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SUMMARY OF HYDRAULIC STIMULATION OPERATIONS IN THE 5 KM DEEP CRYSTALLINE HDR/EGS RESERVOIR AT SOULTZ-SOUS-FORÊTS

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ABSTRACT

Between 2000 and 2005 each of the three 5000 m deep wells (GPK2, GPK3, and GPK4) of the European HDR/EGS project at Soultz (Upper Rhine Graben, France) was hydraulically stimulated through massive water injections. A microseismic monitoring through a network of up to 6 downhole sensors accompanied the stimulation operations and allowed to locate the hypocenters.

The stimulation of GPK2 resulted in a 20-fold increase in productivity and created a rather narrow distribution of microseismic events with a strike direction around N145°E. It appears that this zone has for a great part governed the stimulation. A similar flow rate (50 l/s) was applied to stimulate GPK3, created significantly more events which are widely dispersed, but did not improve much the productivity. The flow zone at 4760 m MD, which was already permeable before, might explain this behaviour. The stimulation of GPK4 was performed in two stages, each with a lower flow rate (30 l/s) in order to reduce the risk of higher magnitude seismicity. The spatial density of the corresponding seismic events is comparable to the stimulation of GPK2, again indicating an effective stimulation and a significant productivity enhancement. In the second stage performed in 2005, a slightly higher volume of water than before was injected. The seismic activity was comparable low and spatially much more dispersed than in the first step. Consequently, the productivity of the well was not improved much.

We conclude that the effect of the stimulation in terms of productivity enhancement can be qualitatively derived from the seismic density distribution. A high seismic density correlates with a significant productivity enhancement whereas a more dispersed distribution results from a less effective stimulation.

INTRODUCTION

Hydraulic stimulation is the most recognized means to improve the permeability of rock formations in a large scale and to connect boreholes over several hundred meters. For the targeting of the wells as well as for the control of stimulation, the monitoring of microseismicity - induced either by fracturing the rock or by shearing the preexisting fractures – is the only tool which gives insight into the underground away from the borehole.

In the European HDR/EGS project in Soultz, hydraulic stimulations and microseismicity monitoring are carried out since the beginning in 1987. The objective of the project is the development of a subsurface heat exchanger in granite for geothermal power production. In the last project phase, a borehole triplet was developed which consist of one injector (GPK3) and two producers (GPK2 and GPK4) at a depth of 5000 m where the formation temperature reaches 200 °C. All wells were stimulated hydraulically after the drilling to connect them to the surrounding fracture network and to enhance the permeability of the reservoir.

The purpose of this paper is to review systematically all hydraulic stimulations of the three wells with focus on the seismic events reflecting the temporal and spatial reservoir development. Through the comparison of stimulation pressures, the hydraulic results and the microseismic behaviour, we deduce probable hydraulically active structures. Moreover, we intend to correlate the spatial seismic density to the productivity enhancement of the single stimulations.

GEOLOGICAL AND TECHNICAL BACKGROUND

Soultz-sous-Forêts is located in the Upper Rhine Graben, close to the western boundary fault (Dezayes, 2005), about 50 km north of Strasbourg. 1400 m of Cenozoic sediments overlay the granitic basement. The temperature gradient varies strongly with depth and indicates a convective cell between the basement and the sediments. At 5000 m depth, 200 °C are encountered. The granitic basement at the level of the open hole sections, from 4500 to 5000 m, consists of a standard porphyritic MFK-granite at shallower level and two mica granite in the deepest part which probably intruded into the upper part.

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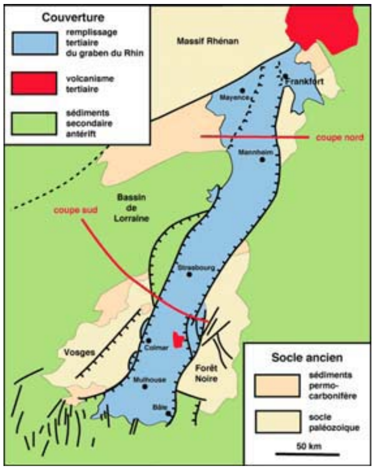

Figure 1: Geological view of the Rhine Graben (Hettkamp et. al., 2004)

The fracture density increases at the top of the two mica granite (Dezayes et. al., 2005a). A large fractured zone in GPK3 at about 4770 m (measured depth) coincides with the boundary between the two granites and forms a hydraulic pathway between GPK3 and GPK22 (Weidler et al., 2002, Dezayes et al, 2005b).

