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Internal geophysics

Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS)

Apport de l'exploration du réservoir cristallin fracturé de Soultz à la connaissance des systèmes géothermiques stimulés

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ABSTRACT

Over the past 20 years, the Soultz experimental geothermal site in Alsace, France, has been explored in detail by the drilling of five boreholes, three of which extend to 5 km depth. Data on geology, fluid geochemistry, temperature, microseismicity, hydraulics and geomechanics have been collected and interpreted by the various teams from the participating European countries and their international collaborators. Two reservoirs have been developed within granite at depths of 3.5 and 5 km. The reservoir at 3.5 km was formed from two wells, 450 m apart, both of which were subjected to hydraulic stimulation injections. The system was circulated continuously for 4 months at 25 kg/s in 1997 using a downhole pump, and yielded results that were extremely encouraging. The impedance reduced to 0.1 MPa/l/s, the first time this long-standing target had been attained. Construction of a deeper system began shortly afterwards with the drilling of 3 deviated wells to 5 km true vertical depth, where the temperature was 200 °C. The wells were drilled in a line, 600 m apart at reservoir depth, and all were hydraulically stimulated and subjected to acidization injections. The 3-well system was circulated under buoyancy drive for 5 months in 2005 with injection in the central well, GPK-3, and production from the two outer wells, GPK-2 and GPK-4. This showed good linkage between one doublet pair, but not the other. Further acidization operations on the low-productivity well led to its productivity increasing to almost the same level as the other wells. Construction of a power plant at the site was completed in 2008 and a trial circulation with a production pump in one well and the other shut-in was conducted with power production. Downhole pumps are now installed in both production wells in preparation for long-term circulation of the system. In this article we present an overview of the principal accomplishments at Soultz over the past two decades, and highlight the main results, issues identified, and lessons learnt.

RÉSUMÉ

Le site expérimental de Soultz-sous-Forêts en Alsace est le siège d'exploration géothermique par forages profonds depuis plus de 20 ans. En effet, un granite caché sous couverture sédimentaire est le siège d'une anomalie thermique dont l'intensité est

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unique en France. Des travaux sur la géologie, la géochimie des fluides, les températures, la micro-sismicité et l'hydraulique du site, ainsi que des calculs prédictifs via de la modélisation couplée ont été réalisés par de nombreuses équipes scientifiques en Europe. La partie supérieure du réservoir fracturé située à 3,5 km de profondeur a été stimulée à partir de 2 forages distants de 450 m. Plusieurs tests de circulation de fluide en boucle (1997, 2005), réalisés entre les puits profonds, ont montré qu'au moins 30 % du fluide injecté pouvait être récupéré dans les puits producteurs et que cette récupération limitée était, par ailleurs, toujours compensée par une contribution de saumure naturelle, caractérisant ainsi la présence de zones fracturées ouvertes, en connexion directe avec un réservoir géothermique profond. En 1997, les 4 mois de circulation avec un débit massique de 25 kg/s ont conduit à des résultats très encourageants, caractérisés par une chute de l'impédance hydraulique à 0,1 MPa/l/s. La réalisation du dispositif souterrain constitué de trois puits déviés, forés à 5 km de profondeur (deux producteurs, un injecteur) a permis d'atteindre une température de 200 °C. Les 3 puits sont alignés parallèlement à la direction principale de fracturation et à celle de la contrainte majeure horizontale SHmax. Distants au fond de 600 m, ils ont fait l'objet de stimulations hydrauliques puis chimiques. Les premières augmentent les performances hydrauliques du réservoir fracturé, mais génèrent une sismicité induite qui peut être parfois gênante pour les populations, avec quelques séismes de magnitude supérieure à 2. Les secondes permettent de dissoudre les remplissages minéraux qui tapissent les fractures (calcite, argiles, quartz secondaire) ou encore les débris de forage qui sont restés piégés à la fin des opérations de forage. L'impact hydraulique des stimulations chimiques est moins fort que celui lié aux stimulations hydrauliques. Ainsi, la sismicité induite et les nuisances associées sont mineures pendant les traitements chimiques. En 2005, le test de circulation réalisé en production artésienne a mis en évidence une bonne connexion inter-puits, mais sur une partie seulement du triplet. En effet, en raison de la complexité du réseau de fractures, une forte dissymétrie hydraulique du dispositif a été mise en évidence. Des stimulations chimiques additionnelles ont été réalisées sur le puits le plus faiblement producteur et ont amélioré ses performances. En 2008, une centrale géothermique binaire a été construite et testée. Des technologies différentes de production (pompes immergées) ont été installées dans les puits de production et le premier kilowatt d'origine géothermique a été produit. Finalement, ce papier présente les principaux résultats scientifiques acquis à Soultz et les principales leçons déduites après plus de 20 années de recherches.

1. Introduction

1.1. EGS in the world

Enhanced (or engineered) geothermal systems (EGS), previously known as hot dry rock (HDR) systems, arose from a concept initiated in Los Alamos (USA) and Cornwall (UK) for exploiting the vast energy resource that resides as heat in the low-permeability rocks which underlie most continental regions at practically-drillable depths. The central concept is to engineer hydraulic linkages between two or more boreholes within the target reservoir to permit circulation of fluid through the hot rock at rates of commercial interest. A great deal of work has been conducted in classic HDR settings to learn how to engineer linkages that have the favourable characteristics of a heat exchanger (see MIT report on the future of geothermal energy (Tester et al., 2006)). The Soultz reservoir significantly deviates from a classic HDR system in as much as it contains permeable structures that host substantial volumes of natural brines. Over 20 years of intense exploration and testing of the Soultz reservoir has produced a huge quantity of geoscientific data that is valuable not only to geothermal development, but to the Earth science community at large.

1.2. The EGS challenges

Soultz-like EGS projects are characterized by the occurrence of large volumes of natural brines contained in fractured crystalline rocks, whose natural permeability is very low due to the poor hydraulic connection within the fracture network. To achieve circulation through the rock mass at rates needed for commercial energy production, the permeability of the rock mass must be increased or "stimulated" by applying various techniques such as hydraulic or chemical stimulation. Hydraulic stimulation acts mechanically by shear dilation through the injection of large-volumes of water at high pressure, but generates nuisances such as induced seismicity. Chemical stimulation dissolves the secondary minerals sealing the natural fractures and thus can also increase the productivity. However, mineral precipitation in the fractures due to water-rock interactions can also decrease the permeability. If the stimulation effect is successful, geothermal wells are then better connected to a far field reservoir which can be exploited by hydraulic circulation. Thus, hot natural brine is pumped from the production well, transfers its energy to the power plant at surface to produce electricity and/or heat and is then re-injected at a lower temperature into the fractured rock mass.

