PROCEEDINGS, Thirty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

CHEMICAL STIMULATION OPERATIONS FOR RESERVOIR DEVELOPMENT OF THE DEEP CRYSTALLINE HDR/EGS SYSTEM AT SOULTZ-SOUS-FORÊTS (FRANCE)

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ABSTRACT

The main objective of the European HDR/EGS-project at Soultz is the installation of a geothermal pilot plant for power production by the end of 2008.
After drilling of the three 5000 m deep wells to form a triplet with two producers (GPK2 and GPK3) and a central injector (GPK3), the wells were hydraulically stimulated through massive water injection. In addition to hydraulic stimulation, a series of chemical stimulation operations were undertaken to achieve increasing the performance of the wells and the near-wellbore permeability of the geothermal reservoir. Several acid systems such as hydrochloric acid (HCl), Regular Mud Acid (HCl-HF) and Organic Clay Acid ($C_6H_8O_7$-HF-HBF_4-NH_4Cl) were injected to dissolve minerals deposits in the wellbore as well as filling materials of fractures in the vicinity of the wells. Also a high-pH chelating agent (NTA) was tested as alternative to the more usual acid treatments.
Whereas acid treatments have resulted in a productivity improvement of the production wells (GPK2 and GPK4) up to 50%, almost no amelioration was obtained in the injection well GPK3. The use of chelating agents resulted in some productivity deterioration of GPK4.
The results of stimulation experiments were evaluated using short-term hydraulic tests, conventional pressure transient analysis, interference pressure data, microseismic monitoring, temperature and flow logs. This combination of evaluation techniques helped in getting insight into the origin of the productivity enhancement.

INTRODUCTION

The European HDR/EGS test site is located in the Rhine Graben near Soultz-sous-Forêts, around 50 km north of Strasbourg in France. The aim is the electricity production by extracting geothermal energy from hot deep crystalline rocks. The first implementation phase envisages the construction of a 1.5 MW geothermal power plant.
In the second phase the production of 100 l/s with at a wellhead temperature of 180°C is targeted. The power plant can then be expanded up to 6 MW. For this purpose an underground heat exchanger has been created through hydraulic and chemical stimulation techniques.
Three wells (GPK3 as central injection well and both GPK2 and GPK4 as production wells) were drilled to 5000 m depth in the crystalline basement to build the HDR/EGS system. The wells were first subjected to hydraulic stimulations. Their productivities were thus enhanced by factors of up to 20. However, some of the induced seismic events during hydraulic stimulation were large enough to be felt by the local population. The potential public concern about seismic events was one important reason for undertaking chemical treatments as additional or even alternative method to hydraulic stimulations. The second and most important argument for chemical stimulation was the evidence of fracture-filling carbonates and other soluble minerals, based on drill cutting and core analysis, as well as on geophysical logs.
Chemical stimulation consists of acid injection into the formation at a pressure below the fracturing pressure to remove near-wellbore permeability damage and material deposited in fractures through dissolution process. This method to enhance the well performance is widely used in oil and gas wells (Economides and Nolte, 2000). Although matrix stimulation has been extensively established as a common workover and stimulation of oil and gas wells, mostly in sandstone and carbonate formations, their application to geothermal wells is recent and leads back to the 1980's (Strawn, 1980; Epperson, 1983; Barelli et al., 1985; Portier et al., 2007). Various chemical treatments have been performed mostly in volcanic and metamorphic formations, principally to reduce near-wellbore damage caused by drilling activities and scaling (Buning et al., 1997; Malate et al., 1997; Malate et al., 1998; Yglopaz et al., 2000, Jaimes-Maldonado and Sánchez-Velasco, 2003; Axelsson et al., 2006).
This paper presents an overview of all the chemical stimulations tested in Soultz and their impact on

injectivity/productivity enhancement. The integration of results from seismic, temperature and flow logging helps in detecting the productive zones of the wells and their changes due to chemical stimulations.

It is to note that the injectivity/productivity of the Soultz wells is time dependant in general. Therefore, values for the injectivity/productivity have to be referred to a specific duration of injection/production. Throughout this paper, the injectivity/productivity is determined after a test duration of three days and is rounded to the next 0.05 l/(s*bar). The experience in Soultz shows that there is no significant difference between injectivity and productivity at moderate pressure changes. The terms injectivity and productivity can be considered therefore as synonymous.

SITE DESCRIPTION

The European HDR/EGS is located near Soultz-sous-Forêts/France in the western edge of the Rhine Graben; about 50 km north of Strasbourg (see Figure 1).

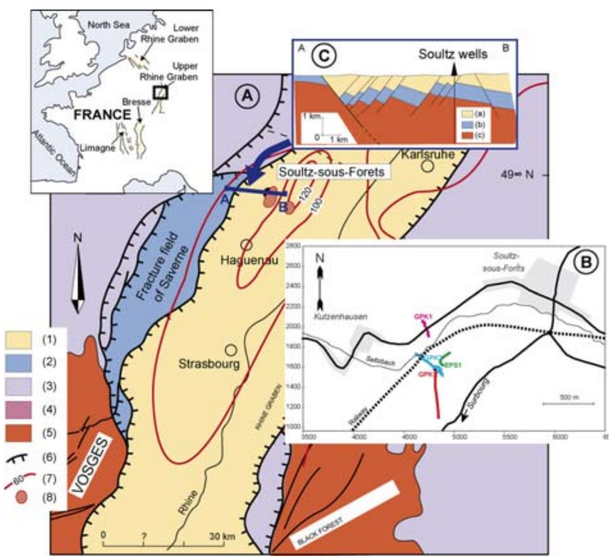

Figure 1: Location of the EGS Soultz site and geology of the Upper Rhine Graben (Hooijkass et al., 2007). A: (1) Cenozoic sediments; (2) Cenozoic volcanics; (3) Jurassic; (4) Triassic; (5) Hercynian basement; (6) boundary faults; (7) other faults; (8) isotherms (in °C) at 1500m depth (Haenel et al., 1979); (9) local thermal anomalies (Haenel et al., 1979); B: local map of the Soultz wellfield showing well trajectories; C: W–E cross-section through the Rhine Graben border and the Soultz site. (a) Cenozoic; (b) Mesozoic; (c) Hercynian basement.