The three wells have a 500 m long non cased open hole section to access this part of the formation (Fig. 2). They were drilled from the same platform, having a bottom hole horizontal distance of 600 m in the granite. First, GPK2 was deepened in 1999 and stimulated in 2000. GPK3 was then drilled into the edge of the stimulated area and was itself stimulated in 2003. In the same way, the targeting, drilling and stimulation of GPK4 passed in 2004 and 2005. Resulting from stress measurements and the orientation of the microseismicity observed during the stimulations, the open hole sections are aligned along an azimuth of N170°-N180° which represents both the direction of maximum horizontal stress and main direction of microseismicity.

The seismic observation wells GPK1, EPS1, 4616, 4501, 4601 and OPS4 (Fig. 2) were for a part especially drilled for the deployment of the seismic downhole network to monitor the microseismicity. The network consists of 4-component accelerometer sensors and geophones or hydrophones. The data were either transmitted in analogue or by landline or radio telemetry to the data acquisition room where they were band pass filtered and digitized. The data acquisition system used an amplitude threshold trigger to detect and record the potential microseismic events. The microseismic event location was performed automatically (Dyer, 2001, 2004, 2005).

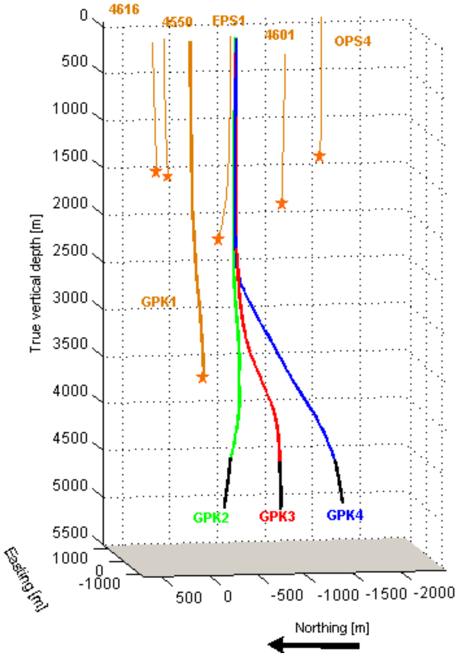

Figure 2: Sketch of the three deep wells building the geothermal borehole triplet: GPK2 and GPK4 are producing wells, GPK3 an injector. The open hole sections are illustrated in black. The surrounding observation wells are orange, the stars indicate the depth level of the installed downhole seismic sensors.

The hydraulic data we will illustrate in this paper are from the surface hydraulic data acquisition system. The detailed analysis of the hydraulic tests was performed, if possible, with data from downhole tools.

The seismic data used in this paper are the located events provided by Ben Dyer (Dyer, 2001, 2004, 2005). The event rates per hour in figures 3-6 are therefore smaller than the ones reported by Dyer, but we preferred to present one consistent data set for each stimulation which is also suitable for a spatial illustration. The amplitudes we interpret in the following are the peak amplitudes of the vertical component of sensor 4550. However, for the stimulation of 2000, we unfortunately missed the amplitude information.

HYDRAULIC STIMULATIONS AND SEISMIC OBSERVATIONS

In general, the stimulations of the three deep wells consisted of the injection of fresh water. Prior to the fresh water, heavy brine with a density up to 1.2 g/cm³ was injected to initiate the opening of fractures at the deeper borehole section. The single stimulations are briefly described below.

GPK2 (2000)

The initial productivity of GPK2 was around 0.02 l/(s*bar). The well was hydraulically stimulated during 6 days by the injection of 23400 m³ of fresh water at increasing flow rates of 31, 41, and 51 l/s (Fig. 3, blue line in upper graph). A rather flat but continuous pressure increase (green line) in the main injection phase indicates that no constant pressure boundary or infinitely conductive structure was connected to the well by this operation. The differential pressure of about 15 MPa in this phase is lower than expected and shows that the reservoir is close to its critical state. The productivity determined during and after the stimulation is 0.4 l/(s*bar), which means a 20-fold increase in productivity. A more detailed analysis of the stimulation in GPK2 can be found in Weidler et al., (2002), and Tischner et al., (2006).

