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CONDITIONS FOR MECHANICAL RE-STIMULATION OF GPK4

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ABSTRACT

The well stimulation experiments conducted during the last years in Soultz provided essential information on the deep geothermal reservoir. The reservoir development monitoring allowed 3D mapping of localized microseismic events (Dyer, 2005); the location, density and magnitudes of these microseismic contain many information on the fracture network and on the system behaviour under injection of high flow rates.
There is a difficulty in finding a concise stimulation methodology to optimize the injectivity and/or productivity of the reservoir. Experience in Soultz does not indicate a simple mechanism for stimulation since different results have been obtained in the past.

This study analyzes in a rigorous and systematic way the information derived from the localization of microseismic events. To derive a spatial pattern of the recorded microseismic events their transient evolution is calculated as "seismic density" for each stimulation campaign. Special attention is paid to the identification of a so-called aseismic zone between GPK3 and GPK4. Its influence on the hydraulic system of Soultz is discussed.
In a second step, information collected by this microseismic density analysis is used and included in a numerical model. The effect of three different injection scenarios are investigated using the new hydro-mechanical finite element simulator HEX-S. Two model runs assume single well injection at variable flow rates, and one considers dual well injection. The computed model simulations allow quantifying the pressure distribution in the reservoir and their impact on aperture change. Therewith, the individual stimulation efficiency is estimated.

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

Data basis

The basis of the following reservoir simulation is a representation of the internal reservoir conditions. The only available 3D reservoir data are derived from microseismic locations. The implicit assumption in the following considerations is that microseismicity reflects a permeability pattern. However as will be shown below, low microseismic activity is not necessarily related to low permeability. The purpose of this section is especially to investigate far field structures or intermediate structures between GPK3 and GPK4.

The microseismic events considered in this analysis are the recorded in Soultz-sous-Forêts since year 2000, i.e. in the deep 5 km reservoir.

- 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

A total of 45'142 located microseismic events are taken into account in this study.
One should note here that seismic events recorded during circulation tests are not taken into 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.

Results

Figure 1 shows the computed density of located microseismic events during the last 4 years in Soultz. Calculations are performed on a 50 m mesh; each point of this mesh represents a cube volume of $50x50x50m^3$, with the number of events counted and normalized for this volume. Results are shown on this figure along 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 (Note: the reference coordinate system corresponds to GPK1 wellhead).

One can clearly observe on Figure 1 an "aseismic" zone located between wells GPK3 and GPK4. Next to the intersection of the two planes drawn the center of this low-density seismic zone is preliminarily estimated as: x = 165 m / y = -1175 m / z = -4975 m.

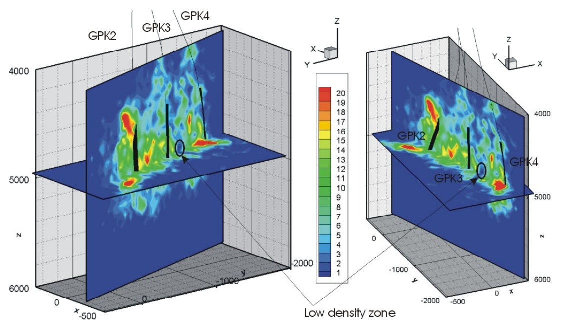

Figure 1: Density of microseismic events recorded during the last 4 years in Soultz. Results are given in number of located events per 50 m side length cube.

In a next step a search algorithm was used to determine the extension and location of this zone automatically: Starting from the low seismic density zone in the reservoir area between GPK3 and GPK4, a plane was determined with minimum 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* to 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* to this plane. As seen in Figure 2 (right), the density of events on that particular plane is noticeably low. The maximum seismic events density in that plane is 13 events / 50 m side length cube.

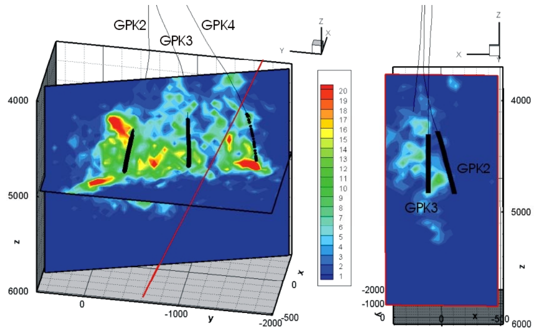

Figure 2: Representation of a low-density structure of orientation N96p64W.

