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Creation and Mapping of 5000 m deep HDR/HFR Reservoir to Produce Electricity

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ABSTRACT

The current phase of the European Hot Dry Rock Project at Soultz-sous-Forêts requires the drilling of two additional deep wells to 5000 m depth into the crystalline basement, to form a module consisting of a central injector and two producers. The first well GPK-2 was drilled to 5000 m in 1999 and stimulated in 2000. The well GPK-3 (the injector) was drilled in 2002 and targeted using microseismic and other data. The bottom hole temperature was 200.6 ºC and separation between the two wells at the bottom is around 600 m. GPK3 was then stimulated to enhance the permeability between the wells. A number of stimulation techniques were tried including "***focused***" stimulation, a novel method of injecting simultaneously in two wells. Microseismic monitoring, flow logging and other diagnostic methods were used during these injections.

The ***"sparse"*** microseismic network at the Soultz site consists of a number of seismic sensors deployed in wells between 1500 m and 3600 m deep with bottom hole temperatures of 130-160 ºC. A 48 channel, 22 bit data digitizing unit was used for data acquisition in conjunction with proprietary software to carry out automatic timing and location in real time. This gave a real time decision-making possibility and control of the reservoir. This was the first time that such an interactive method had been carried out at this site.

Around 90 000 micro-earthquakes were triggered during these injections and about 9 000 events were automatically timed and located in real time. These stimulations created a total reservoir volume in excess of 3 km^3. This is the largest stimulated volume in the development of HDR technology to date.

The data suggest that "focused" stimulation may have a significant advantage over a single well stimulation technique and may be a way forward for efficient stimulation of larger separations between wells, thus improving the economic viability and acceptance of HDR/HFR/EGS systems.

It is recognized that the reservoir creation process generates microseismic events but generation of bigger events (30 events approaching 2ML & one up to 2.9ML during this campaign) may retard the acceptance of this technology in an urban environment. This needs further studies to understand the processes and find a procedure to reduce the incidence of larger events.

1. INTRODUCTION

It has taken over 30 years of research for the concept of Hot Dry Rock (HDR) formulated in Los Alamos (USA) to approach reality at Soultz-sous-Forêts (France). The concept has evolved over that time, and various names have been proposed from Hot Wet Rock, Enhanced Geothermal System, Hot Fractured Rock etc. Different terms apply to different geological and tectonic settings but the principle still remains the same i.e. getting heat out of the deep and hot underground rock mass following permeability enhancement using hydraulic stimulations.

The research at the European HDR site at Soultz started in 1988 following the encouragement of the European Commission to pool the limited available national funds to form a coordinated multi-national team. The main task was to develop the technology needed to access the vast environmentally friendly HDR energy resource. 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), Baumgaertner et al (1995), & Baumgaertner et al (1998) give a brief summary of the various stages of the development of this technology at Soultz since 1987.

The present phase started in April 2001 and will last until September 2004. It is called a Scientific Pilot Plant (Phase 1). The brief is 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. It also includes use of various diagnostic techniques to understand and quantify various properties of the stimulated reservoir. The program also includes the establishment of a database of the potential HDR resource in the Western Europe.

2. BASIC CHARACTERISTICS OF THE SITE

2.1 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 N-S 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.

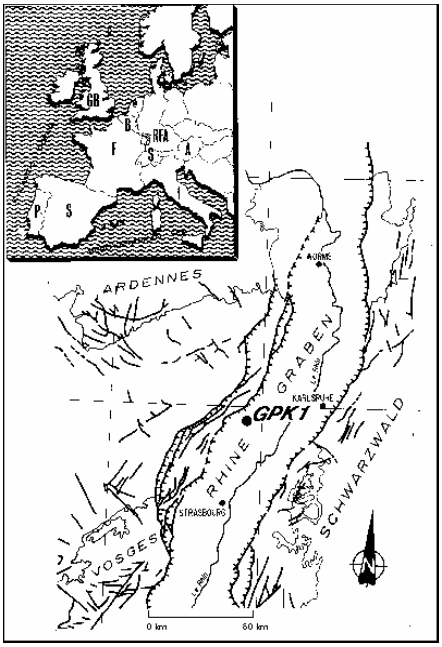


Figure 1: The location of the European HDR site at Soultz-sous-Forêts).