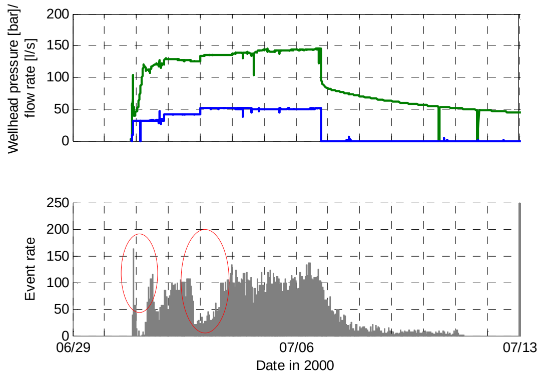

Figure 3: Summary of hydraulic and seismic parameters during the stimulation of GPK2 in 2002. Upper graph: wellhead pressure and flow rate, lower graph: histogram of the event rate of localised events per hour. The red circle indicates periods of trigger change or of missing data.

During this stimulation, about 31500 triggers were recorded of which 14000 seismic events were located. The latter are shown as event rate per hour in Fig. 3. Due to a trigger change level, the onset of seismicity at the start of the injection is a little masked by the two spikes, but it seems that the event rate depends on the flow rate. A rather stable rate of 100 events per hour occurred at a constant flow rate which means that fractures continue to be generated. The seismicity didn't stop with closure of the well, but the event rate as well as the pressure decrease slowly. The magnitudes of the located events range in magnitude between -0.9 and 2.6; the largest event occurred during the shut-in of GPK2. Due to the missing amplitude information, this cannot be discussed here.

GPK3 (2003)

GPK3 as the future injection well had an initial productivity of 0.3 l/(s*bar). The fracturing operation in 2003 consumed 34000 m³ of fresh water (Fig. 4, blue line). During the first 6 days, the injection rate was 30 and 50 l/s with two peaks of 60 and 90 l/s. The following simultaneous injection into GPK3 and GPK2, the 'focused stimulation', (Hettkamp et al., 2004, Baria et al., 2006) aimed at concentrating the fracturing process between the wells GPK2 and GPK3. The third and fourth phase was the shut-in periods of first GPK2 and then also GPK3. Although GPK3 was shut-in stepwise, as recognized from the GPK2 stimulation, stronger microseismic events of magnitude 2.7 and 2.9 occurred and, consequently, the well GPK2 was discharged at 10 l/s to depressurize the reservoir.

The pressure during the stimulation in GPK3 (green line) is characterized by a flow rate-dependent trend and a low overall pressure level. An almost stable pressure is observed only after the fifth day of operation, supposing therefore an effective stimulation only for the last 4 – 5 days at the onset of the 50 l/s injection. The productivity obtained during stimulation was 0.3 l/(s*bar) (Tischner et al., 2007) and persists also during the post-stimulation injection tests.

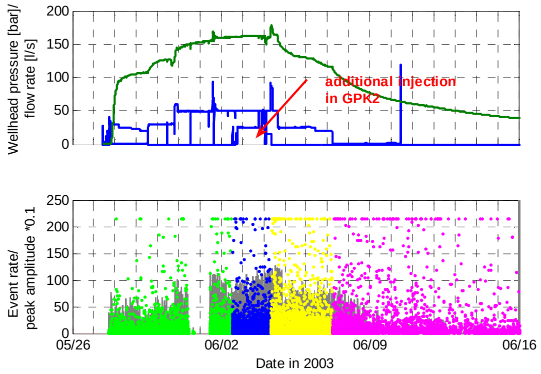

Figure 4: Hydraulic (wellhead pressure and flow rate) and seismic (histogram: event rate, colored dots: peak amplitude in succeeding phases of the injection) observations during the stimulation of GPK3 in 2003. Peak amplitude is in mV and multiplied by 0.1 to match the scale.

