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Editorial

The deep EGS (Enhanced Geothermal System) project

at Soultz-sous-Forêts (Alsace, France)

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1. The EGS concept

The original European Hot Dry Rock (HDR) project at Soultz-sous-Forêts was renamed as an Enhanced Geothermal System (EGS) project in 2001 after ascertaining that the fractured granitic basement rocks of the Upper Rhine graben contained large volumes of hot saline fluid. The EGS[1] concept consists simply of drilling at least two boreholes (a "doublet") into deep fractured rock, extracting hot fluid from a production well and injecting the cooled fluid

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[1]In this issue both "EGS" and "HDR" are terms used by the members of the Soultz team and have been considered synonymous.

back into the fractured reservoir through an injection well, after both boreholes have been stimulated so as to connect the two wells to the natural surrounding geothermal reservoir by artificially enhancing the permeability of the natural network of fractures in their vicinity. This may imply some direct connections between the wells through natural fractures. Contrary to conventional hydrothermal reservoirs, Enhanced Geothermal Systems require stimulation, since the rock mass permeability in the vicinity of the boreholes is generally too low for economic heat recovery. EGS conditions have been identified at drillable depths in many locations within Europe, and are considered such wherever deep and widespread convective hydrothermal systems in the basement rock are able to produce sufficiently high geothermal gradients (Genter et al., 2003). The EGS, in theory, will provide abundant environmentally friendly quantities of heat or electricity in the future.

2. Brief history of the Soultz project

After a preliminary analysis of the regional data, directed at mapping the geothermal resources within the Upper Rhine graben and carried out by BRGM on the French side and by the State Geological Survey of Baden-Württemberg on the German side (Munck et al., 1979), the initial exploration program at Soultz was drawn up by Gérard et al. (1984). Drilling operations and the associated scientific activity started in 1987 within the framework of a European co-operation agreement signed in the village of Kutzenhausen, Alsace, France (Gérard and Kappelmeyer, 1987).

Over the next ten years or so, a series of geological, geophysical and hydraulic investigations was undertaken, as well as the drilling and stimulation of the first boreholes (Table 1); these were followed by the first long-term (4 months) circulation test between boreholes GPK1 and GPK2, at about 3 to 3.5 km depth (Gérard et al., 2002), carried out in 1997 (Fig. 1). The test demonstrated that it is possible to produce hot brine at a stable flow-rate and constant temperature with zero fluid addition when the heat-depleted (cooled) brine is reinjected. The electric power required to operate the geothermal doublet was small in comparison to the thermal energy produced (Gérard et al., 1998). Tracer tests showed that the stable flow and temperature observed could be due to the fact that around 30 per cent of the reinjected fluid was recovered by the production well (Fig. 1).

The objective of the initial phase of the Soultz project was to identify the characteristics of the crystalline rock forming the geothermal reservoir, and to validate the heat extraction process from the technical rather than the economic standpoint. At the end of the 1997 circulation test the decision was taken to continue the experimental work to develop the first EGS pilot project for electricity production. This meant deepening the boreholes to 5 km, where they encountered temperatures of 200°C typical of the Upper Rhine graben (Genter et al., 2003).

In 2005, after 5 years of work, construction of the underground part of the pilot scheme was almost complete. Drilling operations ended in April 2004. Downhole logging verified the parameters of the deep system, in particular the temperature and stability of the open-hole (uncased) sections of the boreholes before stimulation(s). To reduce the risk of hydraulic short-circuiting between wells GPK2, GPK3 and GPK4, the boreholes were directionally drilled from one platform; they are about 600-700 m apart at depth. This configuration has minimized the footprint of the project on the landscape (one single platform) and has made the surface installations much easier, particularly because the fluid transmission pipelines that will be installed in the future will be of shorter length (Figs. 2 and 3).