The development of EGS technology by deep drilling within the upper crustal lithosphere faces many scientific and technical challenges. Among them, a major issue is to improve poor hydraulic connections between production/re-injection wells and the fractured reservoirs by optimizing well trajectories, taking into account of stress field orientation and fracture geometry. Moreover, the physical processes and mechanics of induced seismicity in geothermal systems are still poorly understood and represent a major challenge to be addressed. Finally, the long term hydraulic circulations between wells inducing flow, heat transfer and chemical reactions must be evaluated and their behaviour modelled and forecasted.

1.3. The Soultz adventure

The Soultz geothermal project was initiated by a French-German team in 1986 (Gérard and Kappelmeyer, 1987; Gérard et al., 1984) and has thus been running for more than 20 years. Early phases of the project were supported entirely by public funds from France, Germany, the European Union and a contribution from Switzerland, but since 1996 the work has been increasingly co-funded by the energy industry. The project has produced a substantial body of data that has proven relevant not only to geothermal but also to the geosciences community as a whole. The drilling of three boreholes to 5 km, the deepest penetration of crystalline rock in France, has yielded fundamental insights into the geology, characteristics of natural fractures, fluid geochemistry, temperature and hydraulic properties of deep crystalline rock masses. However, the immediate focus of the various European teams involved in the project (Baumgaertner et al., 1998; Baria et al., 1999; Gérard et al., 2006) has been the development, testing and modelling of two EGS reservoirs within the basement at 3.5 and 5 km depth. A rich and diverse set of data has been collected, including geological (hydrothermal mineralogy, structural geology, petrophysics), hydraulic, borehole logging, microseismic and active seismic data, that provides insight into the hydro-thermo-mechanical and geochemical behaviour of a deep crystalline basement subject to forced fluid flow conditions. These 20 years of scientific and technical activities have produced about 40 PhD theses and more than 200 publications in peer reviewed journals. This article presents an overview of the main phases of the project, and highlights the key results and milestones that mark the progress in this ongoing project to date.

2. Phases of the Soultz project

Work at the Soultz site can be broken into three phases: a preparatory phase, a drilling, exploration and reservoir development phase that extended from 1987 to 2007, and a power plant construction phase. The preparatory phase involved the compilation of existing literature and a site survey conducted using data from existing (oil industry) holes and the reinterpretation of old petroleum reservoir measurements. The drilling, exploration and reservoir development phase consisted of three sequential campaigns (Table 1). After an early phase of exploration drilling (GPK-1, EPS-1) at shallow depth (2 km), GPK-1 was deepened to 3600 m and GPK-2 drilled to 3880m. The Soultz project then obtained convincing results between 1991 and 1997. A 4 month circulation test was successfully achieved between these 2 wells in the upper fractured granite reservoir at 3.5 km. Based on these encouraging results, GPK-2 was recased and deepened, and two further deviated wells (GPK-3 and GPK-4) were drilled down to 5 km depth between 1999 and 2004 to reach down-hole temperatures of 200 °C (Fig. 1). The geothermal wells are fully cased from surface down to 4.5 km depth and are in open section below with an 8.5 inches diameter. Geothermal water is pumped from the production wells (GPK-2, GPK-4) and re-injected at lower temperature into the injection well GPK-3. In plan, the 3 deep-deviated wells are roughly aligned with the N170°E orientation which is the main orientation of both the fracture network and that of the present-day maximum principal horizontal stress (Fig. 2).

The main results and learning curve deduced over the 20 years of the Soultz basement exploration and exploitation can be summarized as follows. The temperature gradient between 2 and 3.5 km was not as high as expected

Table 1
Main phases of the Soultz project between 1984 and 2009.

Tableau 1
Principales phases de développement du projet Soultz entre 1984 et 2009.

1984–1987	1987–1991	1991–1998	1999–2007	2007–2008
Preparatory phase	Exploration phase	Creation of the two wells system GPK1/GPK2 at –3600 m	Creation of the three wells system GPK2/GPK3/GPK4 at –5000 m	Construction of the first power production unit
Literature compilation	Drilling GPK1 at –2000 m	Deepening of GPK1 at –3600 m and hydraulic stimulation	Deepening of GPK2 at –5080 m and hydraulic stimulation	Power plant construction
Seismic survey reprocessing and interpretation	Coring EPS1 at –2227 m	Drilling of GPK2 at –3880 m and hydraulic stimulation	Drilling of GPK3 at –5100 m and hydraulic stimulation	Installation of the LSP pump in GPK2 at –250 m
Permitting and drilling preparation		Circulation test between the 2 wells (4 months)	Drilling of GPK4 at –5270 m and hydraulic stimulation	Inauguration of the power plant mid 2008
			Circulation test between the 3 wells (5 months)	Installation of the ESP pump in GPK4 at –500 m
			Complementary chemical stimulations	Inter wells circulation tests

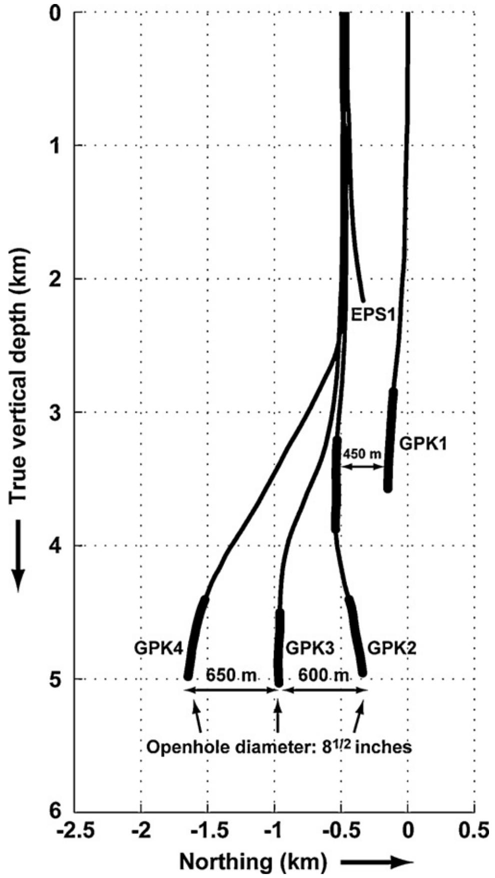

Fig. 1. South-north vertical cross-section through the Soultz site showing the location of the upper and lower Reservoirs. The view shows the three 5 km deep geothermal wells (GPK-2, GPK-3, GPK-4) that are completed open-hole in the lower reservoir, and the wells GPK-1 and GPK-2 that formed the upper reservoir. The thicker lines indicate the open-hole sections of the geothermal wells. Also shown is the cored exploration well EPS-1. Depths are expressed in True Vertical Depths (TVD).