This stimulation triggered 92980 records and about 22000 of them were located microseismic events. The event rate (grey histogram in Fig. 4, bottom) shows a correlation to the flow rate and is reaches its maximum of 130 events per hour in the late part of the dual injection where the absolute flow rate (GPK2+GPK3 injection) is highest. The colored dots on the event rate indicate the peak amplitude measured on the sensor in the well 4550 and the color changes indicate the different phases of the injection. The sensor saturated at about 2.3 V which corresponds 230 in the plot and to roughly a magnitude of 2.3. Although the event rate decreases during the shut-in, the fraction of ‘saturation’ events stays rather high. The strongest events of magnitude 2.6 to 2.9 occurred again in the shut-in phase, like in GPK2, although the different strategy of a ‘stepwise’ shut-in was chosen. This was suggested to avoid too fast pressure changes in the reservoir, but it seems not to influence the strength of seismicity.

GPK4 (2004 and 2005)

The initial productivity of the producer GPK4 was ~ 0.01 l/(s*bar). In order to avoid the development of stronger microseismic events, the stimulation of GPK4 was split in two parts with each a small volume and little duration. The first stimulation in September 2004 used 9300 m³ of fresh water in 3.5 days. A flow rate of 30 l/s, with peaks of 40 to 45 l/s for a few hours each, was applied. In spite of the lower flow rate, the pressure level was higher than during the stimulations of GPK3 and GPK2 and increased very rapidly by 170 bar and decreased slowly to ~165 bar. The high pressure level as well as the slow decrease might indicate the creation of an artificial fracture (Tischner et al., 2006). A weak overpressure was observed in GPK3 (~1.5 bar) and GPK2 (~1.1 bar) as well.

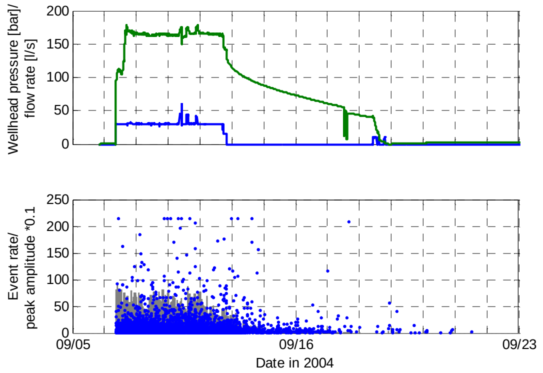

Figure 5: Hydraulic (wellhead pressure and flow rate) and seismic (histogram: event rate per hour, blue dots: peak amplitude) obser-vations during the first stimulation of GPK4 in 2004.

About 5700 seismic events were located during the first stimulation with a maximum magnitude of 2.3 (Dyer, 2005) and are shown in Fig. 5. The observed event rate is low with about 70 events per hour and the fraction of larger events decreases faster during the shut-in than compared to GPK3. Only a few microseismic events saturate the sensor.

The second stimulation (Fig. 6) began in February 2005 with the injection of 12300 m³ of water with flow rates of 30, 45, and 25 l/s. The highest overpressure (180 bar) of all stimulations was reached and indicates a refilling of the already stimulated rock mass but not an efficient stimulation. Moreover, analysis of the shut-in curves of both stimulations of GPK4 indicates that the second stimulation did not further improve the productivity of GPK4. Weak pressure responses in GPK3 (~3.5 bar) and GPK2 (~1.7 bar) were observed during the stimulation of GPK4. The productivity amounts to 0.2 l/(s*bar) at the end of the second stimulation and is retained during the post-injection tests (Tischner et. al., 2007).

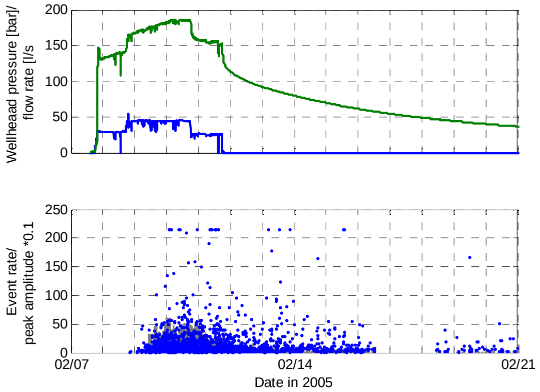

Figure 6: Hydraulic (wellhead pressure and flow rate) and seismic (histogram: event rate per hour, blue dots: peak amplitude) observations during the second stimu-lation of GPK4 in 2005.

