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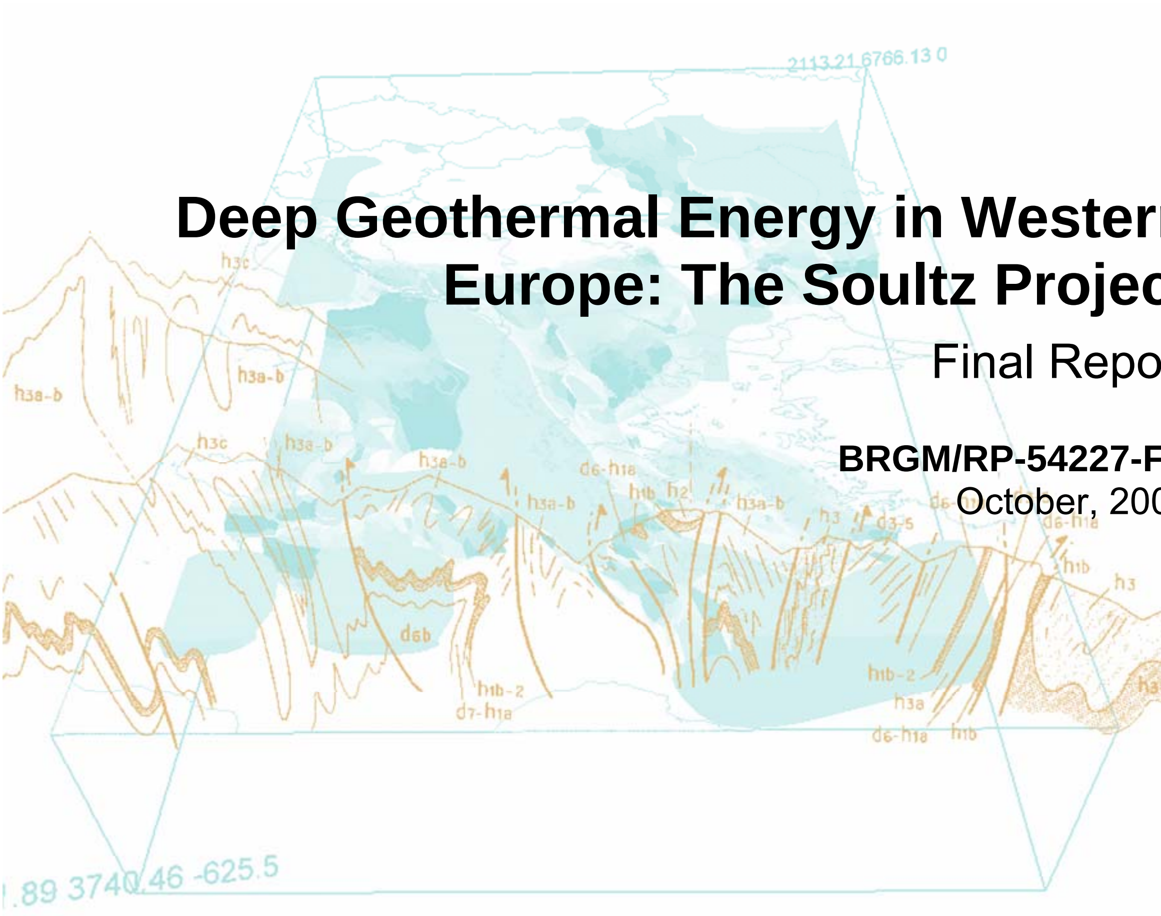

Deep Geothermal Energy in Western Europe: The Soultz Project

Final Report

BRGM/RP-54227-FR

October, 2005

Geoscience for a sustainable Earth

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Study carried out as part of
Research activities 2005-CDG-06

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With the collaboration of
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Keywords: Deep Geothermal System, Soultz-sous-Forêts, France.

In bibliography, this report should be cited as follows:

Dezayes Ch., Gentier S., Genter A. (2005) – Deep Geothermal energy in western Europe: the Soultz project. BRGM/RP-54227-FR, 48 p., 7 fig.

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Synopsis

This compilation summarizes an overview of the research done at Soultz (France) since the beginning of the European deep geothermal project. This project aims to exploit the potential energy of the deep fractured rocks to produce electricity.

The site is located at Soultz-sous-Forêts, in the north-eastern part of France (Alsace), within the Tertiary Rhine Graben. An intense thermal anomaly was known in this area since long time based on an oil exploration (Hass & Hoffmann, 1926). The industrial oil exploitation occurred between 1888 and 1970 and numerous geological data were available to begin the preliminary studies of the deep geothermal project.

The project was initiated by a paper published in 1984 (Gérard *et al.*, 1984) then it started in 1987 with the drilling of the first well, GPK1. That well reached 2 000 m and the bottom hole temperature was 140°C. Several hydraulic injections have been done (Jung, 1991) associated with tracer tests (Pauwels *et al.*, 1991; Gadalia *et al.*, 1992) and temperature and flow logs (Schellschmit & Schulz, 1991). Downhole seismic probes have been developed to locate the microseismic events induced by hydraulic tests (Beauce *et al.*, 1995).

In 1990/1991, an old oil well, EPS1, has been deepened and cored to characterize the granite reservoir and to perform some deep hydraulic tests in view of a future experimental doublet. Unfortunately, the well have had an important not controlled deviation and could not reach the expected depth. However, it was continuous cored from 930 m to the bottom hole at 2 227 m depth and provided a lot of scientific data (Traineau *et al.*, 1991; Genter & Traineau, 1992).

In these both wells, in situ stress measurements have been performed to determine the present-day stress tensor. The results show that the azimuth of σ_H, maximum horizontal stress, is N155°E±3° to N176°E±6° with a normal faulting stress regime (Rummel & Baumgärtner, 1991).

In order to get deeper information, the GPK1 well was deepened to 3 600 m in 1992. The downhole temperature reached only 160°C. However, this well constitutes the first well of a doublet. During the large hydraulic test conducted in this well, induced seismicity was monitored. The microseismic events formed a cloud extending about 400 m on both sides of GPK1 in the N-S direction to NW-SE (Jones *et al.*, 1995). A third well, GPK2, has been drilled southern to constitute the second well of the doublet and obtain a maximum of fluid recovery. GPK2 well reached 3 900 m in 1995 by drilling in destructive mode only. Hydraulic tests have been done in order to characterize the exchanger and to evaluate the potential fluid flow. Both wells have been stimulated by forced fluid injection in order to increase the permeability (Jung *et al.*, 1995; Baumgärtner *et al.*, 1996).

The first circulation tests have been performed between GPK1 and GPK2, 450 m apart at 2 900 m to 3 500 m depth. In 1997, a four months circulation test has been performed where fluid was produced from GPK2 and reinjected in GPK1. Tracers have been injected during the circulation tests. Analysis of the tracer tests shown that the reservoir volume, in which the tracer was disperse, could been estimated of the order of more than 1 million m^3 (Aquilina *et al.*, 1998). During the 4 months circulation test, only 30 % of the fluid injected into the system have been recovered. As production and injection flow was maintained in complete balance, this indicates that the Soultz system is open.

Analysis of image logs shows that fracture network is nearly vertical and about N170°E in relation with the graben tectonic (Genter *et al.*, 1997; Dezayes *et al.*, 2004). Various studies of the present-day stress field show that the maximum horizontal stress axis is also around N170°E. Therefore, the fluid circulation could be easier along this direction. To improve the recovery of fluid, the open hole of exploitation wells could be aligned in this direction.