Fig. 1. Coupe verticale sud-nord au travers du site de Soultz montrant la localisation des réservoirs supérieur et inférieur. Cette coupe montre les trois puits géothermiques profonds (GPK-2, GPK-3, GPK-4), ainsi que la section ouverte en trait plus épais et les puits GPK-1 et GPK-2 qui formaient le réservoir supérieur. EPS-1 est un puits d'exploration entièrement carotté. Les profondeurs sont des profondeurs verticales corrigées de la déviation.

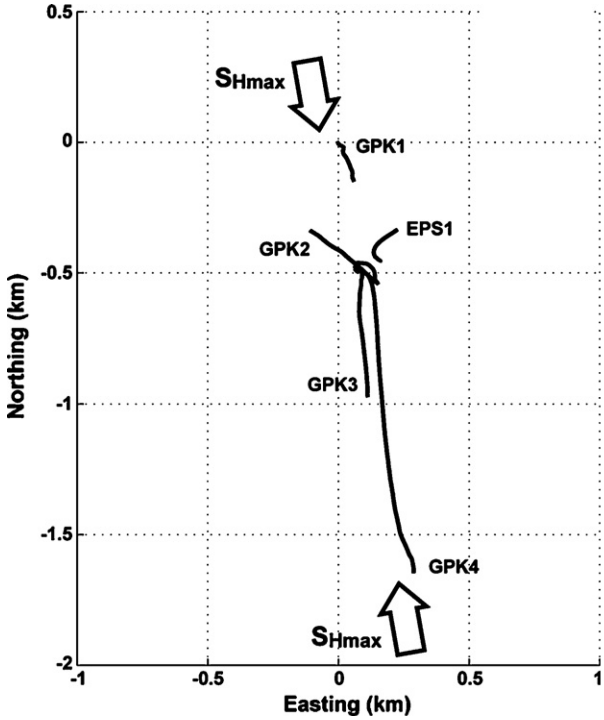

Fig. 2. Local map view of the Soultz site, GPK-1 being a local reference. The trajectories of the deep geothermal wells GPK-2, GPK-3 and GPK4 are roughly parallel to the maximum horizontal stress SHmax. GPK-1 and EPS-1 are former exploration wells.

Fig. 2. Carte locale du site de Soultz, l'origine du repère étant le forage GPK-1. La trajectoire des puits géothermiques profonds GPK-2, GPK-3 et GPK-4 est globalement parallèle à la contrainte horizontale maximale SHmax. GPK-1 et EPS-1 sont des puits anciens d'exploration.

due to the occurrence of natural circulation within fractures. Hence, to achieve the industry's requirement of 200 °C, the boreholes were deepened to 5 km. Geothermal wells were drilled from the same pad in order to simplify the layout of surface equipment. However, although it was challenging to drill deviated boreholes in hard, fractured, crystalline rocks at 5 km depth, the times to completion in each case were only 5–8 months. Drilling and testing experience showed that not all fractures were productive, reflecting the hydraulic complexity of the natural fracture system with its attendant hydrothermal alteration. Finally, hydraulic circulation tests conducted at various depths showed that hydraulic connections between wells up to 600 m apart that can be established are rather good (Fig. 1). However, it is clear that a major contribution to the hydraulic linkage comes from the pre-existing, far-field structures that constitute a natural reservoir.

3. The Soultz geothermal system from regional to concession scale

The Soultz geothermal area is located in the Upper Rhine Graben (URG), which is part of the European Cenozoic rift system that extends from the Mediterranean to the North Sea coast (Ziegler, 1992). The URG started to form during Late Eocene in response to NNE trending Alpine compression (Bourgeois et al., 2007) and in the region of Soultz, the faulted granitic basement is overlain by 1400 m of sediments. The URG's deep thermal structure, which is likely to be related to mantle uplift, was investigated by deep seismic surveys (Brun and Wenzel, 1991). Relief of the rift borders is still important and the Moho topography shows an important rise up to 24 km depth in the southern URG (Dèzes et al., 2004; Edel et al., 2007). The shallow heat flow in the graben ranges between 100–120 mW/m^2 (Pribnow and Schellschmidt, 2000). Extensive borehole data show that the temperature within the graben at depths of 1 km is highly variable, the thermal anomaly at Soultz being particularly high. The mineralogical composition of the Soultz granites is relatively poor in radiogenic elements with less than 7 ppm of uranium (Stussi et al., 2002). This is insufficient to explain the geothermal anomaly which is mainly controlled by natural fluid flow.

The sediments of the Soultz area were already well explored before the project began because they host the Pechelbronn-Merkwiller oil field. The Tertiary filling sediments are marine and lacustrine limestones, marls and evaporites, including the petroleum layers of Pechelbronn, unconformably overlying the Jurassic limestones, the German Triassic layers and the Permian sandstones. These Cenozoic, Mesozoic and Permian sediments have been deposited on the Paleozoic basement, which includes porphyritic monzo-granite and two-mica granite. More than 5000 oil wells were drilled prior to 1970, giving an excellent overview of stratigraphy and structures within the post-Paleozoic sediments. Temperature measurements in ~500 of these wells identified the exceptionally high temperature gradients that define the Soultz geothermal anomaly, and showed that the isotherms are primarily influenced by the tectonic structure of the Rhine graben (Haas and Hoffmann, 1929). As can be seen on Fig. 3, there is a strong lateral variation in geothermal gradient, which is especially marked in the vicinity of the fault at Soultz-sous-Forêts where the hottest zone at 400 m depth is located along the western part of the Soultz horst and is characterized by a NE-SW elongation (Gérard et al., 1984). A structural evaluation of this area was performed by (Schnaebele et al., 1948) in 1948 for oil exploitation purposes. They noted that the area was compartmented by normal faults which induce a horst and graben structure.

In the 1980s several oil companies conducted seismic exploration in order to image fault structures within the sedimentary section. Thus, prior to the drilling of GPK-1, the depth of the top of the crystalline basement was known from both seismic reflection profiles and an old oil well drilled close to the site. This well, denoted as 4616, was drilled down to 1403 m and reached the basement at 1380 m. A core taken at the base of this well showed a granite. The first geothermal exploration well at Soultz, GPK-1 (Fig. 1), was drilled into the top of this area in 1987–1988 (Cautru, 1988; Gérard and Kappelmeyer, 1987). All these data were available and were partly reinterpreted during the preparatory phase of the project, prior to the drilling of GPK-1.

