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HDR PROJECT SOULTZ: HYDRAULIC AND SEISMIC OBSERVATIONS DURING STIMULATION OF THE 3 DEEP WELLS BY MASSIVE WATER INJECTIONS

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ABSTRACT

The aim of the HDR project Soultz is the geothermal power production based on an artificially created heat exchanger at 5000 m depth.
During the years 1999-2004, three wells were drilled down to 5000 m, one injection (GPK3) and two production (GPK2 and GPK4) wells. After drilling, each well was stimulated by massive water injection with volumes up to 30000 m^3 and typical flow rates of 30 - 50 l/s.
Subsequently, injection tests with significant lower rates were performed to determine the productivity (injectivity) of the wells. A good agreement was obtained between the productivity during and after stimulation for all three wells. The stimulated flow paths obviously retain their hydraulic conductivity completely in the post-stimulation period. This observation is very important for planning of hydraulic stimulation operations since the productivity enhancement is predictable. The pressure during stimulation is mainly controlled by rock stress. A higher injection rate leads to a higher productivity during stimulation and consequently afterwards.
At the wells GPK2 and GPK3 a slight increase of downhole pressure was observed during stimulation with constant rate (50 l/s). This characteristic is considered to be typical for shearing of fractures. In contrast, the stimulation of GPK4 was accompanied by a slight but continuous pressure decrease as it is usually observed in stimulation operations dominated by tensile fracturing. Further indication (flow profile) supports the assumption that jacking occurred at least in the vicinity of the borehole GPK4.
It is of special interest that the above mentioned coincidence between productivity during and after stimulation appears to be valid also for GPK4 where tensile fracturing seems to be a significant stimulation process. For the conditions in Soultz, it is generally assumed that the dominant stimulation process is shearing of natural fractures. In view of the observations at GPK4, this assumption should further be investigated.
In order to transfer the experiences of Soultz to other places it is very important to understand to which extent artificial fractures contribute to the reservoir development.

INTRODUCTION

The test site of the HDR project Soultz is located in France on the western edge of the Rhine Graben, some 50 km north of Strasbourg near the German border.
The objective of the project is the development of a subsurface heat exchanger for geothermal power production. During the last years three wells were drilled in granite rock down to 5000 m. Two wells (GPK2 and GPK4) are planned for production whereas the central well (GPK3) will be the injection well. All the three wells were drilled from the same platform. The horizontal distance between the injection well and each of the production wells is appr. 600 m at the target depth of 5000 m (see Fig. 1).

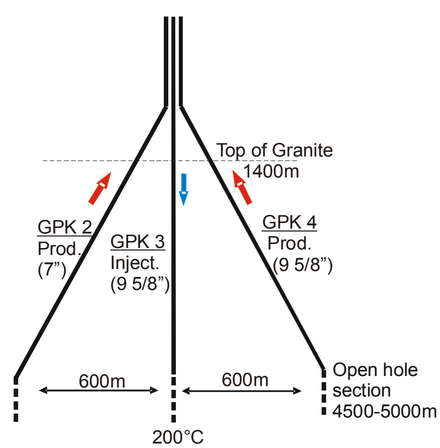

Fig. 1: Scheme of the borehole triplet in Soultz. The casing diameter is given in brackets. Inject.: injection well; Prod.: Production well.

The target areas of the wells are aligned along an azimuth of N170°-N180° in accordance with both the direction of maximum horizontal stress and the orientation of the seismic clouds (for more details see: Hettkamp et al., 2004).

The main challenge of the project is the creation of artificial fractures and/or the stimulation of natural fractures to form a hydraulic link between the wells and to allow the circulation of water up to a rate of 100 l/s. Therefore, each of the wells was subjected to hydraulic stimulation by massive water.

This study presents the main results of hydraulic stimulations with focus on productivity comparison of each well before, during and after stimulation. An important question is whether the stimulated fractures retain their hydraulic conductivity after stimulation.

A huge number of seismic events were recorded with a downhole seismic network during stimulations, giving an inside into the fracturing process. It is discussed if only natural existing fractures are subject to stimulation or if artificial fractures have been created too.

