dual injection reaches faster steady-state in the reservoir than for single injections. This suggests that shorter stimulation periods may become possible.

Already now, different scenarios can be investigated by numerical modeling. The HEX-S fault/fracture model is under continuous development. This should supply more elaborated quantitative comparisons in future.

3 SHUT IN PHASE AND PORE PRESSURE

Simplified considerations of hydro-mechanic processes during stimulation / shut-in are summarized in the following table. Especially the stress / pressure interaction along a fracture and adjacent rock matrix is illustrated, emphasizing the possible impact of pore pressure

Phase	**Hydraulic pressure**	**Impact on effective stress on fracture plane**
1. Initial state	Hydraulic pressure in fracture and pores corresponds to hydrostatic conditions	$\sigma_{eff} = \sigma_n$
2. Injection (short term)	Pressure builds up in fracture system, but not yet in pore pressure in matrix	$\sigma_{eff} = \sigma_n - P_f$ The effective stress will reduce. Under stress field in Soultz shearing will result
3. Injection (long term)	Pressure slowly builds up pores. The impact on stress is calculated from Biot Law	$\sigma_{eff} = \sigma_n + \sigma_{Biot} - P_f$ $= \sigma_n + \alpha \cdot P_f - P_f$ The effective stress starts increasing again. Shearing will slowly stop.
4. Shut-in	Fracture will drain fast, whereas pore pressure drains in the same time constants as it has build up.	$\sigma_{eff} = \sigma_n + \sigma_{Biot}$ $= \sigma_n + \alpha \cdot P_f$ The effective stress is even larger than at initial state. The danger of reversing the shear slippage may occur at distinct points. The seismic moment attributed to these reversed events may even be higher due to larger stress drop.

From these considerations it can be concluded that the risk of larger events increases with injection period. If the pore pressure has build up, the danger of high magnitude, reversed events will strongly increase. The location of these events is not necessarily restricted to far distance but can occur easily next to a borehole.

4 OVERALL CONCLUSIONS

The hydraulic re-stimulation of GPK4 includes the risk of low efficiency and of higher seismicity (see experience from GPK3). Nevertheless, mechanical stimulation have already shown convincing results with 10 times higher increased injectivities.

According to our considerations, the seismic risk and the success of stimulation can be optimized as follows:

1. **Short-term injections (1-2 days):** This prevents pressure build up in the secondary flow zones (pore pressure) and will reduce the impact of reversed shearing during shut-in. Our simulations indicate that the injectivities are generally immediately increased by the pressure build-up in the vicinity of the boreholes. The effectivity of long term pressure build up at larger distance does not seem to be convincing. A successive re-stimulation by short-term injections should also be conceived.
2. **Slow pressure reduction**, avoiding an abrupt shut-in. This would require a continuously reduction in flow rate after maximum pressure (flow) is reached. The time for the reduction should be in the same order like the pressure build-up.
3. **Initial fast and high-pressure rates**: the stronger the near borehole is pressurized the better this area is stimulated.
4. **Short term dual injection GPK3 and GPK4**: Short transients in the matrix can be anticipated, at much larger pressurized volume. If the danger for seismicity prevails in GPK3, a constant ~10 MPa over pressure should be applied (i.e. injection).

Zürich, 26. April 2006