RECENT DEVELOPMENTS IN THE EUROPEAN HDR RESEARCH PROGRAMME AT SOULTZ-SOUS-FORETS (FRANCE)

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ABSTRACT

The site at Soultz-sous-Forêts (France) has been selected as the future European HDR research site (Garnish et al., 1994). An extensive testing programme using a single well has been carried out since 1987 to characterise the rock mass at depth to 3590 m.

The hydraulic tests, carried out in 1993-1994 show the potential of this site for a future European Scientific Prototype. In particular, they have shown that, in this part of the Rhine Graben, the fracture network in the basement is well-developed, with a degree of permeability. While some fluid movement occurs naturally, hydraulic simulation has been shown to increase substantially the overall transmissivity. The site should therefore be suitable for testing the modified, step-by-step concept of HDR which has developed in recent years. The geological setting also offers other advantages, in terms of enhanced temperatures and relatively low stimulation pressures, a characteristic that may simplify the task of developing a circulation system.

A further deep well will be drilled late in 1994, with the aim of developing circulation between the wells during the first parr of 1995.

1. INTRODUCTION

The European HDR project started in 1987 and was funded by France, Germany and the CEC. United Kingdom participated in the various aspect during 1989 - 1991 and joined the project in 1992.

The project is administered and co-ordinated by a core team of three senior staff (British, French. German) who are based permanently on site and provide a link between the funding agencies and the research organisations (Garnish et al., 1994).

The research site is situated at Soultz-sous-Forêts (France) on the Western edge of the Khine Graben, about 50 km North of Strasbourg (Fig. 1). The site is in the former Pechelbronn oil fields and was selected because of the high heat flow anomaly observed from a large number of oil wells. This anomaly is tightly confined and suggests the existence of deep convection.

During the initial phase (1987 - 1989), a well (GPK1) was drilled to 2000 m depth in order to penetrate the crystalline basement at 1377 m depth and obtain basic data. The bottom hole temperature was 140.3°C. The temperature gradient and the heat flow values are high (10.5°C/100 m ; 176 mW/m^2) in the sedimentary cover and quasi normal in the granite basement (2.8°C/100 m; 82 mW/m^2). A number of geophysical measurements were carried out to assess the rock mass conditions at 2000 m depth (Bresee, 1992).

During 1989 - 1991, an attempt was made to drill a continuous cored well to 3500 m using an old oil well (EPS1) located about 400 m SSE of GPK1. The coring started at about 900 m and it proved to be difficult to control the deviation. The well was terminated at the depth of 2280 m. The continuous coring nevertheless gave very useful information on the joint network and the mineralogy in the joints and provided the basis for the interpretation of cuttings and geophysical logs.

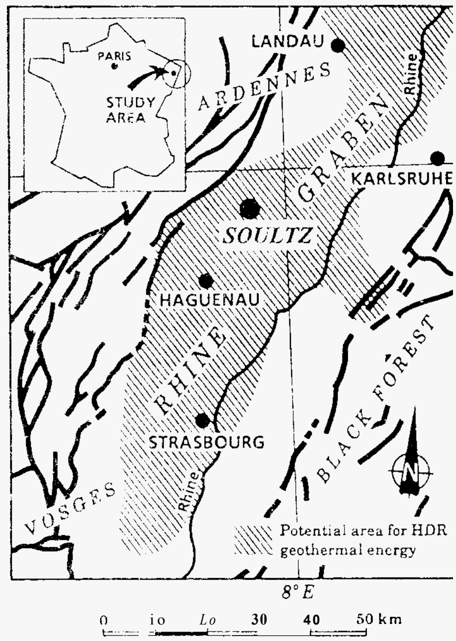

Figure 1 Location map of the Soultz-sous-Forêts site (France)

During 1992 - 1993 the existing well GPK1 was extended from 2000 m to 3590 m depth. Geophysical and other scientific measurements were carried out during and after drilling. Following the drilling of the well, large scale hydraulic tests were carried out to characterise the rock mass. Supporting activities during the injections included microseismic monitoring, production logging, fluid sampling, etc (Baria et al.,1993).

During 1993 - 1995 the existing well GPK1 was put on production (June / July 1994) to assess the productivity and the injection properties of GPK1 following the massive injections in 1993. The existing information available (stress, joints, thermal modes and seismicity) will be used to target the second deep well to around 3600 - 4300 m, depending on the available funds.

2. SITE CHARACTERISTICS

2.1 Geology

The site is in Khine Graben which is part of the Western European rift system (Villemin, 1986). The rift extends for 300 km between Mainz (central Germany) and Basel (Switzerland). The Soultz granite is part of the same structural rocks which form the crystalline basement in Northern Vosges and intrudes into Devonian - Early Carboniferous rocks.