3. The Soultz geothermal system

The Soultz geothermal project is located between Soultz-sous-Forêts and Kutzenhausen in the Upper Rhine valley, about 70 km north of Strasbourg, in Alsace, France. In line with graben tectonics, the granitic basement, covered by a 1.5-km layer of sedimentary formations, is characterized by fractures ranging from micro-cracks to large normal faults. The abnormally high geothermal gradient of about 100°C per km within the sedimentary cover results from deep hydrothermal convection loops within the fractured basement. The present targets for heat exploitation are the fractures at 4.5-5 km depth, where temperatures can reach 200°C.

Based on a detailed analysis of cores, drill cuttings and geophysical logs of five deep wells (Cocherie et al. 2004; Hooijkaas et al., 2006), a fairly consistent geological model was developed for the basement. The sedimentary formations in the area are underlain by a massive porphyritic granite that is highly fractured and hydrothermally altered in the vicinity of numerous large faults at 2.7-3.2 km depth; below this is a granite rich in biotite and amphibole, followed, below 4.7 km depth, by a younger fine-grained, two-mica granite that has intruded the older porphyritic granite.

Hydraulic fracturing stress measurements to 3.5 km depth (Klee and Rummel, 1993), analysis of well break-outs (Bérard and Cornet, 2003), and fault-plane solutions of natural and induced earthquakes and microseismic events (Cuenot et al., 2006) have delineated a stress regime typical of graben tectonics, with a horizontal compression oriented NNW-SSE. A dense brine with a salinity of about 100 g/L was extracted during production tests. Although the granite is fractured, the local natural permeabilities of the fractures are too randomly distributed to guarantee stable flow-rates immediately after drilling and therefore require permeability enhancement by stimulation. Based on well log data from borehole GPK2, Sausse et al. (2006) proposed a combined analysis of geophysical logs and hydraulic tests in order to define the spatial distribution of the natural permeable fractures. Early stimulation experiments demonstrated that permeability enhancement is mostly limited to weak natural fractures in the hydrothermally altered, cataclastic shear zones intersected by the boreholes

(Genter et al., 2000; Dezayes et al., 2004; Evans et al., 2005). These structures probably form the natural conduits for fluid movement through the rock mass under natural conditions. Permeability enhancement during stimulation is the result of shear dislocation on these fractures (Evans et al., 2005; Gentier et al., 2005). Thus, the interaction between local permeable fractures and the natural fluid circulation system is crucial to the success of stimulation techniques in EGS projects. To optimize this approach and increase the probability of success, one has to consider all parameters, including mineralogy of hydrothermally altered rock volumes, geochemical fluid composition, fluid-rock interactions, in-situ stress regime, and the 3-D geometry of the fracture networks from meter to regional scale.

The high quality database now available on the Soultz project forms the basis of the papers chosen for this special issue, which include the major geological aspects (Hooijkaas et al., 2006), the convective hydrothermal system (Bataillé et al., 2006), and an innovative proposal for integrating the data from geophysical and flow logs, with particular emphasis on spectral gamma ray logs (U, Th, K content), to investigate the correlation between hydrothermal alteration and preferential flow paths in granite (Sausse et al., 2006).

4. Current status of the Soultz EGS project

During the 5.5 month circulation test performed in 2005 (Fig. 4), a total of 205,000 m^3 of hot brine were produced from boreholes GPK2 and GPK4, using the buoyancy effect and maintaining a wellhead pressure of 0.8 MPa to prevent mineral scaling. The same amount of fluid was reinjected into the central borehole GPK3 (Fig. 5). The results can be summarized as follows:

- GPK2. Production rate: F2 = 12.5 kg/s; bottomhole underpressure: ΔP2 about 1.2 MPa;

  f2 about 0.7 x F2; $f_{3,2}$ about 0.3 F2; productivity index: about 10 kg/MPa · s.

- GPK4. Production rate: F4 = 2.5 kg/s; bottomhole underpressure $\Delta P4$ about 1 MPa;

  f2 about 0.98 x F4; $f_{3,4}$ about 0.02 F4; productivity index: 2.5 kg/MPa · s.
- GPK3. Injection rate: F3 = 15 kg/s; bottomhole overpressure $\Delta P3$ about 6 MPa;

  injectivity index: about 2.5 kg/MPa · s.
- The induced microseismicity was minor and obviously due to reinjection in GPK3.

