AN ATTEMPT TOWARDS A CONCEPTUAL MODEL DERIVED FROM 1993-1996 HYDRAULIC OPERATIONS AT SOULTZ

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ABSTRACT

The aim of the ongoing research programme at Soultz-sous-Forêts is to understand & define the requirements for heat mining in the specific tectonic conditions of a Graben area.

The recent hydraulic tests have demonstrated the possibilities of developing a very large permeable volume at great depth (around 3000 m) using hydraulic stimulation and then to initiate circulations between wells with large separation (450 m).

A preliminary general conceptual model is proposed. Hydraulic testing of the system developed will be continued in 1997 in order to determine additional parameters for the model of such a large system.

1. INTRODUCTION

The Soultz geothermal HDR research programme is located in the Rhine Graben, 50 km North of Strasbourg, very close to the German Border.

This project is aimed at the development of forced fluid transfers between wells in the deep granitic rocks which are covered by sedimentary rocks with variable thickness (1.4 km at Soultz). It is a heat mining project aiming to recover the heat stored in the rock mass rather than the heat contained in hydrothermal waters.

Even if the characteristics of this site are dominated by a specific and advantageous "Graben tectonic", the expected success will open up a considerable larger geothermal resources in the future leading to a long term continuous development in the exploitation of regional targets. This could expand the present accessible geothermal resources in Europe beyond those which are exceptional and limited to hydrothermal systems.

Activities on site at Soultz started with a preliminary exploration hole in 1987 (2000 m deep) where a bottom hole temperature of 140°C was observed (Schellschmidt & Schulz, 1991). This was interpreted as a result of deep water circulation through a dense fracture network. In order to allow the fluid to migrate, it was considered necessary for some of these fractures to have minor, but non negligible, permeability. This deep water circulation by itself offers a good explanation for the higher temperature gradient observed in the sediments (up to 3 times the normal value) - an

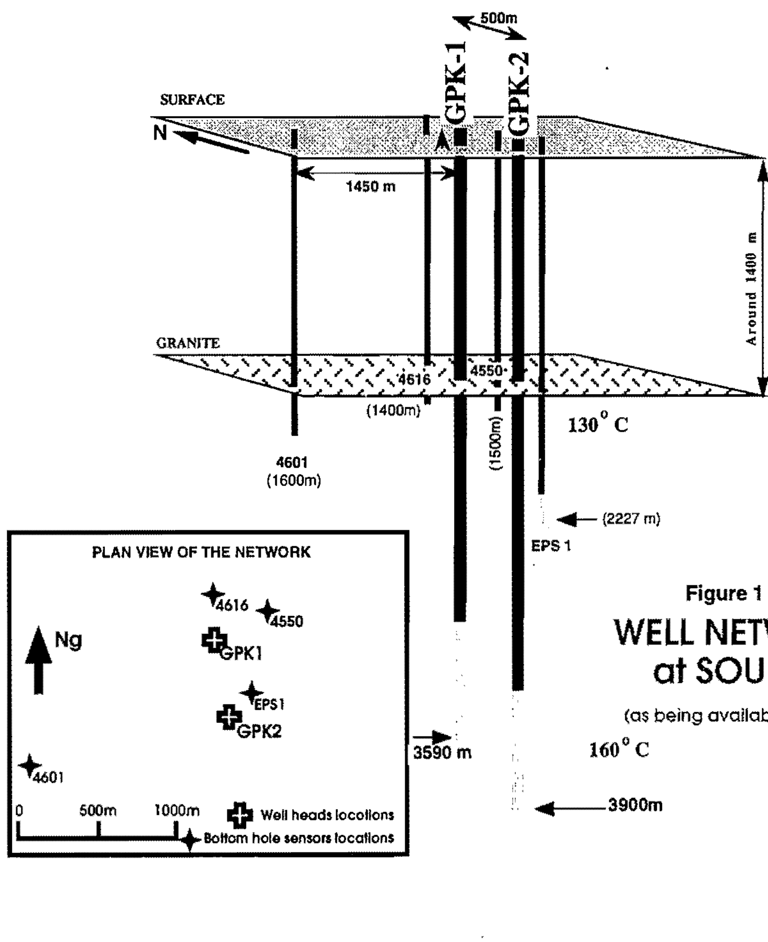


Figure 1
WELL NETWORK at SOULTZ
(as being available 01/03/95)

anomaly which covers an area of about 3000 km^2 in the Rhine Graben, the target for potential future exploitation.

From 1987 to date (Baria et al., 1995), the project has been progressively reinforced in terms of infrastructure on site. In parallel with the step by step enhancement of the network of the wells (figure 1), a series of hydraulic stimulation and circulation tests were performed in order to collect enough data for a preliminary definition of a model. This could then be used as a guide for future experiments leading to a successful scientific pilot plant. This paper makes an attempt to produce such a model that describes or explains the underground behaviour.

2. MAIN DATA USED TO DEFINE THE MODEL

2.1 The stress regime at Soultz

The stress regime at Soultz 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 summarised as:

Least horizontal stress	S_h	$= 15.8 + 0.0149 . (Z - 1458)$
Max. horizontal stress	S_H	$= 23.7 + 0.0336 . (Z - 1458)$
Overburden stress	S_v	$= 33.8 + 0.0255$

The direction of S_H was assessed from borehole images such as FMS/FMI and BHTV. These measurements indicate that between 2000 and 3500 m the direction of S_H is about N170°E.

Extrapolating the above given stress profiles and implementing the fluid density of the brines found in situ shows that even at greater depth fluid injection in favourably oriented joints may be rather easy. It can be expected that the necessary overpressure during injection (downhole) which was found to be in the order of 10-13 Mpa in the depth range investigated so far (2800 - 3600 m, overall these values do agree with the stress measurements) will be in the order of 16-17 Mpa at around 5000 m.

2.2 Geological situation before stimulation

The geological synthesis (Genter et al., 1995) is based on the geophysical logs performed during and immediately after the drilling of the two deep near vertical wells GPK1 and GPK2, and on the cores (Genter and Traineau, 1992a & 1992b) collected in the inclined well EPS1 (figure 1). The well-bore imaging tools (BHTV*, FMI-O+) detected numerous fractures, some of them were drilling induced but most of them were pre-existing natural joints. It would appear that the granite in Soultz contains a very dense fracture network, most of them being subvertical and some embedded in hydrothermalized zones, oriented at N140° to N200°, dipping E or W between 55° and 80°. The vertical nature of the deep wells may cause additional vertical structures not to show up and thus cause some bias against detection of vertical joints.

The natural joints are rather randomly distributed in depth, with a mean frequency of around one per 2 m and a sizeable proportion embedded in "hydrothermalised" granite. The core samples from the hydrothermalised zones show that :

- The rock matrix inside the hydrothermalized zones has a poor mechanical resistance and is rather "porous" compared with the sound granite ;
- most of the joints are plugged by soft and rather porous filling materials i.e. hydrothermal deposits.

Taking into account the fact that for a large proportion the joints are strongly dipping and the sub-vertical inclination of the wells, it would appear that the mean frequency of these joints along an horizontal cross section may be probably higher than 1 /meter.

