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CREATION OF AN HDR RESERVOIR AT 5000 M DEPTH AT THE EUROPEAN HDR PROJECT

R.Baria [1,8], R.Jung[2], T.Tischner [3], J.Nicholls, S.Michelet [1,4], B.Sanjuan[5], N.Soma [6], H.Asanuma[7], B.Dyer[9] and J.Garnish

[1] EEIG "Heat Mining", Kutzenhausen, France, [2] GGA, Hannover, Germany, [3] BGR, Hannover, Germany,
[4] now @ MIT, Cambridge, USA, [5] BRGM, Orleans France, [6] Advanced Industrial Science and Technology (AIST), Tsukuba, Japan,
[7] Tohoku University, Sendai, Japan, [8] now @ MIL-TECH UK Ltd, Woking, UK, [9] Semore Seismic, Falmouth, UK

ABSTRACT

Three 5000 m deep wells (GPK2, GPK3 and GPK4) have been drilled into the crystalline basement at the European HDR research site at Soultz in France to form a modular three well system consisting of a central injector and two producers. The system will be used to produce electricity after the creation of an HDR reservoir. The first well GPK2 was drilled in 1999 to 5000 m depth and stimulated in 2000. A second well GPK3 (the injector) was targeted using microseismic and other data and drilled in 2002. The bottom hole temperature of GPK3 was 200.6ºC and separation between GPK2 and GPK3 at the bottom is around 650 m. Similarly, GPK3 was successfully stimulated in 2003 to create a reservoir between GPK2 and GPK3 (Baria et al., 2000, Baria et al., 2004)

The second producer GPK4 was targeted using the same technique as above and drilled in 2003 to a depth of 4982 m TVD. GPK4 was initially stimulated in 2004 but the injection had to be stopped towards the end of the stimulation because of collapsed casing near the wellhead. Both the microseismic and hydraulic data indicated that the required hydraulic link between GPK4 and GPK3 had not been established. GPK4 was re-stimulated in early 2005 but the hydraulic and microseismic data indicated that a hydraulic link to GPK3 had still not been achieved. Production logging in GPK4 during the stimulation of GPK4 showed that about 20 % of the injected flow were leaving around 50 m above the casing shoe. Microseismic monitoring, production logging and other diagnostic methods were used during these injections.

The microseismic events from the initial stimulation of GPK4 in 2004 migrated from the bottom of the well, approximately NW and SE. The NW direction took the micoseismicity towards GPK3 but it appeared to stop migrating after around 200 m where it encountered the previous microseismic events created in 2003 during the stimulation of GPK3. A similar trend in microseismicity was observed during the second stimulation of GPK4 in 2005. There appears to be some form of a barrier that restricts the growth of micoseismicity towards GPK3. The nature of this barrier is not clear and it may also be responsible for a very poor hydraulic response in GPK3 from the injection in GPK4.

INTRODUCTION

The European HDR research site is situated at Soultz-sous-Forêts on the western edge of the Rhine Graben, about 50 km north of Strasbourg (Fig. 1). Baria et al. (1993), Garnish et al. (1994), Baria et al. (1995), Baumgärtner et al. (1995), Baumgärtner et al. (1998), Baria et al. (2004) and Baria et al. (2005) give brief summaries of the various stages of the development of this technology at Soultz since 1987.

The present phase started in April 2001 and was due to last until September 2004. It is called Scientific Pilot Plant (Phase 1). The brief was to drill two additional deviated 5000 m deep wells to form a three-well system and to create an enhanced permeability fractured rock reservoir by hydraulic stimulations. Due to administrative and technical difficulties, Phase I was extended and some of the work program had to be scheduled in to Phase II.