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.

2.2 Boreholes

The eight 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 EPS-1 are old oil wells that have been extended to 1600 m, 1500 m, 1420 m and 2850 m respectively in order to deploy seismic sondes in the basement rock. Additionally, the well OPS4 was drilled in 2000 to a depth of 1800 m.

The first purpose-drilled well (GPK1) was extended from 2000 m to 3590 m in 1993 (Baumgärtner et al., 1995) and has a 6-1/4" 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 is a 5000m deviated well with the bottom hole located about 600 m south of GPK2 (Fig. 2).

2.3 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 & Schultz, 1991) then increasing to 3°C/100 m from around 3500 m to the maximum depth measured (5000 m).

This irregular gradient suggests that there is a zone of enhanced circulation between the granite basement and the sedimentary cover. The reduction in the temperature

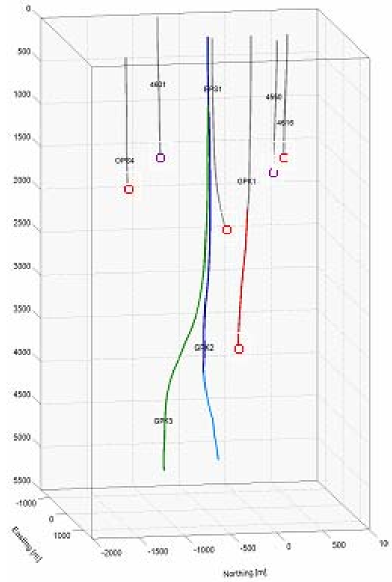


Figure 2: Layout of the boreholes.

gradient and its subsequent increase suggests that there are convective cells present which may extend to greater depth. Thermal modeling and the available data (geochemical and hydraulics) both support this view.

2.4 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.

2.5 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:

(Min. horizontal stress) $S_h = 15.8 + 0.0149 \cdot (Z - 1458)\}$

(Max. horizontal stress) $S_H = 23.7 + 0.0336 \cdot (Z – 1458)\}$

(Overburden) $S_V = 33.8 + 0.0255 \cdot (Z - 1377)\}$

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

Note that this implies a cross-over between S_v and S_H around 3000 – 4000 m depth, with a consequent transition in failure mode from normal faulting to strike-slip.

2.6 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 (Calidus Electronics), linked to a fast seismic data acquisition (Perseids, IFP) and processing system (DIVINE, Semore Seismic). 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 consisting of around 35 stations was installed by EOST in order to be able to characterize larger events.

3. 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 stimulation and subsequent circulation test the acquisition system detected in excess of 90 000 potential seismic events. The event rate was typically around 250 events/hour. The peak rate was just in excess of 580 events/hour, one event every seven seconds.

The seismic trace data were transferred continuously to an automatic timing and event location package, (Divine, Semore Seismic), to obtain real time event locations. The network at the site is ***sparse*** and around 9 000 events were located in this way using auto-picked P and S timing. The event locations could be viewed in the hydraulic control room and other sites remote from the acquisition room over the network. This was the first time at this site that seismic data have been available in real time.

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

4. HYDRAULIC STIMATION OF GPK2 & GPK3

GPK2 was stimulated first in 2000. Subsequently GPK3 was targeted on the basis of the information gathered from various methods including microseismic, hydraulic, stress, jointing etc. GPK3 was drilled to 5000 m depth with the casing shoe set at 4556 m depth.

Although the primary objective of the hydraulic injection was to stimulate the new well GPK3, a number of variations in the stimulation techniques were also carried out. The seismic data are therefore presented in four parts of the hydraulic history (Phases 1 to 4) as shown in Fig. 3. Phase 1 consists of injection in GPK3 of up to 60 l/s, Phase 2 consists of simultaneous injection in GPK2 & 3, Phase 3 consists of shutting in GPK2 and continued injection in GPK3 and then shut-in, and Phase 4 consists of shutting in both wells initially but venting GPK2 at around 10 l/s for 5 days.