Various authors (Garnish et al., 1994; Baumgärtner et al., 1998; Hettkamp et al., 2004; Baria et al., 2005; Gérard et al., 2006) provided summaries of the project's history since its creation.

The HDR/EGS target is a Paleozoic altered and fractured granite overlain by 1400 m thick sedimentary cover. The fracture network ranges from micro-cracks to high-permeability large normal faults filled with minerals from hydrothermal alteration (illite, quartz, calcite…), which are naturally permeable (Genter et al., 1995; Sausse et al., 2006; Hooijkass et al., 2007). The abnormal high temperature gradient of about 100°C/km within the sedimentary cover and the overall non-linear trend results from deep hydrothermal convection loops occurring within the fractured basement.

CHEMICAL STIMULATION OPERATIONS

The chemical stimulation operations were made by injecting acid from the wellhead through the inner casing string (91/2" for GPK3 and GPK4 and 7" for GPK2). Corrosion inhibitors were used to protect the inner casing string. With exception to chemical treatments with HCl, the other operations were conducted by specialised service companies. The equipments were configured to assure the mixing and acid injection in a row.

Table 1 shows the various chemical treatments conducted in the deep Soultz wells (Portier et al., 2007). All the wells were subjected to chemical stimulation with injection of low-concentrated hydrochloric acid. Due to its poor connectivity with the injection well GPK3 after successive hydraulic and chemical stimulations, the production well GPK4 was mostly chemically stimulated.

Table 1: Overview of chemical stimulations of the three deep Soultz wells.

		GPK2	GPK3	GPK4
Conventional acid systems	Hydrochloric Acid (0.09-0.45%HCl)	●	●	●
	Regular Mud Acid (12%HCl-3%HF)			●
Chelatants	Nitrilotriacetic Acid (19% Na_3NTA-NaOH)			●
Retarded acid system	Organic Clay Acid (5-10% $C_6H_8O_7$, 0.1-1% HF, 0.5-1.5% HBF_4, 1-5% NH_4Cl)		●	●

Conventional acid systems

Stimulation with hydrochloric acid (HCl)

Chemical treatments with low-concentrated HCl were performed in the three wells after the hydraulic stimulation (Table 2).

The objective of this low-concentrated but long-extended stimulation was to dissolve secondary carbonates (calcite and dolomite) existing in the fractures.

Table 2: Overview of the stimulations with low HCl-concentration in the three deep wells.

Well	Date	Duration [hours]	Total mass of HCl [t]	HCl-concentration [%]	Diluted HCl injected [m³]	Flow rate [l/s]
GPK2	13.02.2003	6	1.4	0.18	650	30
	14.02.2003	10		0.18	810	15
				0.09		30
GPK3	27.06.2003	12	3	0.45	865	20
GPK4	02.02.2005	48	11	0.2	4700	27.2

In 2003, the first deep well (GPK2) was stimulated by injection of hydrochloric acid. A significant reduction of near wellbore friction losses was observed immediately after the acid front reached the openhole section (Figure 2). Nevertheless, the improvement was most important only at high flow rate above 30 l/s. It is likely that turbulent friction losses inside the wellbore, where a fish is stuck, were reduced due to the acid injection. No clear indications were found for an improvement in the formation around the well GPK2.

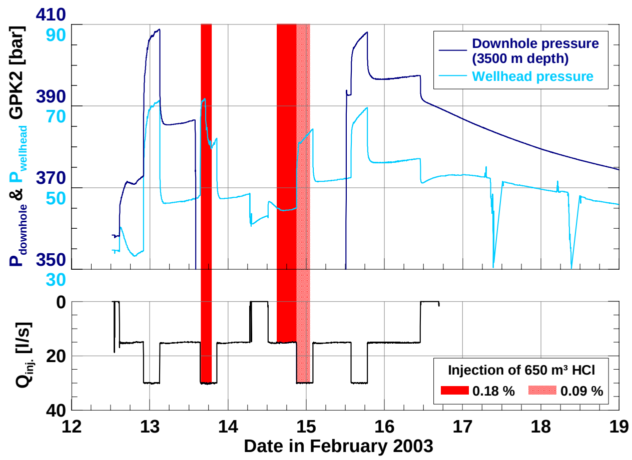

Figure 2: History plot of the chemical stimulation with HCl in GPK2. A significant drop of the pressure difference after HCl-injection was observed.

During a circulation test between GPK2 and GPK3 in 2003, hydrochloric acid was injected in GPK3 over a time period of 12 hours. No reduction of the injection pressure was observed during or after the acid injection meaning that this acid stimulation failed.
The injection of hydrochloric acid in GPK4 in 2005 improved the well injectivity/productivity by 50%, but it is questionable whether this improvement was achieved in the openhole or through leakages in the casing. This point will be discussed later.

Stimulation with Regular Mud Acid (RMA)

RMA was exclusively injected in GPK4. RMA is a mixture of hydrochloric acid (HCl) and hydrofluoric acid (HF) widely used in oil and gas wells. The dissolution of minerals like clay, feldspars and micas (Portier et al., 2006) was intended by applying this acid mixture. A HCl-preflush was first injected to avoid calcium fluoride (CaF_2) precipitation that can lead to well damage. The treatment was carried out in four steps:

- Injection of 2000 m³ of fresh water deoxygenized at 18 l/s, 22 l/s and 28 l/s for more than 24 hours
- A preflush of 25 m³ HCl at 15% (with deoxygenized water) with a flow rate of ~22 l/s
- A main flush of 200 m³ RMA with concentration of 12% HCl and 3% HF and with addition of corrosion inhibitor, at flow rate of ~22 l/s
- A postflush of 2000 m³ fresh water at flow rates of 22 l/s and 28 l/s during 22 hours.