4. Main scientific outcomes from exploration to reservoir development

4.1. Geology

The crystalline basement is encountered at about 1.4 km depth below the sedimentary section, and consists of Paleozoic granites that are highly fractured at all scales, from micro-cracks at grain scale to fracture or faulted zones. In the Soultz granite, two main natural fracture organizations are recognized: individual fractures that are seen in cores and borehole image logs that are pervasively distributed in the rock mass, and fracture zones which are

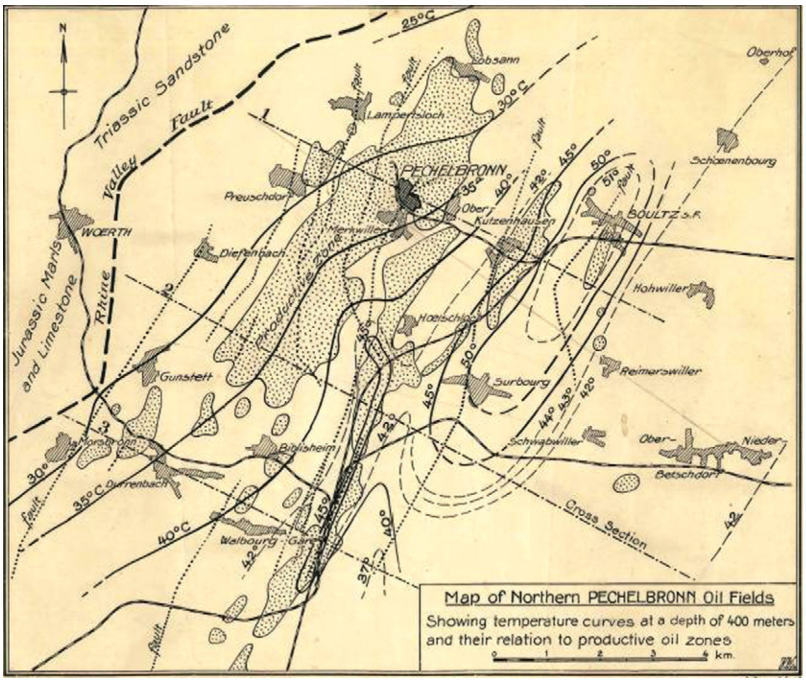

Fig. 3. Historical document showing temperature map at 400 m depth based on oil well measurements in the Pechelbronn-Soultz area, from (Haas and Hoffmann, 1929). Hatched areas represent village location and stippled areas represent oil productive zones.

Fig. 3. Document historique montrant la carte des températures à 400 m de profondeur, établie à partir de mesures réalisées dans des forages pétroliers dans le secteur de Pechelbronn-Soultz, d'après (Haas and Hoffmann, 1929). Les surfaces hachurées représentent les villages et les surfaces en pointillés les zones productives de pétrole.

larger-scale structures of highly clustered natural fractures that have thicknesses of up to 10–20 m. Fracture zones are observed from various borehole data (core, geophysical logs, borehole image logs) but also imaged far from the wells by vertical seismic profiling (VSP) (Sausse et al., 2010) and their microseismic expression during injections (Dorbath et al., 2009; Evans et al., 2005b). Hydrothermal alteration is generally intimately associated with fracture zones.

Many small-scale fractures have been identified from coring and imaging logs in the Triassic and Permian sandstones (i.e. Buntsandstein layer) as well as in the granite basement (Genter and Traineau, 1992). They are nearly vertical and have orientations that vary around N175°E in the Buntsandstein sandstones and from N160°E to north-south in the Paleozoic granites. These directions differ from those observed at the surface in this part of the Rhine graben, which are about N20°E to N45°E. In the granites, about 40 fracture zones have been identified between 1400 and 5000 m depth (Dezayes et al., 2010). These are high-angle structures that predominantly strike ~N160°E ± 10°, although secondary sets that strike N20°E ± 10° and N130°E ± 10° are also present. The fracture zones vary in scale from several tens of metres, suggested by core and imaging logging, to at least several hundred meters indicated by microseismic imaging (Evans et al., 2005b; Genter et al., 2000; Genter et al., 1997). There is also geological and geophysical evidence to suggest that deep wells GPK-2 and GPK-3 may be linked by a fracture zone with an extent of at least 3 km (Sausse et al., 2010). A detailed 3-D analysis of the spatial distribution of fracture zones imaged in the wells has been performed to give a geometrical image of the larger structures in the reservoir (Dezayes et al., 2010; Sausse et al., 2010).

Two petrographically-distinct granite units are encountered in the section to 5 km depth: a grey porphyritic monzo-granite (334 ± 4 Ma) to about 4.5 km depth, and a grey fine-grained two-mica granite (327 ± 7 Ma) below (Cocherie et al., 2004; Stussi et al., 2002). Some Hydrothermally Altered Fracture Zones (HAFZ) showed a low natural permeability, evidenced by the occurrence of brines in the drilling fluid returns (the formation fluid has 100 g/L of dissolved solids) (Vuataz et al., 1990) and in subsequent hydraulic and geophysical testing (Evans et al., 2005a; Schellschmidt and Schulz, 1991). These HAFZ showed both high fracture density and strong hydrothermal alteration (Genter, 1989). Both fossil and present-day natural fluid circulations in the fractures have resulted in a strong dissolution of the primary minerals such as biotite and plagioclase, and a significant deposition of some altered minerals (Fig. 4) such as clay minerals (illite, tosudite), calcite, secondary quartz and sulfides (Genter and Traineau, 1992). Organic matter was also observed in strongly altered granite in EPS-1 well (Ledésert et al., 1996), indicating hydraulic communication between basement and sediments at some time in the past. Most of these geological results were known after the drilling of GPK-1 down to 2000 m and the coring of EPS-1 to 2230 m. Subsequent drilling campaigns to 3.8 km and eventually to 5000 m depth largely confirmed the previous results, and revealed the two-mica granite below 4.5 km.

Fig. 4. Example of hydrothermally altered and fractured granite core taken at 1377 m depth in GPK-1 well showing a nearly vertical sheared fracture.

Fig. 4. Exemple de carotte de granite fracturé et altéré, prélevé à Soultz dans le puits GPK-1 à 1377 m de profondeur. On notera la présence d'une fracture subverticale à jeu apparent cisaillant.

4.2. Stress state

The stress state at Soultz is consistent with a graben setting, with a minimum principal stress that is horizontal and about 53% of the vertical stress. The maximum horizontal principal stress, SH_{max}, is oriented

N169°E ± 14°. The large standard deviation is due to variations in stress orientation that occur more or less continuously along the wells reflecting stress perturbations associated with fractures and fracture zones (Valley, 2007). The alignment of the wells at Soultz was chosen to coincide approximately with SH_{max}. The principal stress magnitudes are given as a function of depth z, by (Valley and Evans, 2007):

S_v [MPa] = 0.3 + 25.60z [km]
Sh_{min} [MPa] = –1.8 + 14.09z [km]
–1.2 + 22.95z [km] ≤ SH_{max} [MPa] < –1.4 + 26.775z [km]

The vertical stress, S_v is derived by integrating density estimates. The minimum principal horizontal stress, Sh_{min}, is obtained from the maximum pressure attained at the casing shoes of the wells during hydraulic stimulations (Cornet and Bérard, 2003), and conforms well to a linear trend down to the deepest measurement at 4.5 km. The maximum principal stress magnitude, SH_{max}, is constrained by the depth distribution of breakouts and drilling-induced tension fractures (DITFs) to be within 10% of S_v, a result that is consistent with the observation that focal mechanism solutions of micro-earthquakes are a mix of strike-slip and normal (Cuenot et al., 2006b), and with constraints imposed by limits on rock mass strength.