During various drilling operations (GPK1 + GPK2 + EPS1), a total length of about 5000 m of granite was sampled logged to a maximum depth of 3800 m. The wells inside the granite crossed some 10 "permeable" fracture zones (faults) identified from their drilling mud losses and/or their thermal signatures just after drilling. These "permeable" fracture zones/faults seem in a large proportion dipping around 70-75° (E and W) and oriented grossly N-S.

* Borehole Televiewer (ultrasonic images of the structures in boreholes)
+ Oriented Formaiton Micro-Imager (borehole wall resistivity image)

On an average one "permeable" fracture zone was found each 500 m along the vertical profiles. Considering their sub-vertical dip angle, the mean normal distance between two of these fracture zones can be estimated at 200-250 m. No obvious hydraulic connection between the "permeable" fracture zones in the crystalline and the major faults seen in the sediments could be identified from vibroseis surveys.

It had also been observed that the center of the distribution of the azimuths of the joint network is oriented around 170°N, which is also the orientation of the maximum horizontal component of the stress field.

2.3 Data obtained during hydraulic injection tests

2.3.1 Hydraulic stimulation of GPK1 in 1993.

During the summer of 1993, the open hole of GPK1 (from the casing shoe at 2850 m to the bottom at 3590 m) was stimulated extensively using cold fresh water. During several stimulation phases a total of 45,000 m^3 was injected at a maximum flow rate of about 50 l/s. Microseimic monitoring was carried out during this period which indicated that the overpressure required to shear the most favourable joints (reservoir extension pressure) was around 6 MPa at about 2900 m depth. Microseismic maps produced during these stimulations (figure 2) show a North South expanse of the events which is consistent with the direction of maximum horizontal stress. There was also some upward migration of events (above 2800 m) towards the latter part of the main injection test (figure 2), when the horizontal extent of the stimulation had reached about 400 m on both sides of the well.

Overall, it can be observed in figure 2, that most of the events are more or less symmetrically distributed down and above the casing shoe of GPK1, between 2500 m and 3200 m. This suggests that the maximum impact of the stimulation occurred in this depth range and the centre of the spread is at the casing shoe as expectable if we consider the fact that it is at this depth that the difference between the minimum horizontal stress value and the hydrostatic pressure is minimum. Two additional impact zones appeared deeper at 3200 m and at 3500 m (at large natural fracture zones).

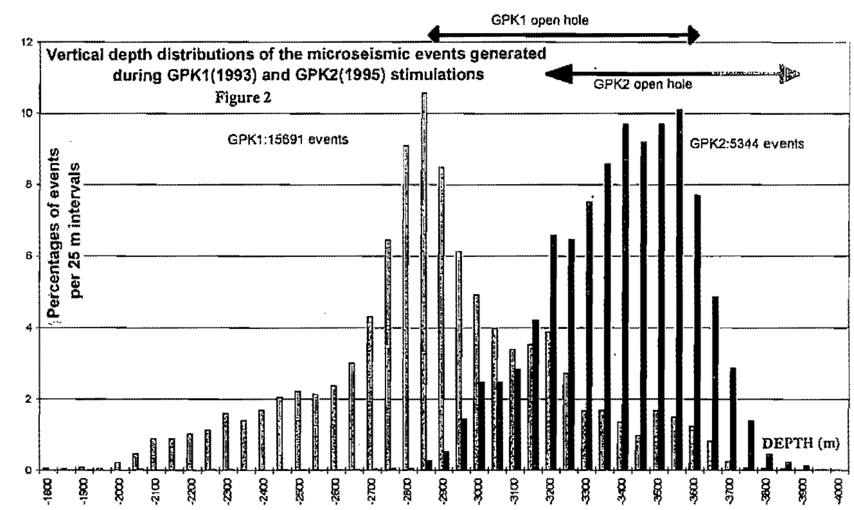


Figure 2

The flow logs carried out during the stimulation of GPK1 showed that the main hydraulic outlet zone was close to the casing shoe (60% within 75 m of the casing shoe). Other significant outlets were observed at around 3.2 and 3.5 km (figure 3), which is in good agreement with the initiation of the microseismicity near the well and the locations of the secondary peaks in the microseismicity depth distribution in figure 2.

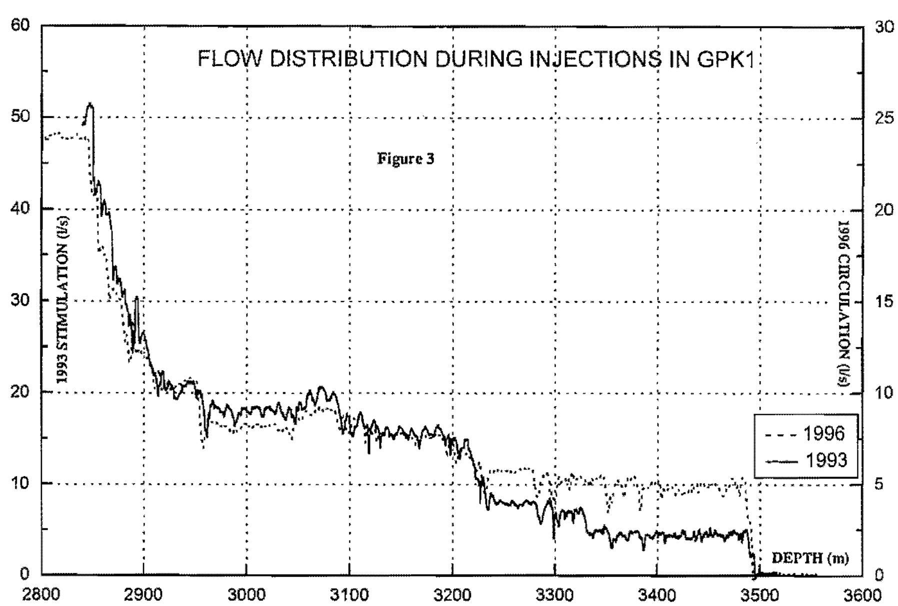


Figure 3

The presence of the major flow exits in the upper part of the openhole section of the well and the progressive upward migration of a part of the microseismic events during the latter stage of stimulation suggests that this was caused by the injection of the fresh water, as the subsequent warming, in a formation full of heavy brine set in a specific tectonic setting.

The density variation could be up to 7% and the Archimedes pressure may contribute to the upward trend for the microseismic events.

Nevertheless, the overall result of the operation was a success from the point of view of the injectivity obtained after stimulation (figure 4). During the main stimulation, around 9 MPa over pressure was necessary to inject 12 l/s. After stimulation less than 2 MPa over pressure was required to inject the same flowrate. For higher flowrates, the injectivity after stimulation improved slightly less i.e. 3.2 MPa was required to inject 18 l/s.