Figure 3 shows the history plot of the stimulation in GPK4. A less pronounced slope is observed after the injection of the treatment mixture than before, indicating an enhancement of the reservoir (blue dash lines in Figure 3).

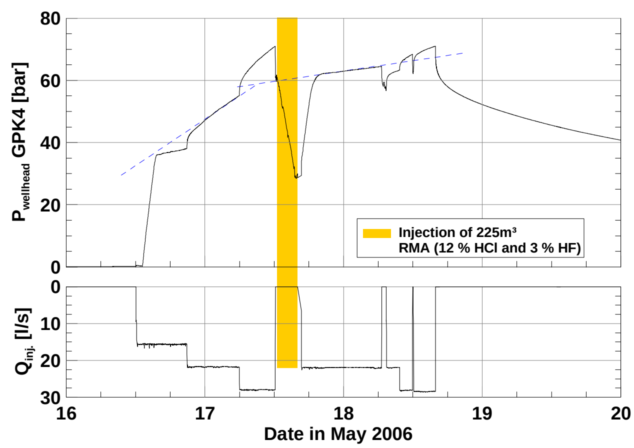

Figure 3: History plot of the chemical stimulation with RMA in GPK4. The slope change of the pressure (blue dash line) for the same flow rate before and after the RMA-injection indicates a gain in productivity.

Stimulation with Chelatants

After the stimulation with RMA, the well GPK4 was subjected to a chemical treatment with chelatants in October 2006. The purpose of this reactant ($C_6H_9NO_6$, nitrilotriacetic acid) is to form complexes with cations like Fe, Ca, Mg, and Al, and thereby to reduce the activity of these cations, leading to an enhanced dissolution of the corresponding minerals (calcite...). Chelatants are less corrosive in comparison to acids like HCl.
The stimulation design was made as follows:

- Injection of ~4500 m³ fresh water to pressurize the reservoir at average flow rate of ~24 l/s for a period of 53 hours
- main flush of 200 m³ (pH 12) constituted of caustic soda (NaOH) and 19% diluted Na_3NTA, at flow rate of ~35 l/s during 1.6 hours
- Postflush of 400 m³ fresh water at 40 l/s
- Two short injections of fresh water at 20 l/s (volume 200 m³ and 250 m³)

Figure 4 shows the history plot of the stimulation with NTA. The analysis of the pressure behaviour after the injection of NTA shows an abnormal increase of the wellhead pressure. During the succeeding short water injections, the wellhead pressure was even higher than shortly before the injection of the reactant, suspecting a plugging of the productive zones. A production test was therefore carried out on October 25, 2006 to remove residuals of the NTA-solution.

At the beginning of the production test, large quantities of magnetite-rich grey sands were produced, followed by a yellow-coloured fluid, probably containing chelatants. A geochemical analysis of water samples showed a neutral pH (7.1-7.4) of the produced fluid, and thus the almost complete removal of the chelating agents from the well. The test had to be stopped after ~ 2000 m³ production due to storage limitations and other planned technical operations.

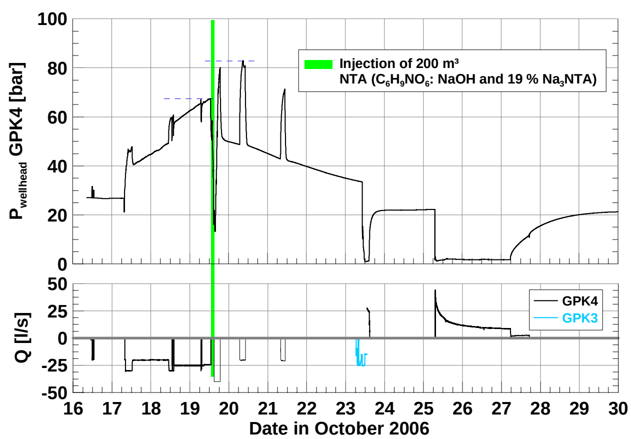

Figure 4: History plot of the chemical stimulation with NTA in GPK4. The wellhead pressure during the injection of 250 m³ water is higher than before the NTA injection, indicating loss in productivity.

Retarded acid systems

The chemical stimulation of GPK3 and GPK4 with Organic Clay Acid (OCA) completed a series of hydraulic and chemical stimulations for productivity enhancement of all deep Soultz wells, which started in 2000. The OCA-stimulation fluid is designed for formations with very high temperature or/and with high clay content that are sensitive to conventional stimulation fluids (HCl). The retardation effect of OCA fluid allows a stimulation going deep into the reservoirs. The OCA-fluid injected was composed of 5-10% citric acid ($C_6H_8O_7$), 0.1-1% HF, 0.5-1.5% HBF_4, and 1-5% NH_4Cl (Schlumberger catalogue).

GPK3

The well was treated on February 15, 2007 by proceeding as follows:

- Injection of 1200 m³ of fresh water at flow rate of 35 l/s
- main flush of 250 m³ of OCA at flow rate of ~55 l/s
- First postflush of 250 m³ fresh water at flow rate of 45 l/s
- Second postflush of ~1070 m³ fresh water at average flow rate of 30 l/s

Figure 5 shows the history plot of the chemical treatment in GPK3. The pressure increase after the first 250 m³ water injection, pumped at the same flow rate as before the chemical treatment, has a slope similar to the one shortly before the end of the preflush (see blue dash line in Figure 5). This preliminary analysis shows almost no gain in productivity.