The geology of the Soultz site and its tectonic settings are described by Cautru, 1987. The pre-Oligocene rocks which form the Graben have slipped down few hundred meters during the formation of the Graben. The Soultz granitic horst (where the site is) has subsided less than the Graben. The Graben is about 320 M years old (Köhler, 1989) and is covered by about 1400 m thick sedimentary layers at the Soultz site.

2.2 Boreholes

Fig. 2 shows the 5 boreholes available at the site which range in depth from 1400 m to 3590 m.

The three boreholes 4601, 4550 and 4616 are old oil wells which have been extended to 1600 m, 1500 m and 1420 m respectively in order to deploy seismic sondes in the basement rock.

In 1990 an old oil well (EPS1) was re-opened and an attempt was made to drill a continuous cored well to 3500 m (Garnish et al., 1994) but the well was terminated at 2850 m as described earlier.

The first purpose-drilled well (GPK1) was extended from 2000 m to 3590 m in 1993. The well has a 7" casing set at 2850 m depth (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 and 1994.

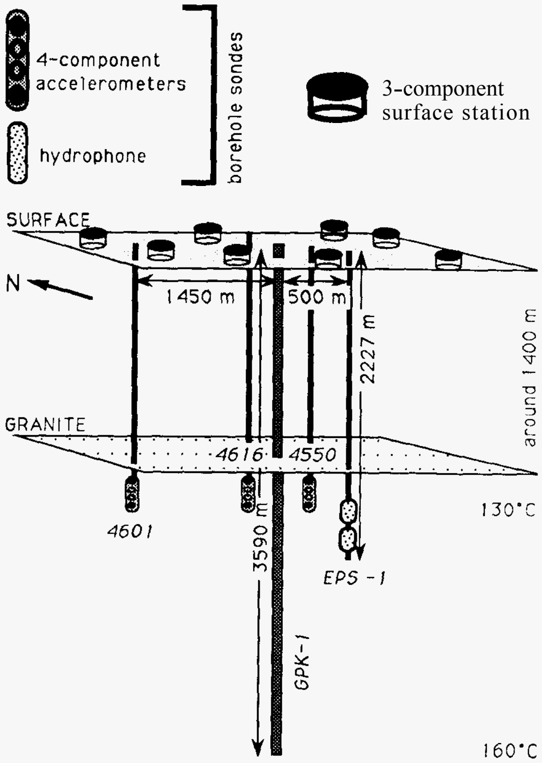

Figure 2 The borehole & seismic network ut Soultz

2.3 Temperature gradient

The temperature field in the Soultz area has been determined using numerous measurements in boreholes located on site (4601, 4616, 4550, EPS1 and GPK1) and away from the site (old oil wells). The variation in temperature gradient (Fig. **3**) can be roughly described as **10.5°C/100** m for the first 900 m, reducing in temperature gradient to 0.1°C/100 m **up** to 2350 m (Schellschmidt & Schultz, 1991) then increasing to **3°C/100** m to 3600 m depth.

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 gradient and the increase again suggests that there are convective cells present which may extend to greater depth (Baria et al., 1994). Thermal modelling and the available data (geochemical and hydraulics) support the view that convective cells exist in this granite (Rhine Graben).

2.4 Joint network

The information on the joint network has been obtained from the 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 (Fig. 4) striking N10 E and **N170 E** 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 higher variations in joint c

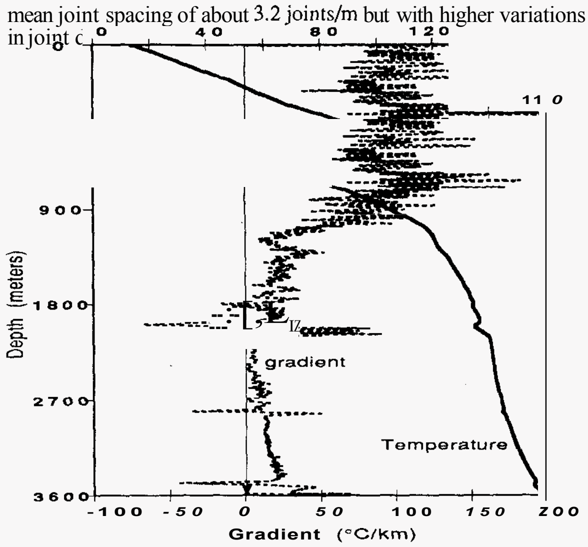

Figure 3 Equilibrium temperature profile in GPK1

Within the joint network, a number of hydrothermalised zones were also observed. Three of these zones caused drilling fluid losses during the drilling operation and are of significance as they indicated a degree of permeability at the wellbore. These were identified at around 2815 m, 3386 m and 3485 m depth in GPK1 (Baria et al., 1994). These can also be observed as anomalies on the DSI Stoneley wave, **VSP** tube wave surveys and on C02 & Ne monitoring during the drilling.