The low value of Sh_{min} implies that shear stresses in the granite are very high. Consequently, many fractures and fracture zones are critically-stressed in as much as they would fail under ambient conditions if their strength was governed by a Coulomb friction criterion with a coefficient of less than 0.95 (Fig. 5 after (Evans, 2005)). The rock mass and the critically-stressed fracture zones within it are clearly very strong, despite the presence of illite within the fracture zones, which is very weak. The strength of the fracture zones is best explained by an internal architecture that involves small-scale fractures connected by relatively intact rock bridges and jogs (Evans, 2005).

4.3. Fluid geochemistry

The collection of a sample of native formation fluid that was free of contaminants, such as drilling fluid proved difficult. The most relevant geochemical data on the nature, origin, circulation and deep temperature of these fluids were obtained from GPK-1 and GPK-2 (Aquilina et al., 1997; Pauwels et al., 1993; Sanjuan et al., 2006a; Sanjuan et al., 2010). Samples collected from the GPK-2 well-head and from depths ranging from 650 to 3470 m have similar chemical and isotopic compositions (NaCl brine with a pH value close to 5) and a high salinity (total dissolved solids (TDS) of about 100 g/L), which suggests that fluids at all depths down to 5 km have a common sedimentary origin and have undergone identical fluid-rock interaction processes. Chemical and gas geothermometers, as well as geochemical modelling simulations, suggest that the native geothermal brine and associated gases (predominantly CO_2) are equilibrated with a mineralogical assemblage at temperatures close to 220–240 °C (> 202 °C measured at the GPK-2 bottom-hole in (Baria

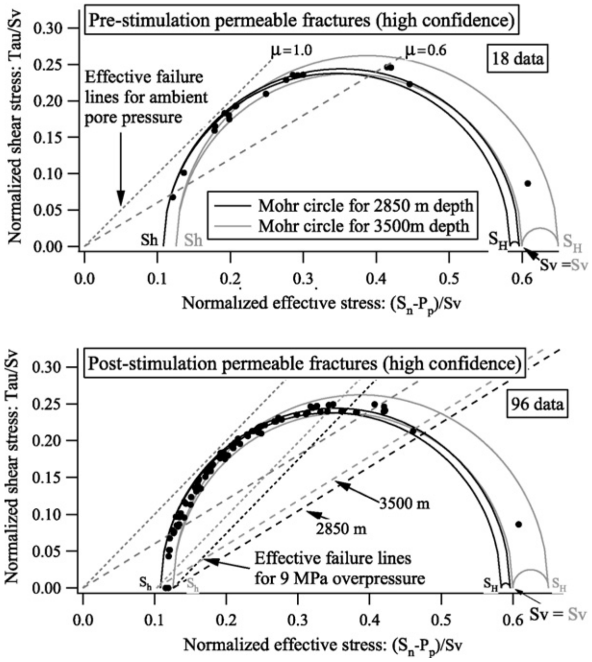

Fig. 5. Mohr circles showing the stress state between 2.85 and 3.5 km from (Evans, 2005). (a) shows the shear and normal stress across fractures that were permeable prior to stimulation. Almost all are critically stressed; (b) shows the same as a) but for the post-stimulation permeable fractures. The failure lines for ambient and 9 MPa overpressure (the stimulation pressure) are shown. The vast majority of newly permeable fractures are critically-stressed. However, many non-permeable fractures (not shown) did not fail but were also critically-stressed.

Fig. 5. Cercles de Mohr montrant l'état de contraintes entre 2,85 et 3,5 km de profondeur d'après (Evans, 2005). (a) montre les contraintes normale et cisaillante s'exerçant sur des fractures perméables avant stimulation : elles sont presque toutes soumises à un état de contrainte critique ; (b) montre les mêmes informations mais pour les fractures perméables post-stimulation, la majorité d'entre elles étant soumises à un état de contrainte critique. Les droites de rupture pour des pressions ambiantes et pour des surpressions de 9 MPa (pression de stimulation) sont présentées. Cependant, de nombreuses fractures non perméables (pas montrées sur la figure) n'ont pas joué, mais étaient également soumises à un état de contrainte critique.

et al., 2001)). Sodium/lithium geothermometers and isotopic lithium values suggest that these equilibrium reactions occurred in a sedimentary rather than a granite reservoir. These constraints collectively suggest that the brine at Soultz has migrated from a reservoir that is situated more towards the Graben centre, where the Triassic sedimentary formations are the deepest and temperatures of 220–240 °C are expected to occur at 4 km depth (Munck et al., 1979). Such migration could have occurred through a complex system of deep faults that is still poorly constrained. A 3D seismic survey would be very useful for imaging the deepest structures of the Rhine graben in the sediments in order to understand better the geological architecture. A tracer test conducted between 2000 and 2002 in the GPK-2 open-hole section below 4.5 km indicated a natural flow rate of native geothermal brine of 1.0–1.2 m^3/h (Sanjuan et al., 2006a,b), which is identical to that calculated from the fluid flow parallel to the Graben strike, based on a convection model and numerical 3D modelling (Bächler, 2003).

4.4. Hydraulics

Hydraulic tests conducted on HAFZs have shown transmissibilities (i.e. the product of permeability and borehole length over which the permeability applies) from zero up to 10^{-11} m^3, whereas the transmissibility of the granite rock mass excluding the high-transmissibility zones is typically 10^{-16} to 10^{-17} m^3 (Evans et al., 2008). The highest transmissibility of 10^{-11} m^3 was measured at a major HAFZ intersected at 2120 m depth in GPK-2 well which, once intersected, resulted in total mud and cuttings loss throughout the subsequent drilling operations. Pre-stimulation testing of the entire GPK-1 open-hole between 2.85 and 3.6 km showed a major transmissive HAFZ at 3.5 km and seven HAFZs of small but non-zero transmissibility spaced every 50–100 m along the well, all of which were critically stressed (Fig. 5) (Evans et al., 2005a). These zones were exclusively activated during the stimulation to become the principal transmissive features in the well. Hydraulic tests performed after hydraulic stimulation showed that the well had been connected to a fault or major fracture zone of large hydraulic capacity through flow paths that emerged into the well at the HAFZs. The hydraulic impedance (i.e. the resistance to flow) of these flow paths exhibited a turbulent-like behaviour that was not limited to the near wellbore region (Evans, 2000; Kohl et al., 1997), suggesting the flow field was not strongly divergent, probably due to channeling. It is likely that the high-capacity fault to which the well connects via the stimulated flow paths is part of a connected system that allows fluids to move through the rock mass over significant distances. Such features are rarely intersected by vertical boreholes because they are high-angle. These considerations suggest a strategy for establishing a satisfactory hydraulic connection between two boreholes to form a doublet, and that is to link them individually to the connected system of major fracture zones and faults through stimulation operations.

