MICROSEISMIC MONITORING OF SINGLE AND DUAL WELL (FOCUSSED) STIMULATIONS OF THE WORLD'S LARGEST POTENTIAL HDR RESERVOIR

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Introduction to the Soultz HDR Geothermal Project

Geothermal exploration and testing has been taking place at the European Hot Dry Rock (HDR) Project, Soultz-sous-Fôrets in Alsace, France since 1993. These activities have sought to exploit the energy of the fractured hot granite basement using the Hot Dry Rock technique. This programme of collaborative European Research and Development has progressed into a project to build an HDR geothermal pilot plant, which is being conducted by EEIG "Heat Mining". In the early phases of the project, several hydraulic stimulation tests were carried out at increasing depths and in 1997 a sustained circulation test between boreholes GPK1 and GPK2 (Figure 1) demonstrated the viability of this heat mining technique.

At the project site the granite is overlain by around 1500 m of oil bearing sediments of the Pechelbronn oilfield. The current phase requires the drilling of two additional wells of 5000 m depth into the crystalline basement to form a three well system consisting of a central injector and two producers. A pilot electricity generation plant will draw heat from the triplet of wells.

The first well, GPK-2, which will be a producer well, was deepened in 1999 to 5000 m at which depth a temperature of 200°C was encountered. GPK2 was stimulated in 2000 to gain an understanding of the deep granite's stress and lithological state at the projected depth of the proposed pilot plant.

The second deep well, GPK-3 (an injector), was targeted using microseismic and other data and drilled in 2002 to a depth of 5091 m and bottom hole temperature of 200.6 ºC. The bottom hole separation of GPK2/3 is around 650 m. GPK3 was stimulated in 2003 to enhance the permeability between the wells.

A number of stimulation techniques were tried including a novel method of injecting simultaneously in two wells. Microseismic monitoring, flow logging and other diagnostic methods were conducted during these injections. The second production well, GPK4, was again targeted using microseismic data and was drilled in 2003/4, completing the HDR triplet at Soultz.

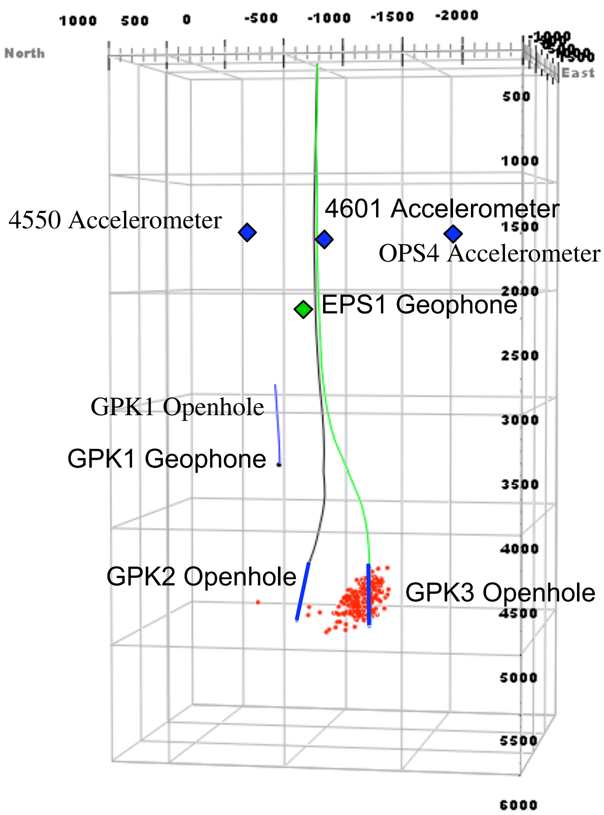

Figure 1. Perspective view of the seismic network. The initial stimulation events between 16:20 and 24:00 27/5/03 are indicated by the red dots.

Hydraulic Stimulation of GPK3 in May/June 2003

Two specific stimulation methods were performed, a single well injection and a dual well injection (focussed injection). Microseismic, hydraulic and production logging data were used to track the development and the growth of the reservoir. More than 90,000 micro-earthquakes were triggered during the injections and around 9,000 of these events were automatically timed and located in real time.