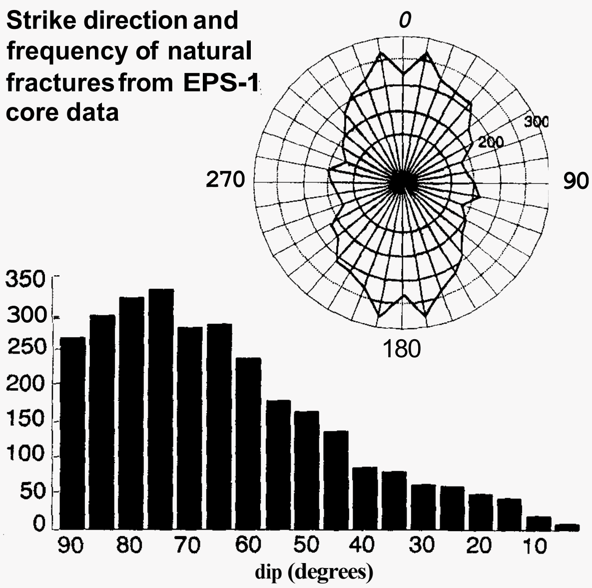

Figure 4 Strike and dip of natural fractures in EPS1

2.5 Stress regime

The stress regime at Soultz was obtained using hydrofracture stress measurement method (Klee and Rummel, 1993) *(see* Fig. 5). The stress magnitude at Soultz as a function of depth (for 1458-3506 m depth) can be summarised as:

S_h = 15.8 + 0.0149 . (Z - 1458) least horizontal stress
S_H = 23.7 + 0.0336 . (Z - 1458) max. horizontal stress
S_v = 33.8 + 0.0255 . (Z - 1377) overburden

It would appear that S_H **is** very close to Sv at around 3000 m depth ; Sh is very low and closer to the hydrostatic pressure which would suggest that it would be relatively easy to inject fluid into the crystalline rock.

The direction of S_H was assessed from borehole images such **as** FMS/FMI and BHTV. These measurements indicate that between 2000 m and 3315 m depth the direction of S_H is about

N170°E but at 3506 m depth (the bottom hydrofracture test position), the direction rotates to **E-W.** It is proposed that this rotation may be a local effect caused by a sub-vertical fault in the vicinity of the well.

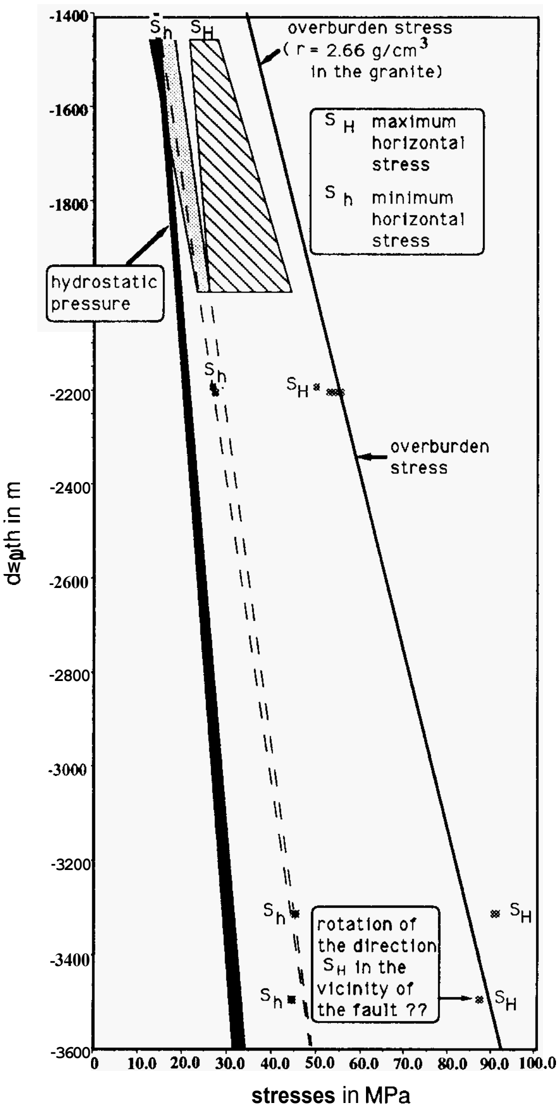

Figure 5 *The stress regime at Soultz*

2.6 Geochemistry

Geochemical monitoring of drilling fluid (Aquilina et al., 1993) was successfully applied to detect water bearing / relatively permeable zones within the well GPK1 down to 3500 m depth (Pauwels et al., 1991; Benderitter and Elsass, 1992). The in-situ fluid is saline with a salinity of about 100g/l.