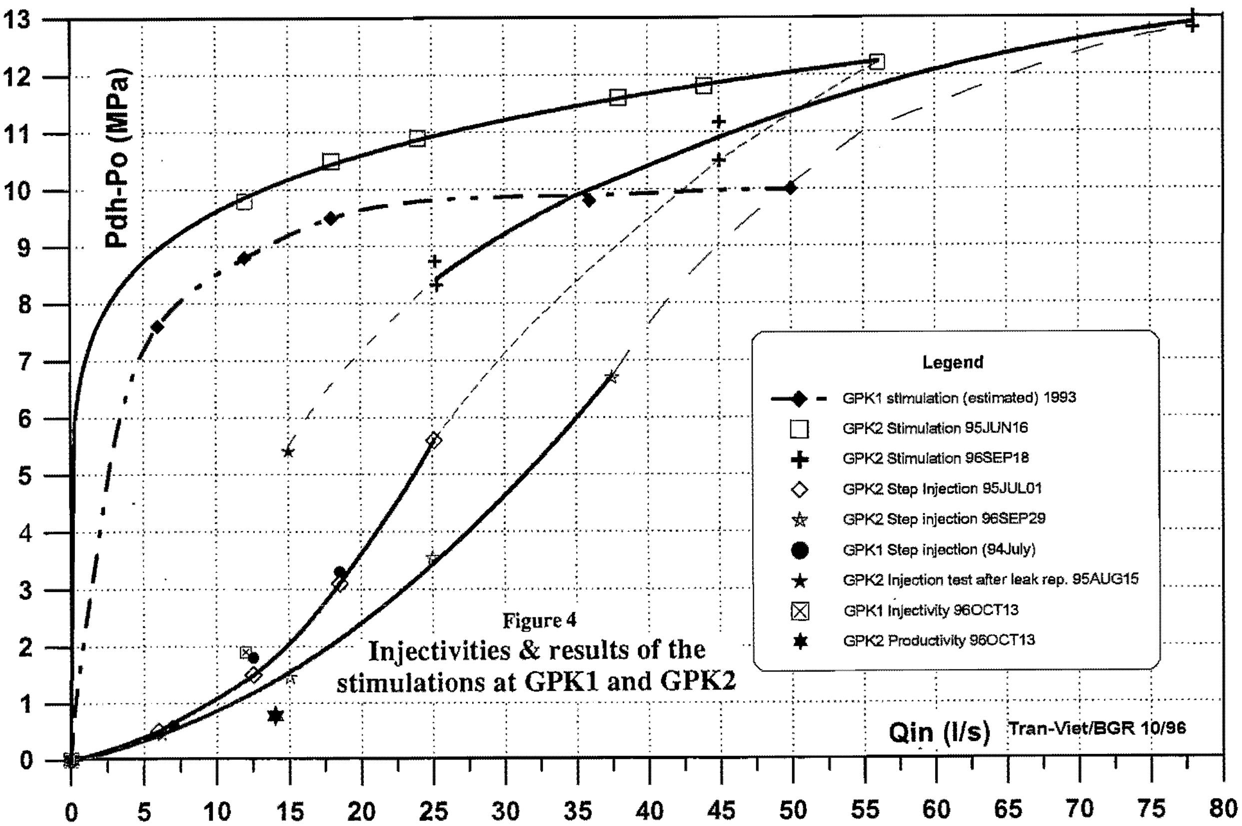


Figure 4
Injectivities & results of the stimulations at GPK1 and GPK2

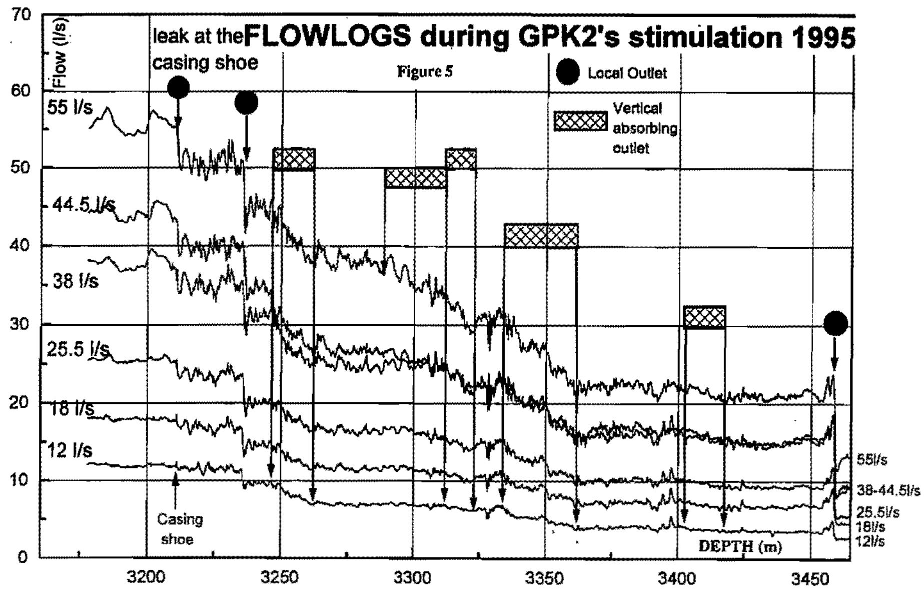
The good correlation between the peaks in the distribution of the density of seismic events and the location of the main water outlets suggests that the microseismic activity (generated by overpressure) is in agreement with the active flow zones (in this case).

Summarising the result of the stimulation of GPK1 in terms of permeability development, it can be stated that the largest improvement of permeability occurred in the vicinity of the casing shoe and, to a lesser degree, at two deeper zones i.e. at 3200 m and 3500 m.

2.3.2 Initial hydraulic stimulation of GPK2 in 1995.

During the summer of 1995, the accessible part of the open hole of GPK2 (from the casing shoe at 3200 m to 3650 m) was stimulated extensively. Following the experience of the large scale stimulation of GPK1, where the lighter injected fluid migrated upwards towards the latter part of the test, it was decided to initiate the stimulation of GPK2 with a slug of cold and heavy brine (300 m^3, d = 1.18) at 30 l/s followed by injection at 12 l/s of stored brine (d = 1.06) produced from GPK1. The operations continued with progressively increasing flow steps (12, 18, 24, 38, 44 & 56 l/s) of fresh water containing a decreasing proportion of brine and consequently a decreasing density for the same temperature. GPK1 was kept on production (~ 12 l/s) up to the 44 l/s injection step. A total of 30,000 m^3 was injected at a maximum flow rate of about 56 l/s. A pressure/flow diagram for this stimulation period is shown in figure 4. The flow distribution is described on figure 5.

Microseismic monitoring (Jones et al, 1995) was carried out during this period (figure 2 ; the 1995 events around GPK2) which showed that the events were roughly distributed to the North and South of the open hole section of GPK2. This is consistent with the direction of the maximum horizontal stress as observed in 1993 in GPK1. Figure 2 shows that the distribution in depth of the microseismic events (unlike the observation in GPK1 where 60% of the fluid left within 75 m below the casing shoe) is not dominated by a single major stimulated zone. The distribution is more widely spread (Nicholls, 1995) (as expected !) along the open hole length and the



main peak is translated downward 300 m under the depth of the casing shoe. The events above 3000 m depth appear as being in a negligible proportion. The seismic map also shows that there is a horizontal trend in the seismic events at around 3500 m depth towards and possibly intersecting GPK1.

The data from microseismic and flow logs indicate that the technique of using heavier fluid (of progressively decreasing density for the same temperature) for stimulation in this tectonic setting gives some possibility of controlling the upward or downward reservoir growth.

The term controlling implies in this context that the colder fluid mixture (cooled in-situ brine) which at the early stage of the stimulation (pre-pad) is heavier than the in-situ hot brine will create a differential density and viscosity barrier (a bubble which will become later a kind of complex shell) between the fluid mixture injected and the in-situ brine.