4.5. Stimulation

Hydraulic stimulation is the principal reservoir development technique that has been used to increase the low natural permeability of the HAFZs penetrated by the different Soultz wells. The permeability increase is believed to be governed mainly by a shearing mechanism occurring on pre-existing fracture planes, although the details of the geometry of the flow paths produced are uncertain (Evans et al., 2005a,b; Gentier, 2004). For example, shearing of an offset fracture pair can produce a conduit that channels flow normal to the shearing direction (Evans et al., 2005b; Jung and Weidler, 2000). There is also evidence for localised, opening-mode (tensile) fracturing below the casing shoes of some boreholes, where wellbore pressure during stimulation tends to approach the local minimum principal stress level (Cornet and Jones, 1994; Evans et al., 2005a; Jung et al., 2008; Schindler et al., 2008). However, vertical tensile fractures observed at the borehole walls above 3 km are in most cases induced by cooling during drilling or by swabbing pressures during trips and, whilst good indicators of the directions of the principal horizontal stresses (Valley, 2007), are unlikely to extend significantly from the wellbores.

Almost all wells at Soultz have been subjected to a hydraulic stimulation, and in all but one case the injectivity/productivity index (i.e. the injection flow rate per unit wellhead pressure under steady-state conditions) was significantly improved. For the intermediate depth well GPK-1 stimulated between 2.8 and 3.6 km, the improvement was a factor of 15 (Evans et al., 2005a). For the three deep wells, each stimulated between 4.5 and 5.0 km true vertical depth (TVD), the improvement for GPK-2 and GPK-4 was a factor of about 20, whereas that for GPK-3 was only a factor of ~1.5, although GPK-3 already had the highest initial index prior to stimulation (Nami et al., 2008; Portier et al., 2009). In all cases, the improvements reflect increased transmissibility of HAFZs, usually at the major altered fractures within the zone. In well GPK-1, these major fractures showed measurable post-stimulation dislocations of millimetres to centimetres (Cornet et al., 1997; Evans et al., 2005a). Estimation of the post-stimulation injectivity/productivity indices of the three deep wells was complicated by the failure to reach steady-state conditions in the post-stimulation characterization tests. It should be noted that in each of these wells, the downhole injectivity and productivity indices appear to be the same, so the terms are used interchangeably. Thus, single-well injectivity/productivity indices were estimated based upon the wellhead pressure and flow prevailing 3 days only after the start of the test, with the other wells shut-in (Nami et al., 2008). The measured indices were 4.0 l/s/MPa for GPK-2, 3.5 l/s/MPa for GPK-3, and 2.0 l/s/MPa for GPK-4.

A variety of chemical stimulations were conducted on all deep wells after the hydraulic stimulations (Nami et al., 2008; Portier et al., 2009). The improvement in 3-day injectivity/productivity index by the acid treatments was a factor of about 1.25 for GPK-2, about 1.15 for GPK-3, and about 2.5 for GPK-4 (Table 2). It should be noted, however, that the large increase in productivity for GPK-4 was largely due to the development of leaks in the casing whose origin is currently uncertain. If only the open hole is considered, the improvement achieved by the acid treatments was a factor of 1.5–1.75. The net 3-day single-well injectivity/productivity indices after the acidizations were: 5.0 l/s/MPa for GPK-2, 4.0 l/s/MPa for GPK-3, and 5.0 l/s/MPa for GPK-4.

4.6. Microseismicity

Microseismic activity was monitored with both down-hole and surface networks during all stimulations to map the locations where shear failure was occurring (Cuenot et al., 2006a; Horalek et al., 2008). Typically, several thousand microseismic events would be recorded by the down-hole seismic network during a stimulation, and somewhat fewer by the surface seismic network (Baria et al., 2004; Cuenot et al., 2008a; Charléty et al., 2007; Dorbath et al., 2009). High-precision mapping of the seismicity associated with the injection into GPK-1 illuminated the large scale geometry of HAFZs within

Table 2
Summary of the chemical stimulations performed in the three 5-km deep Soultz from (Portier et al., 2009).

Tableau 2
Synthèse des résultats de stimulations chimiques réalisées dans les trois puits profonds de Soultz après (Portier et al., 2009).

Well	Date	Concentration of chemical agents	Stimulation results
GPK2	February 2003	One test in two steps: HCl 0.09% and HCl 0.18%	Well-head pressure drop and productivity increase 0.5L.s^{-1}bar^{-1}
GPK3	June 2003	HCl 0.45%	Injectivity 0.35L.s^{-1}bar^{-1}
	February 2007	OCA (organic clay acid) HT	Weak impact 0.4L.s^{-1}bar^{-1}
GPK4	February 2005	HCl 0.2%	Productivity: 0.2–0.3L.s^{-1}bar^{-1}
	May 2006	Preflush: HCl 15% RMA (regular mud acid) HCl 12%-HF 3%	Maximum enhancement of injectivity: 35%
	October 2006	NTA (nitrilotriacetic acid) 19%	The formation of a plug increased wellhead pressure - Productivity: 0.3–0.4L.s^{-1}bar^{-1} (after RMA and NTA treatments)
	March 2007	OCA HT	Productivity: 0.4–0.5L.s^{-1}bar^{-1}

the active volume and provided insights into their internal microstructure (Evans et al., 2005b). Comparison of the seismic responses to stimulation of the three deep wells showed that they are dependent to some degree on the nature of the HAFZs encountered in each of the wells (Dorbath et al., 2009). The open-hole section of deep well GPK-2 is characterized by a dense network of medium-scale fracture zones, and the seismic cloud is rather compact and includes ~700 events of magnitude higher than 1 (Fig. 6). The initial injectivity/productivity index of this well was low, but was increased by a factor of 20 by the stimulation. The open hole section of well GPK-3 is hydraulically dominated by a very large HAFZ at 4.7 km measured depth (MD) that absorbed about 70% of the injected fluid and gave the well a high initial injectivity of 3 l/s/MPa. Stimulation produced 250 events larger than magnitude 1.0 (Fig. 7). However, the proportion of events with magnitudes larger than 2 was greater for GPK-3 than for GPK-2. This observation could indicate that the characteristics of the seismicity around GPK-3 are influenced by the large-scale fracture zone. However, the increase in injectivity/productivity index after stimulation was small.