4.1 First phase

The stimulation commenced on 27th June with the injection of heavy brine (density around 1.2 kg/l) at a rate of 30 l/s. When the supply of brine was exhausted the stimulation proceeded with cold fresh water. The purpose of the brine was to stimulate preferentially the deeper and so hotter part of the openhole.

This practice had been shown to be successful during previous stimulation of GPK2. The injection rate was increased to 50 l/s on 30th May with one short period at up to 90 l/s.

The onset of seismicity occurred at around 2.6 MPa overpressure, which was consistent with the observations in2000, and suggests that the state of stress on the stimulated joints may be close to critical (just as has been seen at every

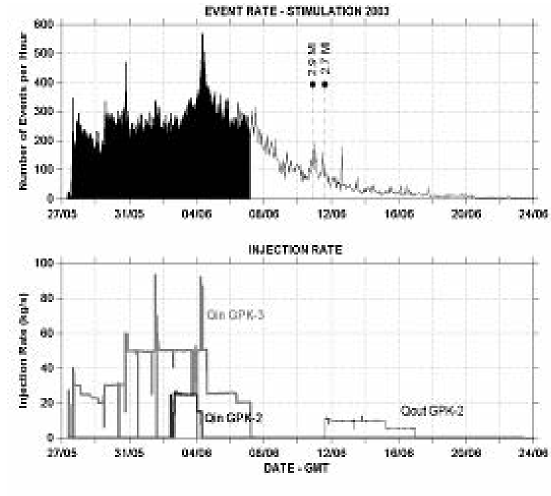


Figure 3: Event rate and injection rate during the stimulation in 2003

other HDR site investigated; this is probably not a coincidence (Pine and Batchelor (1984)). The seismicity at the start of the GPK3 injection was located around the main flowing zone at 4760 m detected on the flow log (Figure 4). The events developed towards GPK2 in a downward direction. Over the period of this phase of the injection the event distribution continued to develop north and south of the GPK3 openhole but the progress slowed towards GPK2 (Figure 5a).