Since the existence of such a structure seems to be obvious from steady-state data it will now be investigated more in detail. By this, it is intended to obtain a more complete depiction of its true nature since its hydraulic impact could be crucial for the stimulation of the area between GPK3 and GPK4.

Transient analysis of GPK4 stimulation microseismicity

Figure 3 shows the injection scenarios performed in GPK4 during two stimulation campaigns.

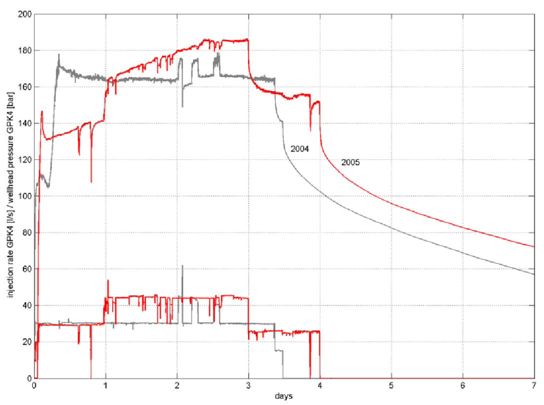

Figure 3: Imposed flowrate and measured pressure in well GPK4 during Sept. 2004 stimulation (in gray) and Feb. 2005 stimulation (in red)

<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=259200s and t=345'600s, implying a constant well pressure during this phase of injection (this result can be observe on both GPK4 stimulation campaigns; see Figure 4 and Figure 5).

This observation figures out that the pressure distribution in the reservoir has reached nearly steady state before the third day of injection, during the first GPK4 stimulation campaign.

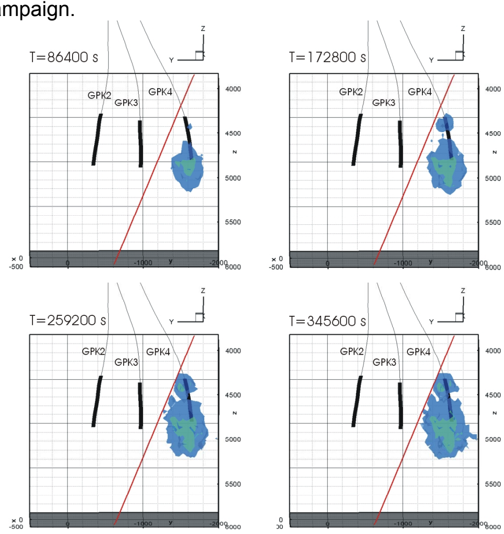

Figure 4: Evolution of the density of microseismic events during GPK4 September 2004 stimulation. Blue envelope: d = 3 events per 50 m side length cube; green envelope: d = 15 events per 50 m side length cube. Times are given from beginning of injection.

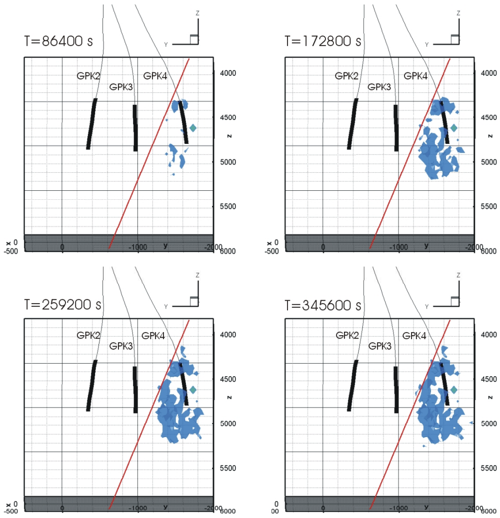

Figure 5: Evolution of the density of microseismic events during GPK4 February 2005 stimulation. Blue envelope: d = 3 events per 50 m side length cube. Times are given from beginning of injection

Comparison of the three stimulation results in terms of density of microseismic events

If the link between seismic events location and flow paths is not yet clearly established, it is now commonly accepted that seismic events occur because of a raise of pressure, implying a decrease of the effective stress and a shear mechanism (Evans et al., 2004). The dynamic growth of the seismic cloud can therefore give an idea of the local pressure increase and subsequent effective stress decrease. In order to compare the effective stress evolution during the stimulation campaigns of each well, the density of seismic events was computed during the six first days of each well stimulation campaigns (see Figure 6).