SiO_2 was also tried as a geothermometer to estimate the temperature of the in-situ fluid. The sample of in-situ fluid extracted at 1815 m depth shows the temperature of 137°C from dissolved silica, which agrees with in-situ temperature data. Temperature estimated from cation and isotopic geothermometers range between 177°C and 236°C suggesting that the fluids were at high temperature before sampling and had no time to reach equilibrium with rock at the measured temperature (except for silica).

One of the main observation was the similarity in the chemistry of fluids from the sedimentary cover and the deep granite. This supports the view that the fluid has common origin and that there are convections in the granite.

2.7 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 sondes (4 equally oriented in space), a hydrophone string and a Venturon (very fast) seismic data acquisition and processing system. These sondes were cemented at the bottom of old oil wells (4616,4550, 4601). The hydrophone string was deployed in EPS1. The seismic network was calibrated using 2 explosive shots at depth in GPK1.

In addition, a surface network consisting of eight (3 components) stations was installed in order to be able to characterise larger events.

3. HYDRAULIC TESTING IN 1993

During the period between 1989 to 1992 the wells GPK1 and EPS1 have been subjected to hydraulic testing but this hydraulic characterisation of the rock mass was limited to a depth around 2200 m. Following the completion of the GPK1 well to 3590 m depth, various production and injection tests were carried out to characterise the hydraulic behaviour of the injected fluid in a Graben setting.

The 1993 programme of hydraulic testing started in May 1993 and lasted until the end of October 1993 (Baria et al., 1994 ; Jung, 1994a).

The initial tests consisted of putting GPK1 on production after the completion of the well. This was carried out by pumping 41 m^3 of fresh water into GPK1, letting the re-injected water warm up and then venting. The well started flowing initially at 1.5 l/s but settled to about 0.03 l/s. To accelerate the process, a downhole elecmc pump was deployed at 157 m depth. The production rate was 2 l/s initially but then settled to 0.5 l/s. A total of 525 m^3 of water was produced during the test. Geochemical analysis showed that the fluid recovered was similar in composition to that found in the upper part of the granite and the sedimentary cover.

Additional pressure build-up test (with artesian flow 0.11 l/s) showed the determination of a large fracture zone at 3485 m depth with a larger storage coefficient of 17 m^3/MPa, a specific yield *(C)* of 0.7 l/s per MPa, an apparent transmissivity (T) of about 0.2 Dm and apparent permeability (K) of 300 µD.

The second test consisted of isolating the bottom hole section with a packer and initiating fractures in the competent rock. The injection started at 1.6 l/s and then increased in steps to 6 l/s. At this point there was hydraulic communication between the open hole and the section being tested. The test was abandoned after injecting 100 m^3 of fresh water. The hydraulic data did not indicate any new fracture growth (tensile failure) but fluid migration took place by shearing an existing joint, as evidenced by the onset of microseismic events at a wellhead pressure of 6 MPa. These events were located very close to the well and below the packer.

The third test consisted of isolating the main permeable zone at 3485 m by sanding off the bottom of the well to 3400 m and injecting in steps up to 36 l/s in the open hole section between 2850 m and 3400 m. During this test around 25,300 m^3 of fresh water was injected in 12 injection steps at flow rates between 0.15 l/s and 36 l/s (Fig. 6). This was followed by a day of shut-in and two days of venting. A total of 1,200 m^3 of fluid was vented. The values obtained for injectivity, apparent transmissivity and permeability (assuming radial flow) for the 550 m open hole were C = 0.05 l/s per **MPa,** T = 0.014 Dm and K = 2 µD respectively.

Production logs were carried out during this test to assess the changes in the flow distribution in the well. The spinner log (Fig. 7) shows a number of outlets from the well which can be grouped together in 4 major intervals: 2850-2900 m, 3090-3100 m, 3230-3240 m and 3320-3325 m.

The interpretation of the flow suggests that as long as the injection pressure remained less than the minimum principal stress (ie flowrate less than 18 l/s), the percentage contribution of the injected flow in the lower zone (3230-3240 m) increased from **5%** (0.3 l/s) up to 40% (4.8 l/s), while the contribution of upper zones kept decreasing. As the injection pressure approached the minimum principal stress magnitude for upper zone (2850-2900 m), the trend reversed and the percentage contribution of the lower zone decreased from 40% (4.8 l/s) to 25% and the upper zone increased to 65% (23.4 l/s). During venting, 70% of the flow was produced in the upper zone (Nicholls, 1994a & 1994b).