INITIAL PRODUCTIVITY OF THE WELLS

After drilling of GPK2 and GPK4, low-rate injection tests were performed to determine the initial productivity of both wells. (Productivity and injectivity are assumed to be identical as the experiences in Soultz suggest). Figure 2 shows the low rate injection test of GPK4 as an example. The observed pressure did not stabilize, meaning that the well productivity is time dependent. The extrapolated differential pressure (≈ 60 bar) yields an initial productivity of around 0.01 l/(s*bar) after 2 days of injection.

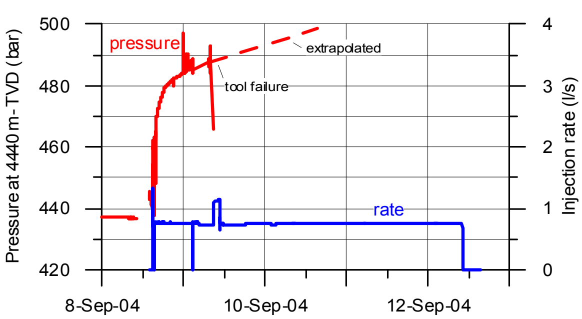

Fig. 2: Downhole pressure and flow rate during the low rate injection test in GPK4 in Sept. 2004. The wellhead pressure is not shown and can not be evaluated because of the lack of density data of the water column in the well during injection. TVD: True vertical depth.

Similar injection tests at the other production well (GPK2) in February 2000 also resulted in a low initial productivity of around 0.02 l/(s*bar) after two days of injection (Baria et al., 2002 p. 33-42).

The situation was different for the injection well GPK3. This well intersects a natural permeable fault structure in the open hole section and has thereby an initial productivity much higher than GPK2 and GPK4. The initial productivity of GPK3 can roughly be estimated to 0.2 l/(s*bar) based on the pressure recording of a circulation test between GPK2 and GPK3 in 2003.

The approximate initial productivities after test periods of 2 days are summarized below:

GPK2: 0.02 l/(s*bar)
GPK3: 0.2 l/(s*bar)
GPK4: 0.01 l/(s*bar)

In order to allow the circulation of 100 l/s in the triplet system the post-stimulation productivity of each well has to be in the range of 0.5 – 1.0 l/(s*bar). The difference between initial productivities and the target values points out the challenge of stimulation in Soultz.

HYDRAULIC STIMULATION OF THE WELLS

The three deep Soultz wells were stimulated by massive water injections, individually. Each stimulation commenced with the injection of heavy brine (volume < 800 m^3, density ≈ 1.2 kg/l) to initiate the stimulation as deep as possible in the borehole. Subsequently, large volumes of fresh water were injected. Table 1 contains an overview of the hydraulic stimulation operations.

Well	Year	Duration (d)	Volume (m^3)	Flow rate (l/s)	seismic events
GPK2	2000	6	23400	50	14000
GPK3	2003	11	34000	50	21600
GPK4	2004 2005	3.5 4	9300 12300	30 45	5700 3000

Tab. 1: Overview on the hydraulic stimulations of the Soultz wells. Column 5 lists the dominant flow rate during stimulation and column 6 the number of localized seismic events.

Figure 3 shows the differential pressures and flow rates for the three stimulation operations.

The well GPK4 was stimulated twice. However, the injection volume at the second hydraulic stimulation was only slightly higher than at the first stimulation. It can be shown that the second stimulation of GPK4 in 2005 hardly improved the productivity of the well. This stimulation will therefore not be discussed here.

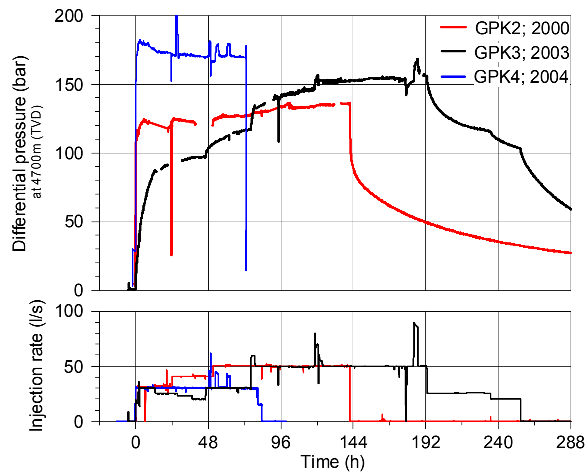

Fig. 3: Differential pressure at reservoir depth and flow rate for the three stimulation operations. The pressure at 4700 m was derived from the measured pressures at 4406 m (GPK2), 4472 m (GPK3) and 4437 m (GPK4) by adding the pressure of the water column in between. A unique formation pressure of 460 bar at 4700 m (TVD) was then subtracted to determine the differential pressure.