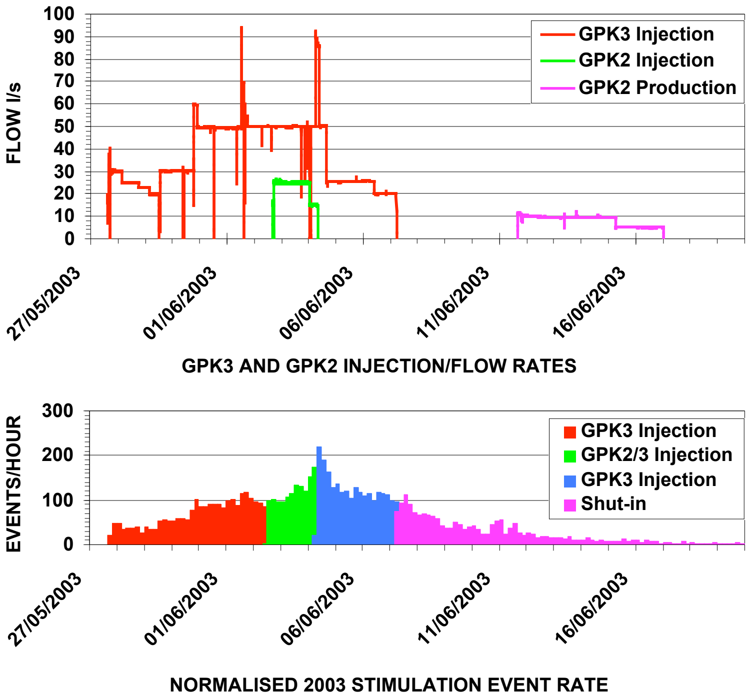

Figure 2. Seismic event rate and corresponding injection and production flow rates in GPK2 and GPK3. NB. These data have been normalised to a higher event detection threshold level used in 2000.

The stimulation commenced on 27th June with the injection of heavy brine with a density of 1.15 kg/l at an injection rate of 30 l/s (Figure 2). When the supply of brine was exhausted the stimulation continued with cold fresh water. The purpose of the brine was to preferentially stimulate the deeper and so hottest part of the openhole. This practice had appeared to be successful previously in stimulating GPK2. The injection rate was increased to 50 l/s on 30th June with two short periods at up to 90 l/s.

A simultaneous injection of 3300 m^3 into GPK2 commenced on 2nd June and finished on 4th June. From this point the injection into GPK3 was reduced in steps (Figure 2).

The decision to perform the secondary injection into GPK2 and the overall control of the hydraulic programme was to a large extent based on an interpretation of the microseismic events.

Microseismic System

The seismic activity generated during the stimulation was monitored continuously using a dedicated system based on subsurface sensors and also a surface seismometer network operated by L'Ecole De Physique Du Globe at the University of Strasbourg. The results presented here are from the subsurface network operated by the EEIG. The sparse subsurface network consists of three, 4 component accelerometers located at depths of around 1500 m in the observation wells 4550, 4601 and OPS4 (Figure 1) at bottom hole temperatures of 130 ºC and two, 3 component geophones (Calidus) deployed in boreholes EPS1 and GPK1.

The seismic data from the monitoring wells were continuously transmitted by a combination of landline and radio telemetry, to a 48 channel, 22 bit data, data acquisition system (Perseids; IFP). The data acquisition was set up in conjunction with proprietary software (DIVINE; Semore Seismic) to carry out automatic timing and event location. During the stimulation the event rate was typically around 250 events/hour and the peak rate was just in excess of 500 events/hour or one event every seven seconds.

The seismic trace data were continuously transferred from the data acquisition system to the processing software to obtain real time event locations. Around 9,000 events were located in this way. The event locations could be viewed in the hydraulic control room and at other sites remote from the acquisition room over the network. This was the first time at this site that large numbers of seismic event locations were available in real time providing the possibility of real time decision making which was vital to the stimulation strategy and control of the reservoir.

Preliminary Interpretation

The stimulation proceeded in four phases, GPK3 injection, GPK2 and GPK3 dual injection, GPK2 shut-in/GPK3 flow reduction and GPK2/3 shut-in followed by GPK2 venting. The distribution of seismicity is quite distinct in each of these phases and clearly illustrates the response of the reservoir to the respective hydraulic processes. The seismicity of each successive phase is shown in Figure 3. The overall growth of the seismicity is NNW (Figure 4), which is consistent with the regional stress field and previous experience. The E-W dimension of the seismicity (Figure 4) is 600 to 1000 m.