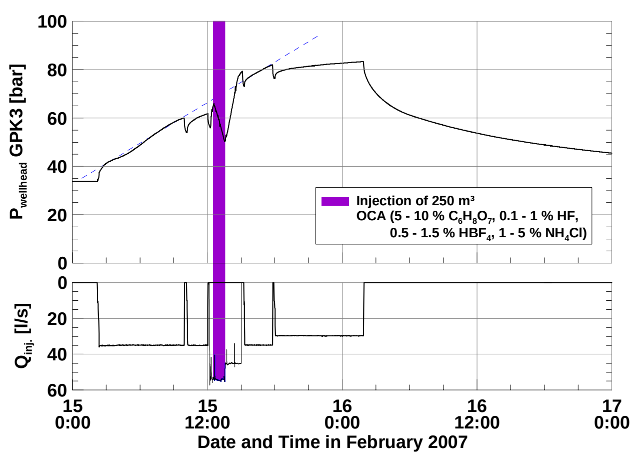

Figure 5: History plot of the stimulation with OCA in GPK3. A nearly similar pressure trend is observed before and after the OCA-injection at the same flow rate. No gain in productivity was achieved.

GPK4

The well GPK4 was stimulated on March 21, 2007 with Organic Clay Acid according to the following steps:

- Preflush of fresh water at average flow rate of ~30 l/s
- main flush of 200 m³ OCA-fluid at ~55 l/s (density: 1.04 g/cm^3)
- Posflush of fresh water at 40 l/s and 35 l/s

The wellhead pressure and the flow rate during the chemical treatment with OCA are shown in Figure 6. During the preflush-phase, a fast increase of the wellhead pressure, immediately followed by a stronger trend of the pressure buildup was observed, although the injection flow rate at the time was constant by ~30 l/s (dotted red circle in Figure 6). This abrupt increase of pressure slope suggests some plugging of the well.
After the displacement of OCA-fluid into the formation the pressure was almost constant although a constant injection rate usually leads to a pressure increase under Soultz conditions.
The wellhead pressure reached a value of ~120 bar just before the injection of OCA and rose up to a maximum of 130 bar during the postflush phase until the shut-in.

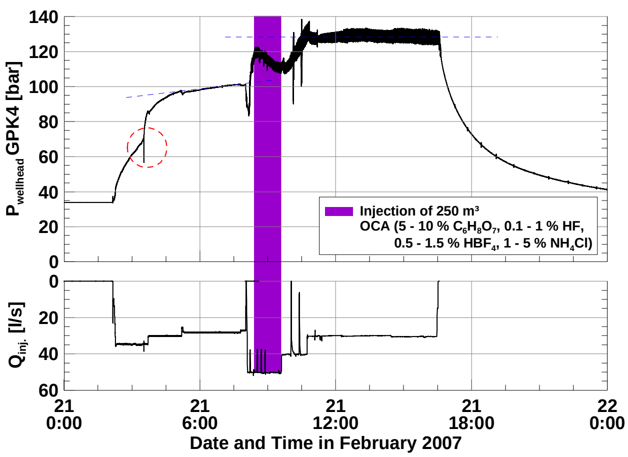

Figure 6: History plot of the stimulation with OCA in GPK4. Steady-state behaviour of the pressure is observed during the postflush phase.

A flat pressure trend at a very high level is typical for a fracturing process. Consequently fracturing effect has to be considered additionally to acid effect. If some outlets of the well were plugged during injection, as it is indicated by the pressure curve, the fracturing pressure might be exceeded even for a "low" flow rate of 30 l/s. In that case the pressure is controlled by the rock stress.

HYDRAULIC TESTS FOR THE EVALUATION OF CHEMICAL STIMULATIONS

GPK2

Hydraulic tests were carried out in this well to evaluate the impact of the hydraulic stimulation. No relevant test was performed in this well after the chemical stimulation with HCl. However the injectivity index after this chemical treatment could be evaluated from the circulation tests in 2003 (between GPK2 and GPK3) and 2005 (between GPK3 and the two production wells GPK2 and GPK4). The injectivity after this HCl-treatment was estimated at ~0.45°l/(s*bar).

GPK3

At GPK3 an injection test was carried out in August 2004 (04AUG17) after the hydraulic and chemical stimulation with HCl. This test served as reference for the evaluation of the succeeding chemical stimulations (Figure 7).

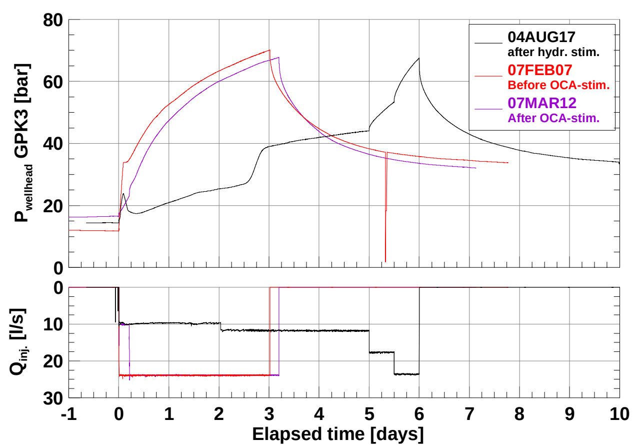

Figure 7: Injection tests performed in GPK3. The maximum wellhead pressure during the injection test after the stimulation with OCA is almost the same as during the injection test after the hydraulic stimulation in 2004.