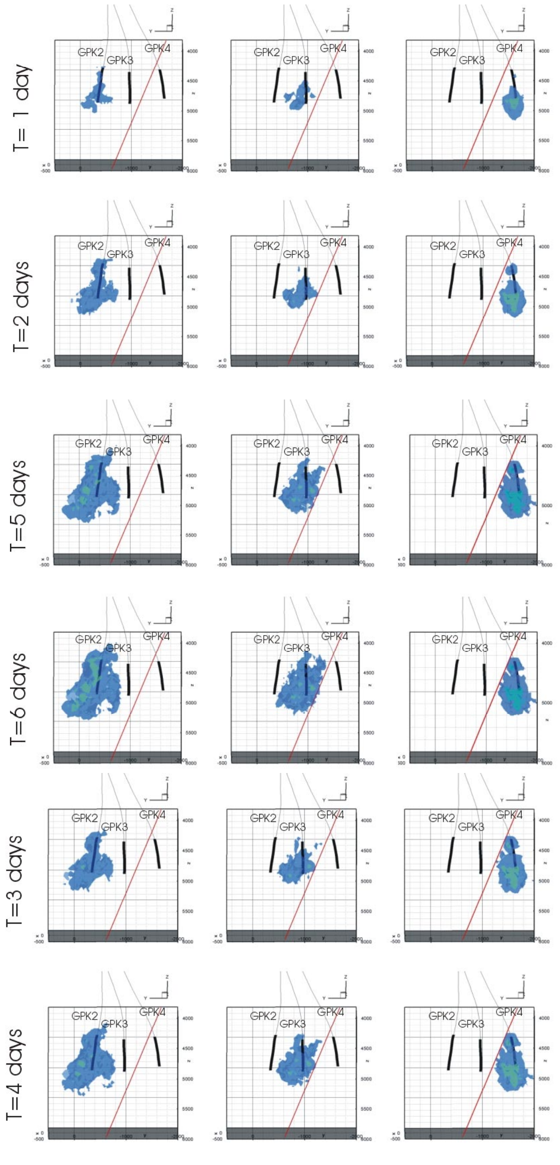

Figure 6: Transient development of GPK2, GPK3 and GPK4 microseismic density distribution (Δx=50m). Lateral view on the 3D seismic density distribution

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 most incorrect localizations (Dyer, 2005), 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 in Figure 7. As one can observe on this figure, the aseismic zone previously pointed out still appears on this analysis.

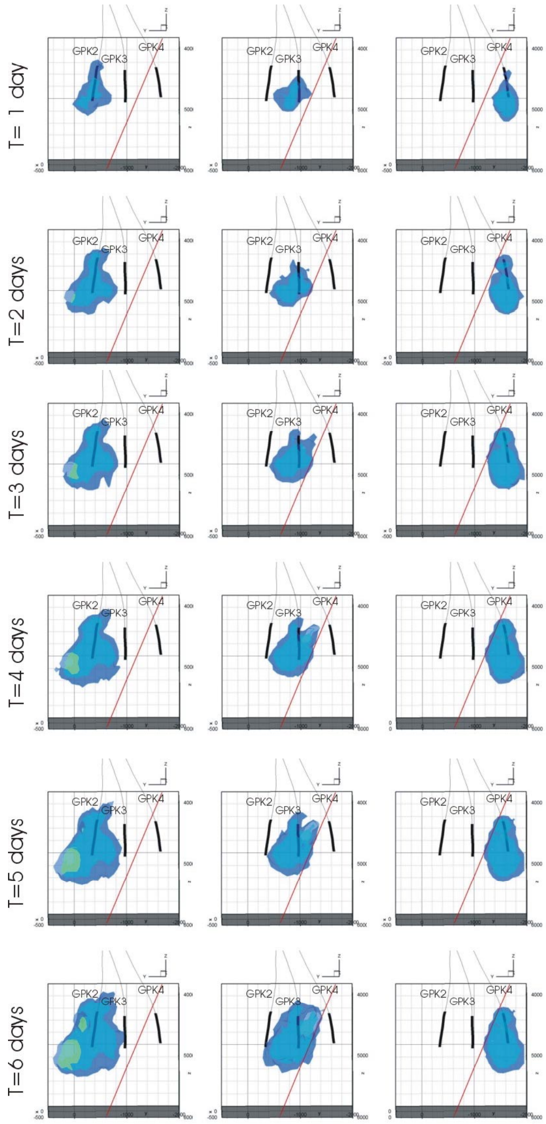

Figure 7: Transient development of GPK2, GPK3 and GPK4 microseismic density distribution (Δx=100m); Lateral view on the 3D seismic density distribution