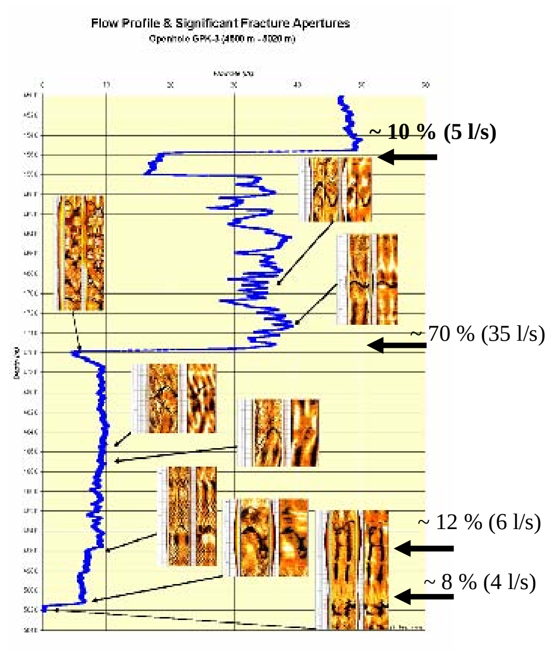


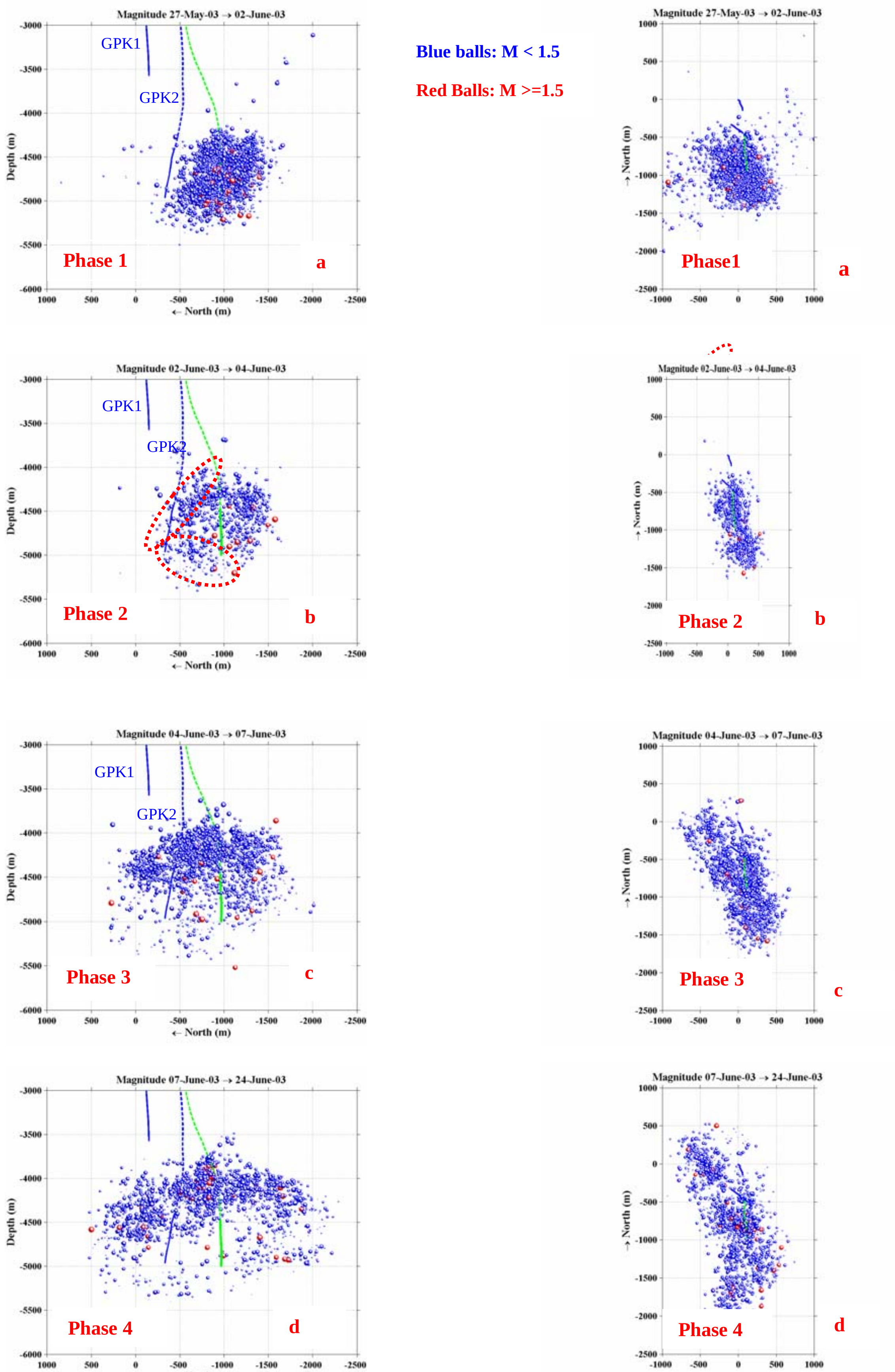
Figure 4: Flow profile and significant fracture apertures (courtesy of Glen Homeier and Jonathan Nicholls).

4.2 Second phase

The concept of "focused" stimulation was based on the experience and observation in 1995. During the initial stimulation of GPK2 in 1995, when the well was only 3600 m deep, it was observed that the seismicity moved from GPK2 towards GPK1 but started to bypass the well

GPK1. GPK1 was used at the time to produce in-situ brine needed to inject in GPK2. It became apparent that the

Figure 5: Vertical North to South sections through the seismic event distributions during the GPK3 stimulation phases.



production from GPK1 was causing a reduction in the in-situ pore pressure near the well and therefore inhibiting the shearing of the joints. The production from GPK1 was stopped and almost immediately seismicity started to migrate towards GPK1.