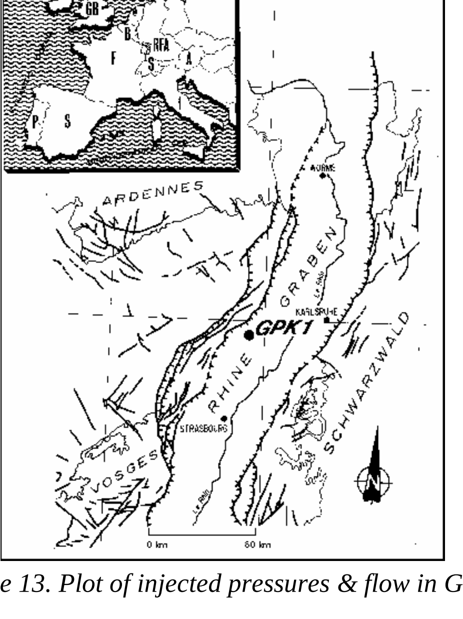

Figure 13. Plot of injected pressures & flow in GPK4

BASIC CHARACTERISITICS OF THE SITE

Geology

The European HDR test site is in the Northern flank of the Rhine Graben, which is part of the Western European rift system (Villemin, 1986). The rift extends approximately NS for 300 km from Mainz (central Germany) to Basel (Switzerland). The Soultz granite is part of the same structural rocks that form the crystalline basement in the Northern Vosges, and intrudes into Devonian, Early Carboniferous rocks.

The geology of the Soultz site and its tectonic setting have been described by Cautru (1987). The pre-Oligocene rocks that form the graben have slipped down a few hundred meters during the formation phase of the graben. The Soultz granitic horst (above which the site is located) has subsided less than the graben. The graben is about 320 million years old (Köhler, 1989) and is covered by sedimentary layers about 1400 m thick at the Soultz site.

Boreholes

The nine boreholes available at the site are shown in Fig. 2. They range in depth from 1400 m to 5000 m. The five boreholes #4601, #4550, #4616 and EPS1 are old oil wells that have been extended to 1604 m, 1500 m, 1414 m and 2227 m respectively in order to deploy seismic sondes in the basement rock. Additionally, the well OPS4 was drilled in 2000 to a depth of 1537 m.

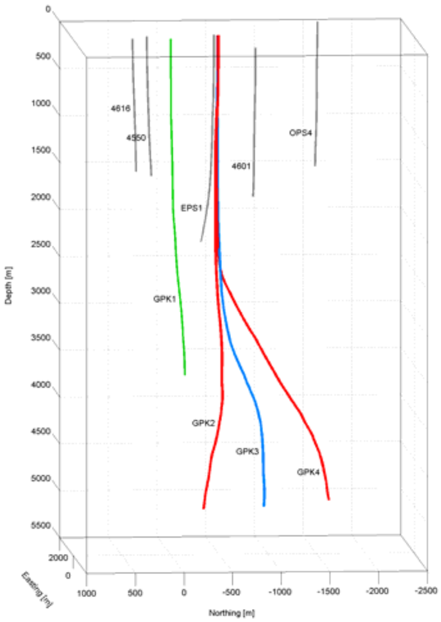

Figure 1: Layout of the boreholes

The first purpose-drilled well (GPK1) was extended from 2002 m to 3590 m in 1993 (Baumgärtner et al., 1995) and has a 6 ¼" open hole of about 780 m. GPK1 was used for large-scale hydraulic injection and production tests in 1993, 1994 and 1997 but presently it is used as a deep seismic observation well. GPK2 is about 450 m south of GPK1 and was drilled in late 1994 to a depth of 3890 m and subsequently deepened to 5000 m in 1999. GPK3 and GPK4 are 5000 m deviated wells with the bottom hole located about 600 m and 1200 m south of GPK2.

Temperature Gradient

In the Soultz area the temperature trend has been determined using numerous measurements in the boreholes. The variation in temperature gradient can be roughly described as 10.5°C/100 m for the first 900 m, reducing to 1.5°C/100 m down to 2350 m (Schellschmidt and Schultz, 1991) then increasing to 3°C/100 m from around 3500 m to the maximum depth measured (5000 m).

Joint Network

Information on the joint network at the Soultz site has been obtained from continuous cores in EPS1 and borehole imaging logs in GPK1 (Genter and Traineau (1992a) and (1992b)). The observations suggest that there are two principal joint sets striking N10E and N170E and dipping 65°W and 70°E respectively (Genter and Dezayes, 1993). The granite is pervasively fractured with a mean joint spacing of about 3.2 joints/m but with considerable variations in joint density.