A total of 7000 m³ fresh water was injected at flow rates of 12, 18 and 24 l/s for a period of 6 days. The injectivity derived from this test was about 0.35 l/(s*bar).
The second injection test in GPK3 was conducted after the RMA and before the OCA-stimulation, on February 07, 2007. In this constant rate test, a total volume of 6230 m³ was pumped during 3 days at a flow rate of 24 l/s. The injectivity calculated from this test was again estimated at about 0.35 l/(s*bar).
The impact of the OCA-stimulation was evaluated by a third injection test. It consisted of a short step of 10 l/s to slowly cool the well, followed by an injection of 24 l/s for more than 3 days (07MAR12). No significant pressure reduction, compared to the previous tests, was observed after the OCA-stimulation in GPK3 and consequently, a significant improvement of the productivity was not achieved. The injectivity index after 3 days is about 0.40 l/(s*bar), very close to the one calculated before this chemical treatment (0.35 l/(s*bar)).

GPK4

The impact of the stimulation operations at GPK4 was evaluated before and after each stimulation by performing a unique step rate injection test. About 4500 m³ of fresh water were injected at increasing flow rates (9 l/s, 18 l/s and 24 l/s) in one-day step. The characteristics of the wellhead pressure at the beginning of the tests is highly influenced by both temperature and density effects. The density effect disappears rapidly, after injection of one borehole volume, whereas the temperature effect vanishes slowly. Former tests showed that the additional temperature drop induced by an increase of the flow rate from 9 l/s to 18 l/s after one day of injection is small. Therefore, it is possible to evaluate the wellhead pressure from the beginning of the second injection phase on. In particular, changes of productivity can be evaluated by comparing the wellhead overpressure, from the beginning of the second injection step on (see Figure 8).

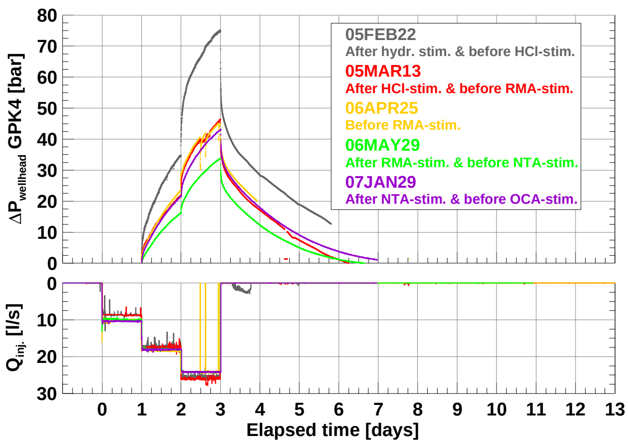

Figure 8: Comparison of the wellhead overpressure (from the second step on) during the step rate tests in GPK4.

After the second hydraulic stimulation of GPK4 in 2005, the first step rate injection test was carried out in GPK4 (grey-coloured curve in Figure 8). The analysis of this tests gave a productivity index, after three days of injection, of ~0.20 (l/s*bar).

The chemical treatment with HCl yielded a gain in productivity of GPK4 (red curve in Figure 8). The productivity index after this stimulation was evaluated at 0.30 l(s*bar).

The step rate test 06MAY29 (green-coloured curve in Figure 8) performed after the RMA-stimulation shows that after three days of injection the wellhead overpressure from the second step is about 35 bar, that means ~11 bar less than before the stimulation (step rate test 06APR25 (yellow and red-coloured curves in Figure 8). The RMA-stimulation has therefore resulted to an enhancement of the productivity index from 0.30 to 0.40 l/(s*bar).

Similar to the previous stimulation of GPK4 with RMA, a step rate test was performed in January 2007 to assess the stimulation effect with NTA (purple-coloured curve in Figure 8). The wellhead overpressure in GPK4 after the NTA-injection was ~9 bar higher than before the chemical treatment, and led to a productivity index of ~0.30 l/(s*bar). The use of chelants has however led to a negative impact on productivity, although conclusive results from labor experiments on calcite dissolution with chelating agent were recorded (Mella et al., 2006; Rose et al., 2007). It is likely, that during the injection of chelatants, which are also used as cleaning agents, scales from the casing were detached and transported into the reservoir, plugging its access to some extent.

No injection test has been performed after the OCA-stimulation. An assessment of the well was however possible, by analysing the production tests carried out before and after this stimulation.

The average production rate in the test after the OCA-stimulation was ~ 1.4 times higher than before, concluding a gain in productivity (see Figure 9). The productivity index was ~0.40 l/(s*bar) before and ~0.50 l/(s*bar) after the OCA-stimulation.

Unlike the previous production tests, the temperature curve of the production test performed after the OCA-stimulation showed a decreasing trend even after 4 days of production and despite the highest production rate. Obviously a part of the production came from the upper part of the well (see discussion).

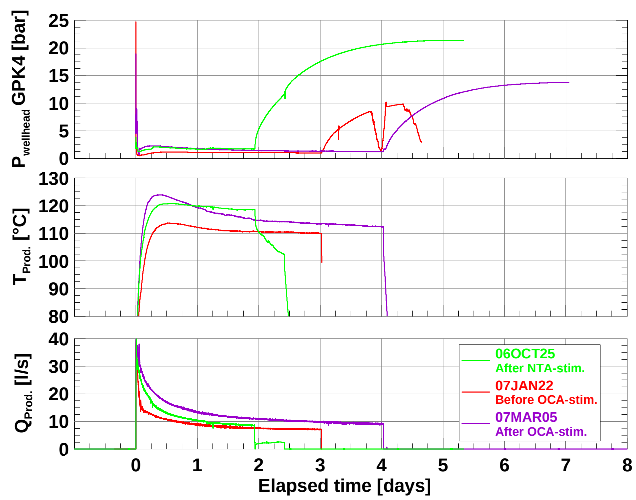

Figure 9: Compilation of all production tests performed in GPK4.