After roughly 5 months of circulation, about 25 per cent of the injected fluorescein tracer was recovered from borehole GPK2, but only about 2 per cent from borehole GPK4 (Sanjuan et al., 2006). Detailed interpretation of this test will of necessity be based on the results of earlier injection tests and observed microseismicity (e.g. Charléty et al., 2006; Cuenot et al., 2006), and on the results of fluid/rock chemical reaction studies (André et al., 2006).

The stimulation operations performed on the three deep boreholes GPK2, GPK3 and GPK4 have progressed so far that we can consider initiating a long-term circulation test once work has been done on improving the hydraulic performance of GPK3 and GPK4. This should be accomplished by the end of 2006. The long-term test is targeted at (1) evaluating the geothermal resource between 4.5 and 5 km depth, (2) achieving a better understanding of the kinetics and of reservoir behaviour during heat extraction, (3) determining the power required to maintain fluid circulation, and, finally, (4) investigating material corrosion phenomena and scaling prevention within the system.

5. Targets for the future

From the result of the 2005 circulation test, it is evident that the productivity/injectivity of the wells is governed by the spatial distribution of the natural permeability of the fractures in the hydrothermally altered granitic rocks, a distribution controlled by the tectonic regime at Soultz. Consequently, this natural fracture system, the chemical composition of the fracture-filling materials and the in-situ stress regime are of major importance for stimulation and possible hydraulic interconnection of the production and injection boreholes. The major targets are (1) to achieve maximum production rates and (2) to minimize power consumption in maintaining fluid circulation, while simultaneously keeping (3) induction of microseismic events at very low frequency and magnitude and (4) the temperature of the produced fluid as stable as possible. It is evident that, for an EGS operation such as that at Soultz, great care must be taken when defining strategy in order to achieve an efficient balance between an eventual, more or less direct, inter-well underground heat exchanger[2] and the main fluid flow from the “sustained” natural geothermal reservoir[3].

In the near future, this strategy will entail improving the connection between borehole GPK4 and the far-field natural fracture network and, perhaps, borehole GPK3 as well. Similarly, the fairly poor injectivity of borehole GPK3 must be improved, but without triggering seismic events of such high magnitude or frequency as to disturb the local population. The stimulation experiments will be accompanied by modelling studies. Despite the complexity of the medium and the uncertainty in the results of previous tests, several modelling approaches have been shown to contribute to the design of hydraulic stimulation tests that yielded valuable results. For example, Megel et al. (2006) describe tests on the potential impact of very high density brine injection during the initial stimulation phases; Baujard and Bruel (2006) demonstrate the contribution of fluid density to optimizing injection pressure, while Auradou et al. (2006) model the flow chaneling after the opening of fractures, all of which are presented in this issue. Other partners of the Soultz EGS project are, in the meantime, also addressing the effects of combined thermal, hydraulic and mechanical stimulation, which will be the subject of future publications.

[2] As of November 2006, the maximum at Soultz has been 30% of the total production of one well.
[3] As of November 2006, the minimum at Soultz has been 70% of the total production of one well.

In the medium term, the objective is to construct the first EGS pilot plant for producing electricity (in the order of 1.5 MW) in 2007. Attention is already focussed on:

- pumping technology, using downhole pumps in the production boreholes and surface reinjection pumps for fluids of high salinity and high temperatures and, hence, variable density (Champel, 2006);
- the risk of inducing microseismicity of magnitude or frequency that is environmentally unacceptable;
- corrosion and scaling problems in borehole casings and all components of the pipeline circulation system;
- operation of the cooling system and surface heat exchanger;
- thermodynamic conversion technology.

The long-term prospective is to engage in the construction and operation of a commercial-scale EGS-prototype by the year 2010. Such a prototype could generate up to 25 MW electrical power and become a standard module by the year 2015, after extensive testing and improvement of the first pilot plant. This objective will also entail a careful evaluation of the economics of EGS technology (Delacroix, 1999), which is addressed in this issue by Heidinger et al. (2006).