This implied that if stimulations were carried out in both wells simultaneously then the overpressure in the reservoir between the wells would be the result of superposition of the injection pressures. This would elevate the pressure between the wells significantly more than that from a single well stimulation; in other words this would help to stimulate or shear the joints in the area which has always been traditionally difficult to manipulate. Although this seemed a reasonable approach, the infrastructure needed and the logistics of stimulating both wells at the same time was daunting.

GPK3

Due to better planning and restructuring of the available resource in 2003, it was possible to inject in both wells simultaneously for a limited period. This type of stimulation had never been tried in the HDR environment and it was decided to name it as "focused" stimulation. This technique may facilitate selective stimulation of certain part of the reservoir between the wells by manipulating the injection pressure in each.

In an effort to stimulate the region south of GPK2 it was decided to inject simultaneously into GPK2 and GPK3. The separation at the bottom of the two wells is in excess of 600 m. During this phase around 50 l/s was being injected in GPK3 and injection of about 20 l/s was started in GPK2.

The distribution of events due to the relatively short GPK2 injection developed significantly towards the upper part of the reservoir (figure 5b). A deep region of seismicity also developed. These new regions of seismicity are indicated by the red dash ellipses in Figure 5b. There is very little seismicity immediately adjacent to the GPK2 openhole as this region was previously stimulated in 2000. It is a characteristic of the stimulations at Soultz that the seismicity is concentrated in unstimulated parts of the reservoir, as would be expected.

4.3 Third phase

In the third phase of the stimulation (Figure 5c), GPK2 was shut-in and the injection into GPK3 was increased to 90 l/s for 3 hrs and then progressively reduced in three steps in order to avoid larger seismic events, which were believed to be caused by rapid pressure drop.

Nonetheless, the event distribution demonstrates that the reservoir continued to develop to the north of GPK3, predominantly at the top of the reservoir. There is also a distinct zone of seismicity beneath GPK2 and GPK3, suggesting that a deep flowing zone has been stimulated.

4.4 Fourth Phase

In the fourth phase (Figure 5d), initially when GPK3 was also shut-in, the microseismic events continued to be generated instead of decaying rapidly as occurred during the stimulation at 3600 m depth. This observation, in conjunction with the slower decay in the shut-in curve, suggests that the leak-off was not as large and therefore the system was relative tight compared to that at 3600 m depth. Secondly, two large events (2.9 and 2.7 ML) were generated on 11th June 2003. As these could be felt at surface, some measures to reduce such events were required. GPK2 was

vented at around 10 l/s to reduce the pressure in the reservoir.

The seismic events were generated on the periphery of the reservoir with the majority of them (including the larger events) concentrated at the top of the reservoir (Figure 5d). This may be due to a thermal effect as the cold injection water heats up within the reservoir causing an upward pressure due to the buoyancy effect. The seismicity continued to be generated but with a gradual decline for at least two months after the venting test.

During the 2000 stimulation of GPK2, it was observed that there was no pressure response in GPK1. Seismic events migrated upwards during this stimulation but the microseismic cloud appeared to stop as if there were some upper barrier. During the stimulation of GPK3 (2003) there *was* a pressure response in GPK1, indicating that this barrier may have been breached. It is worth stating that the events did not develop sufficiently upwards to connect into the region of the reservoir created previously at the bottom of GPK1. This suggests that the stimulated region of the GPK3/2 reservoir has remained isolated in the deeper, hotter granite where the potential geothermal resource is greatest.

Following the stimulation a circulation test was performed. This demonstrated that the target productivity of GPK2 of 1 l/s/bar had been reached. The injectivity of GPK3 was 0.3 l/s/bar. This is less than desired but it is expected that this value will improve following cleaning operations and the stimulation of the new well GPK4.