Concluding remarks on possible hydraulic impact

After approx. 3 days of injection the extension of the microseismic cloud does not increase significantly any more in the deep Soultz reservoir. Therefore, it can be concluded that the hydraulic pressure front has also increased to its maximum. Due to storage effects in the rock matrix the magnitude of pressure will still be able to increase, causing additional microseismicity within the cloud. However, features outside the pressure front will remain intact. Using the injection rates applied, the determined subvertical nearly

E-W striking plane with minimum density of seismic events between GPK3 and GPK4 will therefore not be submitted to shearing even after long time injection

This zone has certainly a distinct hydraulic characteristic and may play a key role during the stimulation. In order to weight its possible impact on the reservoir flow field different arguments could be cited that provide hints on the nature of this structure. Theoretically, both, no-flow boundaries or drainage systems could produce such aseismic zones.
The following arguments may support a characterization as highly conductive zone that drains the fluid into a far field fault zone and thus prevents any pressure increase:

- "Fingering" of microseismic density indicates flow into this zone (see Figure 6)
- 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 of the aseismic zone with GPK4 at ~4450 m depth, high fluid-losses have been encountered during drilling

The following arguments may support a characterization as high impedance zone with extreme low natural fracturization (i.e. possible no-flow boundary)
- Orientation nearly perpendicular to Sh_{max};
- 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

- Following these arguments it is clear that both extreme models could quantitatively explain individual observations such as tracer breakthrough and provide only an ambivalent characterization. The strongest argument for a high impedance zone is the orientation of the aseismic zone that does not coincide with the general microseismic trend. Since such faults necessarily exist on Horst structures such as Soultz and since extreme low fracturization is hardly to imagine for the general permeability pattern (Kohl et al., 2000), there seem to be stronger arguments favoring a high conductive zone than a high impedance zone. In the following considerations, it is therefore anticipated that the aseismic zone corresponds to a subvertical structure that is well linked to N-S striking drainage systems such as the Soultz - and the Kutzenhausen-fault. Due to its orientation, we can expect a low compliance for normal stress variations and especially little shearing.

POSSIBLE SCENARIOS OF HYDRAULIC STIMULATION OF GPK3 AND GPK4

The HEX-S model (Kohl and Mégel, 2005) 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.

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 (see Figure 8)

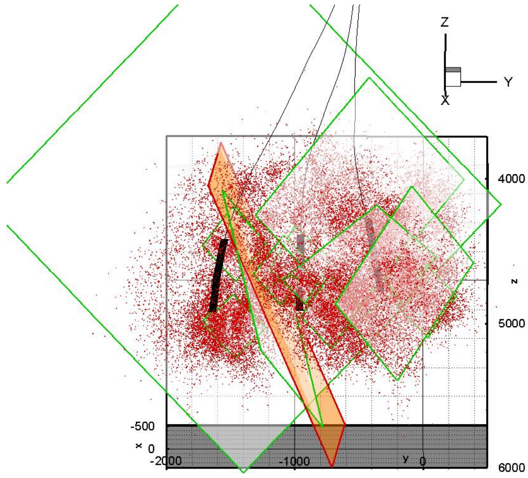

Figure 8: Determination of fault planes from microseismic distribution

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 faults not intersecting the boreholes 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 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 estimated.

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)

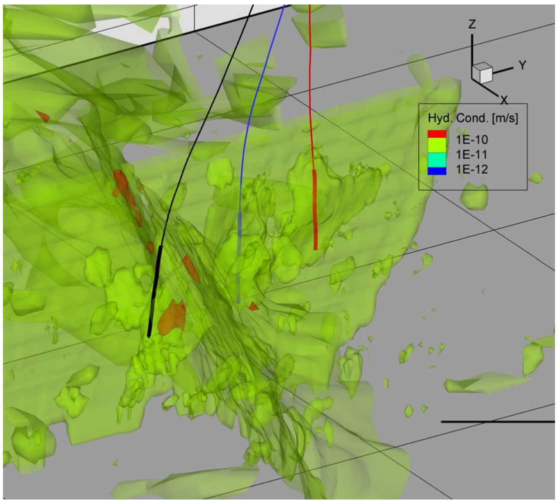

Figure 9: Calculated hydraulic conductivity distribution and GPK2 (red), GPK3 (blue) GPK4 (black) boreholes. The hydraulic conductivity is calculated for "scenario 1" after 1 day of injection in GPK4. The N-S trending Soultz fault (parallel to y-axis) and the E-W trending aseismic zone (parallel to x-axis) can be clearly identified. The red color next to GPK4 indicates deterministic fracture at in the open hole section.