As the circulation tests within the upper level were successful, it was decided to exploit a lower level at 5 000 m depth, where the temperature reaches 200°C, in order to develop a geothermal resource aiming at electricity production. Then, in 1999, GPK2 was extended to 5 084 m and two other wells, GPK3 and GPK4, have been drilled to build a triplet exchanger, in 2002 and 2004 respectively. The deep wells have been stimulated hydraulically. The apparent permeability of GPK2 and GPK4 has been increased but the permeability of GPK3 was not at all improved probably because of a major fracture zone, which took the major part of the injected fluid (70 %). Recently, to develop the hydraulic performance of the wells while limiting microseismic event magnitude and occurrences, chemical stimulations have been tested. As preliminary results, these chemical stimulations increase clearly the permeability of the wells (Gérard *et al.*, 2005). Since July 2005, a short-term circulation test has been running between GPK3 (injection) and GPK2-GPK4 (production) in order to characterize the system in terms of hydraulics. During the test, naphthalene disulfonate compounds are injected as tracers in order to contribute to the knowledge of the fluid pathways within the granitic reservoir (Sanjuan *et al.*, 2004).

The 18 years of research at Soultz have permitted to better understand the deep geothermal system and gradually evolve the deep geothermal conceptual model. It appears that the Soultz reservoir is constituted by an interconnected randomly permeable fracture network within an impermeable granitic rock mass. This network presents two scales of fractures. The small-scale fractures constitute a fine interconnected network. The large-scale fractures constitute the most important reservoir. These fractures are large fracture or fault zones developing hydrothermal alteration (Genter *et al.*, 1998), which could be consider at small-scale as equivalent to a porous medium bearing natural brine. Around the wells, the hydraulic stimulation tests have permitted to increase the permeability mainly by shearing acting on pre-existing fractures. Then, some irreversible openings have been created by dilation within the fractures (Gentier *et al.*, 2005).

The deep geothermal technology started to fulfill renewable energy needs, as the available fossil fuels slowly reduce. The advantages of this deep geothermal technology are mainly its large potential resources and accessibility over large areas of the Earth's surface (Genter *et al.*, 2003). However, several geoscientific key parameters must be known during the reconnaissance phase and before the design of the geothermal system: temperature regime, deep-seated geology, distributions of fractures and present-day stress field.

Contents

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1. Introduction

The European deep geothermal project, located at Soultz-sous-Forêts (Rhine Graben, France), aims to exploit the potential energy of the deep fractured rocks to produce electricity (Gérard & Kappelmeyer, 1987; Kappelmeyer *et al.*, 1991). The BRGM (French Geological Survey) has been acting as one of the major research actors since the beginning of the project. BRGM research team is a leader in terms of geology (forecast geological cross-sections, borehole logging interpretation, petrography and structural studies, thermo-hydro-mechanical modeling), geochemistry (deep fluid studies, tracer tests), geophysics at the beginning of the project (microseismic monitoring and vertical seismic profile) and drilling management for the first drilling operations.

In Europe, three deep geothermal projects have been undertaken after the precursor technology developed at Fenton Hill (USA) in the 1970's (Duchane, 1998). The goal of this latter project was to create an HDR system, i.e. a vertical hydraulic fracture reservoir between two deep wells connected by hydraulic fracturing within hot, dry and massive rock mass. In Europe, the first project started in 1977 on the Rosemanowes site (Cornwall, UK) and stopped in 1992. At the same time, in 1977/1978, the German project started in Bad Urach (Swabisch Alps), after an interruption from 1994 to 2000 it was temporally stopped in 2004 due to borehole instabilities in a deep well and other problems. A third project started in 1987 at Soultz-sous-Forêts (France). In 1993, the Soultz site was chosen as the location for the European HDR research project under the auspice of the European Community. More recently, a new deep geothermal project was initiated in Switzerland (Basel), financed by the Swiss Ministry of Energy and private institutes, for co-generation electrical power and urban heating system. Some exploration studies was carried out in the Southern part of the Rhine Graben and the first deep exploitation well of the Swiss Deep Heat Mining (DHM) project will be drilled in early 2006 in Basel.

The European deep geothermal site of Soultz is a research project, which was funded at the beginning by public fund from European Community, Great Britain and German ministries and French ministry of research via the Energy and Environmental Agency (ADEME), the Geological Survey (BRGM) and the National Scientific Research Center (CNRS).

At the present day, 4 wells have been drilled at Soultz with depth ranging from 3.6 to 5 km, plus 5 observation wells either drilled or recovered from past oil research activities. From 1987 to 2001, the project was a scientific project with a lot of associated studies and technical developments carried out by research teams in order to determine the feasibility of the deep geothermal concept. In 2001, the project entered into a phase of a scientific pilot plant construction and industrial energy companies joined the consortium created in 2001 (www.soultz.net).

This technical report presents a historical synthesis of the work, which has been performed at Soultz since the beginning of the project. This project could be separated in three phases: 1) an exploration phase, 2) the creation and testing of a doublet in the upper part of the granite (3.5 km depth); 3) the creation of a triplet deeper (5 km depth). All this work, and associated scientific studies, help to develop a conceptual model of the site and to propose a model for its geothermal behaviour.

BRGM reports associated to the Soultz project are compiled in Annex 1.

2. The choice of the Soultz site

The site is located in the north-eastern part of France (Alsace), within a Tertiary rift zone called the Rhine Graben (Figure 1). Based on oil exploration, an intense thermal anomaly was known in this area since long time. Hass & Hoffmann characterized it in 1926 and showed that the temperature could reach locally more than 50°C at 400 m. In the Soultz wells, the temperature reaches 200°C at 5 000 m (Figure 1). The thermal anomaly is due to deep circulations of fluid through a large-scale fault system and the existence of the sedimentary cover playing the role of heat insulation. This temperature anomaly has permitted the maturate of the organic matter and then to create the famous Pechelbronn oil field embedded in sediments, which are superposed to the granite.

Bitumen in the Pechelbronn area is known since the XVth century (Figure 2). Its industrial exploitation occurred between 1888 and 1970 (Figure 2). Numerous wells have been drilled: in 1905, 1164 wells had been drilled representing a cumulative length of 290 km, the deeper well reached 600 m depth. In 1927, in the oil well number 2905 of Pechelbronn, the first geophysical logging operation has been performed by the team of Conrad and Marcel Schlumberger, who funded the famous Schlumberger Company, leading oilfield services provider.

In 1910, a hydrothermal spring had been discovered and exploited for thermal bath until 1992 (Figure 2). As the presence of oil at shallow depths, this hot spring occurrence is a consequence of the geothermal anomaly.