5. MODELLING

A numerical scope calculation for the following two cases has been performed (Geowatt AG, Zurich) to highlight the possible hydraulic behavior under stimulation condition:

1) Stimulation in a single borehole
2) Simultaneous stimulation in two boreholes

Therefore, a 3D hydraulic model was set up assuming typical conditions of the Soultz reservoir at 5.0 km depth (i.e. initial far-field permeability = 10mD (10^{-14}m^2), initial near borehole permeability = 1D (10^{-12}m^2) and the stimulation rates of GPK3 (i.e. 100 l/s). The 3D model used two boreholes at 500 m apart, each borehole with a 500 m open hole section. The model consisted of ~40,000 nodes and was especially refined near the two boreholes.

The results of these calculations are illustrated on the pressure field along the direct line between the boreholes (Figures. 6 & 7) and on the shape of the pressure isosurface (1 MPa, 3 MPa, 5 MPa, see Figures 8 & 9).

Clearly, the pressure contour of case 1(Figure 6) is on a much lower level than that of case 2 (Figure 7). In these settings, the critical 3 MPa will not be reached in the center. However, in the two-borehole stimulation (case 2) this pressure level is already reached after 3 hrs.

6. PRELIMINARY OBSERVATIONS AND CONCLUSIONS

1. The onset of shearing was observed at around 2.6MPa overpressure.

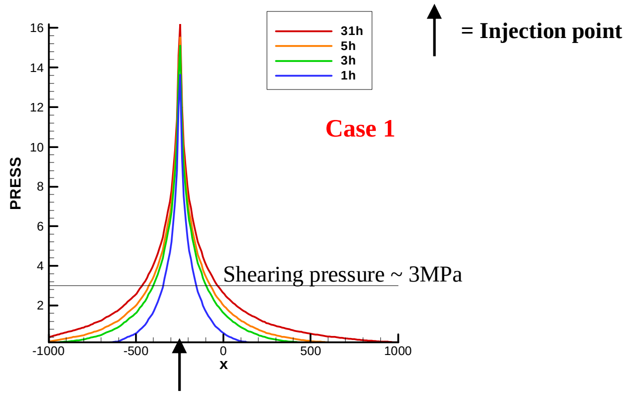


Figure 5: Pressure evolution along the direct connection of the open borehole sections with time of run 1.

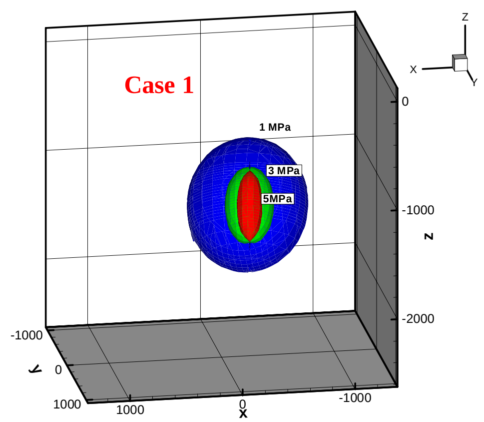


Figure 6: Isobars (1 MPa, 3 MPa, 5 MPa) after 30 h (nearly steady-state) of run 1.

2. Around 90 000 microseismic events were recorded and about 9 000 were automatically located in real time during the stimulation.

3. The availability of microseismic event data in real time provided a significant benefit in monitoring and controlling the hydraulic operations during the stimulation of GPK3.

4. The seismic event rate follows the injection pressure/flow but only decayed slowly after the shut-in compared to the rate observed in 2000.

5. Broadly, the seismicity started at around 4700 m depth in GPK3 and migrated approximately N-S.

6 On average, the large events are distributed throughout the seismic cloud

7. During the "focused" injection, the seismicity is distributed evenly between the wells and predominantly below the GPK2/GPK3 casing shoes.