Even further in the future, it is envisaged that EGS-type geothermal power plants might be created in other European regions with geological, thermal and hydraulic conditions similar to those tested within the Upper Rhine valley at Soultz, as well as in other regions with different characteristics. Projects of this type are already in preparation in locations with high heat demand (e.g. Grosse et al., 2004). Standardization of EGS/HDR modules and plant management will significantly reduce the development and construction costs so as to compete with more conventional hydrothermal systems such as those in Tuscany (Italy) and elsewhere.

6. Conclusions

Over the past 20 years, a number of European research teams have worked on putting together a detailed picture of the deep hot granitic basement at the site of the Soultz EGS project. The underground geothermal reservoir consists of a network of interconnected fractures and large faults of randomly variable permeabilities. The fractures with distinct hydrothermal alteration halos can be interpreted as the equivalent of a heterogeneous porous medium filled with natural brine. By hydraulic and chemical stimulation, the natural permeability of the fracture network has been significantly increased around the boreholes through induced shear and chemical leaching.

Although some crucial problems still exist for an efficient production and reinjection scheme for the three existing 5-km deep boreholes, a valid conceptual model for energy exploitation has been developed specifically for the site at Soultz. This model will lead to the construction of the first EGS power plant as a prototype for future standard EGS schemes for extracting the heat stored in subsurface rocks. At present, enhancement of the hydraulic performance of deep boreholes is of the highest priority.

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Table 1. Milestones in the implementation of the Soultz EGS project

Year(s)	Milestones
1984	First formal draft of the Soultz project
1987	Drilling of the first well (GPK1) to 2000 m
1990	Creation of a network of seismic observation wells using old oil wells and detailed exploration down to 2250 m by continuous coring
1992	Deepening of GPK1 to 3600 m; temperature measured: 165°C
1995	Drilling of the second well (GPK2) to 3878 m (horizontal distance between wells: 450 m)
1997	Successful circulation test (25 L/s) between GPK1-GPK2 wells over a four-month period
2000	Deepening of GPK2 to 5010 m; temperature: 203°C. Open-hole stimulation between 4.5 km and 5 km
2002	Drilling to 5 km of well GPK3, in the immediate vicinity of GPK2. Horizontal distance between open holes GPK2-GPK3: about 650 m
2003/2004	Open-hole stimulation in GPK3 and circulation tests GPK3 → GPK2. Drilling to 4985 m of well GPK4. Horizontal distance between open holes GPK3-GPK4: 700 m
2004/2005	Open-hole stimulation in GPK4, followed by circulation tests between the central injection well (GPK3) and the two lateral production wells GPK2 and GPK4

Figure Captions

Fig. 1. Schematic block diagram of the 1997 circulation test performed at Soultz when heat was extracted at a rate of 10 MW. The pumps used to circulate the fluids consumed less than 250 kW of electricity.

Fig. 2. Vertical N-S cross-section through Soultz boreholes EPS1, GPK1, GPK2, GPK3 and GPK4.

Fig. 3. Plan view of the Soultz EGS site showing the horizontal projections of the trajectories of boreholes EPS1, GPK1, GPK2, GPK3 and GPK4.

Fig. 4. The Soultz Enhanced Geothermal System site. (a) View of the site after well drilling had been completed; (b) steam released from the separators during the 2005 circulation test.

Fig. 5. Schematic diagram showing flow rates and downhole over (or under) pressure for the Soultz wells during the 2005 circulation test between injection well GPK3 and production wells GPK2 and GPK4. F and f: fluid flow rates; ΔP: over (or under) pressure at reservoir level.