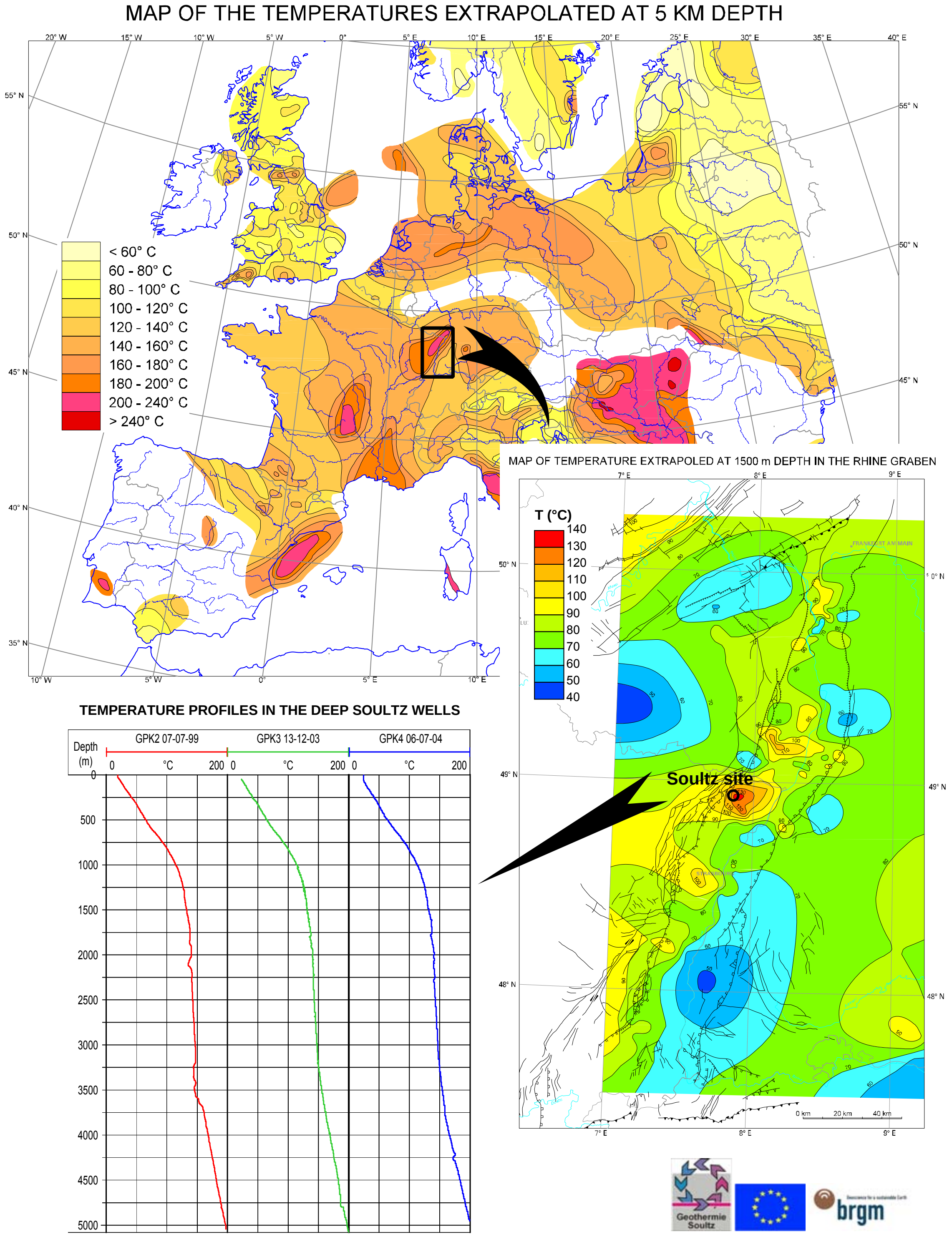

Figure 1 – Deep temperature in Europe and in the Soultz site (Genter et al.*, 2003).*

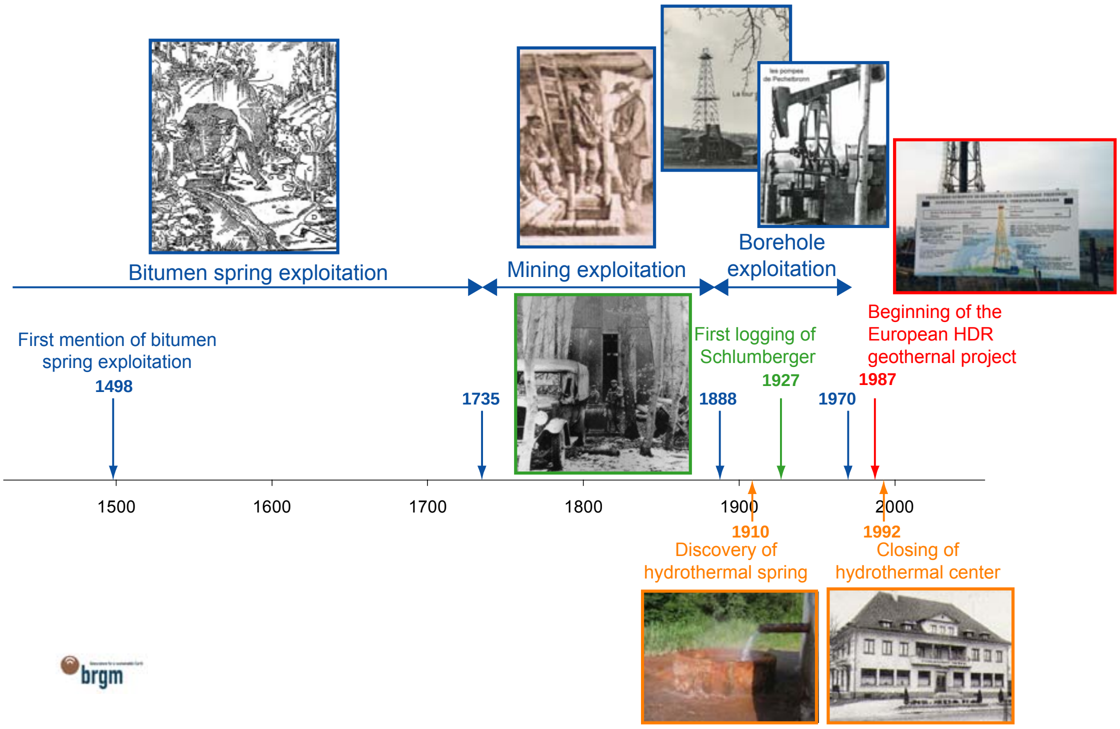

Figure 2 – Saga of Pechelbronn oil exploitation and the Soultz geothermal project.

3. Exploration phase (1987-1991)

The numerous wells, seismic profiles and geological data, linked to the Pechelbronn oil field development, have helped to bring a good geological knowledge of the graben structure and to begin the preliminary studies of the future deep geothermal project (Figure 3).

The synthesis of these basic data, acquired during the oil field exploration, has permit to establish different cross-sections, representing the sedimentary cover and the top of the granite basement (Figure 3). These cross-sections done by BRGM geologists, using vibroseismic data provided by TOTAL, permit to determine the location of the wells above a local horst structure to reach the hidden Paleozoïc granite at around 1 400 m, whereas in the middle of the graben, the top of the basement is located at a maximum of 6 000 m depth (Figure 3).

In 1987, the first exploration well, GPK1, reached 2 000 m, drilled in destructive mode with spot coring representing about 50 m length of granitic cores (Figure 4). The temperature at the bottom depth was 140°C.

Several injection tests have been done in this well between 1988 and 1991 (Jung, 1991; Figure 4). During these tests, BRGM geochemists tested and injected numerous chemical products in order to trace the fluid circulation. Different types of tracers, artificial or natural, have been studied in this period (Pauwels *et al.*, 1991; Gadalia *et al.*, 1992).

Different temperature and flow logs have been carried out in relation with hydraulic tests by the German partners (Schellschmitt & Schulz, 1991). The flow log analysis permits to locate the water entries or outlets along the open hole section. The recorded temperature profile illustrates the evolution of the thermal gradient with depth, which shows a fluid convective circulation within large-scale fractures.

After the first geological studies in GPK1, BRGM geophysists subcontracted to CGG VSP (Vertical Seismic Profile) survey in order to identify the extensions of fractured zones in GPK1 and to obtain a velocity model required to locate the microseismic events induced by hydraulic tests (Beauce *et al.*, 1995). These microseismic events have been monitored by three seismic probes located in three seismic peripheral observation wells at depths of 843 m, 963 m and 1 360 m respectively in order to limit attenuation due to the thick sedimentary cover. The 3-axis downhole seismic probes have been developed by BRGM geophysists to withstand high temperatures and severe corrosion conditions (Beauce *et al.*, 1995).