The pressure at GPK2 is almost independent on the flow rate. After raising the flow rate up to 50 l/s a slight but continuous pressure increase is observed. This pressure behavior corresponds to the perception of shear fracturing where the pressure is mainly controlled by formation stress. The slight pressure increase is assumed to be caused by increasing friction losses in the fractures as the effective stimulated area extends.

During the first 3-4 days of GPK3-stimulation the pressure clearly depends on the flow rate and the pressure level is low compared to the other stimulations. Due to the initial high productivity of the well flow rates up to 30 l/s can be injected without significant stimulation. It seems that only after 4 days of injection and after increasing the flow rate to 50 l/s a considerable stimulation starts to develop. Accordingly, GPK3 appears to be effectively stimulated only for the last 4-5 days.

A significant different pressure response was observed during the GPK4 stimulation. The differential pressure is higher than at the other wells although the lowest flow rate (30 l/s) was injected only. Further, the pressure decreases slightly but continuously. Both features are indications for a fracturing process controlled by tensile fracturing and not by shearing.

It is interesting to evaluate the differential pressure at the end phase of the stimulations particularly when the pressure is almost stabilized.

From these values the productivity at the end of stimulation can be derived (rounded to the nearest 0.05 l/(s*bar)):

GPK2: 50/135 l/(s*bar) = 0.35 l/(s*bar)

GPK3: 50/155 l/(s*bar) = 0.30 l/(s*bar)

GPK4: 30/170 l/(s*bar) = 0.20 l/(s*bar)

The productivity of GPK2 and GPK4 during the stimulation is many times higher than before stimulation whereas the productivity of GPK3 is only 50 % higher than in the pre-stimulation phase.

In the next chapter the question is addressed if the productivity during stimulation retains after stimulation that means after pressure release.

PRODUCTIVITY AFTER STIMULATION

Injection tests were performed after stimulation to quantify the productivity enhancement induced by hydraulic stimulation. The flow rate applied at these injection tests was significantly lower than during stimulation to keep the pressure below the fracture opening pressure.

Figure 4 shows the post-stimulation injection test in GPK2. Fresh water was injected at a flow rate of 15 l/s over a time period of 7 days. The productivity of the well can directly be derived from the pressure decline after shut-in. Four days after shut-in, the pressure decreased by 42 bar as depicted in figure 4 and thus resulting in a productivity of 0.35 l/(s*bar).

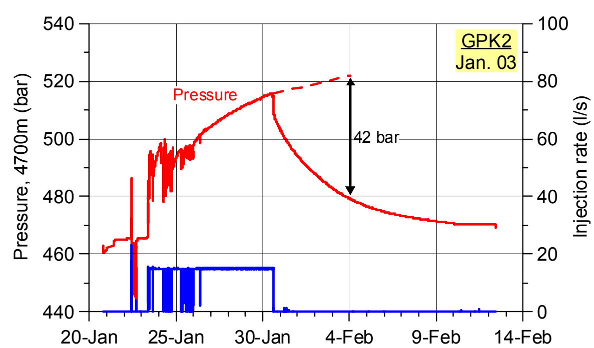

Fig. 4: GPK2 injection test in January 2003 after hydraulic stimulation. The pressure is extrapolated from the measured one at 3500 m (TVD).

The corresponding injection tests in GPK3 and GPK4 were conducted as step rate tests. Figure 5 illustrates the injection test at GPK3 in August 2004. The pressure at the last two injection periods and during shut-in can almost perfectly be matched with a fit based on a formation linear flow model.

The pressure of a similar injection test in GPK4 (March 2005) could also be fitted very well.

The fitting curves were used to calculate the productivity versus time of the wells GPK3 and GPK4 (figure 6).