8. Delayed time-lapse visualization of the seismicity during the period of focused injection shows that the majority of the stimulation between the wells was done in around

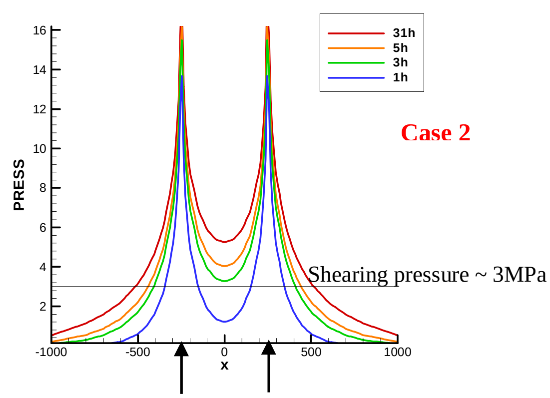


Figure 7: Pressure evolution along the direct connection of the open borehole sections with time of run 2.

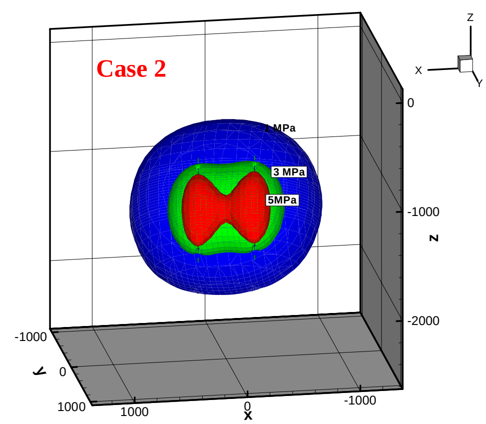


Figure 8: Isobars (1 MPa, 3 MPa, 5 MPa) after 30 h (nearly steady-state) of run 2 (right). The stimulated volume marked by the 3 MPa case is significantly larger (~10 times) than that one of run.

18 hours of injection. This supports the view that high pressure built up occurred between the wells during the focused injection, which manifested itself as microseismic events.

9. Subsequently, the seismicity continued to expand N – S and structures above the casing shoes developed strongly, probably caused by the buoyancy effect of the injected fluid.

10. The successful extension of the reservoir to encompass the previously stimulated region around GPK2 created atotal of reservoir volume in excess of 3 km^3. this is the largest ever stimulated volume in the development of HDR technology in conjunction with the largest separation between the injection and production well to date (over 650 m).

11. The apparently near critical state of stress in the reservoir region may also have been an important factor in the successful stimulation of a large reservoir volume. It should be stressed, however, that this effect has been seen at every HDR site tested to date and may be the norm.

12. In excess of 400 events were above 1.0 ML and around 30 events were above 2.0 ML.

13. The largest 2.9 ML event was recorded on the 10th June 2003 at 22:54 (GMT time).

14. Although stimulations were considered to be successful, the generation of large events needs further investigation into stress migration and lockup. Subsequently, a stimulation and circulation strategy must be developed to reduce bigger seismic events if this technology is to be acceptable in an urban environment.

POSSIBLE FUTURE SCENARIO

During the stimulation of the third deep well GPK4, an attempt will be made to use microseismic data not just for locating shearing joints but to estimate pore pressure in the expanding reservoir using a numerical model to evaluate on line reservoir growth & it's properties (figure 10).

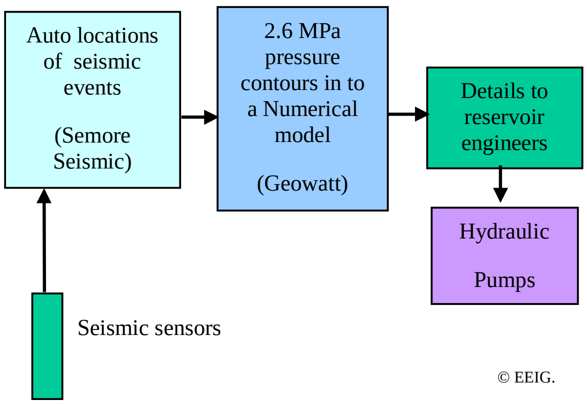


Figure 10: A schematic for a coupling between microseismic, numerical model & reservoir engineering.

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