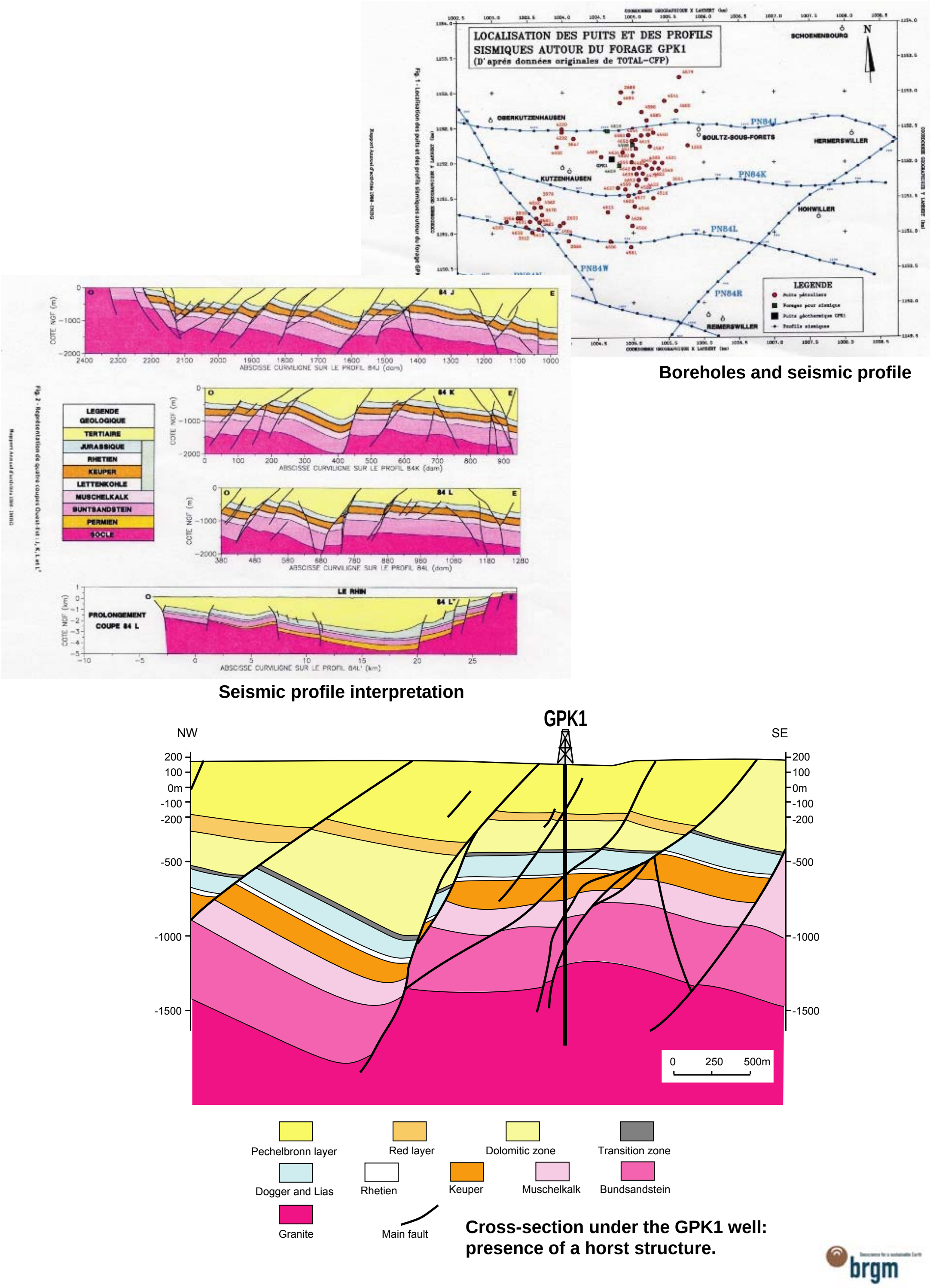

Figure 3 – Underground knowledges at the beginning of the Soultz project.

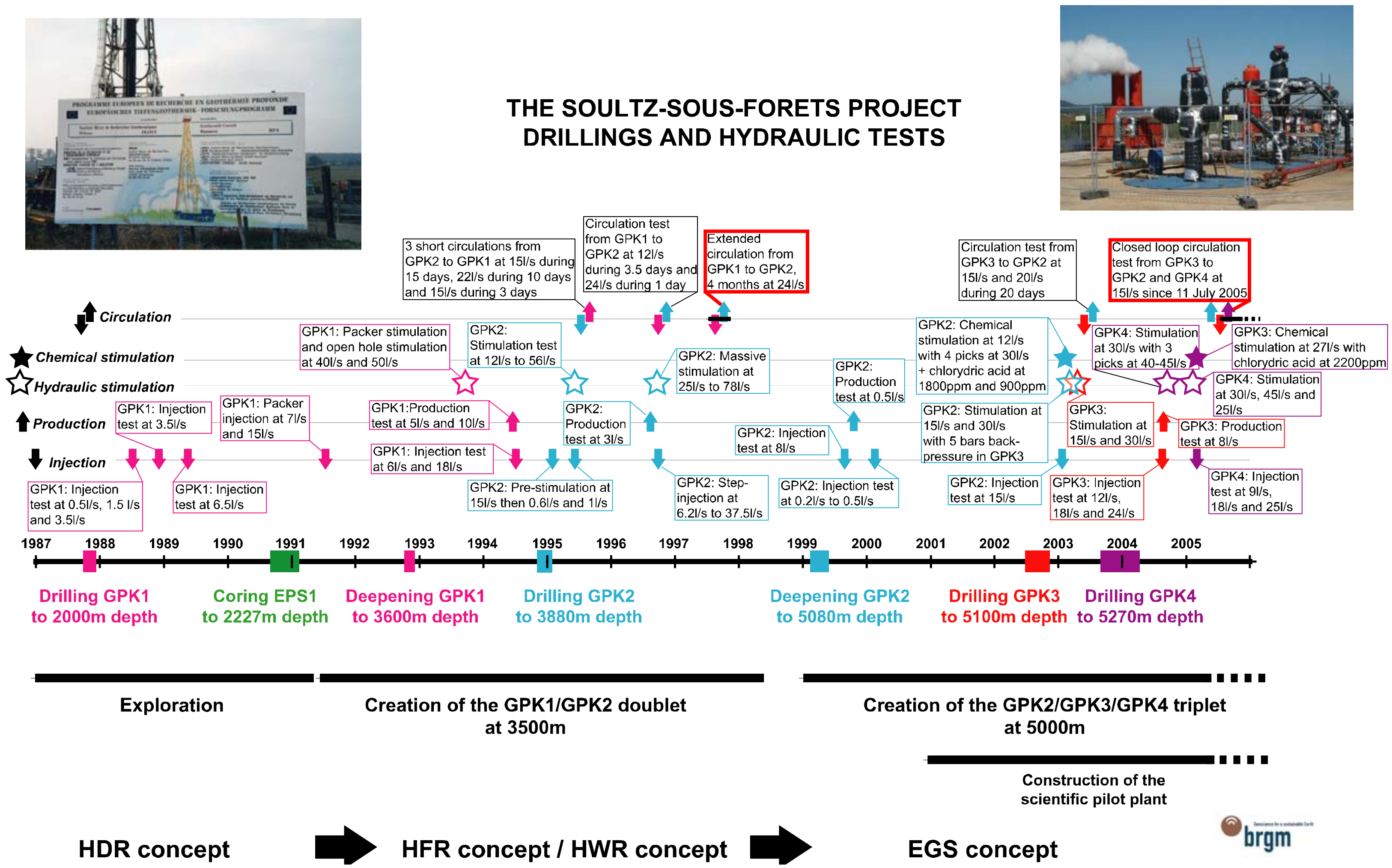

Figure 4 – The Soultz Project time schedule drillings and major hydraulic tests.