Stress Regime

At the Soultz site, the stress regime was obtained using the hydrofracture stress measurement method (Klee and Rummel, 1993). The stress magnitude at Soultz as a function of depth (for 1458 - 3506 m depth) can be summarized as:

$$S_h = 15.8 + 0.0149 \cdot (Z - 1458) \quad \text{- Min. Horizontal stress,}$$
$$S_H = 23.7 + 0.0336 \cdot (Z - 1458) \quad \text{- Max. Horizontal stress,}$$
$$S_V = 33.8 + 0.0255 \cdot (Z - 1377) \quad \text{- Overburden,}$$

Where S_h, S_H, S_v in MPa and Z = depth (m).

The direction of S_H is N170°E.

Microseismic Network

A microseismic network has been installed at the site for detecting microseismic events during fluid injections and locating their origins (Fig. 2). The equipment consists of three 4-axis accelerometer sondes and 3-axis geophone sondes, linked to a fast seismic data acquisition and processing system. The sondes were deployed at the bottoms of wells #4550, #4601, EPS1, OPS4 and GPK1. Additionally, the teams from Tohoku University and AIST, Japan, carried out continuous digital recording.

In addition, a surface network was installed by EOST in order to be able to characterize larger events.

Real Time Reservoir Control System

The seismic activity generated during the stimulation was monitored continuously using a dedicated system based on subsurface sensors. The seismic data from the monitoring wells were continuously transmitted to the acquisition room by a combination of landline and radio telemetry. During the two stimulations of GPK4 and associated tests, around 35,000 events were captured and around 10,000 events were located.

The seismic trace data were transferred continuously to an automatic timing and event location package to obtain real time event locations. The event locations could be viewed in the hydraulic control room and other sites remote from the acquisition room over the network.

In parallel, Tohoku University & AIST group also carried out auto locations in a batch process to confirm the real time locations.

A brief circulation test between GPK2 & GPK3

GPK2 and GPK3 were successfully drilled and stimulated in 2000 and 2003 respectively (Baria et al. 2000, Baria et al. 2005, Hettkamp et al. 2005).

A brief circulation test was established after the above stimulations using GPK3 as the injector and GPK2 as the producer. Figure 3 shows seismic event rates and production flow rates from the two wells and Figure 4 shows the location of microseismic events during the circulation test.

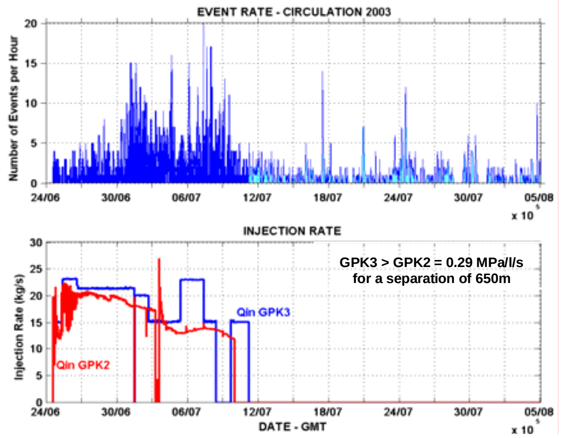

Figure 3: GPK2 & GPK3 circulation test

It is apparent from Figure 3 that the production flow rate is declining even after various attempts to keep the injection rate constant. The microseismic event rate is continuing during and after the circulation, which suggests that the reservoir was still expanding. Events generated during this test can be seen in Figure 4 and these are well below the two deep wells, in a new area. This may be an indication that the rock mass at this depth could be represented as a closed system and not as an open system as was observed at 3500 m depth.