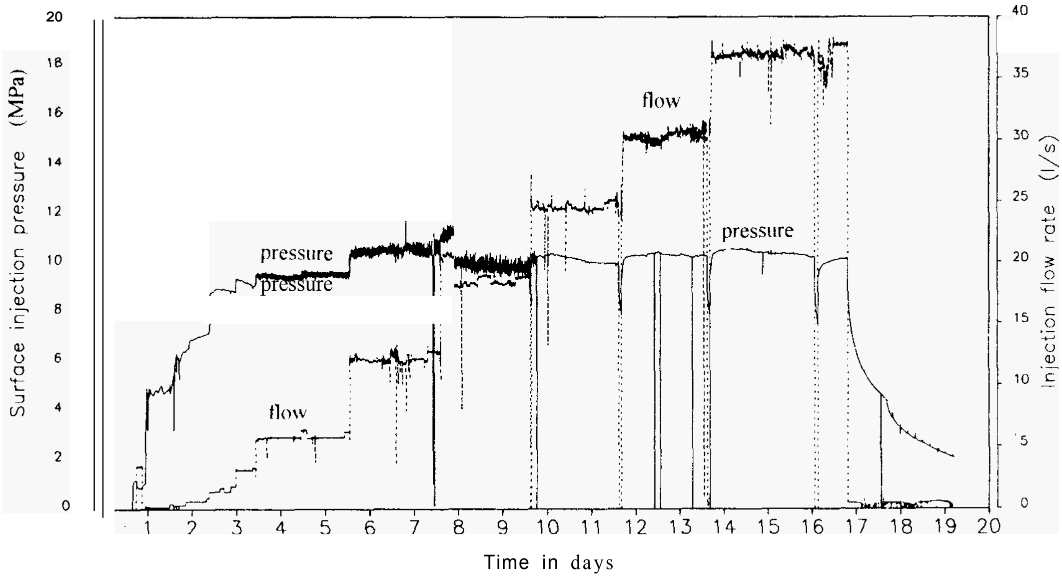

Figure 6 Hydraulic history during the open hole injection (2850-3360m) in GPK1

The above observation indicates that once the flowrate reaches 18 l/s (10 MPa on the surface) pre-existing fractures just below the casing shoe start to be jacked open. This results in near constant injection pressure and a trend for the growth of the reservoir to go upwards.

During the 3 day shut-in period the wellhead pressure declined rapidly indicating that the reservoir created had a high storage capacitance (around 410 m^3/MPa). The subsequent short venting test (1,200 m3) showed that the salinity increased progressively and 12% of the produced fluid was formation water, with silica content of 192 mg/l.

Microseismic monitoring was carried out continuously. The microseismicity started at injection rates of 0.3 l/s (6 MPa) and the location of microseismic events agreed with the injection flow profile in the well.

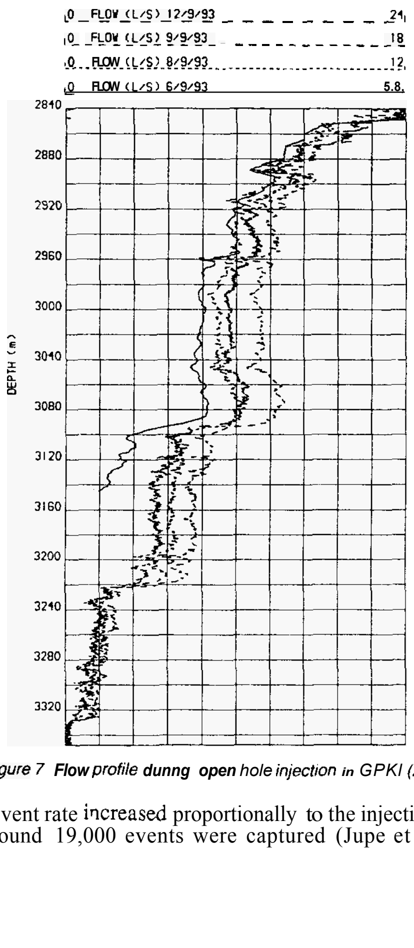

Figure 7 Flow profile dunng open hole injection in GPKI (2850- 3360m)

The event rate increased proportionally to the injection rate; a total of around 19,000 events were captured (Jupe et al., 1994), of which around 8,000 were located during the test. The evolution of the microseismic cluster indicates predominantly **NNW-SSE** growth (Fig. 8), with some tendency to migrate upward. The microseismic cluster encompassed a volume of about 240 x 10^6 m^3 (1000 m high x 800 m long x 300 m wide).