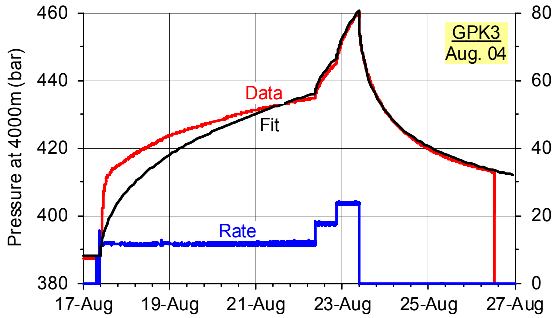

Fig. 5: GPK3 injection test in August 2004. The beginning of the injection is dominated by a significant skin that apparently disappears during injection. The fit was obtained from a pressure match during shut-in based on a formation linear flow model.

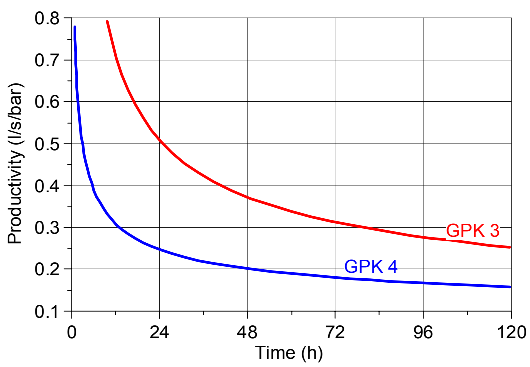

Fig. 6: Post stimulation productivity as a function of time of the wells GPK3 and GPK4. The curves were derived from pressure matches (see figure 5).

Since the well productivity is time dependent, it is necessary to evaluate the productivity after a time equivalent to the stimulation period in order to compare the productivity during and after the stimulation. GPK2 was stimulated with a rate of 50 l/s for a period of 4 days. GPK3 seems to be effectively stimulated only for a period of 4-5 days (see above) whereas GPK4 was subjected to stimulation for 3 days. The corresponding productivities after stimulation are (rounded to 0.05 l/(s*bar)):

GPK2 (4 d): 0.35 l/(s*bar)

GPK3 (4 d): 0.30 l/(s*bar)

GPK4 (4 d): 0.20 l/(s*bar)

Thus, the post stimulation productivity is essentially the same as at the end of stimulation. The stimulated fractures obviously retain their hydraulic conductivity completely.

MICROSEISMICITY

Microseismic monitoring plays a key role in investigating the reservoir stimulations in Soultz.
Subsequently, microseismic observations are discussed with respect to hydraulic communication between the wells and with respect to the underlying stimulation process (shearing or tensile fracturing).
Six wells in the depth range of 1500 – 3500 m have been used as seismic observation wells (Dyer, 2005). The recorded and localized seismic events during stimulation allow tracing the development of the reservoir and serve as indication for the hydraulic connection between the wells (Baria et al., 2004).
Figure 7 illustrates the density distribution of all seismic events observed during the stimulations 2000-2005 in a plane view. It can be concluded that the region between GPK2 and GPK3 was higher stimulated than the region between GPK3 and GPK4. Hydraulic interference tests confirm this observation. The weak link between GPK3 and GPK4 is still the main issue of the reservoir development up to now.

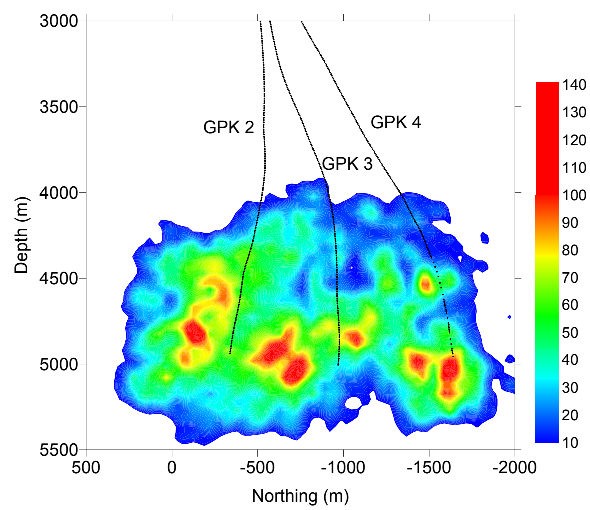

Fig. 7: Color contour plot of the event density in 50x50 m cells in the plane of the graph. Perpendicular to this plane the cells are unlimited. All events localized during the stimulations 2000, 2003, 2004 and 2005 were included.