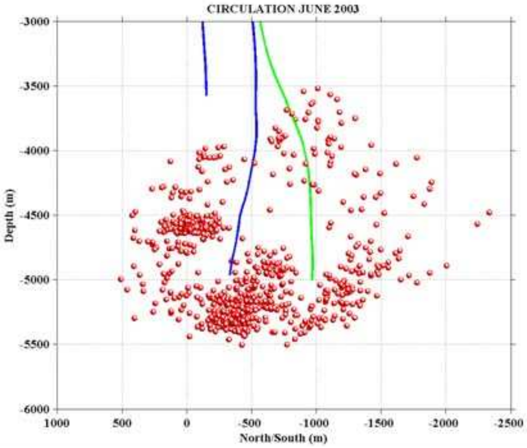

Figure 4: Microseismic events generated during the circulation test between GPK2 & GPK3

Results of a tracer test showed that a good reservoir had been created with a breakthrough time of around 4 days and a flow impedance of around 0.29 MPa/l/s. Part of the philosophy of the stimulation procedure adopted was to reduce larger seismic events by not increasing or decrease rapidly the injection pressure. Around 30,000 m^3 and 50,000 m^3 of water were injected during the stimulation of GPK2 and GPK3. Two 'felt' seismic events (2.5 Ml and 2.9 Ml magnitude) were generated during the shut in after the stimulation of GPK2 and GPK3 respectively. This would suggest that the injection of a larger volume of water may create greater stress disturbance and may be responsible for the generation of bigger seismic events. This may be a reflection of the residual strain energy stored in the rock mass.

DRILLING AND HYDRAULIC STIMULATION OF GPK4 IN 2004

The second producer GPK4 was targeted using the same technique as GPK3 and was drilled in 2003. GPK4 is a highly deviated well drilled in granite and steps out by around 1200 m from its wellhead. The bottom hole temperature of GPK4 was 200.9ºC and separation between GPK3 and GPK4 at the bottom is around 720 m. The completion of the well is shown in Figure 5.

During the stimulation of GPK3 in 2003, there were constraints on certain aspects of hydraulic investigation, including the concern that a sudden shut-in might cause the initiation of larger seismic events. This meant that the hydraulic tests performed during the stimulation of GPK3 did not have an adequate shut-in.

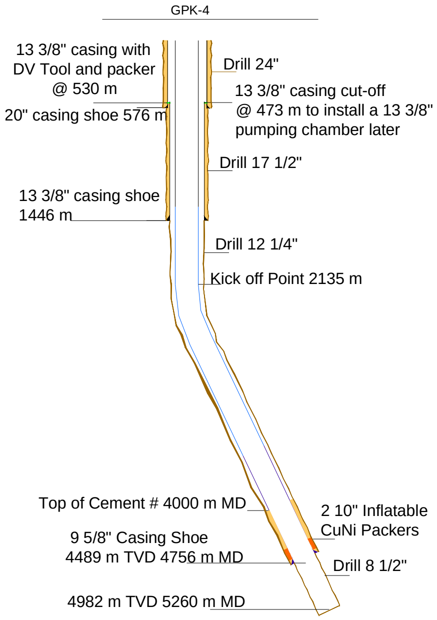

Figure 5: Completion of highly deviated well GPK4

The flexibility of the hydraulic set up in 2004 provided an opportunity to quantify some of the characteristics of GPK3 prior the stimulation of GPK4. The investigation consisted of determining the post-stimulation injectivity and productivity of GPK3. 7000 m³ of fresh water was injected in GPK3 at 12, 18 and 24 l/s. During this period GPK2 was active (pressurised) and GPK4 was killed. The injectivity of GPK3 was calculated to be 0.4 l/s/bar, although the target value for high flow rates is 1.0 l/s/bar. This indicates that it behaves like a relatively closed system. There was also a clear pressure response in GPK4 to the injection test in GPK3.

A production test was also carried out in GPK3 to evaluate its productivity and to clean the near wellbore region. Around 2710 m³ of fluid was produced from GPK3 while keeping a backpressure of 12 bars and observing the behaviour of the flow.

The productivity of GPK3 was calculated to be 1.0 l/s/bar assisted by buoyancy effect. This was an improvement, although there is a clear indication that the production flow was decreasing as a function of time.

Following the injection test in GPK3, a low flow rate injection test was carried out in the new well GPK4 to assess the undisturbed injectivity. The well was filled with brine of 1.19 g/cm³ prior to the stimulation. Around 250 m³ of brine was injected in GPK4 at a flow rate of 0.8 l/s over 4 days. GPK2 and GPK3 were made active by pressuring the wells.