The fourth test was designed to hydraulically stimulate the main permeable zone at 3485 m using two expansion packers. A stepped injection was carried out starting at 3.5 l/s, followed by shut-in. During the next step (6 l/s), the packer failed and the test had to be abandoned. A total of 440 m^3 of fresh water was injected. Microseismic events occurred at a wellhead pressure of 6 MPa, as in the previous tests. About 100 events were detected and these clustered around the interval between the packer and the top of the sand.

The fifth test was carried out to characterise the natural permeable zone at 3485 m and to assess the hydraulic flow response of the whole open hole, including the permeable zone. 40 l/s of fresh water were injected for 4 days (9.5 MPa) and 50 l/s (10 MPa) for 1 day. A total of 19,300 m^3 was injected and 650 m^3 was vented. Flow logs during the injection showed that only 10% of the injected fluid (2,000 m^3) went into the natural permeable zone and over 70% left at the artificially created zone below the casing. Flow logs carried out during the venting test show that about 15% (1.65 l/s) was recovered from the natural permeable zone and the majority was recovered from the zone stimulated artificially.

Altogether about 150 seismic events were detected on the surface network with a maximum magnitude of about 1.9 ML. Data is still being evaluated but the predominant mechanism observed from Fault Plane Solutions is the normal faulting (Helm, 1994).

4. HYDRAULIC TESTING IN 1994

The development of HDR technology in the European context was based on the idea of using a Graben setting (Soultz concept) to overcome some of the difficulty encountered at other HDR sites (Baria, 1990).

A Graben setting was selected because of high temperature encountered at shallower depth, relatively low minimum stress gradient and the likely hood of finding relatively open joints / faults at depth. The massive injection of 1993 had shown that, although the permeability of GPK1 was originally low, this improved significantly after stimulation of the well. The production and injection tests planned for 1994 were essential and designed to evaluate the permanent changes made near the wellbore and the connectivity of the joints near the well to the far field.

4.1 Production tests

The 1994 programme of hydraulic testing started in early June and

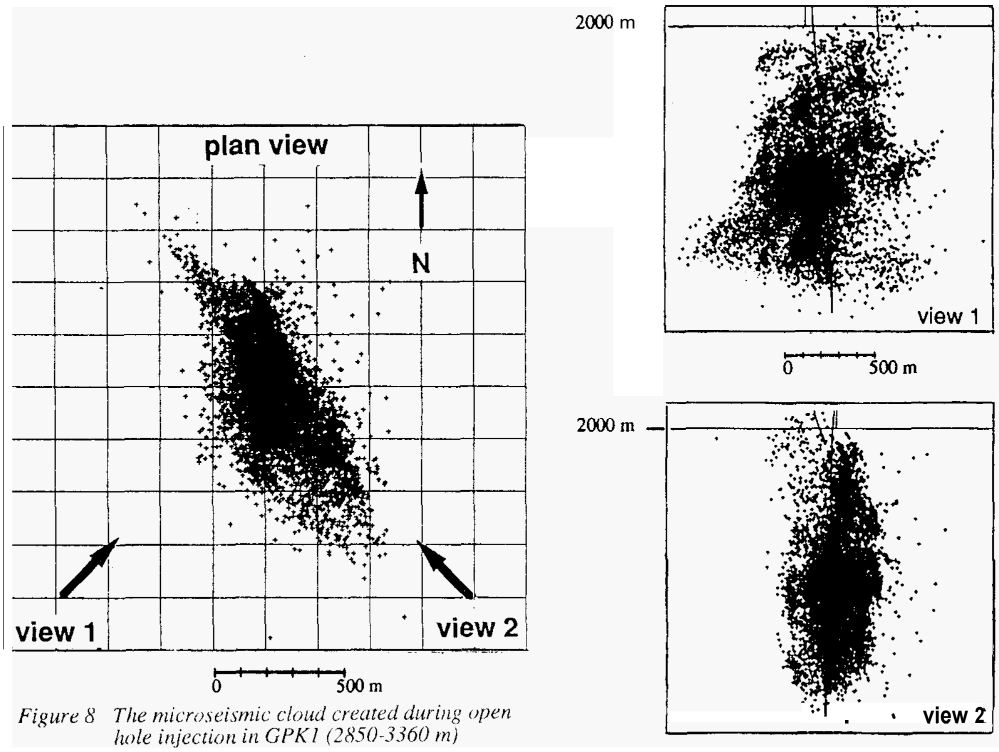

Figure 8 The microseismic cloud created during open hole injection in GPK1 (2850-3360 m)

lasted until the end of July (Gérard et al., 1994 ; Jung, 1994b and 1994c).