Several seismic events induced during stimulation operations attained a magnitude 2.0, the maximum being 2.9 during the injection into GPK-3, and were felt by the neighbouring population, provoking unwanted alarm. The highest magnitude events tended to occur shortly after the end of injection, during the shut-in phase. Studies to better

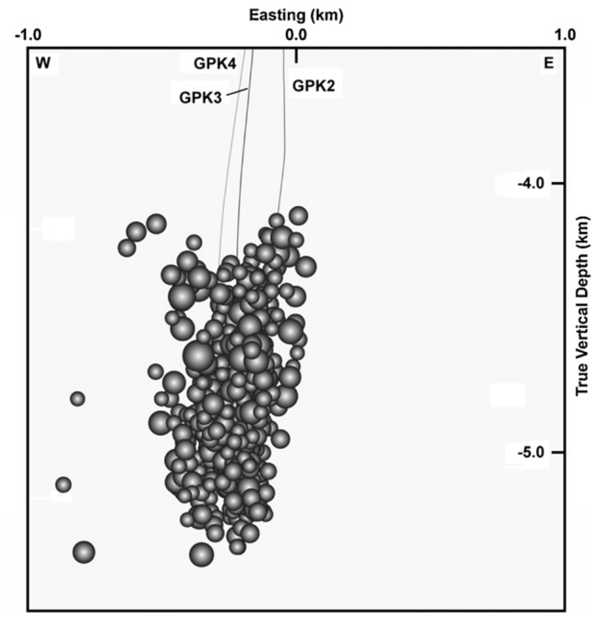

Fig. 6. The 2000 stimulation of GPK-2: Vertical cross-section through the cloud of induced seismic events ($M > 1$) along a line N20°W from (Dorbath et al., 2009). The magnitude scale for the microseismic events is plotted on Fig. 7.

Fig. 6. Stimulation du forage GPK-2. Coupe verticale N20°W passant au travers du nuage sismique pour les séismes induits de magnitude supérieure à 1 (Dorbath et al., 2009). L'échelle des magnitudes pour les microséismes est représentée sur la Fig. 7.

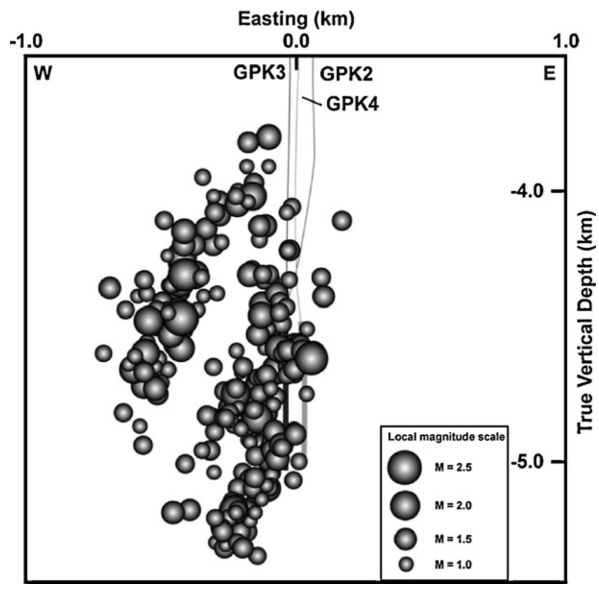

Fig. 7. The 2003 stimulation of GPK-3. Vertical cross section through the cloud of induced seismic events ($M > 1$) along a line N9°W (Dorbath et al., 2009).

Fig. 7. Stimulation du forage GPK-3. Coupe verticale N9°W passant au travers du nuage sismique pour les séismes induits de magnitude supérieure à 1 (Dorbath et al., 2009).

understand injection-induced microseismicity, particularly with regard to the generation of the larger events, are on-going. It is considered very important to identify ways of avoiding disturbance to populations living close to geothermal projects that involve hydraulic stimulation operations.

4.7. Thermics

Temperature measurements were routinely performed in all wells at Soultz. The temperature profile to 5 km depth measured in well GPK-2 at conditions close to thermal equilibrium is presented in Fig. 8. The profile is typical of all deep wells, with temperatures of 200 °C being reached at 5 km depth. The localized disturbances at 2 km and 3.4 km reflect remnant cooling from drilling or from stimulation injections conducted at those depths. The profile can be divided into three sections with different geothermal gradients reflecting different heat transport processes. The upper section lies entirely in the sediments from the surface to 1 km depth and has a very high gradient of about 110 °C/km, indicating heat transport is predominantly conductive. The intermediate depth section from 1 km to about 3.3 km depth is characterized by a very low gradient of about 5 °C/km, which suggests heat transport is dominated by advection, probably in the up-flowing limb of a convective system that is active in the granite and Triassic sandstones (Le Carlier et al., 1994). This implies significant natural fluid movement is occurring within faults and fracture zones, at least between 1.0 and 3.3 km (Fig. 8). Below 3.3 km, the geothermal gradient increases again to 30 °C/km and becomes linear with depth, indicating a return to a conduction-dominated heat flow regime. This might be explained as indicating that faults and fracture zones have insufficient connected permeability below 3.3 km depth to allow convection to develop (Le Carlier et al., 1994; Pribnow and Schellschmidt, 2000).

5. Performance of the upper and lower systems during circulation

The 1991–1998 phase of the Soultz project culminated in the 4-month continuous circulation of the upper-reservoir doublet system formed by the open hole sections of GPK-1 and GPK-2 which were 450 m apart (Aquilina et al., 1998; Baria et al., 2001; Baumgaertner et al., 1998; Bruel, 2002). Several limited-duration circulation tests have also been performed in the lower reservoir to date: without downhole pumps in 2005, and with one downhole pump and with power generation in 2008 (Cuenot et al., 2006a; Gérard et al., 2006; Sanjuan et al., 2006a,b). The