The seismicity (Fig. 6) was less numerous than during the first stimulation of GPK4 in spite of the higher flow rate and pressure. Only 3000 event were located with an event rate of about 50 events per hour. The late onset of seismicity corresponds to the thesis that the first part of the injection, as described above, only filled the reservoir instead of having a fracturing effect.

Summary Of Stimulations: Improvements On Wells And Hydraulic Characteristics

The success of the stimulations is summarized in Table 1 which lists the main stimulation flow rates together with the improvement in productivity and the number of located seismic events. The following hydraulic characterizations as results of post-stimulation tests are summarized from Tischner et al., (2006), and might deliver insight into these observations.

It is striking that the stimulations of GPK2 and GPK4, both wells being initially non-productive, were very successful and improved the productivity of the wells by a factor of 20. This observation is in agreement with the overall characteristics of the rather flat or even decreasing pressure curves recorded during the stimulations: for GPK2 and at least the first stimulation of GPK4, they indicate an effective stimulation where the pressure is clipped by the fracturing process.

Well	Duration [d]	Volume [m³]	Flow rate [l/s]	Productivity [(l/(s*bar)]	Loc. seismic events
GPK2	6	23400	50	0.02 -> 0.4	14000
GPK3	11	34000	50	0.2 -> 0.3	21600
GPK4	3.5 4	9300 12300	30 45	0.01 -> 0.2	5700 3000

Table 1: Summary of main stimulation parameters for the stimulations in GPK2, GPK3, and GPK4.

Nevertheless, the post-stimulation injection tests for both wells yield different results: a formation linear flow regime is observed for GPK2 which indicates that a conductive fracture is connected to this well. For GPK4, the test results indicate a bilinear flow regime which means that pressure losses do not only occur in the formation but also in the fracture itself. The high pressure level during the stimulation supports this observation since the pressure losses in the fracture mainly control the pressure level and here indicate a low conductive fracture. The qualitative pressure trend, a decrease of pressure at constant flow rate, is typical for the creation of tensional fractures which would require a higher pressure to open and which, in general, would have a lower conductivity than shear fractures.

In contrast to GPK2 and GPK4, the well GPK3 could not be improved, although the highest volume has been injected and the largest number of seismic events and also the strongest events were recorded. The post-stimulation tests showed that this well is also characterized by formation linear flow regime, but with an infinitely high conductive fracture connected. The surface area and storage of this structure have been calculated from post-stimulation tests and are up to 47000m² and 2 – 5 m³/bar. Since the well was already more productive prior to the injection, an effective stimulation could only be performed in the last days of the operation and it seems that probably a great amount of the injected water penetrated into the formation without a significant stimulation effect.

Another, more general result is published by Tischner et. al. (2006) and indicates that the fractures keep their productivity after stimulation. By this, the 'target' productivity can be determined already during the stimulation.

LINK BETWEEN HYDRAULIC AND GEOLOGICAL OBSERVATIONS

The hydraulic characteristic of an infinitely high conductive structure connected to GPK3 is also found in UBI (Ultrasonic Borehole imager) analysis and geology: GPK3 intersects a large open fracture zone at 4760 m (measured depth) which was also initially high productive and took 60 -70 % of the injection flow (Fig. 7).

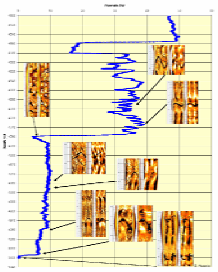

Figure 7: Compilation of GPK3 flow log (blue line) and sections of UBI-log showing that the observed fracture zone is hydraulically high conductive.

As mentioned earlier, geological studies found that this structure connects the wells GPK3 and GPK2 (Dezayes et. al., 2005b) and runs below GPK4 in 5100 m. This connection is also visible hydraulically in the reaction of GPK2 to drilling in GPK3 and vice versa.