The azimuthal orientation of seismic events can be visualized in horizontal depth slices within the depth range of 4900-5000 m, where the most seismic events occured (figure 8). Figure 7 and figure 8 clearly show that predominantly planar structures have been stimulated that are aligned in a strike direction of N-S to NW-SE.

The events during the stimulation of GPK2 (fig. 8a) are concentrated along the direction N145°E. During stimulation of GPK3, a large number of events were released but spatially widely dispersed compared to the events triggered by GPK2 or GPK4. It seems that a great amount of the injected water penetrated into the formation with little stimulation effect. This observation corresponds to the pressure characteristic as mentioned above.

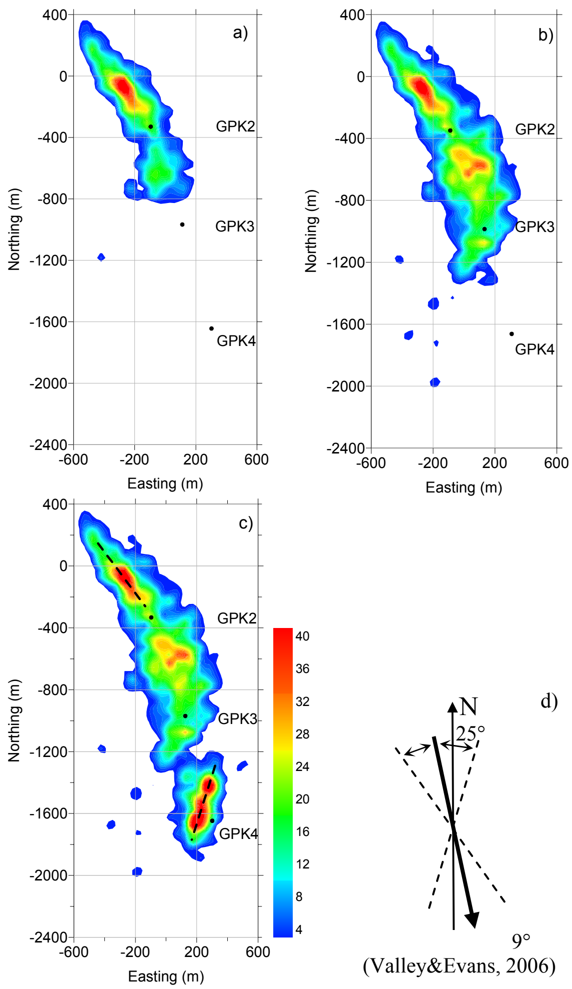

Fig. 8: Color contour plot of the event density in the depth range 4900 – 5000 m. The event density was determined in 50x50 m cells in the plane of the section and 100 m perpendicular to the section.

a) Event density after stimulation of GPK2 (2000)

b) Event density after stimulation of GPK2 (2000) and GPK3 (2003)

c) Event density after stimulation of GPK2 (2000), GPK3 (2003) and GPK4 (2004+2005)

d) Illustration of the orientation of seismic events of the GPK2 and GPK4 events referred to the direction maximum horizontal stress (S_H).

A dominant strike direction can be derived again for the stimulation of GPK4 where the events are concentrated along the direction N15°E (fig. 8c).

In a recent study on the stress state in Soultz by Valley & Evans (2006), the orientation of maximum horizontal stress was determined from wellbore failure observations with N169°E±14°. The orientations of seismic events for GPK2 and GPK4 stimulations differ from this direction by an angle of 25° clockwise (GPK4) and counterclockwise (GPK2). However, both directions fit very well to preferred directions for shearing if a strike-slip regime is assumed. The assumption of a strike-slip regime is likely, because the maximum horizontal stress can be higher than the vertical stress component (Valley & Evans, 2006). The observed orientations of seismic events thus support the assumption of shearing as the dominant stimulation process.