During the successive phases of the stimulation processes:

- *the average density of the fluid of the external shell will become similar to that of the in-situ hot brine because of the warming. This shell will expand as more fluid is injected.*

- *The decreasing proportion of brine from GPK1 in the stimulation fluid will cause the shell to be filled with a mixture of fresh and saline water in decreasing proportions from the external boundary to the core of the bubble. In parallel, the temperatures will decrease from the boundary to the core of the bubble and consequently the densities of the various fluids inside the bubble will remain rather constant during the major part of the duration of the stimulation. This will retard any tendency for upward migration of the injected fluid mixture caused by the Archimedes principle.*

After stimulation, the fluid contained in the "invaded" volume (the "bubble") will progressively warm up and will become internally progressively homogenised through convection. This mixture will have a progressive tendency to become lighter due to warming inside the shell and in parallel to become heavier at the boundary due to mixing. At the end of the process a general upward percolation will appear as a general trend but it will be strongly smoothed by the described phenomena.

As expected, the pressures required for the stimulation of GPK2 were higher for similar flow rates than those for GPK1 (figure 4). This is due to the greater depth at which the stimulation occurred. Nevertheless, it was observed that the injectivities obtained in GPK2 after stimulation were very similar to the values obtained for GPK1 (figure 4), even though these values from GPK2 may be considered as slightly optimistic as steady state conditions had not reached fully during injectivity testing in 1995.

2.3.3 <u>The second hydraulic stimulation of GPK2 in 1996.</u>

The second stimulation of GPK2 was performed in the summer of 1996. A total of 28,000 m^3 fluid was injected between 3200 m and 3650 m in three flow steps (25, 45 & 78 l/s) with a maximum wellhead pressure of 13 MPa for 78 l/s. One of the main reason for restimulating GPK2 was to be able to return to the injectivity values obtained during the final stimulation of GPK2 in the summer of 1995. The productive joints in this well had been progressively plugged during a circulation test carried out without filtering and exposing the formation fluid to oxygen towards the end of test period in 1995 (testing had to be done with the available equipment on site). The second reason was to evaluate the correlation between the higher flowrate used for stimulation and the value of the resulting injectivity.

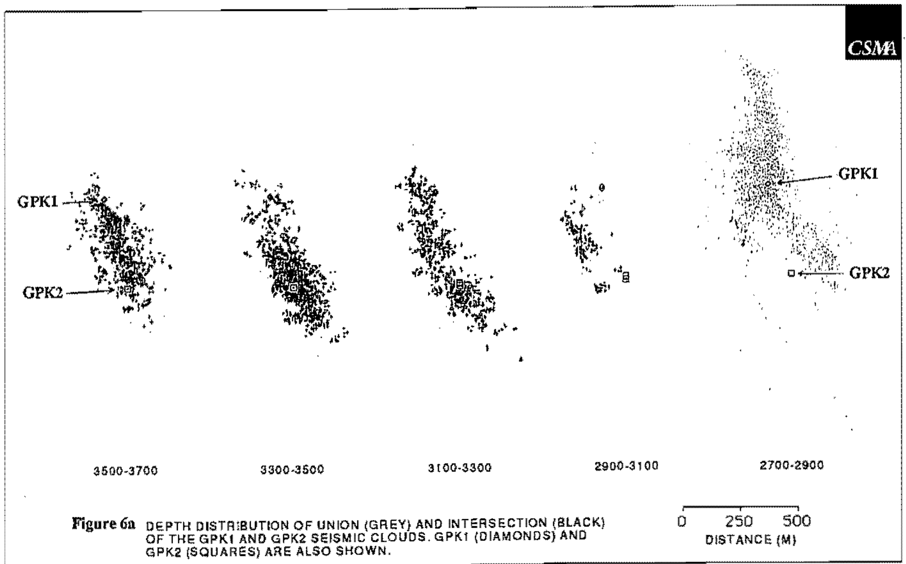


Figure 6a DEPTH DISTRIBUTION OF UNION (GREY) AND INTERSECTION (BLACK) OF THE GPK1 AND GPK2 SEISMIC CLOUDS. GPK1 (DIAMONDS) AND GPK2 (SQUARES) ARE ALSO SHOWN.

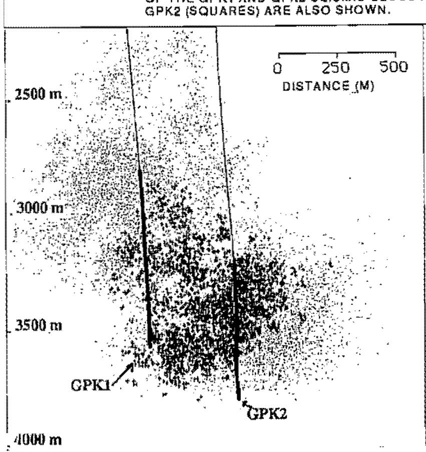


Figure 6b SIDE ELEVATIONS OF THE UNION (GREY) AND INTERSECTION (BLACK) OF THE GPK1 AND GPK2 CLOUDS. VIEWED FROM AN AZIMUTH OF N235E.

Microseismic monitoring and flow logs were also carried out during this operation. There was no microseismic activity during the 24 and 45 l/s injection step. There was intense activity during the 78 l/s injection starting near the wellbore of GPK2 and progressing outwards in the North/ South direction as observed before (figure 6). The overall seismicity can be divided into two groups, one forms a structure connecting a zone near 3500 m in GPK1 with the 3470 m level in GPK2. The second structure starts at around 3350 m in GPK2 with an approximately NW-SE azimuth and dipping towards GPK1. The seismic "cloud" contains a lot of events which are in the same area to those created during the stimulation of GPK1 (see "dark points" on figure 6a and 6b).

The flow logs carried out in GPK2 during the stimulation showed that there was only a minor redistribution in the flow profile. The only noticeable redistribution occurred after the increase from 25 l/s to 45 l/s when the flow leaving 3460 m began to reduce in percentage but the flow below 3560 m increased and accounted finally for around 3-4% of the total flow.

Another important observation was that during the stimulation of GPK2 a cross flow in GPK1 was noticed with GPK1 shut-in. A steadily increasing flow of up to 5 l/s entered GPK1 at 3500 m (4 l/s) and 3300 m (1 l/s) then left higher up in the well between 3200 m and 3000 m (~ 20%) and within 40 m under the casing shoe (~ 80%). In parallel an increase of pressure in GPK1 was noticed. The rate of pressure continued to increase at a constant rate of 0.3 MPa /day and reached 1.5 MPa at the end of the stimulation (values measured at the casing shoe) - see figure 7.

Overall, the strategy followed for stimulation was very similar to that followed in 1995 (except for the high saline fluid used in 1995 for the initiation of the stimulation). Figure 7 summarises most of the hydraulic results obtained.

It would appear that the density/temperature plume progressively deployed in the formation during the early phase of the injection (cold brine from GPK1 initially pure then mixed with cold fresh water in proportions decreasing with time) was again "heavy" enough to sufficiently prevent upward reservoir growth even though up to 13 MPa were required for injection of 78 l/s. This conclusion is supported by the fact that:

- The microseismic observation did not show any significant upward growth, suggesting that there was limited upward pressure migration.

- The pressure increase (figure 7) observed in the annulus of GPK1 and in the peripheral wells (4616 and 4550) was very small and considerably lagging in time with the injection pressure (max. 0,06 MPa/day - delay > 20 hours in the annulus of GPK1 ; 0,002 MPa/day in 4616, 0,001 MPa/day in 4550 - delay > 48 h).