In 1990/1991, an old oil well (n° 4589, 830 m deep) has been deepened and cored to characterize precisely the granite reservoir and to constitute the second well of a future experimental doublet (Figure 6). This well, named EPS1, was planned to reach 3 500 m but an important uncontrolled deviation led to stop it at 2 227 m depth. It was equipped latter by pressure sensors to estimate the hydraulic connections between the different wells during the hydraulic tests. This EPS1 well is a deepening of an old oil well (4589) stopped at 830 m depth. The first hundred meters (830 m to 930 m) have been drilled in destructive mode. Continuous coring began at 930 m with 78 mm core diameters to 1 997 m and 57 mm diameter from 1 997 m to 2 227 m depth. The basement was reached at 1 410 m depth. Then, 487 m of sedimentary cores and 810 m of granitic cores were collected and fully investigated in terms of structural geology and petrography by BRGM. This well provided lot of scientific data to characterize the deep-seated geology of the Soultz site and constitutes still now a reference well.

The core collection of GPK1 and EPS1 permits to get a precise knowledge of the upper part of reservoir in terms of petrography, mineralogy, alteration type and alteration process, fracture types and fracture zones (Traineau *et al.*, 1991; Genter & Traineau, 1992). The core sections were also calibrated by several conventional logging (caliper, spectral gamma ray, sonic, image logs, etc.) to match the geophysical signal with the geological observation (Figure 7).

During the late 1988, eight Hydraulic Tests on Pre-existing Fracture (HTPF method) have been performed in the 1 458-2 000 m depth range of GPK1 (Rummel & Baumgärtner, 1991). However, these tests are questionable due to technical problems caused by using conventional packer technology in the hostile downhole environment (temperature of up to 140°C and high gas and salt content of the borehole fluid; Rummel & Baumgärtner, 1991). The inversion five tests yielded σ_H, maximum horizontal stress, with azimuth N155°E±3° to N176°E±6°, depending the geometry of stimulated fracture. Later, in 1991-1992, a series of four HydroFracs (HF method) has been conducted in EPS1 and GPK1 using aluminum packers to improve the hydraulic isolation. However, no fracture orientation was obtained (Klee and Rummel, 1993). The magnitude of the stress shows a normal faulting stress regime $\sigma_h < \sigma_H \leq \sigma_v$, typically of the tectonic situation of a graben structure (Rummel and Klee, 1995).

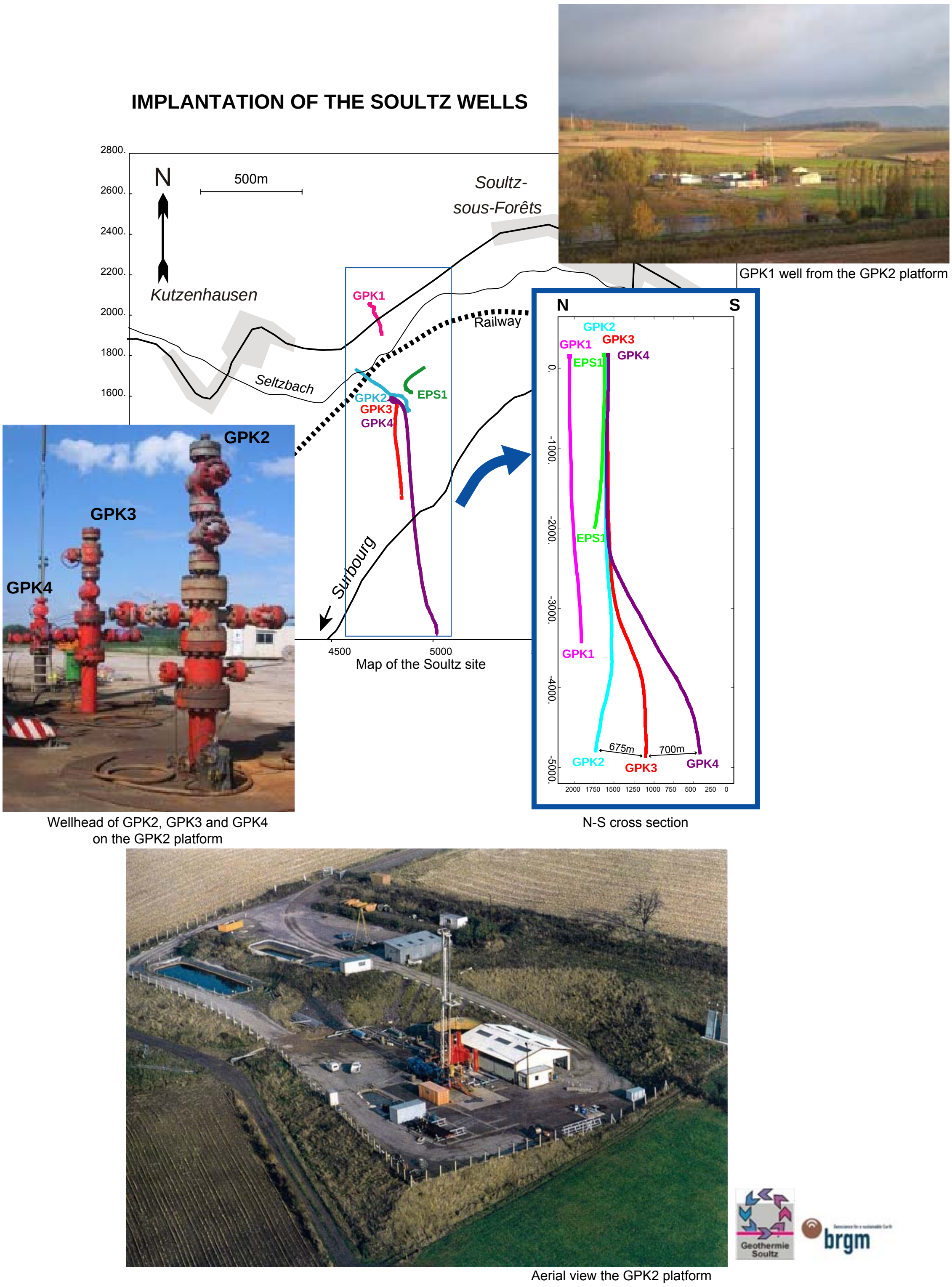

Figure 6 – Location of the Soultz wells (map, cros-section, aerial picture).