The results indicate that the injectivity of GPK4 was <0.015 l/s/bar, very low and comparable to that of GPK2 in 2000. No pressure communication to either GPK2 or GPK3 was observed.

This was followed by the main stimulation test, which consisted of injecting ~9,134 m³ of fresh water at a predominant injection flow rate of 30 l/s over 3.5 days, although three unsuccessful attempts were made to increase the flow rate to 45 l/s. The injection pressure required to pump 30 l/s was around 17 MPa, which is very close to the limit of the pump. The data obtained are shown in Figure 6.

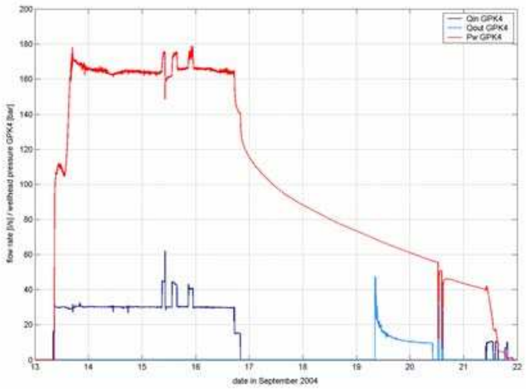

Figure 6: Stimulation of GPK4 in 2004

During the injection in GPK4 at 30 l/s, the wellhead pressures of GPK3 and GPK2 were also monitored. A flow log was also carried out to identify flowing zones and flow exits in the openhole section of GPK4 while injecting, which is shown in Figure 7. The flow log shows that the majority of the flow left the well GPK4 at the bottom (~60%), with two other identifiable exits at around 4775 m and 4825 m MD that took ~15% each.

After 3 days of pumping for the stimulation of GPK4, the PTF sonde stopped working and it was decided to withdraw it from the well to repair it. While withdrawing the sonde, it was observed that the sonde could not be pulled into the riser. In view of the difficulty, the stimulation experiment of GPK4 had to be stopped and the reservoir killed to investigate and rectify the cause of not being able to withdraw the PTF sonde.

On dismantling the wellhead assembly of GPK4, it was noticed that the upper part of the 9 5/8" casing had collapsed, reducing the accessible diameter of the

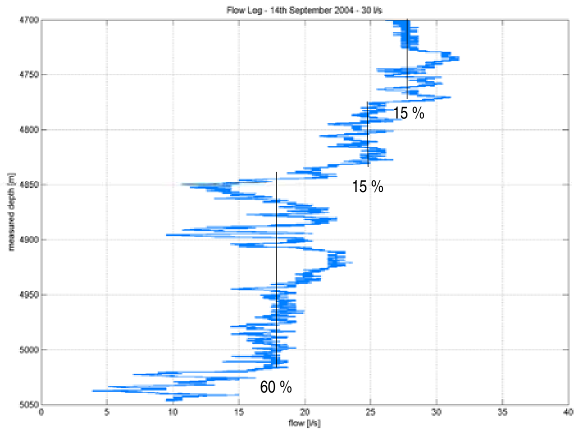

Figure 7: Flow log during stimulation of GPK4

casing and therefore making it impossible to withdraw the PTF sonde. The collapsed part of the casing was cut off and the logging tool and the wire line cable were recovered. Further investigation showed that cuttings, created during the drilling of GPK4 and mixed with lubricating oil, had somehow got behind the 9 5/8" casing and formed a seal just below the landing ring on the casing. This seal, in conjunction with the packer assembly which allows the casing to expand, had trapped water between the two that could not escape. When the casing shrank during the injection, because the trapped water could not leak away the casing came under enormous pressure and collapsed locally.

The results of the hydraulic data show that significantly high pressures were required to stimulate GPK4 (~17 MPa at 30 l/s). It was difficult to inject 45 l/s because of the high pressure required. It became apparent, nevertheless, that further stimulation will be necessary to reduce the flow impedance to GPK3. The shut-in curve indicated that it is a relatively tight system and may be classified as a so-called “closed” system.