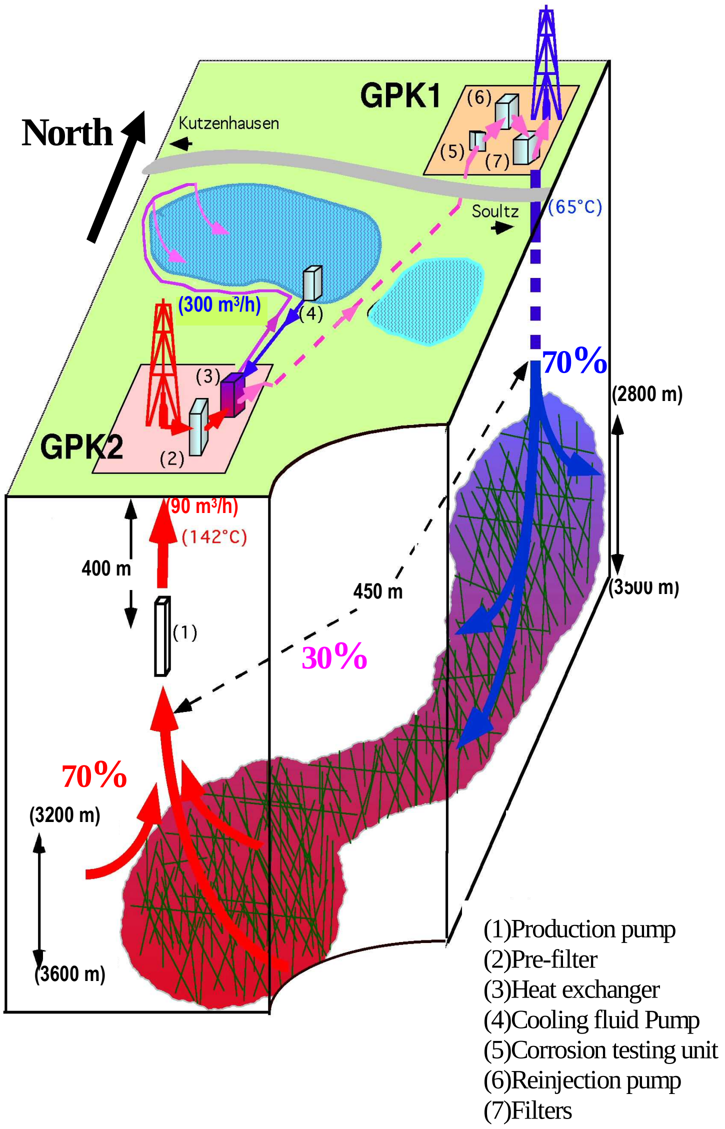
North
Kutzenhausen
GPK1
(6)
(5)
(7)
Soultz
(65°C)
(300 m³/h)
(4)
(3)
GPK2
(2)
70%
(2800 m)
(3500 m)
(90 m³/h)
(142°C)
400 m
(1)
450 m
30%
70%
(3200 m)
(3600 m)
(1)Production pump
(2)Pre-filter
(3)Heat exchanger
(4)Cooling fluid Pump
(5)Corrosion testing unit
(6)Reinjection pump
(7)Filters