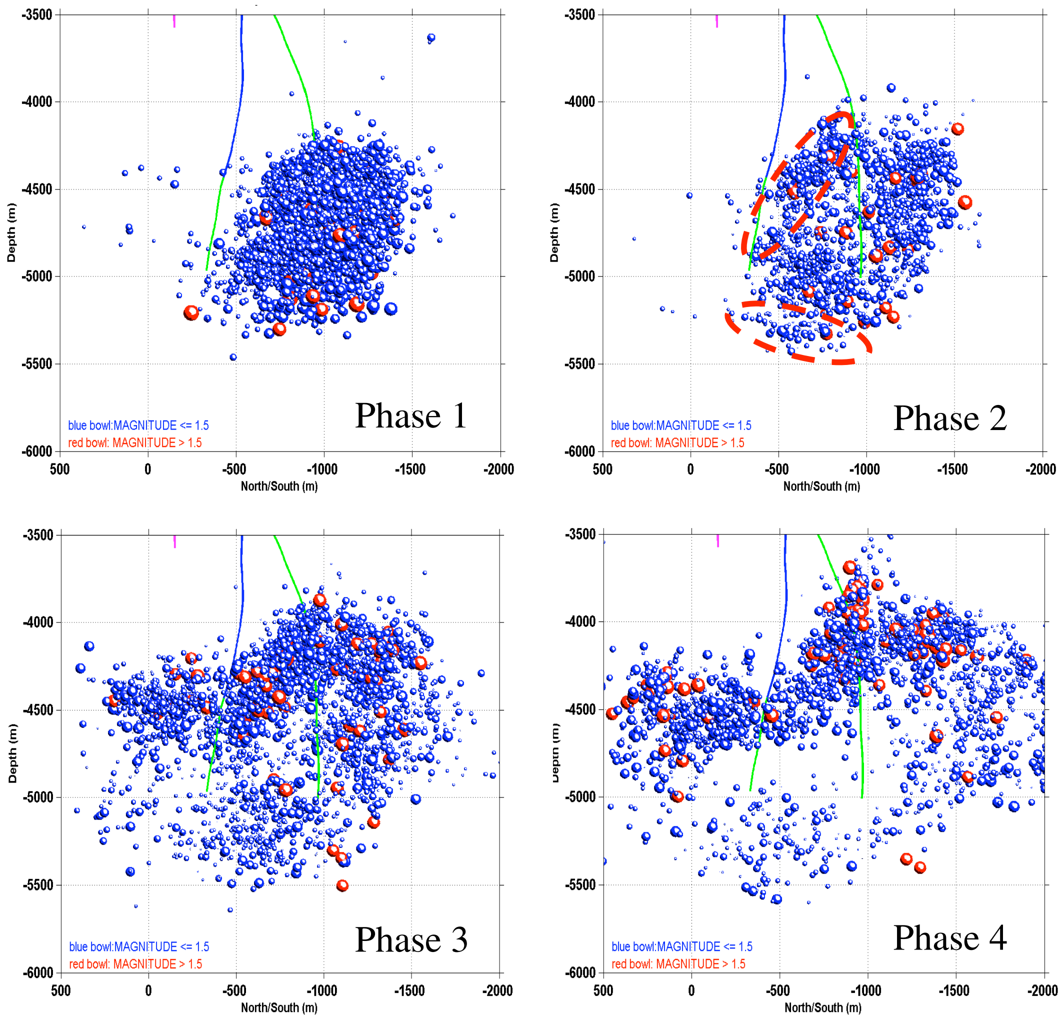

Figure 3. Vertical North to South sections through the seismic event distributions during the GPK3 stimulation phases. The dashed red line in Phase 2 denotes the active regions coinciding with the GPK2/3 dual injection.

The onset of seismicity occurred at 2.64 MPa overpressure. This was similar to the overpressure at the onset of seismicity observed in 2000 and suggests that the state of stress is close to critical. The seismicity at the start of the GPK3 injection (Figure 1) was located around the main flowing zone at 4760 m detected on the flow log. The events developed towards GPK2 in a downwards direction. Subsequently, events also developed from the upper flowing zone at 4570 m. 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.

In an effort to stimulate the region south of GPK2 it was decided to inject simultaneously into GPK2 and GPK3. This process is referred to as a dual well, focussed injection. The technique was expected to increase the pressure between the wells and so enhance the stimulation effect.