Microseismic monitoring was carried out during the stimulation of GPK4 and the data obtained are shown in Figure 8. The figure shows the locations after 6 hours (heavy brine period, red); 12 hours (fresh water injection; orange); 1 day, yellow; 2 days, green; 3 days light blue and 6 days, dark blue).

The analysis of the microseismic locations shows that the events occurred first below the well and then migrated upward and around the bottom of GPK4.

The microseismic and the hydraulic data indicated that good progress was being made towards creating a hydraulic link between GPK4 and GPK3 but a satisfactory link was not established yet. This can also be seen when comparing the density map of the seismic events created during the stimulation of

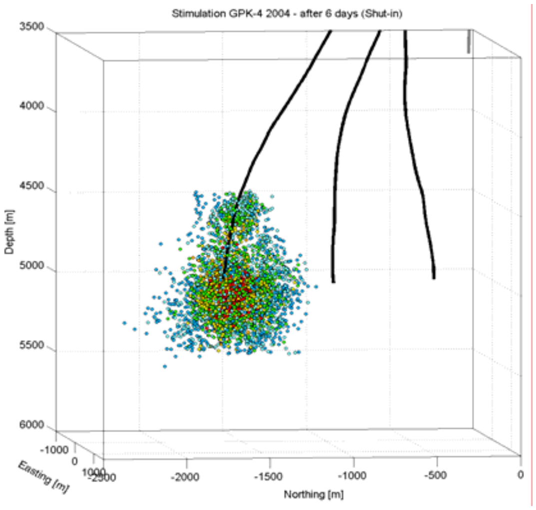

Figure 8: Microseismic locations of GPK4 in 2004

GPK3. Figure 9 shows the elevation of the microseismic density map created during stimulation of GPK3 in 2003 and GPK4 in 2004. There is a clear indication that the connection has not been fully established yet and that further stimulation will be necessary to improve the link.

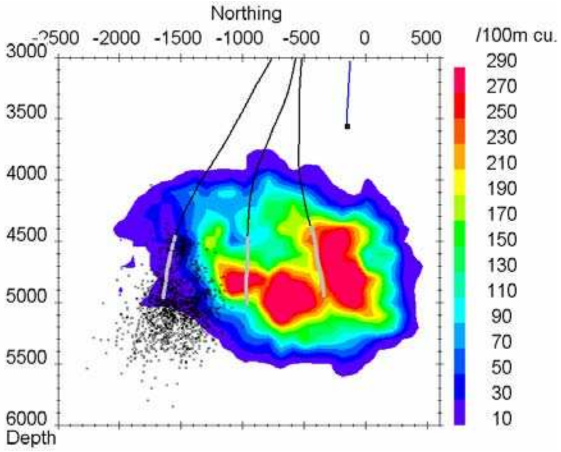

Figure 9: Density map of seismic events during the stimulation of GPK2 & GPK3 plus events located during the first stimulation of GPK4

SECOND STIMULATION OF GPK4 IN 2005

The Christmas trees of the three wells were dismantled and heavy-duty casing was used to construct the new upper part of the 9 5/8" casing. After the completion and testing of the wellheads, plans were prepared to stimulate GPK4 again. This included injecting ~13,000 m³ of water at flow rates of 30 and 45 l/s, followed by a shut-in. An additional test was also included to test the effectiveness of acidization technique to reduce the near wellbore impedance. This entailed injecting ~5,000 m³ of fresh water in three flow rate steps followed by shut-in, then ~6,000 m³ of water with HCl (30m³ HCl

30%) followed by shut-in, and repeating the initial injection test of ~5,000 m³ to look for any change in the wellhead pressure.

Figure 10 shows the wellhead pressure and flow rates used during the first (grey) and second (red) stimulation of GPK4. The response of the two wells (GPK2 & GPK3) was similar to that found during the first stimulation i.e. some pressure response but no hydraulic communication. It would appear that the stimulation pressure exceeded 18 MPa and the shut-in curve looks very similar, suggesting that the system in the vicinity of GPK4 is relatively closed.