The low conductivity of the 'modeled' fracture (obtained from hydraulic analysis) around GPK4 and the indications for a tensile fracturing process might probably represent an axial fracture along the borehole wall. Flowlogs run in GPK4 since 2005 indicate such a constant fluid loss along the borehole wall (Fig. 8). Such a tensile fracture could be operative only in the vicinity and therefore does not

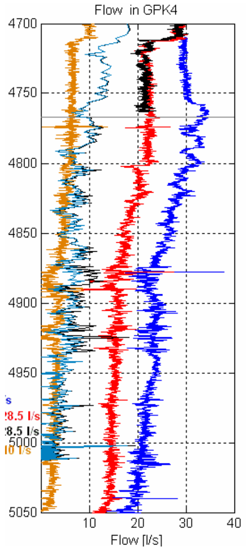

Figure 8: Flow logs in GPK4. From the casing shoe at 4756 m down to about 4870 m, a continuous flow loss is observed in several measurements.

mean a contradiction to the general knowledge that shearing is the main permeability creating process.

We can summarize that the hydraulic observations are in agreement and can be qualitatively explained by the geological observations. We will now focus on a correlation between the hydraulic results of the stimulations and the meaning of the recorded microseismicity.

LINK BETWEEN HYDRAULIC AND SEISMIC OBSERVATIONS

Correlation Of Seismicity And Injected Volume

For a fast evaluation of the stimulation success, a measure of energy release by the seismicity is desirable. McGarr (1976) suggested that a measure of deformation during water injections is the total volume of injected water. Furthermore, he found a linear relation between the total seismic moment and the injected volume. Michelet (2002) proved that this relation holds for the stimulation of GPK2, as is shown in Fig. 9.

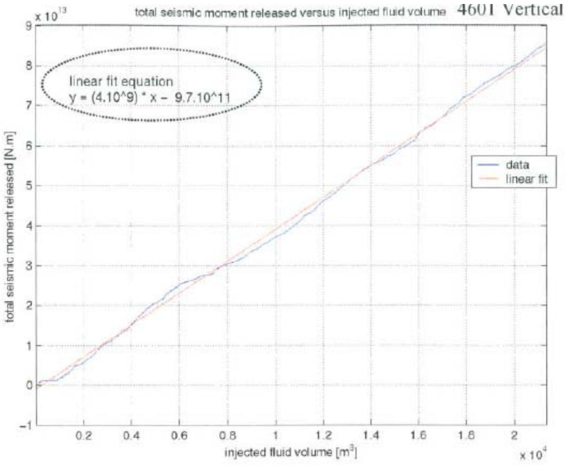

Figure 9: Cumulative seismic moment vs. injected volume. (Figure taken from Michelet, 2002)

The conclusion was that the injection flow rate could be a means to control the earthquake strength and therefore to control the effectiveness of the stimulation.

Since the seismic moment cannot be inferred from the locations of the microseismic events without using the recorded waveforms, we were looking for another way to correlate a measure of energy/deformation to the injected volume.

For this purpose, at each moment, we calculated the total number of events which happened until this time, the cumulative amplitude from the sensor 4550, and also the cumulative volume. Then we made a crossplot of cumulative number of events, respectively cumulative amplitude, versus injected volume.

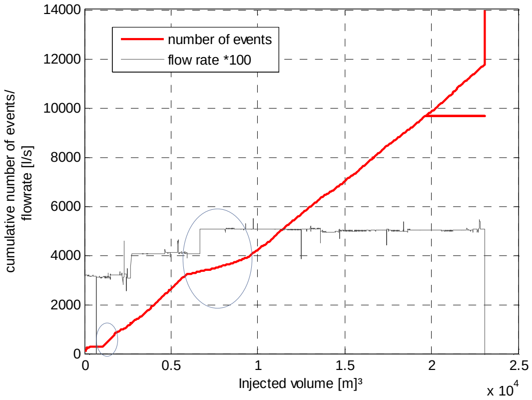

Figure 10: Crossplot of cumulative event number versus injected volume for GPK2.

The result for GPK2 is shown in Fig. 10. The red line indicates the number of events in dependence on the injected volume. The grey line is the injected flow rate, for an orientation and comparison with Fig. 3. The two ellipses indicate the area of data quality reduction like in Fig. 3.