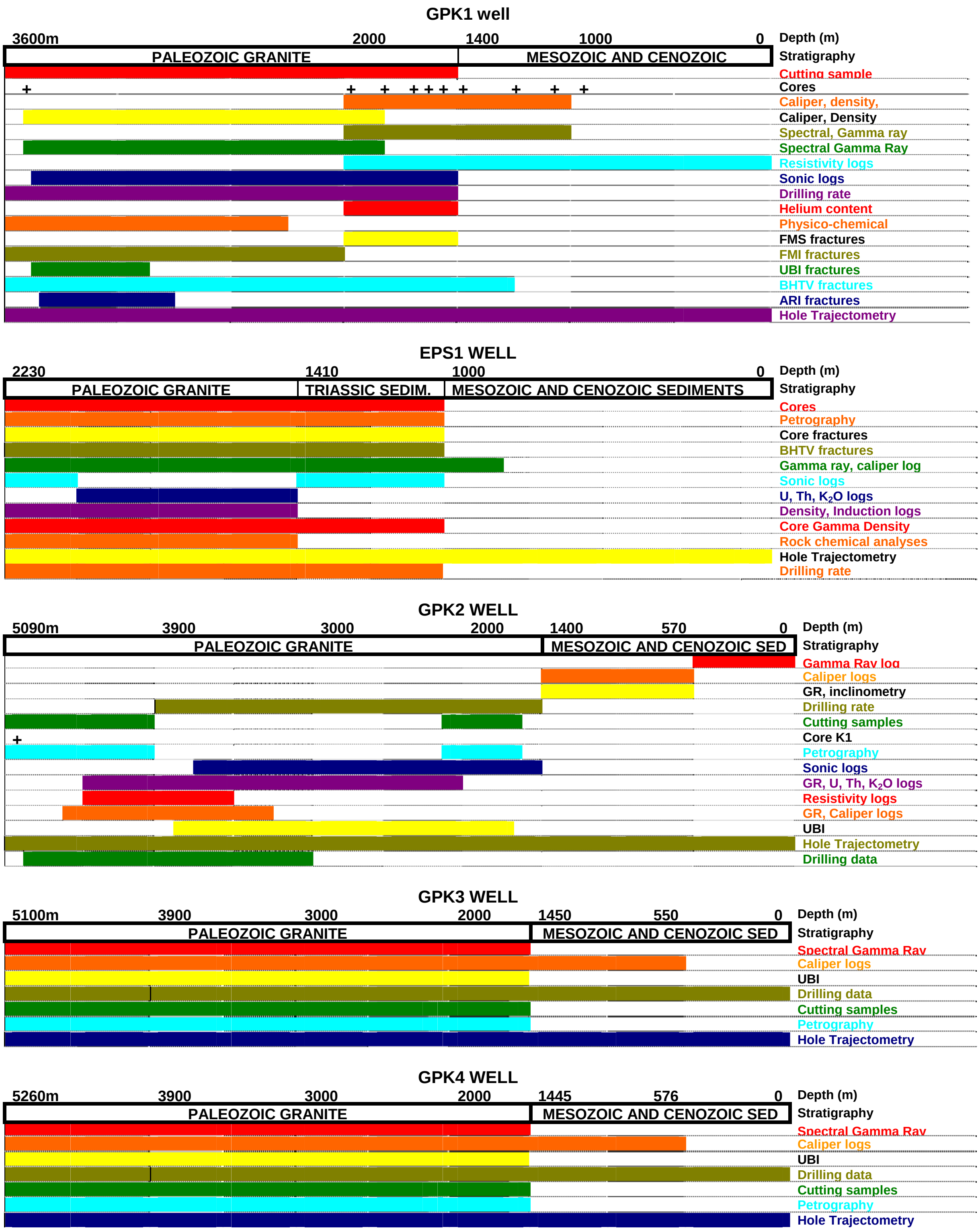

Figure 7 – Data log collection in the wells at Soultz.

4. Creation of a doublet at 2 900 to 3 500 m (1992-1997)

The thermal gradient based on temperature profiles logged in the first well, within the sedimentary cover and the first part of the granite, lets to forecast a higher temperature at 3 500 m. Then, the GPK1 well had been deepened to 3 600 m in 1992, but the downhole temperature reached only 160°C. It constitutes the first well of a doublet (Figure 6).

During the large injection tests conducted in GPK1, induced seismicity was monitored with both the downhole and a surface seismic network. This latter was constituted by three permanent stations, located between 2.5 km and 7 km from the GPK1 well head, and 11 temporary stations, closed to the well and deployed only for the duration of the injection tests. About 20000 events have been recorded by the downhole tools and 165 events with the surface network, which recorded the largest events at magnitude 1.9 (Jones *et al.*, 1995; Cornet *et al.*, 1997). The microseismic events form a cloud extending about 400 m on both sides of GPK1 in the N-S direction between 2 700 m and 2 900 m depth, but with N145°-160°E direction between 3 200 m and 3 600 m depth (Jones *et al.*, 1995; Cornet *et al.*, 1997).

Whereas the temperature at 3 600 m depth did not reach a temperature as higher as expected, a third well, GPK2, has been drilled near the EPS1 well in 1994/1995 to constitute the second well of the doublet (Figure 5). Its location had been mainly determined based on the study of the induced microseismic event cloud recorded during the stimulation of GPK1, which was fitting well with the direction indicated by the fracture network and the main horizontal stress field azimuth (Figure 6). GPK2 reached 3 900 m in destructive mode only. As GPK1, the GPK2 well has been drilled in 8”1/2 diameter cased in 7” then terminated by an open hole in 6”1/2 diameter along the 665 m deepest meters.

As for the first drillings, the geological work done during drilling operations was made on-site by BRGM geologists to collect cuttings and determine the lithology. Gas control, geochemical monitoring and the deep fluid analyses have been also performed by BRGM geochemists. Numerous geophysical data have been logged in these wells (Figure 7). Most of them have been followed by BRGM geologists and studied to characterize petrography, alteration, fractures, etc. (Genter *et al.*, 1995; Dezayes *et al*. 1995; Genter *et al*. 1997). These studies have also permitted to select the most appropriated logging tools to characterize the deep geothermal system, which are Spectral Gamma Ray, for lithology, Ultrasonic Borehole Imager, for fracture network, and Caliper, for hole shape and cave detections.

Hydraulic tests have been done by German and Socomine (Soultz project management) teams in these wells in order to characterize the exchanger and to evaluate the potential fluid flow, which could circulate between the two wells. The preliminary tests performed at Soultz are injection and production tests in order to determine the initial injectivity and productivity of the wells. After having characterized the permeability around the wells, some hydraulic stimulation tests have been performed in order to increase this permeability of the rock mass by forced injection (Jung *et al.*, 1995; Baumgärtner *et al.*, 1996). The fluid is injected by increased flow rate steps up to 50 l/s in GPK1 and 78 l/s in GPK2. At the beginning of the stimulation, low flow rates imply an important increase of the overpressure in the well. Conversely, above about 10 MPa for GPK1 and 12 MPa for GPK2, high flow rate could be injected in the system with low increments of overpressure. After stimulation, the permeability was increased in an irreversible way. For a flow rate of 12 l/s, the injectivity was increased by a factor 4 and 6 for GPK1 and GPK2 respectively.

The first circulation tests have been performed between the two wells, GPK1 and GPK2, 450 m apart at 3 000 m depth, in order to test and to valid the connection between the two wells. Three tests have been done (Figure 5):

- a serie of three short circulation tests in 1995, where GPK2 was the injection well and GPK1 the production well;
- two short circulation tests in 1996, where fluid was injected in GPK1 and produced in GPK2 in reverse order than the first circulation test;
- an extended circulation test during 4 months, in 1997, with the same scheme than the previous one.

During all the circulation tests, tracers have been injected and analysed by BRGM geochemists (Aquilina *et al.*, 1998). Two types of tracers were used: natural tracers as conservative species (chloride) of the geothermal brines, and artificial tracers such as stable isotopes (deuterium) and inorganic or organic compounds (iodides, Amino-G, rhodamin, fluorescein, benzoate). From the tracer tests, the reservoir volume has been estimated of the order of more than 1 million m^3 (Aquilina *et al.*, 1998). The breakthrough time observed from these tests was three to four days, which shows a maximum apparent velocities of 6.3 m/h and mean apparent velocities of 0.25-0.45 m/h (Aquilina *et al.*, 1998). During the four months circulation test, only around 30 % of the fluid injected into the system have been recovered. Production and injection flows were maintaining in complete balance due to the fact that only the producted fluid was reinjected. The complement part of fluid corresponds to in situ geothermal fluid present in the rock mass. Then, this indicates that the Soultz system is open. The created exchanger seems to be connected to a larger ”geothermal reservoir”.