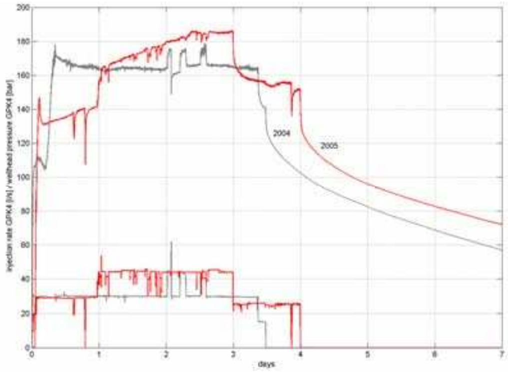

Figure 10: Comparison of wellhead pressures and flowrates for the first and second stimulation of GPK4

The hydraulic data from the test to assess the effectiveness of acidization is shown in Figure 11. The injected pressure and flow rates used are shown in red and blue respectively. Although initially it would appear that the pressure required to inject ~25 l/s after the acidization phase is low (~9 MPa), a flow log carried out during the last injection showed that something like 20% of the flow was leaving 50 m above the casing shoe. Subsequent analytical analysis showed that this pressure reduction (13 to 9 MPa) could easily be accounted for by the leak in the casing.

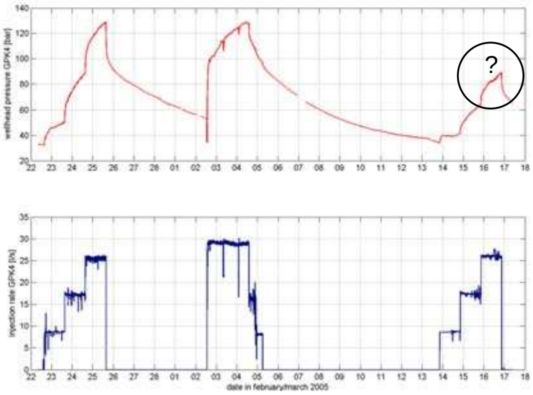

Figure 11: Pressure and flow for the acidization test

Examination of the microseismic events generated during this phase shows that events were generated at the boundary of the existing reservoir and thus do not help to raise pressure near the wellbore as expected.

Microseismic events located during the stimulation in 2005 (black), the initial test before the acidization and the acidization test (pink) and the test after the acidization (red circles) are shown in Figure 12.

Events located during the stimulation of GPK2 and GPK3 are shown as a contour map with highest event density represented by red colour and the lowest density represented by the colour blue.

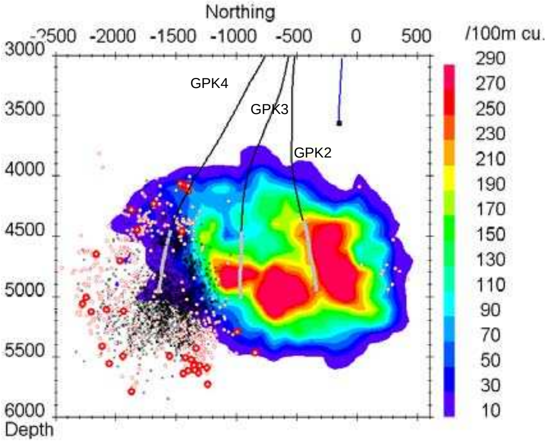

Figure 12: Microseismic events located during the stimulation of GPK4 in 2004 & 2005

The figure shows that the stimulation carried out in GPK4 in 2004 and 2005 started near the bottom of GPK4 and then migrated outwards but stopped expanding towards GPK3 at the boundary of the previous stimulation in GPK3, almost as if there were a barrier which stopped the pressure from migrating towards GPK3. The microseismic cloud expanded in every other direction except towards GPK3. During the subsequent test to evaluate the acidization (pink & red circles) the reservoir again continued to expand in all directions except towards GPK3.

A plot of the pressures required for injections against the flow rates for all the injection tests carried out in GPK4 are shown in Figure 13.

The figure shows that the best injectivity achieved is around 0.25 l/s/bar, significantly lower than that required for a production well which should be better than 1.0 l/s/bar.

This higher impedance barrier between GPK3 and GPK4 can also be identified in the microseismic data.