The results obtained both from tracer tests (Sanjuan et al., 2007) and from the analysis of the microseismic activity triggered by the hydraulic stimulations (Baria et al., 2004; Baria et al., 2006) have clearly identified a good connection between GPK2 and GPK3. However, a high impedance barrier between GPK3 and GPK4 was observed. The main issue of the reservoir development was therefore to ameliorate the weak link between GPK3 and GPK4. From the step rate test performed in GPK4, the pressure response in GPK3 and GPK2 was observed throughout the stimulation operations to follow the connection to GPK4 as illustrated in Figure 10.

Almost no pressure response was observed in GPK3 and in GPK2 during the first two stimulations. However, a sensitive pressure response was measured in the two wells after the stimulation with RMA. The difference pressure in GPK3 is higher than in GPK2 because of its proximity to GPK4. For the same reason, the reaction time is in GPK3 shorter.

It is likely that due to the chemical treatments of GPK4 different geological structures were stimulated than due to the first hydraulic stimulations in 2004/2005. The pressure propagation to GPK2 might be explained by the improvement of a structure between GPK3 and GPK4, reaching an already connected structure between GPK2 and GPK3.

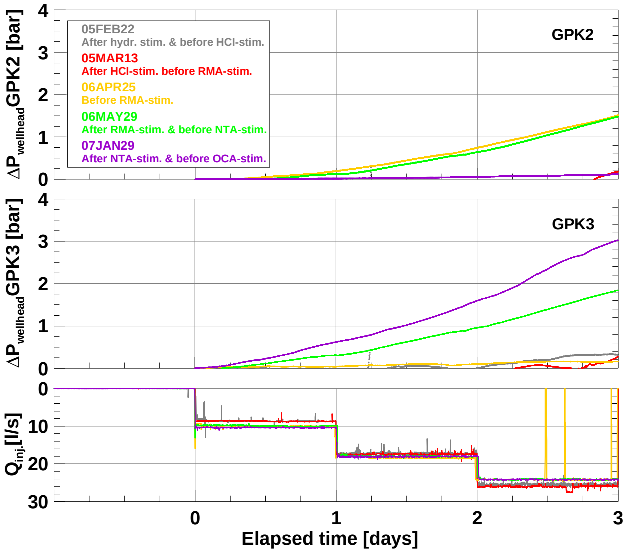

Figure 10: Pressure response of the ambient wells (up: in GPK2, middle: in GPK3) during the step rate injection tests in GPK4. The well GPK3 was deactivated during the test 06APR25 prior to the RMA-stimulation, while GPK2 was deactivated during and after the OCA-stimulation.

DISCUSSION

Overview of the productivity of the deep Soultz wells

Figure 11 summarizes the development of the calculated productivity of GPK3 and productivity of GPK2 and GPK4 with time, starting in 2000.

The values shown here are injectivities/productivities obtained from post-stimulation hydraulic tests, as described in this paper. All hydraulic and chemical stimulations are evaluated as well as the performance of the wells during circulation.

While GPK3 did not change much its productivity with all applied stimulations, the productivity of GPK4, in contrast, was improved by the chemical treatments. These trends are discussed in more detail later in this section.

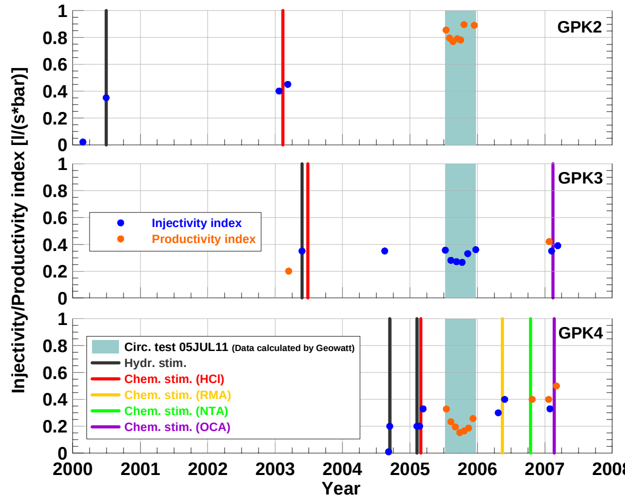

Figure 11: Compilation of the productivity of the deep Soultz wells before and after each stimulation. The dots in the shaded area were derived from the circulation test 2005 and calculated by Geowatt, 2006.

Marginal productivity enhancement after OCA-stimulation in GPK3

The weak impact of the acid stimulations in GPK3 coincides with the existence of a large infinite conductive fracture as the dominant outlet. GPK3 is connected to a natural fracture zone which takes 60-70% of the total flow (Figure 12, left). This status was already the initial state of the well directly after drilling and could not be improved much.

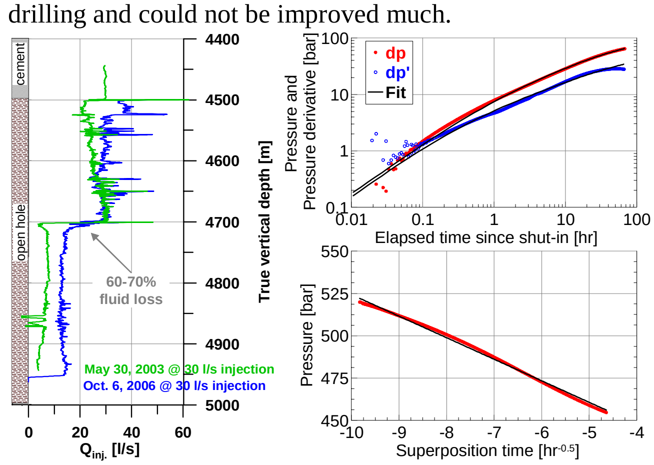

Figure 12: Left: Caliper-corrected flow profiles in GPK3 from 2003 (cyan) and 2006 (blue). Depth is given in true vertical depth (TVD). Right: Pressure transient analysis of the injection test (07JUN04) performed in GPK3 in June 2007. Up: Log-Log diagnosis of the shut-in phase Down: Downhole pressure as function of the square root of the superposition time.