Analyses of numerous temperature and flow logs, performed during the hydraulic tests, show that the circulation occurs within some permeable fractures presenting hydrothermal alteration. The comparison of image logs (UBI, Ultrasonic Borehole Imager; Figure 7) before and after stimulation shows that all these flowing fractures have suffered shearing of millimeters to centimeters (Cornet *et al.*, 1997; Evans *et al.*, 2005).

Analysis of image logs shows that the fracture network is nearly vertical and about N170°E, with high density, in relation with the graben tectonic (Genter *et al.*, 1997; Dezayes *et al.*, 2004). Different studies and *in situ* measurements of the present-day stress field show that the maximum horizontal stress axis is around N170°E and the vertical stress axis corresponds to the major stress axis in the upper reservoir (Rummel & Baumgärtner, 1991; Tenzer *et al.*, 1991; Tenzer *et al.*, 1992; Klee & Rummel, 1993; Rummel & Klee, 1995; Dezayes *et al.*, 1995; Jones *et al.*, 1995; Genter *et al.*, 1995). As the fracture network and the present-day stress field are parallel, the fluid circulation could be easier along the N170°E axis. Therefore, the knowledge of the present-day stress field and the orientation of the fracture network are key parts of feasibility studies for deep geothermal development.

5. Creation of the triplet at 5 000 m (1998-2005)

As the stimulation and circulation tests within the upper level were successful, it was decided to exploit a lower level at 5 000 m, where the temperature was expected to reach 200°C, to produce electrical power (Figure 5). For that, the design of the wells has been changed in order to improve the recovery of fluid. Based on the knowledge of the fracture network and the present-day stress field acquired during the last phase, the open hole of the wells, which constitute the access to the exchanger, must be aligned close from the N170°N direction. According to the recovery rate obtained at the upper level, it was envisaged to build a triplet with one injection well between two production wells, to increase as much as possible the recovered injected fluid volume (Figure 6).

Then, the GPK2 well was extended to 5 084 m, in 1999, to evaluate the underground conditions and to constitute one of wells for future circulation (Figure 5). The well has been deepening in destructive mode to 5 048 m depth and a core has been collected between 5 048 m and 5 051 m (Figure 7). To reach 5 084 m depth, a 6”1/4 drill bit was used for possible stress measurements (Figure 8). However, no stress measurements have been performed at this depth due to some technical difficulties.

Two other deep wells, GPK3 and GPK4, have been drilled to build the exchanger in 2002 and 2003/2004 respectively (Figure 5). GPK3 will be the injection well and GPK4, the second production well (Figure 6). The triplet design has been performed to tend to have the maximum of productivity at 5 km depth with help of previous scientific results. To reduce cost and delay of the future exploitation, the two wells GPK3 and GPK4 were drilled from the same platform as GPK2, but deviated in depth to reach a horizontal distance of about 700 m between the open holes, between 4 500 m and 5 000 m vertical depth (Figure 6).

GPK3 and GPK4 were drilled in destructive mode as future exploitation wells (Figure 8). Each well was deviated with a mud downhole motor from 2 683 m depth for GPK3 and 2 135 m depth for GPK4 (Figure 6). The maximum inclinaison is 25.5° (from to vertical plane) to N180°E at 3 592 m depth for GPK3 and 34° to N170°E at 4 210 m depth for GPK4. The trajectories of the wells become gradually vertical with depth to obtain sub-vertical open hole sections (Figure 6).

The drilling of the deep wells have been performed succesfully. One major problem to overcome was the presence of large-scale fractures, which form fluid losses zones or caves as in the GPK2 well (Figure 7). Some outflows of geothermal brines occurred but they were fully controlled by drillers. Only one deep drilling problem occurred in GPK4 well when the drill string stuck at about 5 000 depth due to tighthole and pack off by cutting accumulation in the 8”1/2 open downhole. After perforations of the string, all the drilling equipments came free and were tripped out of hole.

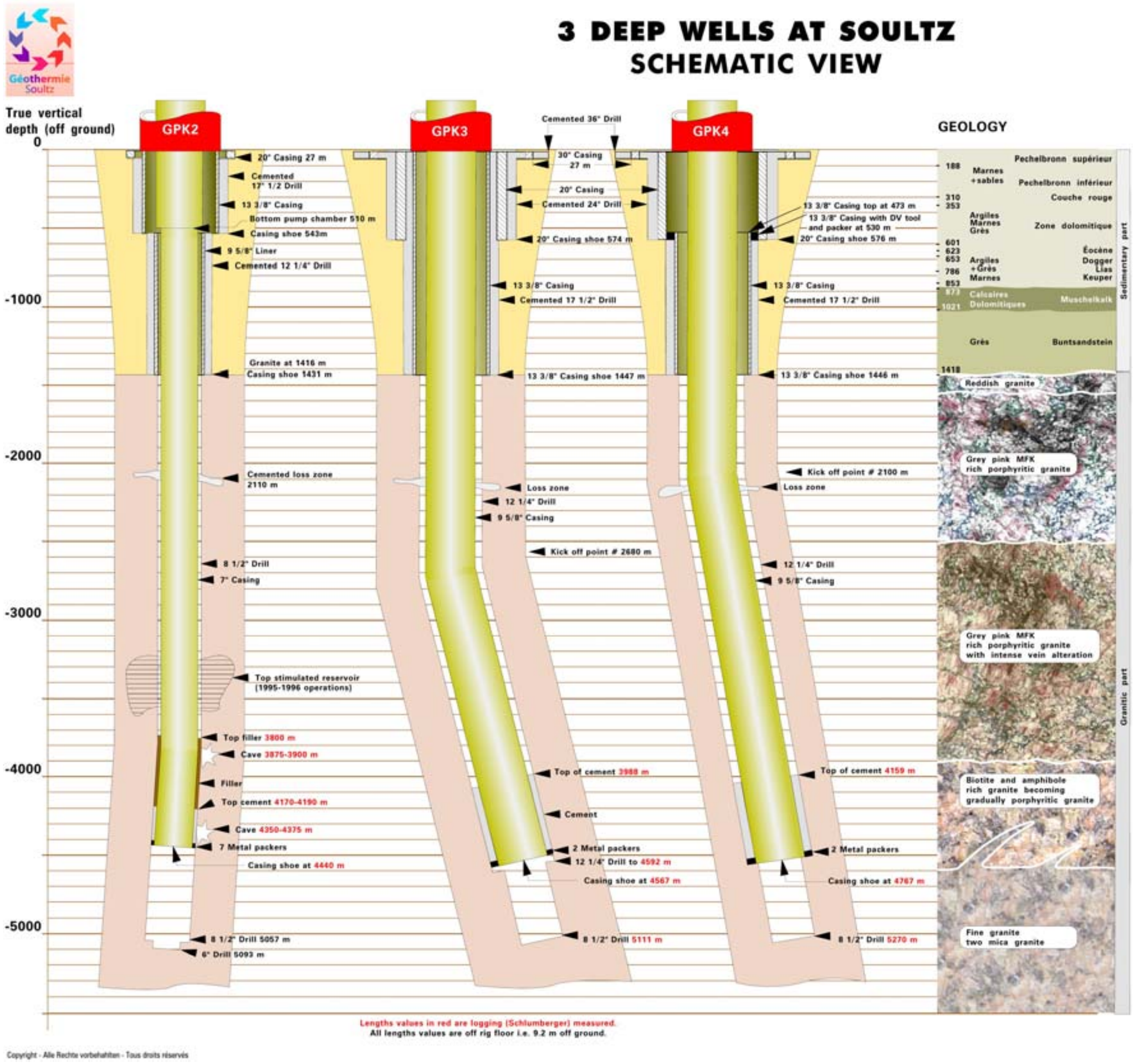

Figure 8 – Completion of the 3 deep wells and schematic geological cross-section at Soultz.