Figure 1

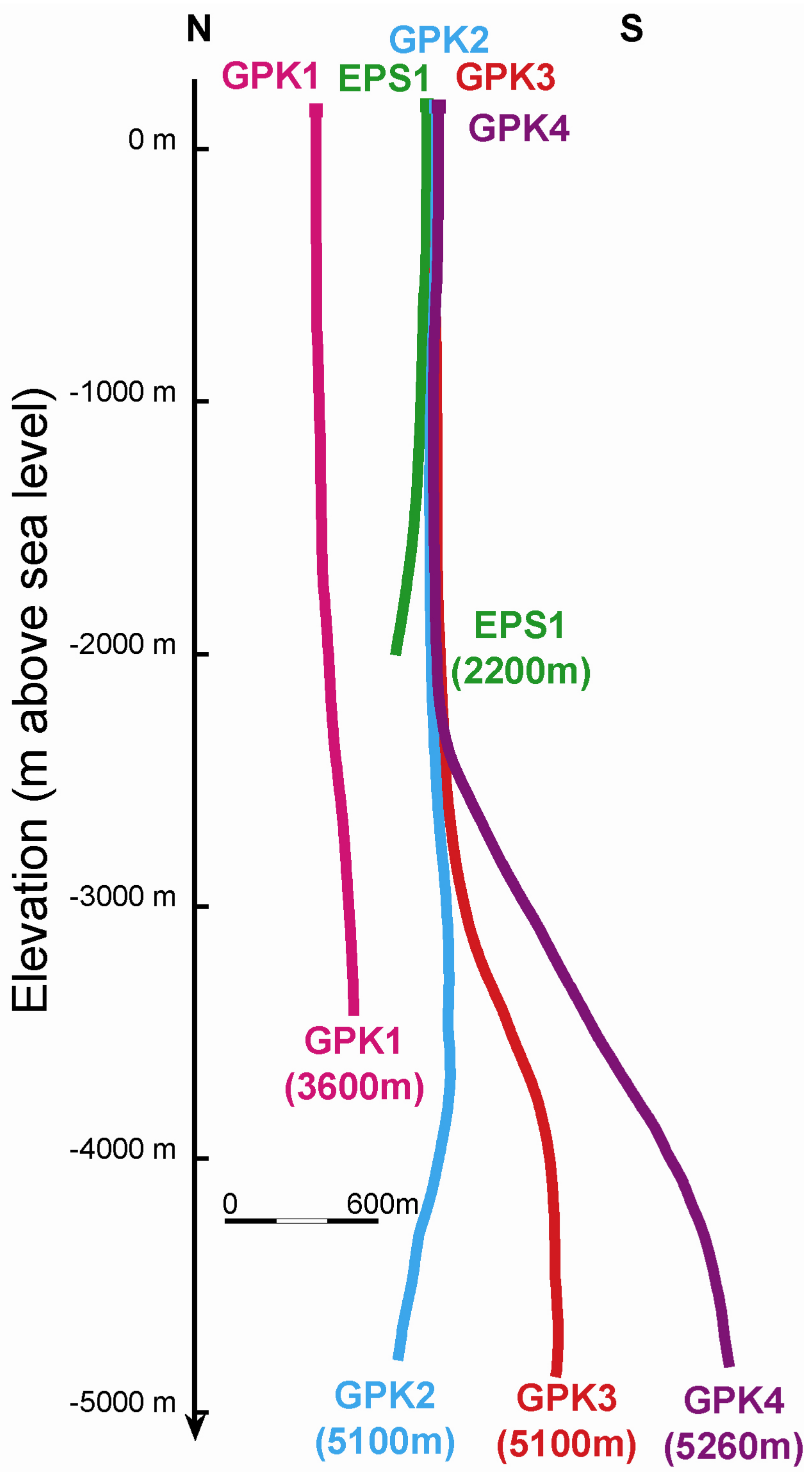
N
S
GPK1
EPS1
GPK2
GPK3
GPK4
0 m
-1000 m
-2000 m
-3000 m
-4000 m
-5000 m
Elevation (m above sea level)
EPS1
(2200m)
GPK1
(3600m)
0
600m
GPK2
(5100m)
GPK3
(5100m)
GPK4
(5260m)