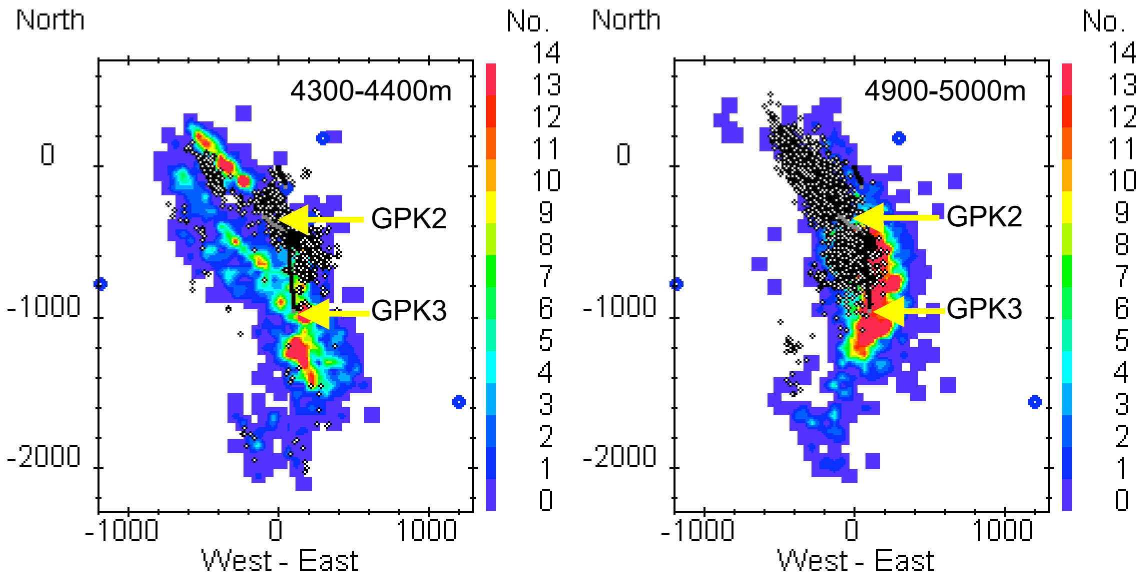

Figure 4. Seismic event density within a 50m grid on horizontal sections 100m thick. Events located during the GPK2 stimulation in 2000 are superimposed as black circles. Borehole casings are shown in black and the openholes in grey. The seismic sensors are shown as blue circles.

The event distribution due to the relatively short dual well injection developed rapidly towards the north, particularly in the upper part of the reservoir. A deep region of seismicity also developed. These new regions of seismicity are indicated by the red dash ellipses in Figure 3, Phase 2. 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 un-stimulated parts of the reservoir as would be expected.

The focussed injection appears to have been significantly more effective than a single well stimulation. After 6 days of single well injection the progress of the stimulation had become very slow. Following the focussed injection, the stimulated region expanded again encompassing the region stimulated by the injection into GPK2 in 2000. The method has the potential to enable stimulations to be performed over much greater borehole separations, perhaps more than 1000 m, which would increase the reservoir volume and improve the economic potential of HDR geothermal.

In the third phase of the stimulation, GPK2 was shut-in and the injection into GPK3 was progressively reduced. None the less, the event distribution demonstrates that the reservoir continued to develop to the north, predominantly at the top of the reservoir. There is also a distinct zone of seismicity beneath GPK2 and GPK3 suggesting a deep flowing zone has been stimulated. In the fourth phase, when GPK3 was also shut-in, the events are concentrated at the top of the reservoir. This is thought to be due to a thermal effect as the cold injection water heats up and rises within the reservoir.

A very important observation in the fourth phase was 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 which 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 to be able to improve this value with cleaning operations and the stimulation of the new well GPK4.

To illustrate the event distribution with depth the event density has been calculated using a grid 50 x 50 m horizontally and 100 m in depth and is shown for two depth intervals in Figure 4. The 2003 event density is shown by the contoured values and the 2000 event locations within the same depth interval are plotted as black circles to distinguish them.

At the tops of the GPK2 and GPK3 openholes narrow NNW-SSE lineaments can be seen in both the contoured data (2003) and the 2000 data (open circles), depth range 4300-4400 m. Between the openhole regions of GPK2 and GPK3 there is an increasingly strong overall North-South alignment in the 2000 and 2003 events with depth towards the bottoms of the wells represented by the 4900-5000 m interval. However, within this overall N-S alignment, underlying NNW-SSE trends are apparent. To the south and north of the interwell region as well as above and below the openholes, the NNW-SSE alignments are prevalent. This suggests that the higher hydraulic pressure between the deeper parts of the openholes is influencing the overall direction of the stimulation in that region. Microseismic monitoring has enabled these two distinct directions of reservoir growth to be imaged.

Conclusions

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 at Soultz. Detection of the possibility of breaking through into the shallower reservoirs and the economic and practical incentive to minimise the stimulation programme indicate that real time processing has significantly increased the utility and value of microseismic monitoring.

The successful extension of the reservoir to encompass the previously stimulated region around GPK2 created a total reservoir volume in excess of 3 km^3. It also unambiguously demonstrated that GPK3 had been targeted successfully. The process of targeting GPK3 was based on the interpretation of the seismicity generated during the stimulation of GPK2. The same process was followed to target GPK4, which has an openhole section approximately 600 m south of the GPK3 openhole, using the microseismic data from the GPK3 stimulation.

The deep connection indicated by the event distribution below GPK2 and GPK3 and the isolation of the whole stimulated region from shallower reservoirs are very encouraging with respect to the potential of the geothermal resource being developed for the pilot plant. 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.

The dual well, focussed, stimulation technique appears to have been very effective in reducing the time and water volume required to complete the stimulation. It is also possible that in the future the focussed stimulation technique may allow greater control of the growth of the reservoir and borehole separations of >1000 m could be possible. These factors would help improve the economic viability and acceptance of HDR geothermal systems.

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