Computed stimulation results can be observed on the following figures; Figure 10 shows a cross section of the pressure distribution in the reservoir for the three scenarios, and Figure 11 shows pressure values along a profile going through both wells GPK3 and GPK4.

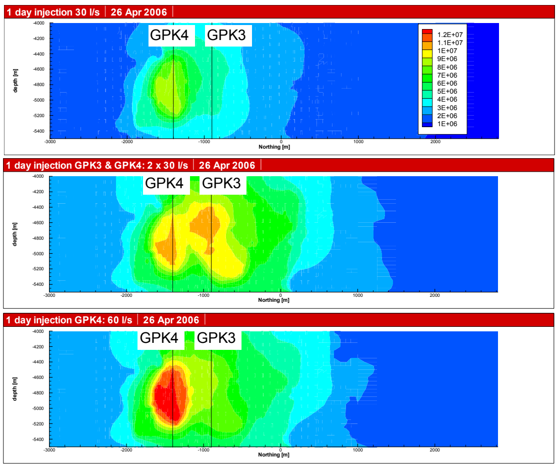

Figure 10: Calculated hydraulic pressure after 1 day of injection along a subvertical 2D section through GPK3 and GPK4 for each scenario ("1" top, "2" center" and "3" bottom). The pressure next to the boreholes are clearly identified.

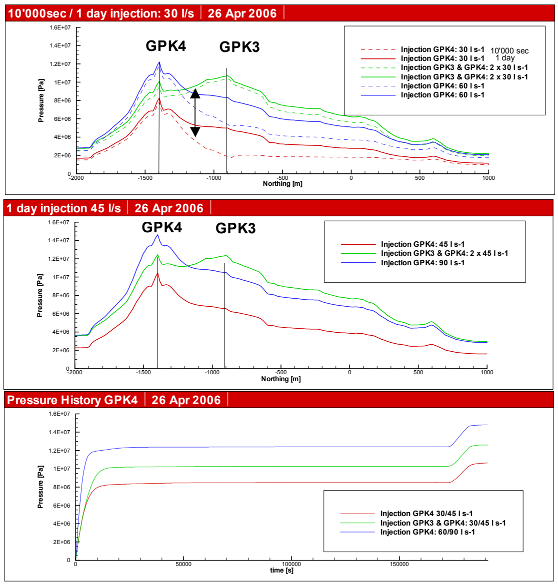

Figure 11: Hydraulic pressure distribution along a profile in 4750 m depth for each scenario (top frame: first injection step at t=10'000 s and 1 day; central frame: second injection step at t=1 day after step change) and pressure history in GPK4 (bottom frame). "Scenario 1" is represented in red, "scenario 2" in green and "scenario 3" in blue)

From Figure 11, 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!

CONCLUSIONS

The hydraulic re-stimulation of GPK4 includes the risk of low efficiency and of higher seismicity (see experience from GPK3). In the past, mechanical stimulation have been applied with different success: sometimes they didn't improve injectivity, sometimes they produced 10 times higher injectivities.

At the specific reservoir location between GPK3 and GPK4 a proper hydraulic characterization of the aseismic zone is definitely necessary for the success of the GPK4 re-stimulation. Continuous monitoring and localization of microseismicity is therefore important.

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

Already today it can be demonstrated that the pressure field produced by dual injection reaches faster steady state in the reservoir than by single injections. This suggests that shorter stimulation periods may become possible. This has certainly an important economic benefit.

According to our considerations, the seismic risk and the success of mechanical 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 limit the size of the affected area. Our simulations indicate that injectivities are generally immediately increased by the pressure build-up in the vicinity of the boreholes. From our analysis, it has not been demonstrated in Soultz that pressure build-up at larger distance can be achieved by long-term injection. Several successive short-term injections could produce better results for a re-stimulation.
2. **Fast pressure reduction**, avoiding long-term shut-in. This would require an as fast as possible pressure venting of the boreholes, after maximum pressure levels (flow) have been reached.
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).

These measures do not take into account the impact from chemical stimulation. Similarly to point 1, several successive chemical / mechanical stimulation experiments could be an adequate strategy for the reservoir development at Soultz since they are complementary in nature: acidization with HCl rather affects the near borehole vicinity whereas mechanical stimulation could influence the natural fracture network at larger (~200 m) distance.

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