The production test consisted of three phases. The first phase consisted of unthrottled production for a day, the second phase consisted of throttled production for 7.5 days and the third phase consisted of unthrottled production for about 2.7 days . The production had to be throttled because problems of disposal of the produced water and concern about injecting more than 5 l/s into EPS1.

The produced hot fluid went through a cyclonic separator, a cooling tank and a heat exchanger before being injected into EPS 1 at around 35°C. Hydraulic, microseismic, geochemistry and production logging data was recorded/sampled almost continuously.

The well was put on production by injecting 110 m^3 of fresh water into GPK1, letting the fresh water warm up for 4 days and then venting the system. A total of 6,200 m^3 of brine was produced during this test with a maximum flow and temperature of 18.5 l/s and 122°C respectively.

The production was maintained by the artesian pressure and buoyancy effect. The analysis of production tests data indicate that long term production under unthrottled conditions would be in the order of 8 to 10 l/s for a buoyancy of 1 MPa. This is supported by the interpretation of pressure build up during shut-in tests. The shut-in test also suggests that the joint network is connected to a constant pressure boundary or at least to a region of much higher transmissivity than inside the joint network near the wellbore.

The density of the production fluid stabilised from the initial value of 1.055 g/cm^3 to 1.06 g/cm^3 after 3 days. This indicates that only about 10-15% of the fresh water is contained in the produced fluid as the density of the in-situ formation fluid is 1.069 g/cm^3. The production of this fluid at 1.06 g/cm^3 is encouraging when considering that around 50,000 m^3 of fresh water was injected into this rock mass only about 8 months ago. This indicates that the joint network **is** connected to a large permeable natural system.

The production flow logs carried out during **5** l/s and 8 l/s show that the majority of produced fluid (70%) came from the artificially stimulated zone in 1993 ie the majority of the flow took place at depth between 2850 and 2960 m with about 10% from the main naturally permeable zone at 3885 m depth. This may have been caused by the poor stimulation of the natural permeable feature.

The seismicity located during this test centered around the bottom of EPS1 (the injection zone) forming a N/S structure with an extension **of** about 200 m from the well (Jones, 1994). The general trend of the events was horizontal.

4.2 Injection tests

The injection tests consisted of the injection of fresh water into the full open hole section of GPK1 at flowrate of 6 l/s (**1.5** days), 12 l/s (3 days) and 18 l/s (3.5 days), with a shut-in test at the end (Fig. 9). A total of 9,600 m^3 of water was injected. Hydraulic, microseismic and production logging data was recorded continuously during this test.

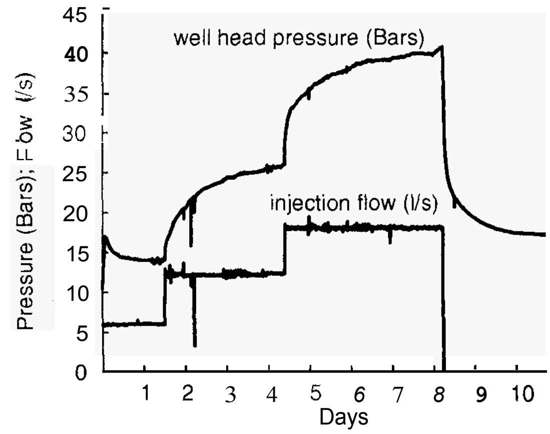

Figure 9 Open hole injection in GPK1

It took several days for the injection pressure to stabilise, except for the first step. This supports the view that the well is connected to a big reservoir. The comparison between the downhole pressures required to inject at 6 l/s, 12 l/s and 18 l/s in 1993 and 1994 are shown in table 1. During the injection test in 1994, 18 l/s can be injected at 3.4 MPa compared to 9.5 MPa in 1993 (see table 1). No seismicity was observed during this test. This suggests that in a graben setting, once the wellbore is adequately stimulated, significant fluid can be injected at very lower pressure.

The downhole flow profile performed for 12 l/s and 18 l/s (Nicholls, 1994c) showed that the majority of the flow (about **75%)** left just below casing through the artificial fracture zone (2850-2960 m) and only about 10% left at 3500 m (the main naturally permeable zone).