Figure 2

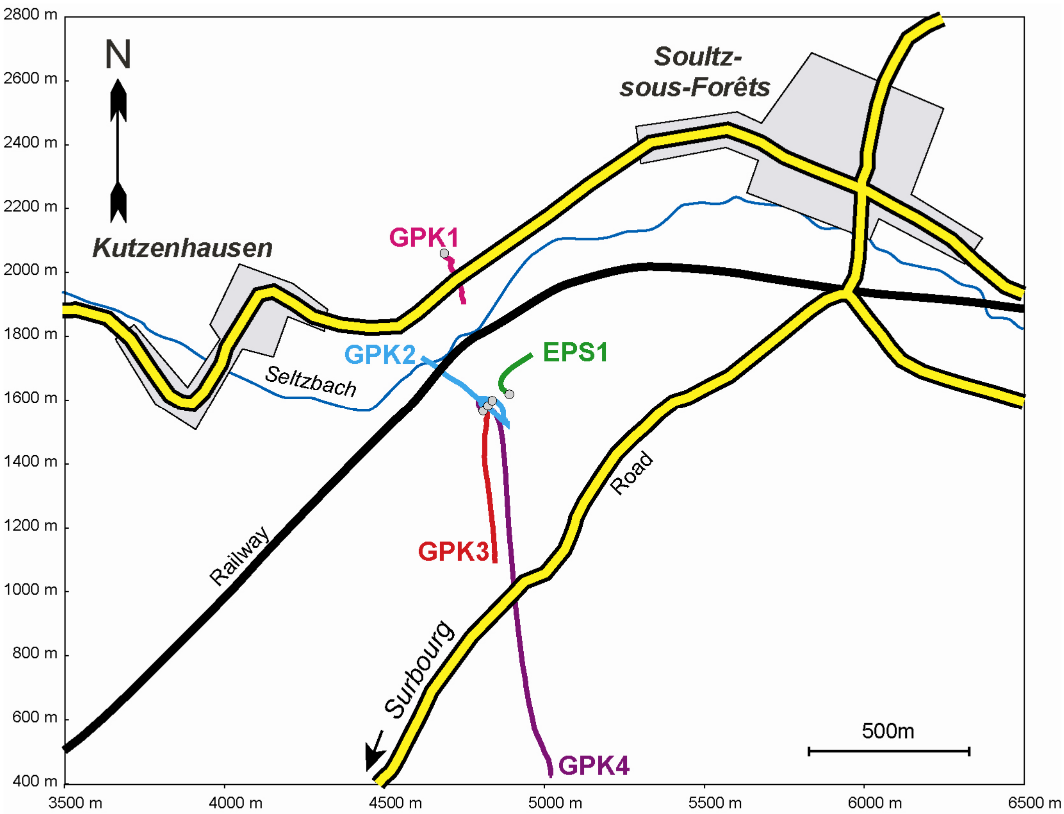
2800 m
2600 m
2400 m
2200 m
2000 m
1800 m
1600 m
1400 m
1200 m
1000 m
800 m
600 m
400 m
3500 m
4000 m
4500 m
5000 m
5500 m
6000 m
6500 m
N
Soultz-
sous-Forêts
Kutzenhausen
GPK1
GPK2
EPS1
Seltzbach
GPK3
GPK4
Railway
Road
Surbourg
500m

Figure 3

Figures 4,a and 4,b

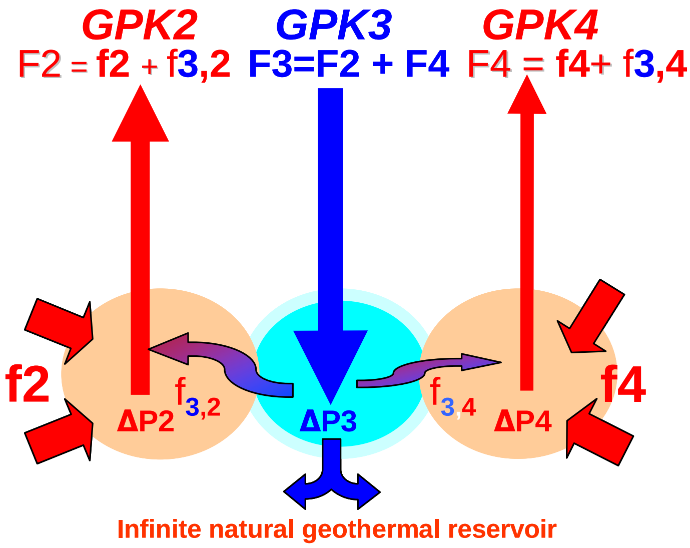
GPK2
F2 = f2 + f3,2
GPK3
F3=F2 + F4
GPK4
F4 = f4+ f3,4
f2
ΔP2
f3,2
ΔP3
f3,4
ΔP4
f4
Infinite natural geothermal reservoir

Figure 5