Figure 12, right shows the diagnosis plots of the shut-in phase after an injection test performed in GPK3. The flow is characterised by a pressure change proportional to the root of time (1/2-unit slope in both the pressure and pressure derivative curves as well as linear trend of the pressure as function of the root of the superposition time, Bourdet, 2002). Thus, the hydraulic behaviour of GPK3 is dominated by a formation linear flow, a typical flow regime for large, infinite conductive fractures intersecting the formation.

The effective fracture area was estimated between 25000 and 50000 m² and the formation transmissibility was about 0.05 to 0.2 Dm (Tischner et al., 2006). There is no potential to improve the well by dissolving minerals from these fracture faces and therefore, a substantial productivity enhancement by using chemical stimulation can not be expected.

Improvement of GPK4 productivity by chemical treatments

As described in this paper in detail, the productivity of GPK4 was improved by the chemical treatments with RMA and OCA, whereas the NTA operation diminished the productivity. The question of where in the well or reservoir the acid improves the permeability is discussed here in more detail.

Figure 13 shows a compilation of data available after the HCl-acidizing in 2005 but before any of the chemical treatments were applied in 2006.

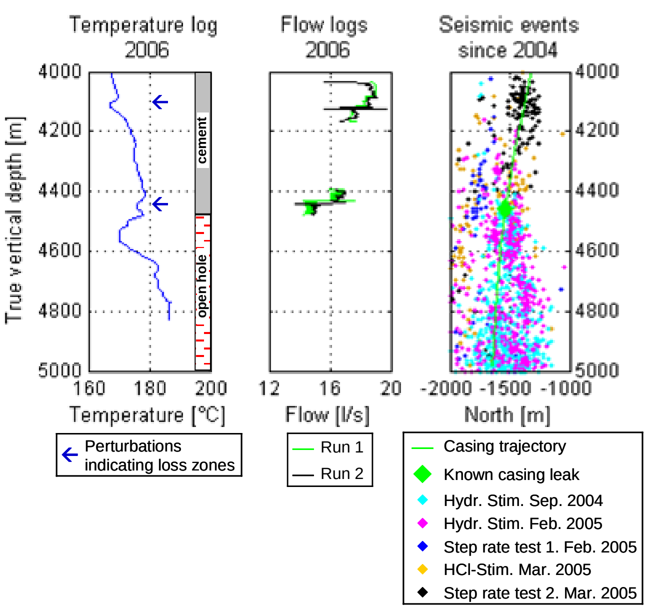

Figure 13: Compilation of measured temperature and flow (left and middle) in April 2006 prior to any further chemical stimulation, together with microseismic events recorded during the hydraulic and chemical stimulation in 2004 and 2005.

Already after the HCl-acidizing in February 2005, a correlation between seismicity during this operation and the leakages in the casing (at 4110 and 4440 m TVD respectively) on the one hand and the productivity improvement on the other hand were discussed.

While the lower leak was already known since 2005, the upper one became only obvious after the temperature anomalies were recorded in 2006. The correlation with the accumulation of seismic events at 4110 m TVD is striking, and also the improvement of productivity by 50% indicates that the main part of permeability creation has been done here.

This scheme of productivity enhancement by chemical stimulation correlating with seismicity during chemical treatments with RMA and OCA is also found. The flow log and the seismicity recorded in between those operations are illustrated in Figure 14.

The events which are clearly located at the level of the upper leakage (~4110 m TVD), trending south- and upward, carry forward the development of the seismic cloud observed during the step rate test in March 2005. These observations led to address the issue whether the acid injections had impact, as intended, only in the openhole.

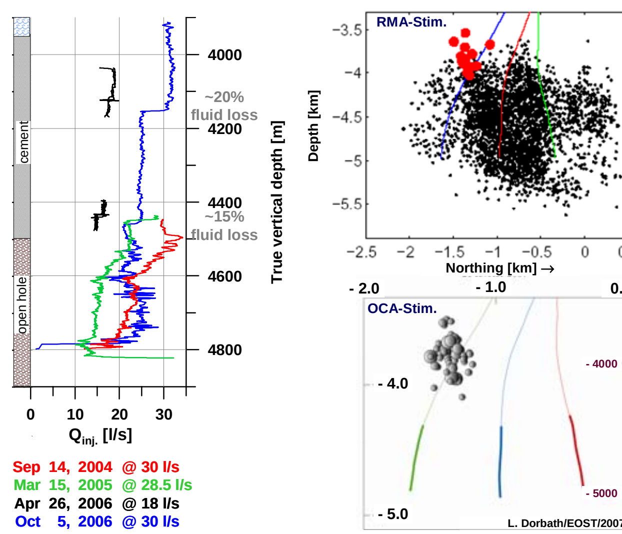

Figure 14: Seismic events during chemical treatments with RMA (left, red circles) and OCA (right) in GPK4, illustrated in side view. No seismicity was observed during the intermediate stimulation with NTA. Source of figure: Louis Dorbath, EOST.

A conclusion from flow logs alone is difficult and a direct evidence for a productivity enhancement could not be found, especially since the well is not fully accessible (Figure 13). Therefore, and because of the high and almost constant pressure during the stimulation with OCA, we take into account the hydraulic stimulation of fluid pathways in the cemented casing section.