- The water level in the well EPS1, which proved in 1995 to be the most reliable indicator for any injection into the annulus of GPK2 (at that time a failure of the sealing at the casing shoe, has shown a connection to EPS1 via a major fault at 2175 m in GPK2) did only start to rise once the production from GPK1 was stopped and GPK1 was shut-in. It is proposed that this demonstrates again that GPK1, while producing, acts as a drainage valve for- and controls the impacts of GPK2's pressure changes on the pressure in the upper section of the granite. It can also be observed that after stopping of the injection into GPK2 the water level in EPS1 dropped very slowly, over a period of several days, thus indicating that a rather large volume is being drained.

Evidently EPS1 reacts to pressure changes in GPK1 *(at a distance of around 500 m along the maximum horizontal stress direction)* more than in GPK2 *(a distance of around 70 m along a direction orthogonal to the maximum horizontal stress).* No sign of a new or more intense upward fluid / pressure migration could be observed.

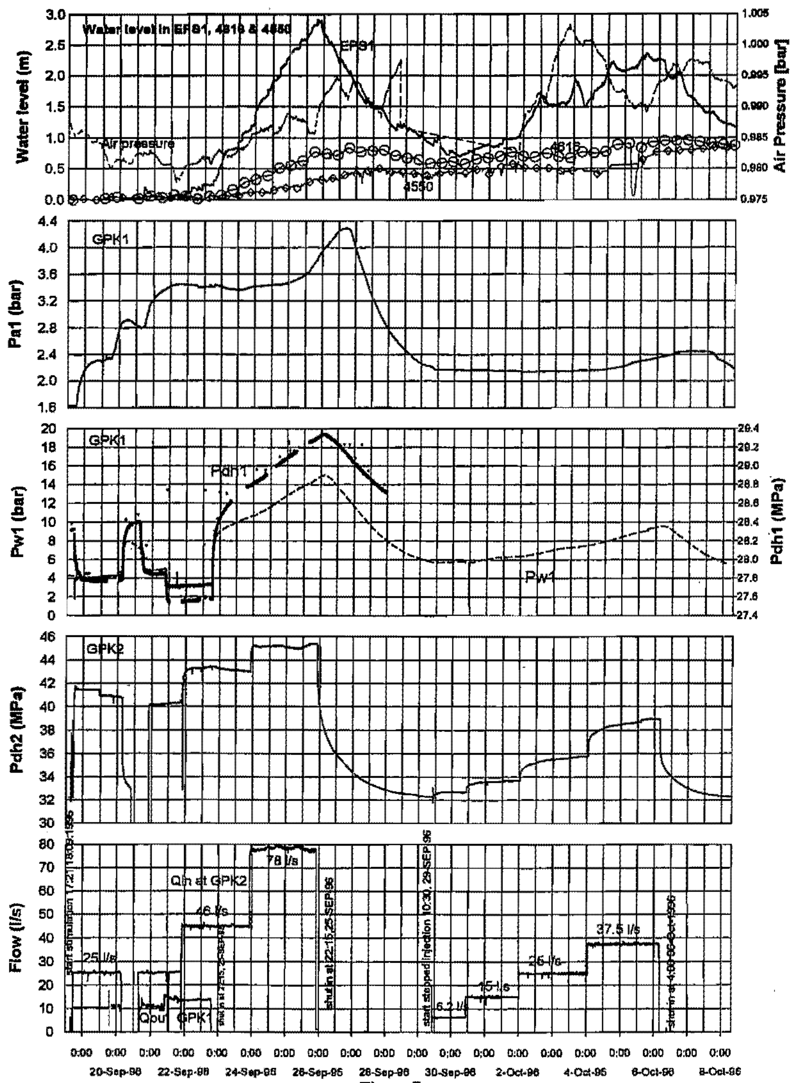


Figure 7

- The flow distribution in GPK2 during the 78 l/s injection in 1996 is very similar to the one observed at 55 l/s in 1995 (figure 5 and figure 8) especially no new outlets in the upper section of the open hole appeared.

  Figure 9 is an attempt to present the obvious and predominant hydraulic / pressure links at great depth at Soultz:

- The first hydraulic link is shown by the fact that the pressure wave generated in GPK2 during the stimulation propagates initially towards the deepest section of GPK1 (> 3200 m). This is confirmed through the inflow observed at 3500 m and 3290 m while GPK1 was shut-in during the stimulation.

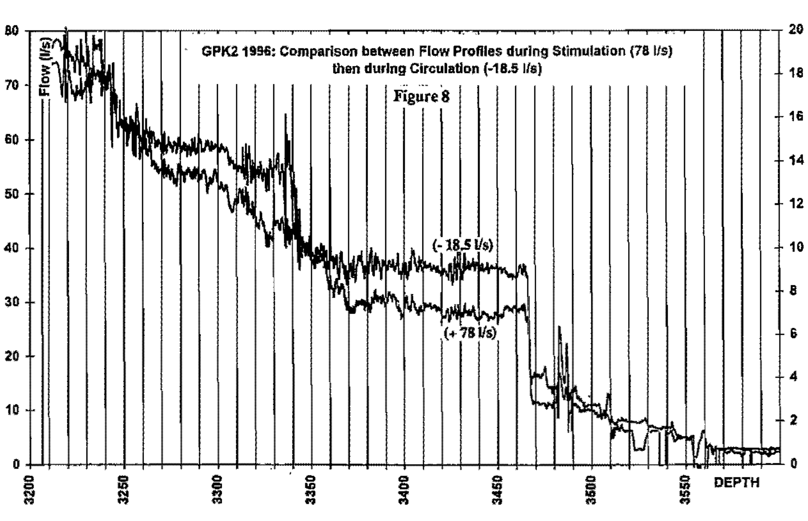
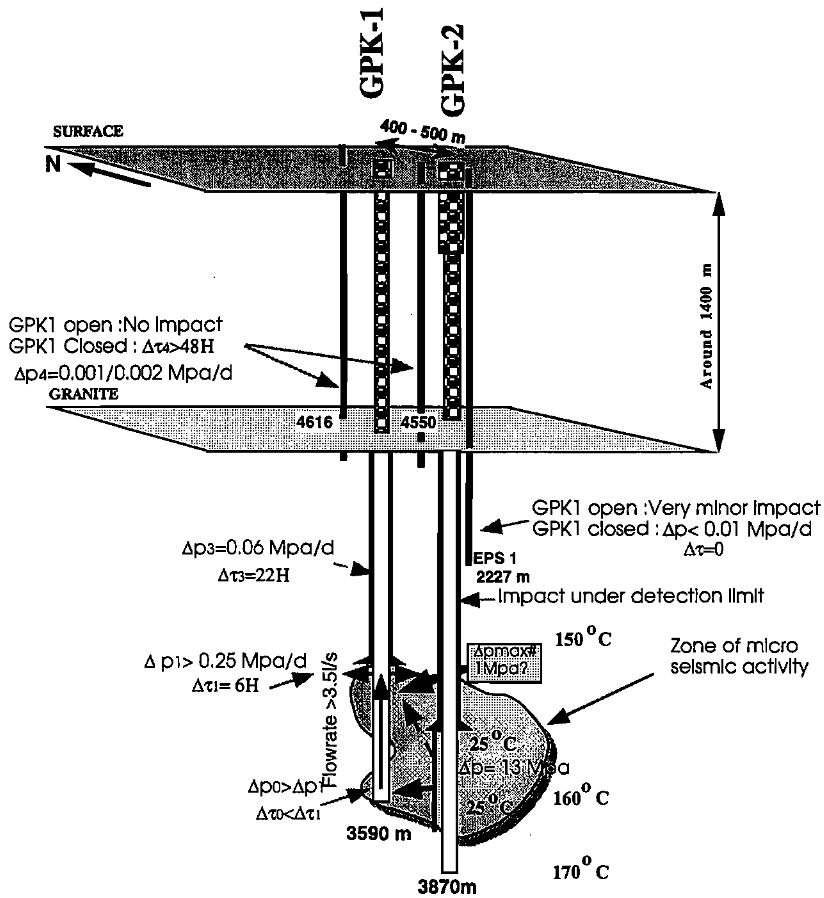