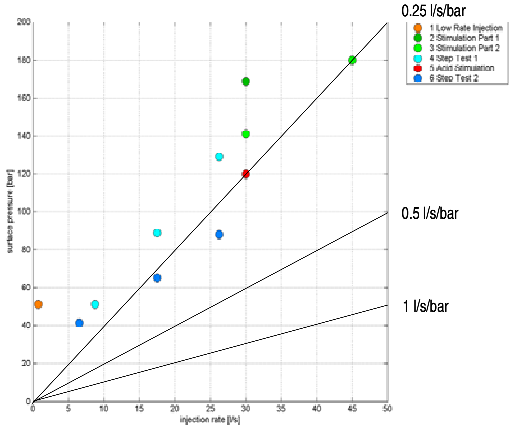

Figure 13. Plot of injected pressures & flow in GPK4

Figure 14 is a density contour of the events located during the stimulation of GPK2, GPK3 and the first stimulation of GPK4. The red contours representing higher densities of events during the stimulation of GPK3 and GPK4 do not appear to overlap. There appears to be some form of a barrier stopping the pressure in this region to be raised enough to shear joints and create the required permeability.

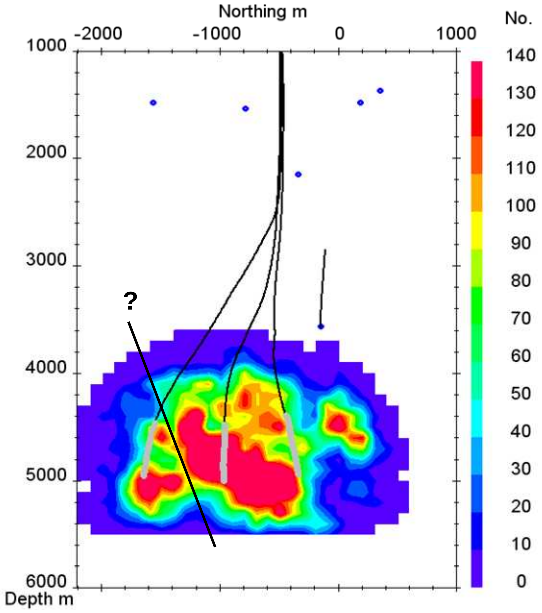

Figure 14. Event density map of the stimulations of GPK2, GPK3 and the first part of GPK4

This observation of higher impedance between GPK3 and GPK4 and acceptable impedance between GPK2 and GPK3 is also supported by the tracer experiments which show that it takes something like 4 days to travel from GPK3 to GPK2 but significantly longer from GPK3 to GPK4.

A brief circulation test was carried out after the stimulations of GPK4. Around 15 l/s was injected in GPK3 and around 11 l/s and 4 l/s were recovered from GPK2 and GPK4 respectively. This is an unbalanced system and, in view of the extensive and prolonged stimulation carried out GPK3 (~50,000 m³ was injected), the critical state of stress and a history of generating bigger seismic events (2.9 Ml), it seems prudent to improve the connection between GPK3 and GPK4 to reduce the risk of bigger events. This is also necessary if Soultz HDR system is to be recognised as a viable three well system.

POSSIBLE WAY FORWARD

The reservoir, as it stands, is unlikely to work as a balanced system and it is essential therefore to stimulate GPK4 by using available methods. The analysis of the hydraulic and seismic data suggests that in this environment bigger events may be linked with the volume injected or stored in the reservoir. The focused injection technique (i.e. pressurizing both wells simultaneously) (Baria et al. 2004) used during the stimulation of GPK3 may be a solution, as it offers a capability of raising pressure significantly in the middle of the two wells and breaking the barrier with relatively small volumes of fluid in 24-48 hours of injection.

This is not the only method, and other methods such as very high flow rates (120 l/s), viscous gel, etc., are also available.

In principle, the project has broken many barriers and has achieved targets which have not been achieved anywhere else. The reduction of drilling cost for deep wells, circulation without water losses, well separation of over 600 m, large stimulated volumes, lower impedance between GPK2 and GPK3 of around 0.29 MPa/l/s, multi-national cooperation are some of these achievements.

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