For this purpose, we analyzed the stress conditions at the leakage levels. Valley & Evans, 2007 proposed an estimation of the stress state below 3500 m by following the assumption that the maximum pressure attained during the stimulation provides a direct estimation of the minimum horizontal stress (Cornet & Bérard, 2003; Cornet et al., 2007). The following estimation of the minimum horizontal stress function of the true vertical depth was derived by Valley & Evans, 2007:

$$\sigma_{h\ min}\ [\mathrm{MPa}] = -1.78 + 14.06\ z\ [\mathrm{km}] \quad (1)$$

The estimation of downhole pressure during the stimulations is presented in Figure 15.

The maximum pressure during the hydraulic stimulations (gray-coloured symbols) almost matches the estimation of the minimum horizontal stress. During the stimulation with the OCA-fluid, the wellhead pressure in GPK4 reached ~130 bar. An estimation of the pressure gradient in the reservoir by assuming an average reservoir temperature of 70°C, gives a value of ~13.6 MPa/km, very close to the estimation of Valley & Evans, 2007.

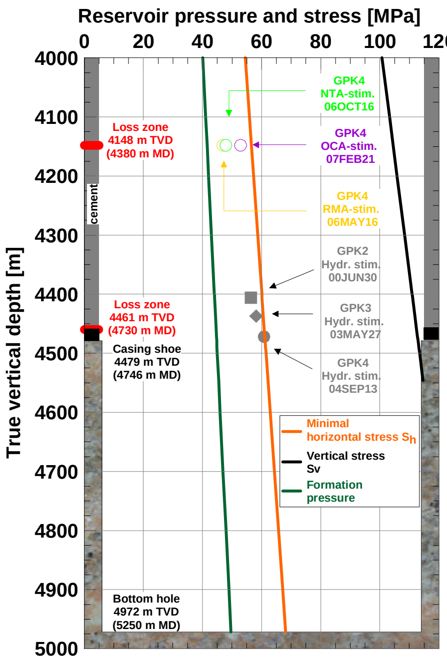

Figure 15: Estimation of the minimal horizontal stress at the HDR/EGS test site in Soultz (Valley & Evans, 2007) and maximum downhole pressure recorded during the stimulations in GPK4. The downhole pressure at the first outlet during the OCA-stimulation (purple circle) is close to the fracture reopening pressure.

As already mentioned in the OCA description, we have to take into account some plugging of the lower part of the well during the preflush and postflush of this operation. Therefore, a high flow rate up to 30 l/s may have entered the formation through the casing leakages. Thus, hydraulic fracturing around the casing leakages corresponds very likely to the observed seismicity.

Regarding the fact that we reached pressure conditions which enable a hydraulic fracturing process during the OCA-stimulation, it is questionable whether the acid itself had any impact on the productivity. The mechanical stimulation alone is able to explain the productivity improvement, the seismicity and also the improved hydraulic communication (Figure 10) between GPK3 and GPK4 after this injection of OCA.

In a future circulation, the improved hydraulic connection between GPK3 and GPK4 will lead to a higher production from GPK4. On the other hand the production temperature from GPK4 should be lower due to the production from upper recharge zones.

CONCLUSION

The deep Soultz wells have been stimulated hydraulically and chemically, in order to develop the underground reservoir prior to electricity production. The results of the stimulation operations are summarized as follows:

GPK2

The well has a productivity of ~0.50 l/(s*bar) in single well tests. Due to a good hydraulic communication with GPK3, the well GPK2 has a productivity of ~0.80 l/(s*bar) under circulation conditions, caused by the increasing reservoir pressure. This difference shows the importance of a reinjection into the same reservoir during a future circulation.

The chemical stimulation with HCl mainly reduced flow resistance in the borehole itself which might consist of the restriction and the lost tool and cable. Nevertheless, a significant turbulent flow regime occurs in the well.

GPK3

The productivity index of GPK3 is about 0.40 l/(s*bar) and remained almost unchanged after successive stimulation operations with HCl and OCA. An infinitive conductive fracture with a large fracture area between 25000 and 50000 m² intersects the open borehole at 4700 m MD and hampers a further improvement by chemical stimulations.

GPK4

The productivity of the well was 0.20 l/(s*bar) after hydraulic stimulations and has improved to ~0.50 l/(s*bar). In comparison to GPK2, the hydraulic communication with GPK3 was weaker prior to the chemical stimulations and therefore GPK4 was less productive than GPK2 during the circulation in 2005.

The chemical stimulations with RMA and OCA improved the productivity of the wells by 30 and 25% respectively, but we attribute at least a part of this gain to a simultaneous hydraulic stimulation of two loss zones in the cemented part of the casing. Stress conditions during the OCA stimulation were favourable for a hydraulic stimulation and were probably caused by a plugging of the well during the pre- and postflush. Moreover, we found a correlation of the upper leak (4110 m TVD) with an accumulation of seismic events. Therefore, a gain of productivity only from the openhole section and the reservoir at 5000 m depth is not likely.
The chemical stimulations with RMA and NTA additionally improved the hydraulic communication between GPK3 and GPK4.

The chemical stimulation campaign, performed at Soultz generated an improvement factor of 1.12 to 2 of the injectivity/productivity. The effectiveness of chemical stimulation can be further improved by using techniques to divert the treatment fluid toward selected zones in the reservoirs (drill pipe, coiled tubing...). As already mentioned, chemical stimulations were performed by injecting acid from the wellhead through the casing string. The stimulation zone was therefore the whole openhole section of the wells (500 to 650 m length). Particularly in fractured crystalline formations, where the reservoir permeability is strongly controlled by the pre-existing natural fracture network, a "focussed" acidizing of this high-permeable joints and fracture zones is essential.

ACKNOWLEDGEMENT

The study was performed within the framework of the European "Hot Dry Rock" project Soultz. The project is funded by the European Commission, the French Ministère de l'Enseignement supérieur et de la Recherche, the German Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, the Projektträger Jülich in Germany and by the members of the EEIG "Heat mining".

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