Figure 8

The second hydraulic link can only be explained through indirect observations. The pressure increase observed in GPK1, once it was shut-in, cannot be explained by the inflows of some 5 l/s at 3300 m / 3500 m depth which flows upward in the well feeding the previously stimulated top zones below the casing shoe. It is known from previous hydraulic testing that considerably higher injection rate is required to fill and linearly pressurise the stimulated rock volume around GPK1 at the observed rate of 0.3 MPa/day reaching 1.5 MPa. The steady state injection pressure for 5 l/s had been defined to less than 0.5 MPa in 1995 ! This observation implies the existence



- Pressures situation/evolutions during GPK-2 restimulation - - autumn 1996 -

Figure 9

of a second hydraulic link between GPK1 and GPK2 which connects the zone stimulated at the casing shoe of GPK1 to the deeper open hole section of GPK2. This link was still present (pressure increasing at a constant rate in GPK1) when the stimulation had to be stopped due to the limitations of the available equipment.

The moderate daily pressure increase in the annulus of GPK1 (reduced by a factor of 4 in comparison to the situation at the casing shoe) and the large time delay (multiplied by 4 in comparison to the situation at the casing shoe) suggests a minor hydraulic connection between the natural permeable fractures crossing the annulus of GPK1 and the parts of the stimulated rock volume extending around the casing shoe of GPK1. It is apparent that there is no major direct connection between the open hole and the annulus of GPK1.

The water level in the Buntsandstein showed only a very weak response (< 1 m increase) during stimulation of GPK2. This observation supports the view that only a weak link exists between the deep fracture system in GPK1 and GPK2 and the aquifers in the sediments.

Summarising, it can be stated that both targets for the 1996 stimulation were achieved. The well and its vicinity were cleared of the plugging material as shown by the result of the production test. **Furthermore, the injectivity was greatly improved by the higher flowrate used and is in direct proportion to the increase in flow.**

2.3.4 <u>Observed results during the short production and circulation tests</u>

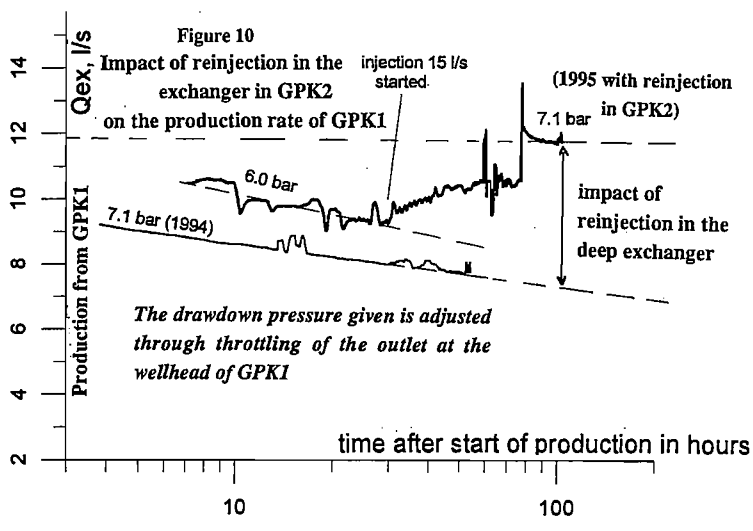


Figure 10 Impact of reinjection in the exchanger in GPK2 on the production rate of GPK1

In 1994, GPK1 was put on production using the buoyancy effect following the stimulation test. The buoyancy effect produced a drawdown of -0.71 MPa (-7.1 Bar). A decline of the production flow from around 9 l/s to 7 l/s was observed after 100 hours (figure 10). A similar test was carried out again in 1995 when GPK1 was put on production and the flow started to decline as observed before. However, the flow from GPK1 increased immediately when reinjection (12-15 l/s) was carried out in GPK2 . The production from GPK1 stabilised at around 12 l/s for an equivalent drawdown pressure as before. The production from GPK1 immediately responded to the injection in GPK2 and the productivity increased by more than 50% (figure 10). This is equivalent of a productivity of 17l/s/MPa.

During an another circulation experiment in 1995 (GPK1 ---> GPK2) using a downhole pump, the production from GPK1 was stabilised at around 21 l/s for a total drawdown pressure estimated at about -2.4 MPa (i.e. a productivity of about <u>9 l/s/MPa</u>, no fluid losses ; total injected volume = total produced volume).

A preliminary reverse circulation test was performed in 1996 following the restimulation of GPK2 (GPK2 --> GPK1). Again using the buoyancy effect, a drawdown in the order of -0.8 MPa in GPK2 produced 18.8 l/s (i.e. a productivity > 20 l/s/MPa), supported by reinjection in GPK1 (figure 11). **This is a clear improvement compared to the previous productivity value obtained during circulation tests at similar flowrates.**