Table 1 : Injection pressures for **various** flow rates

Flowrate	**Downhole* overpressure required in 1994**	**Downhole** overpressure required in 1993**
6 l/s	**0.4** MPa	7.6 MPa
12 l/s	1.8 MPa	8.8 MPa
18 l/s	3.4 MPa	9.5 MPa

* measured at 2830 m   ** measured at 2800 m

5. MAIN CONCLUSION

The production and injection tests have just been completed (July 1994) and the data are still being evaluated. Some of the preliminary conclusion are:

a. In a graben setting, where the minimum stress is relatively low (close to the hydrostatic pressure), significant fluid can be injected with a modest well head pressure. In the case Soultz, 30-50 l/s or more could be injected at the well head pressure of 10 MPa. The major flow zone for both injection production, was around 2850-2960 m. This is compatible with the minimum in-situ stress at around 2.9 km depth.

b. After the drilling **of** GPK1 to 3590 m depth, production test showed that less than 0.05 l/s of natural fluid (ie brine of > 100 g/l) can be produced. Following the large scale injection in 1993, the production tests in 1994 show that about 8 l/s can be produced over a very long period. This suggests that the interconnection of the joint network near the well bore (and perhaps further away from the well bore) have been enhanced permanently to allow access to the fluid in the joints. This also indicates that there is likely to be an open joint network (in Rhine Graben) with some fluid movement.

c. **A** significant improvement of the transmissivity was achieved at Soultz by large scale injection. Prior to the injection the transmissivity was 0.2 Dm (dominated by the permeable fault) and during the production test the transmissivity was estimated to be more than around 1 Dm (with minor contribution from the permeable fault).

d. Microseismic monitoring during the injection tests in 1993 detected two main microseismic clusters (structures). The first was associated with the open hole injection with the main fault isolated while the second included the fault. During both tests there was strong correlation between the flow exit points and the intensity of microseismic events. The upper microseismic structure is centred around 2900 m depth with some trend upward and to the north. The lower structure is centred around 3400 m and trends towards the south.

Both microseismic structures are elongated approximately in the NNW-SSE direction with overall horizontal extension of about 800m on either side of the well at depth. Taking into consideration the joint, stress and flow logs during the injection tests, the overall microseismic structure suggests that the majority of the flow in the rock mass at depth **took** place along natural joints (shearing) but strongly influenced by stress regime (S_H direction). This is consistent with observation at other HDR sites.

e. The temperature at 3600 m is less than expected but there is some indication near the bottom of GPK-1 that the temperature gradient is increasing up to around **3.1°C/100m.**

6. 1995 PROGRAMME

The 1995 program will consist of drilling a second well (GPK-2) to between 3600 m and 4300 m, measuring essential in-situ properties, establishing a hydraulic link between GPK1 and GPK2, improving the hydraulic connection between the wells (if necessary) and obtaining the data to plan the scientific prototype in 1996 onwards.

The main objective of the second deep well is to demonstrate a successful circulation loop between GPK1-GPK2 at a depth range between 3300 and 3600 m. Secondary objectives are to assess the in-situ properties at around 4300 m depth ; the depth of a Scientific Prototype (post 1996).

The data from the 1993 and 1994 have been used to target GPK2 at about 400 m South of **GPK1** ; close to EPS1. The main data set used for targeting GPK2 is the microseismic events generated during the high flow rate injection in 1993. Analysis of the microseismic data (Jones et al., 1995) has shown that a number of microseismic structures exists at all depths within the 1993 microseismic cloud. Image processing techniques have been used (Jupe A., 1994)) to enhance these structures associated with the flow exit at 3500 m and below. As the strikes **of** the microseismic structure are approximately **NNW-SSE,** the trajectory of GPK2 has been designed to traverse the deep structure from **SW** to **NE.** To attain this target, the GPK2 will be required to kick off around 2700 m depth with a deviation of between **5°-10° towards NE** direction.

7. THEFUTUKE

The above geological condition in a Graben setting may provide a better opportunity to achieve target parameters set earlier (Garnish et al. 1992) and the concern expressed regarding the "classical" HDR development. The "Soultz Concept" which consists of a well developed natural fracture network with some degree of permeability in a crystalline basement may provide a logical step forward for further development, with a starting point closer to the established conventional geothermal system.

It is proposed that a multi well system (Scientific Prototype) be created post 1996 at the European HDR site in Soultz. This will be managed by an Industrial Group with an aim to develop the technology for an Industrial Prototype to be defined later.

The data obtained to date does indicate that the pervasively jointed rock mass at around 3000 m at Soultz has the potential to be developed into an HDR reservoir. Connectivity of the natural joint network system seems promising, assisted by major permeable zones which may assist the process. The existence of natural brine with modest flow could also assist in compensating for possible fluid losses.

It is recognised that flow losses with a two well system during the 1995 programme will probably always exceed what is desired but this will be addressed in the post 1996 programme with additional wells targeted to optimise the hydraulic impedance, fluid recovery, thermal life of the reservoir and temperature of production fluid. The circulation results at the Hijiori site (Japan) indicate that a multiwell system is very promising (NEDO, 1993).

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