The onset of seismicity is rather direct with the start of the injection. The correlation between the event number and the injected volume is linear, which suggests that a constant number of events is released per injected volume.

This relation is confirmed for the stimulation of GPK3 which is shown in Fig. 11. Two data sets are plotted: green, blue and yellow lines are the cumulated events, the magenta colored line presents the cumulated amplitudes.

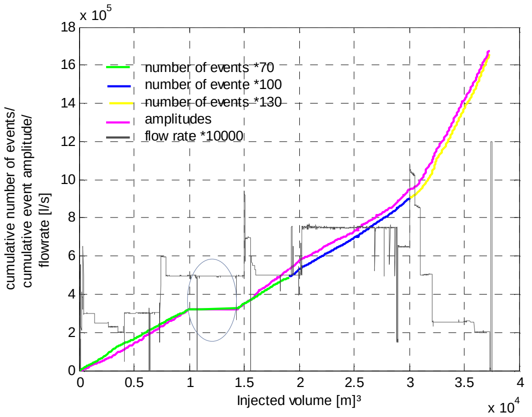

Figure 11: Cumulative events and amplitude versus volume for GPK3. The colors of the cumulative event number indicate, as in Figure 4, the phase of injection. Blue is dual injection, also visible from the high flow rate of almost 80 l/s. The ellipse indicates a data gap.

From this experiment we can deduce that not only the number of events is linear to the volume but also the cumulative amplitude. This also implies that cumulative amplitude and event quantity are proportional. This might be due to the high number of events with relatively little fraction of big events – or by thy averaging effect of the calculation of the sum. At least, these proportionalities should be regarded closer in the future.

Moreover, the slope of the event/amplitude versus volume relation seems not clearly to be related to flow rate changes. During the first 10.000 m³, the slope is rather constant although the flow rate increases, and the same is valid after 20.000 m³. This is only possible when the event rate increases in the same way as the flow rate which also should have to be tested in the future.

The whole characteristic changes only after the dual stimulation and more events or amplitude release per volume are observed.

For the two GPK4 stimulations, the same linearity is illustrated in Fig. 12 and 13. It is obvious again that the second stimulation of GPK4 was not effective at the beginning, since the seismicity starts only after the injection of 5000 m³.

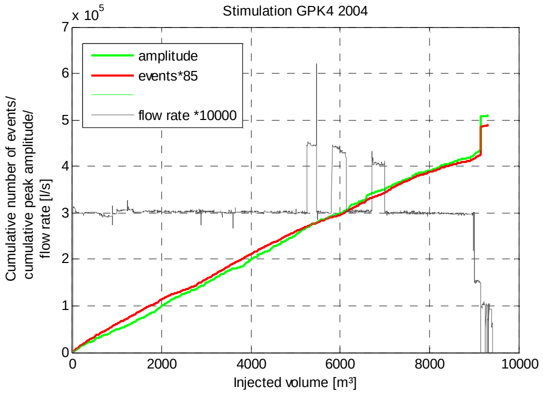

Figure 12: Cumulative events and amplitude vs. injected volume for the first stimulation of GPK4.

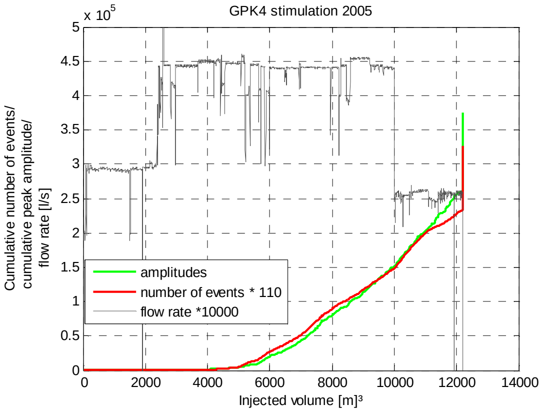

Figure 13: Cumulative events and amplitude vs. injected volume for the second stimulation of GPK4.

As a summary we can say that, for all stimulations, both the cumulated event number and cumulated sensor amplitude correlate linearly with the injected volume. Despite from the factor, this correlation is similar to the correlation of total released seismic moment per injected volume and might therefore be used as a fast measure of release energy during a stimulation.