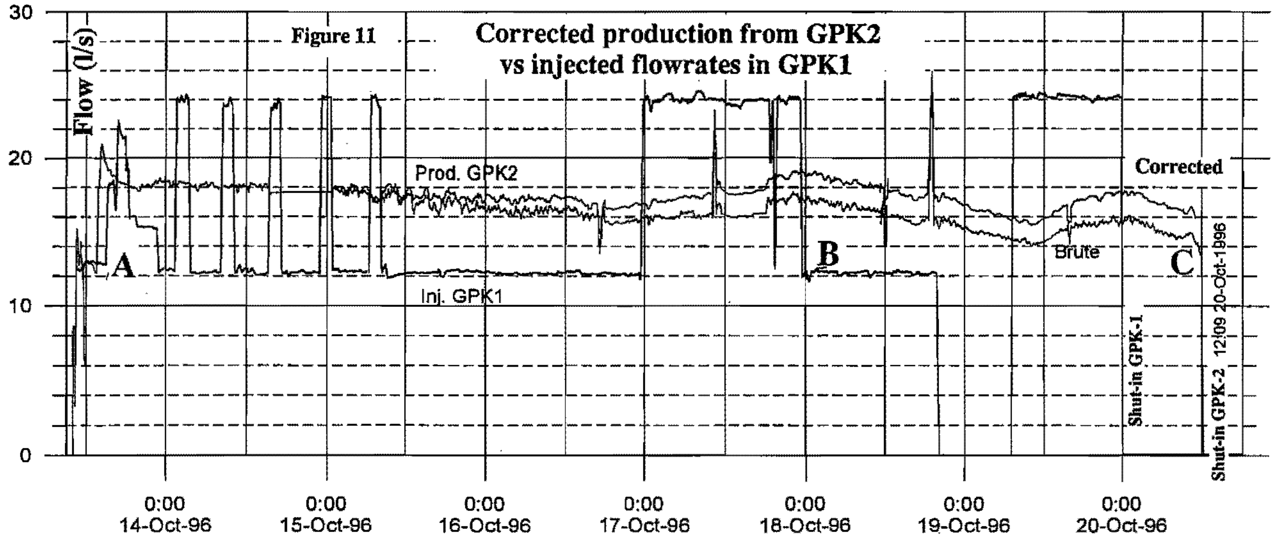


Figure 11 shows a part of the hydraulic history for the above reverse circulation test. An interference test was performed between GPK2 and GPK1 for reservoir analysis. From point A to B (14 October to 18 October), 100% of the produced volume was reinjected. The mean corrected production was at about 18 l/s. The "corrected" production flow was computed after compensation of the downhole pressure drift during the tests. From point B to C (18 October to 20 October) only 60% of the total volume produced was reinjected and consequently the mean production dropped down to about 16 l/s and still declining. The experiment had to be stopped because of the limited storage capacity on surface. The transient part of the data indicates that the system has a large storage capacity but the hydraulic link between the two wells is also emphasised by the increase of the production flow when reinjecting.

Flow logs carried out in GPK1 during this period show that the injection flow profile was generally very similar to that found during the end of the stimulation phase (figure 3), except for an increased proportion (* 2 !) leaving from the permeable fracture at 3500 m. The most important differences between the two experiments were the density of the fluid and the reinjection pressure. It appears that the distribution of the flow leaving GPK1 is rather sensitive to these parameters.

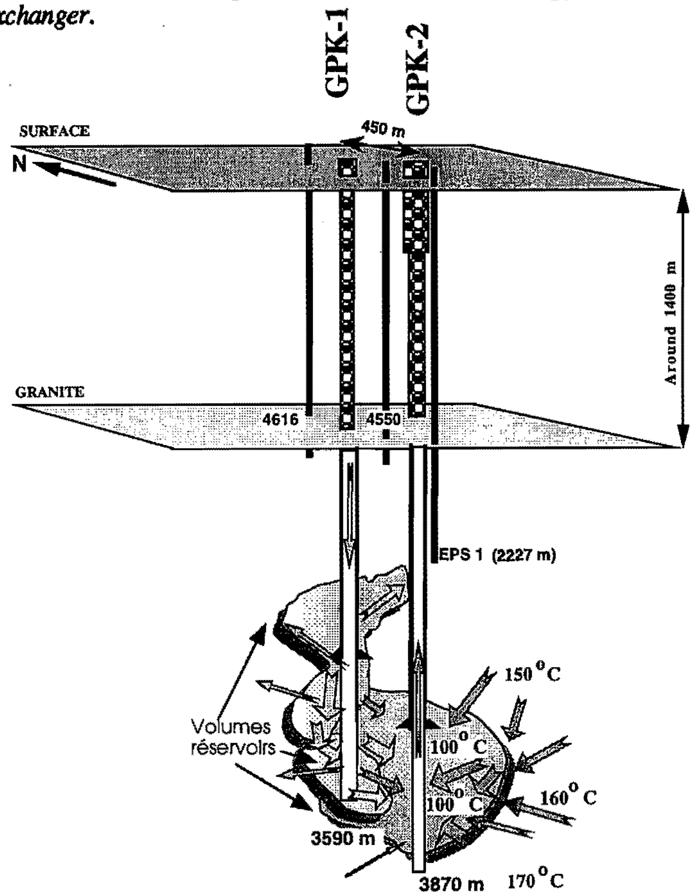
Production flow logs carried out in GPK2 show that the general profile for the stimulation and production tests are very similar except that the (production) flow inlets are more concentrated at 3 specific inlets. The first one is at 3245 m (15% ; 45 m under the casing shoe), the second one at 3340 m (25%) and the third one at 3470 m (35%). (Figure 8).

3. AN UNDERGROUND MODEL DERIVED FROM THE AVAILABLE DATA

An attempt is made here to put forward a model that fits with the observations made from the available data. It is recognised that this is not a unique model and the model will change as more data are acquired or a different interpretation is put forward of the available data. Nevertheless for the time being it appears to fit with the data previously described.

The overall "conceptual model" is represented by a schematic as shown in figure 12. It summarises the present status of our understanding and lays foundation for a medium term circulation test which can be performed without any modifications to the present completion of the wells.

After the drilling of both deep wells, the open hole sections of the wells had very low permeability close to the wells and this was enhanced significantly at high flowrates, large volumes and high pressures. The stimulated areas were mapped using microseismic monitoring, representing a volume of rock mass where sufficiently high pressures were attained to make favourably aligned joints to shear first and thus produce an enhanced degree of permeability. This stimulated volume is defined here as a *reservoir* and is different from the actual volume of the rock mass which takes part in the transfer of the energy from the hot rocks to the cold circulating fluid i.e. the *heat exchanger.*



- Schematic interpretative model of induced circulations during 1996 tests-

FIGURE 12

The apparent structure of the underground can be described using figure 12. Both, the stimulations of GPK1 and GPK2 are represented in this figure as volumes in the underground. These two volumes can be regarded as the most actively stimulated part representing the "reservoir-volume" occupying about 0.2 km^3. They are defined using the microseismic events located during various stimulations (figures 2 & 6). These volumes can be associated with the highest event density. Both volumes around GPK1 and GPK2 show an anisotropic growth with the major and minor axes roughly in the direction of the maximum and minimum horizontal stress, respectively. This is consistent with our understanding of the interaction of the injected fluid, the stress regime and the joint network.

The main link between the wells appears to be at around 3.5 km depth.

The average permeability (vertical and horizontal) of the stimulated rock volume can be considered as higher compared to the adjacent rock volume which has not been stimulated.

It is suggested that there is some hydraulic interaction between the stimulated rock (the reservoir volume) and the surrounding unstimulated virgin rock mass. Although this virgin rock is considered as less permeable, due to the large external surface area of the volume affected by stimulation, numerous fractures are intersected.

Furthermore, it was repeatedly observed that the injectivity/productivity of the wells increases with an increasing injection flow during massive stimulation but it is not clear whether this is due to the flow or volume, or a combination of both. It is proposed that the increase in the permeability of the rock mass during stimulation and the subsequent circulation is obtained by a number of mechanisms. These are as follows:

a. microseismic events are generated by the shearing of critically aligned natural joints and this causes the joints to remain open by riding on the asperities. The degree of residual aperture depends on a number of conditions such as the normal stress, condition of the rock mass (fresh altered) grain size (size of asperities), injection pressure. It is also well established that to restimulate or enhance permeability of a previously stimulated rock mass requires the injection pressure to exceed that used for the initial stimulation. This is well documented from microseismic observations, numerical modelling etc.

b. It is probable that there is a readjustment of stresses locally (in the reservoir region) because of the high flowrate large volume injection which may result in a larger aperture of the hydraulically activated fracture(s) through closure of respective compression of (minor) neighbouring fractures.

c. It is also probable that the extraction of the energy from the hot rock mass will cause a contraction of the rock blocks and thus a readjustment of the stresses causing the predominantly active joints with larger aperture to open further.