For the two last deep wells (GPK3 and GPK4), only caliper, spectral gamma ray and acoustic image logs have been performed based on previous studies (Figure 7; Dezayes *et al.*, 2005). As the study of cutting samples was very difficult in these wells due to their fine-grained size, a specific procedure was develop by BRGM with the spectral gamma ray log in order to have a better idea of the rock mass petrography by using the Hierarchical Ascending Classification statistical method. The fracture network was characterized by BRGM geologists used acoustic image log, which is an oriented image of the borehole wall. Major fractures (fracture density based on image logs is 4 times fewest than based on core observation) could be detected and their orientation was measured. By these analyses, BRGM geologists have investigated the main characteristic of the deep-seated geology of the granite reservoir.

The deep wells have been stimulated by forced hydraulic injection as for the upper level. These tests have increased the productivity of the GPK2 and GPK4 wells. The initial injectivity of GPK3 was high due to the presence of a huge fracture zone in the middle part of the open hole section. This injectivity was not at all improved by hydraulic stimulation.

Recently, to limit microseismic event magnitude and occurrence, it was decided to test chemical stimulations. This type of stimulation consists in an injection at moderate flow rate (10-30 l/s) of water with hydrochloric acid added. This acid injection should dissolve the calcite filling the fractures, in order to increase the porosity and then the permeability around the wells. As a preliminary result, these chemical stimulation tests increased the injectivity of the wells of 15 % (from 0.4 $l.s^{-1}.bar^{-1}$) for GPK2 and 40 % for GPK4 (from 0.25 $l.s^{-1}.bar^{-1}$ to 0.4 $l.s^{-1}.bar^{-1}$), but no obvious impact on GPK3 injectivity (Gérard *et al.*, 2005).

During the hydraulic tests, the seismicity is monitored by two types of array: around 20 permanent and temporary surface seismological stations in addition to the three permanent downhole stations. Several thousand of seismic events with magnitude less than 2.9 are recorded induced by each tests (Cuenot *et al.*, 2005). These seismic events form a dense cloud, which is oriented in agreement with the main trend of the regional fracture system. For some of them, the focal mechanisms could be determined in order to understand the mechanism of fracture displacement. It appears that the stress field is normal-faulting regime in the upper part, to around 4.5 km depth, and strike-slip regime in the deeper part. The largest microearthquakes magnitudes (> 1.4) may be associated with some major structures, which could have been activated during the stimulation tests (Cuenot *et al.*, 2005).

From July to December 2005, a circulation test has been running between GPK3 (injection) and GPK2-GPK4 (production). The fluid is produced in GPK2 at 12 l/s and GPK4 at 3 l/s, using only buoyancy effect, then reinjected in GPK3, after circulation in an surface heat-exchanger to decrease the temperature to around 60 °C. This circulation test should help to characterize the system in terms of hydraulics. A longer circulation test is forecast with the help of production pumps to obtain a thermal characterization and to design the surface power plant. And finally, a long-term circulation test should be performed to validate the deep system and the surface installations.

During the injection tests of this phase, the naphthalene disulfonate compounds and fluoresceine are successfully used as tracers because they remain stable with temperature and are not reactive with the environment (Sanjuan *et al.*, 2004). The goal of these tracer tests is to detect hydraulic connections between wells, to know the fluid velocities between wells and within the reservoir and to estimate the proportions of the injected fluids in the discharged fluids versus the geothermal reservoir brines. The study of tracer tests also permit to determine the connected reservoir volume and contributes to the knowledge of the fluid pathways within the granitic reservoir (Sanjuan *et al.*, 2004).

6. Present-day conceptual model of the Soultz geothermal system

At the beginning of the project, the HDR concept consisted in creating a fracture, within an hot and massive rock mass, by hydraulic injection. The water should be injected in a well, circulated into the fracture and warmed up, then to be recovered by a second well in a totally closed system. The 18 years of research at Soultz have permitted to better understand the deep geothermal system and to gradually evolve from the HDR to the EGS concept. At Soultz, the first studies have shown that the granite is highly naturally fractured and that natural fluid (brines) is present within the largest fractures, which are hydrothermally altered. Then, the effect of hydraulic stimulation contributes mainly to re-activate by shearing the pre-existing fracture zones in the vicinity of the wells. The geothermal system consists on an exchanger between the wells and this exchanger is connected at a more larger and open system. Now, the adapted concept to Soultz is closed to an EGS (Enhanced Geothermal System) concept and rather far from the initial HDR concept.

The last experiments and deep-seated geology studies have permitted to precise the conceptual model. It appears that the Soultz reservoir is constitute by an interconnected permeable fracture network within an impermeable granitic rock mass. This network presents two scales of fractures. The small-scale fractures constitute by fine interconnected network. The large-scale fractures, which constitute the most important reservoir. These fractures are large fracture or fault zones developing hydrothermal alteration (Genter *et al.*, 1998), which could be consider at small-scale as a porous medium bearing natural brine.

Around the wells, the stimulation tests have permitted to increase the permeability mainly by shearing in fractures or dissolving calcite in the close vicinity of the wells. Then, some irreversible openings have been created by dilation or leaching within the fractures (Gentier *et al.*, 2005; Gérard *et al.*, 2005).

7. Conclusions

The deep geothermal technology started to fulfill renewable energy needs, as the available fossil fuels slowly reduces. The concept is simple but the development of the technology is complex and still remains in an experimental phase. Our understanding of both system creation and behaviour has significantly evolved during the different phases of the Soultz project. It is clear now that there is not an unique concept for the deep geothermal systems.

However, several key parameters must be known during the reconnaissance phase and before the design of the geothermal system:

- The relationship between depth and temperature is one of the key economic criteria because it will provide the depth to which the wells have to be drilled. The main objective depends from the temperature which could reached: generate electrical power and co-generation with hot water for heating seem the most promising targets.
- Deep-seated geology: crystalline basement has been preferred medium in order to optimize the deep drilling conditions. The knowledge of the petrography of the rock mass and of its hydrochemical mineralization is important to envisage chemical stimulations.
- The distribution of fractures with depth and their orientation is also very critical. In the Soultz case, the hydrothermalised fracture zones play a dominant part for flows of in-situ brines in natural convection and for connecting the wells to the external geothermal reservoir and between them.
- The stress regime is an another critical factor for the creation of the exchanger and for heat extraction. The main orientation of fractures in relationship with the maximum principal stress direction is essential for fluid circulation.

The advantages of the deep geothermal system are mainly its large potential resources and accessibility over large regions of the Earth's surface, and, of course, the environment respect (Genter *et al.*, 2003). However, there is no on-going commercial deep geothermal system plant yet in existence to provide real data on building, operating and maintenance costs for planning future units.

8. Acknowledgements

The authors are grateful to Dr. A. Gérard for the review of the manuscript and the GEIE EMC Soultz team, as well as to Dr. B. Sanjuan (BRGM) and M. Degouy (CFG Services) for their help.

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Annex 1

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