Correlation Of Seismicity And Event Distribution

The different success of the stimulations is obvious in Table 1: while GPK2 and GPK4 improved their productivity by a factor of 20, GPK3 could hardly be improved. A correlation to geological features like the big fracture zone in GPK3 is already proven. The question remains whether the spatial distribution of the seismicity is also correlated to the overall picture of the three wells. Fig. 14 presents depth slices with contour plots of event density (the number of events per volume of, here, 50x50x100 m). The depth are chosen to cut the open hole sections. The highest concentration of seismic events is, in each depth slice, around GPK4, and less pronounced around GPK2. The center of seismicity is, as Dyer, (2001), already mentioned, 100 to 200 m offset of GPK2. In contrast, GPK3 shows only a less dense distribution of microseismicity.

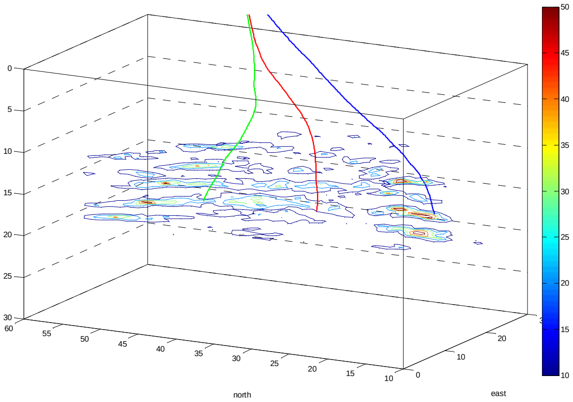

Figure 14: Depth sections of the spatial density of located events. Box size for the density calculation is 50x50x100 m. GPK2, as in Fig.2, is green, GPK3 red, and GPK4 blue.

This becomes clearer for one single depth slice from 4900 – 5000 m (Fig. 15) where the distribution around GPK3 occurs much more dispersed and with lower event concentration than the other two regions.

Therefore we conclude that, at depth levels which are interesting for a hydraulic connection between the wells, the productivity enhancement is correlated with seismic density. The picture of the dispersed density around GPK3 fits again to the thesis that the fracture zone has lead the injected water into the surrounding formation without a significant stimulation effect.

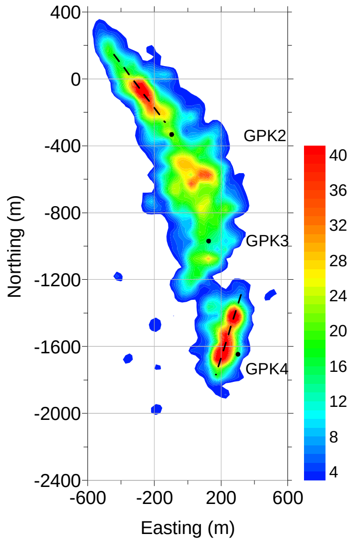

Figure 15: Seismic event density in the depth 4900 – 5000 m.

CONCLUSION

The stimulations of the three deep wells in 4 steps activated a rock volume of about 3 km³ of the formation. The GPK2 stimulation improved the productivity of the well by a factor of 20 and was an efficient stimulation. GPK3, the dual stimulation, improved only little the productivity due to a permeable fracture zone which probably lead the water too far to the outer zones. GPK4 was stimulated twice, and at least the first stimulation had a comparable success to GPK2. It has been shown in an earlier paper by Tischner et. al., (2007), that the productivity reached during the stimulation is completely retained afterwards.

The microseismic event distribution observed during the stimulations of GPK2, GPK3, and GPK4 differs for each stimulation and seems to be related to the degree of productivity improvement: the occurence of high seismic activity (that means a high abundance of events per volume) correlates with a noticeable productivity improvement like for GPK2 and GPK4 while a more diffuse structure and lower number of events per volume correlates with a minor improvement of productivity, as observed in GPK3.

For each stimulation, the total number of events released during the injection as well as the cumulative sensor amplitude correlate linearly with the injected volume. This correlation is similar to the correlation of total released seismic moment per injected volume.

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