FLOWLOGS

Indications about the fracturing process in the vicinity of the well can also be derived from flowlogs. Figure 9 shows flowlogs for GPK3 and GPK4. The flow profile of GPK3 can be considered as typical for the Soultz wells if the experiences from GPK2 and from shallower wells are included too. One outlet (here at about 4700 m) dominates the flow profile and accounts for more than 70 % of the total outflow. However, the flow profile of GPK4 has a completely different characteristic. Over a long vertical length (4500 m – 4800 m) the flow rate decreases continuously. Such a flow profile can only be explained by fluid loss through a long vertical fracture in the well. Taking into consideration the pressure curve during stimulation of GPK4 (figure 3), it is very likely that a long tensile frac was created while stimulating this well. Thus, not only preexisting natural fractures were stimulated but at least artificial fractures were created in the vicinity of the well GPK4 as well.

The orientation of this tensile frac should follow the direction of the maximum horizontal stress (N170°E). However, the orientation of the seismic cloud (N15°E) seems not to match the hypothesis of tensile fracturing. An explanation of this discrepancy might be that tensile fracturing was the dominating process only in the early stimulation phase. Later on, when the tensile frac extended and natural fractures were reached, shear displacement on these surfaces became the dominant failure mechanism. On a larger scale – conclusions based on the spatial distribution of seismic events can only be drawn on a larger scale – shearing controls the stimulation process in accordance with seismicity.

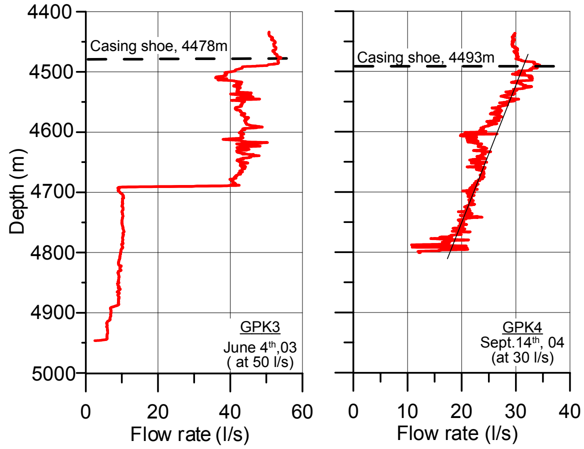

Fig. 9: Flowlogs performed in the open hole section of GPK3 and GPK4 during stimulation. Due to a restriction in the borehole GPK4 the flowlog could not be run to bottomhole.

DISCUSSION AND CONCLUSION

Massive water injections over several days were performed in Soultz to stimulate the wells. The goal of these long extended stimulation operations was a maximum reduction of shear stress on the stimulated fracture faces and the simultaneous activation of large rock volumes. The longer the fluid pressure is kept above the critical shear stress, the better the shear stress will be reduced. Ideally, after those water stimulations no closing of the fractures should occur and the productivity of the well during stimulation should be same as after stimulation.

Indeed, the above consideration of well productivities leads to the conclusion that the productivity after stimulation is essentially the same as during stimulation. This statement holds for all three deep wells in Soultz.

As a consequence, the productivity enhancement due to such an operation becomes predictable. The pressure during stimulation is mainly controlled by rock stress. The higher the injection rate the higher is the productivity during stimulation and consequently after stimulation. The predictability of the productivity enhancement is a great advantage of those operations and must be emphasized compared to other stimulation methods.

The concept of massive water injections may have the disadvantage of triggering larger seismic events as it recently occurred in the geothermal project of Basel (Switzerland). However, if selected intervals of a well are stimulated one after another by water injections (multifrac), the water volume for each operation can be reduced. The result of each frac can be predicted and the overall productivity should be the sum of the individual frac operations. Thus, a multifrac concept could be a more advantageous stimulation concept especially to minimize the seismic risk.

Microseismic observations suggest shearing as the dominant stimulation process. On the other hand, the flow log in GPK4 and the pressure response at GPK4 obviously indicate the creation of a long extended tensile frac during stimulation. Likely, in the initial phase of stimulation of GPK4 a tensile frac was created whereas later on shearing became the dominant stimulation process in accord with seismic observations.

Although, it is generally assumed that preexisting natural fractures are subjected to shearing during stimulation, a part of the productivity enhancement seems to stem from the creation of artificial fractures. For transferring the experiences of Soultz to other places it is very important to understand to which extent artificial fractures contribute to the reservoir development. This question is very important and needs further investigations.

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