It is most likely that a number of these mechanisms work together to produce the enhanced permeability observed during the stimulation and the subsequent circulation. But what is helpful is the Graben setting with:

1.- overall relatively low values of stress
2.- especially its low minimum horizontal stress which is very close to the hydrostatic pressure
3.- its dense joint network which is partly filled with rather porous hydrothermal deposits
4.- its hydrothermal altered rock beds (incorporating numerous joints) which themselves have a rather high porosity and probably lower mechanical strength.

This means that only relatively low pressures are required to open favourably oriented joints. Furthermore the critical shear stresses in Soultz are also rather low (typical Graben stress regime). If the fluid pressure gets very close to the critical shear stress for optional oriented planes then there is a good possibility that this would cause an incipient failure of critically aligned joints and would assist the natural migration of fluid at great depth and would explain the natural residual aperture observed in the joint network at depth.

An additional observation made during the stimulation tests at Soultz is also stated here:

The post-stimulation step injection tests performed both in GPK1 and GPK2 revealed non linear relations (with a quadratic term) between the injection pressure and the flowrate used. This relation can be explained by turbulent flow. If this occurs locally or over longer distances is still a matter of debate. However, the high flowrate re-stimulation of GPK2 in 1996 showed a clear reduction of the non-linear term of the pressure / flowrate relation thus demonstrating that these appearant turbulences can be reduced by the appropriate engineering.

The relatively open joint network at Soultz is also seen as being able to support the upward slow percolation of the injected fluid as this injected fluid becomes hotter and the density begins to drop relative to the in-situ fluid (Archimedes principle). This upward migration of the lighter fluid will be associated with local convective loop and will draw-in the in-situ fluid causing the two fluids to mix. The degree of mixing will most probably depend on the interaction of the pumping pressure, joint apertures, temperature contrast and the viscosities. It can also be assumed that as the veins of mixed fluid (depending on the salt content) become more dense as they cool, starts to sink downward then will migrate upward again thus forming convective loops and continuing the mixing process.

A mechanism like this may be appropriate for explaining the rapid evolution of the salinity of the produced fluids observed after the stimulation of GPK1 and GPK2. GPK1 was stimulated using fresh water (over 45000 m^3 injected) but when the well was put on production, the produced fluid started with fresh water first but then showed a rapid mixture with formation fluid (brine). During the short production test (10,000 m^3, figure 11) the mean proportion of natural brine in the produced fluid increased again from 0 to around 50%. Then, in GPK2, a downhole conductivity log was run following the hydraulic experiments in the well (- 40,000 m^3 injected) in 1996 and after having produced around 10,000 m^3. The data showed that the salinity of the water produced was nearly homogeneous regardless of the depths of the inlets implying a nearly homogeneous mixing of fluids.

From these observations one can deduct that it is likely that very large mixing currents (or convective cells) are occurring across the whole "reservoir volume" inside and at the boundary of the heat exchanging area. These observations support not only the previously described model of an "internal motor" generated by density variations caused by temperature and salinity differences but also the image of a rock mass in which numerous open joints interact allowing also some vertical fluid migration within the "reservoir volume".

Taking into account all these observations, four major effects for the development of the HDR technology at Soultz could be expected:

- In view of the internal mixing of the fluid in the rock mass, it is expected that the thermal life of the reservoir will be longer than in a system without some degree of inherent background permeability.

- The effect of the interaction of the densities in conjunction with the low value of the minimum horizontal stress gradient showed that it is possible in a partly open system of a Graben setting to control the upward or downward growth of the stimulated volume using a stimulation fluid with appropriate salinity which evolves.

- For the circulation experiment planned for 1997 it is expected that some downhole migration / circulation will be observed. Cold brine reinjected in GPK1 leaving the well high up in the open hole section (main outlet just below the casing shoe) will be forced downward due to the described density effect and is expected to drain a part of it towards the production well GPK-2 at greater depth with a downhole pump.

- The open nature of the enhanced and the background fracture network would indicate that a down hole pump is essential for this type of system to maintain the balance between the injected and the produced fluid at high flowrates.

4 MAIN CONCLUSIONS ABOUT THE MODEL AND FUTURE EXPERIMENTS

4.1. Main conclusions about the model

A preliminary set of conclusions about the proposed model are:

- In a Graben setting, the rock mass at depth has some degree of permeability created by a partially open fracture network but this is far from sufficient to provide the right characteristics for an efficient heat exchanger needed for heat mining. Large volume and high flowrate stimulations are necessary to create the required characteristics.

- the stimulated part of the rock mass is defined as the reservoir 'as mapped by microseismic' and represents a volume of a certain size where a specific pressure level has been reached sufficient to shear the natural joints. The heat exchanger is defined as a volume inside the reservoir volume of the rock mass where a majority of the transfer of the heat from the hot rocks to the injected fluid takes place within the reservoir.

- the border between the stimulated reservoir and the virgin rock mass is not hydraulically separate because the joint network (with some degree of permeability) is continuous and therefore it reasonable to assume that there is some hydraulic interaction at the boundary. This "boundary volume" can be visualised as the area where the density of the microseismic events is low (figure 2).

- during circulation between the two wells, it is expected that the path the fluid follows from one well to the other is very complex (distorted by local convective loops) and travels through one subvertical stimulated "reservoir volume" with enhanced permeability to the other, driven by the buoyancy effect and the pressure from the injection an production pumps. This will generate a very complex 3 D geometry of the exchanger.

- the physical size of the reservoirs appear to be big with a very large storage capacity which will strongly damp the hydraulic behaviour of the exchanger. It would appear that the system may reach a hydraulic equilibrium (i.e. production balances the injection) by the interaction at the boundary where the fluid can either leave or enter depending on the suction pressure of the downhole pump.

- the anticipated balancing of the injected and produced fluids will occur at the boundary during the early stages of the circulation test but it is also envisaged that this activity will interact with much larger external faulted system near the stimulated reservoir. This may greatly extend the thermal life of the system.

4.2 Future experiments

In order to improve our understanding of the underground process and the model, it is suggested that future research should be organised in such a way that:

- future experiments should be designed in order to learn more about the internal structure and properties of the heat exchanger and the hydromechanical behaviour governing the fluid transport between the wells

- the design of these experiments should allow sufficient flexibility so that the experiments can be modified subsequently to the obtained additional data if required.

Our present understanding of the heat mining concept is based upon what we feel as being a reasonable knowledge on the creation of a reservoir and the properties that can control it, but upon rather poor knowledge of the actual properties of the heat exchanger. To evaluate the heat exchanger requires a circulating system for a prolonged period in order to reach a steady state and to carry out diagnostic techniques such as the tracers experiments, geochemical analyses, hydraulic analyses, thermal drawdown studies, etc.

Supporting technologies need to be evaluated which should include the handling of problems such as precipitation, corrosion etc.

At present it is proposed to carry out a medium term circulation for around 4 months in 1997 to assess these properties. This will consist of production from GPK2 at about 20-35 l/s using a down hole pump, cooling the fluid down to around 50-80ºC and injecting this in GPK1.

The data from the experiments in 1993, 1995 and 1996 have indicated that there is a potential for further development of the deepest and hottest connection between the two deep wells. In future, this aspect can be further developed in order to target a specific interesting zone, if an opportunity arises - one more step toward the engineering of a deep underground exchanger.

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