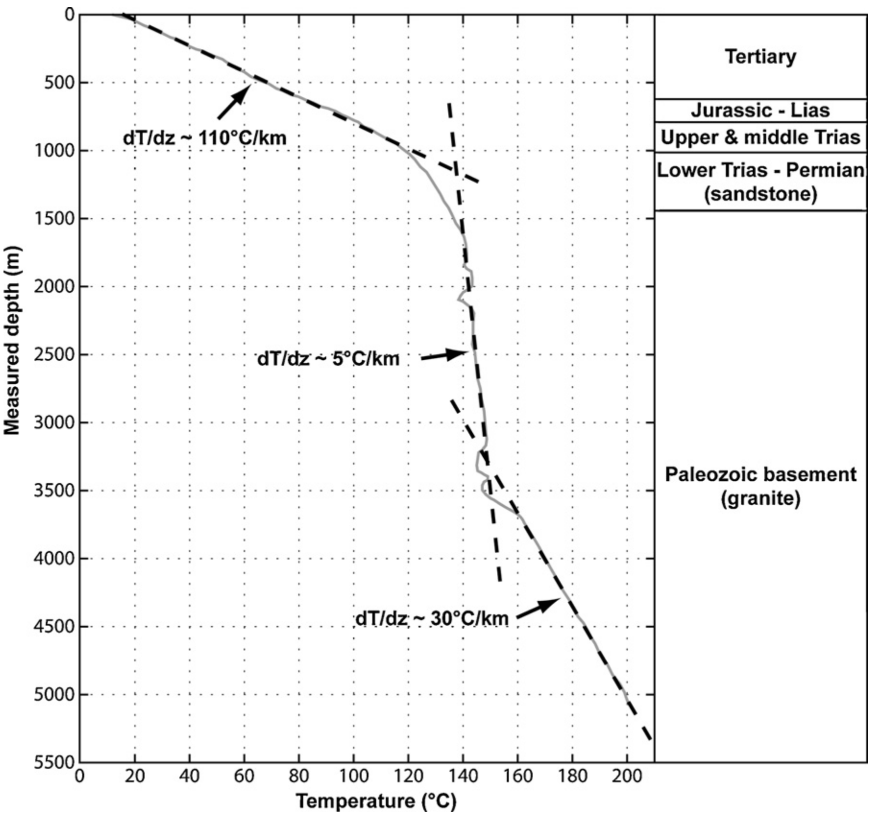

Fig. 8. Equilibrium temperature profile obtained from log run in GPK-2 several months after drilling operation finished. (Data from LIAG-Hannover, Germany). Main geological units are presented versus depth.

Fig. 8. Profil de température réalisé à l'équilibre plusieurs mois après la fin du forage dans le puits GPK-2 de Soultz (données collectées par LIAG Hanovre, Allemagne). Les principales unités géologiques sont présentées en fonction de la profondeur.

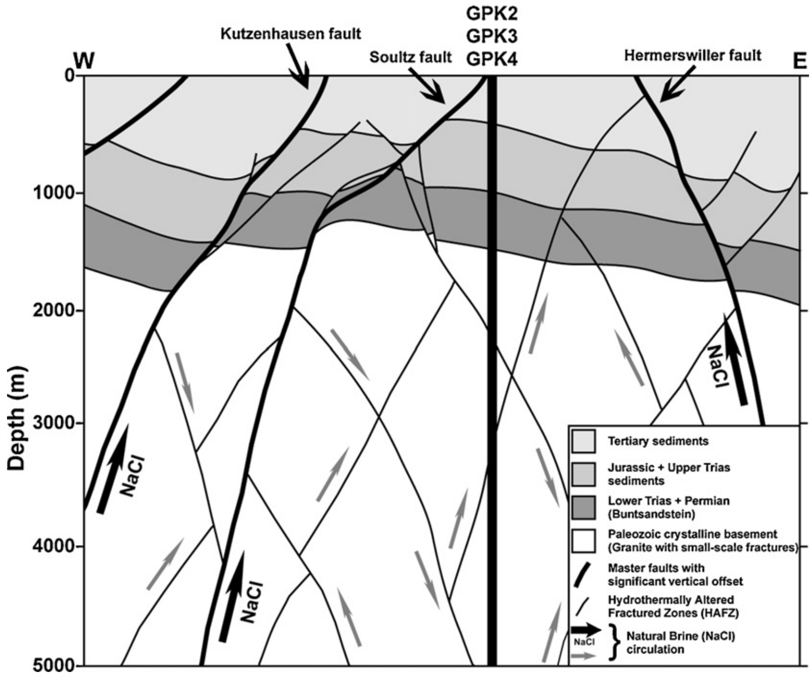

Fig. 9. Conceptual schematic West-East geological cross-section of the Soultz horst based on (Cautru, 1988), showing the main geological units and a conceptual view of the deep, interconnected faults and fractures system. The thick, black, vertical line represents a simplified projection of the geothermal well trajectories. Natural NaCl-rich brine circulations are indicated by black and grey arrows.

Fig. 9. Coupe schématique conceptuelle ouest-est du horst de Soultz, d'après (Cautru, 1988), présentant les principales unités géologiques, ainsi qu'une vue conceptuelle du système profond de failles et fractures interconnectées. Le trait vertical épais représente une projection simplifiée de la trajectoire des puits géothermiques. Les circulations naturelles de fluides riches en NaCl sont matérialisées par les flèches noires et grises.

main results of the circulation tests are described in this section.

The upper reservoir between 3.0 and 3.6 km depth was the first truly engineered geothermal system to be constructed at Soultz (Fig. 1). In 1997, this reservoir was successfully circulated for four months at a mass flow rate of 25 kg/s in closed-loop mode at fluid pressures far below the stimulation pressure levels. A down-hole pump was installed at 430 m depth in the production well (GPK-2) to improve recovery by taking advantage of the natural far field permeability. Fluid mass balance (i.e. zero fluid loss) was maintained throughout the circulation with minimal energy consumption. During this experiment, 244,000 tons of brine at temperatures up to 142 °C were produced from GPK-2 and re-injected in GPK-1 at a temperature of 40 °C using a centrifugal pump. The GPK-1 wellhead injection pressure declined from 4 MPa to 2 MPa during the test (Aquilina et al., 1998; Baumgaertner et al., 1998). The decline was slow and steady for the first half of the test, but then underwent a rapid drop after 60 days, an event that coincided with the termination of scaling inhibitor injection. Flow logs indicate that the gradual change reflected declining impedance of a HAFZ at 3225 m (Evans et al., 1998), whereas the steep drop was largely due to an impedance drop at a HAFZ just below the casing shoe. Both have been ascribed to rock shrinkage due to cooling (Evans et al., 1998; Bruel, 2002). By the end of the circulation, the system circulation impedance was only 0.1 MPa/l/s. This was the first time that this long-standing commercial target had been attained in any EGS system worldwide, and then for the largest well separation of 450 m ever attempted (Evans et al., 2008). The specific gravity of the production fluid increased during the test from 1.048 g/cm^3 in July to 1.063 g/cm^3 in November 1997 (Rummel et al., 1997), reflecting a progressively larger fraction of formation water in the produced fluid. This, together with the relatively small quantities of tracer (i.e. 30%) recovered from tests, indicates that production was accessing fluid stored in the 'far-field', probably in the network of major fracture zones and faults present in the rock mass (Fig. 9). Nevertheless, the tracer results also showed a rapid response, indicating that at least some of the principal flow paths linking the wells were direct. Application of a discrete fracture network model to the multi-scale fractured reservoir conditioned by the tracer response suggested that a 5% production temperature decrease could take place after 20 years of operating the doublet at a circulation rate of 25 l/s (Bruel, 2002). The usable thermal power produced for a re-injection temperature of 40 °C attained ~11 MW thermal by the end of the 1997 test.

The first circulation test of the triplet of wells penetrating the lower reservoir (4.5–5.0 km) (Fig. 1, Table 1) took place for 5 months between July and December 2005. The wells had been hydraulically and chemically stimulated by that time, although some further acidization treatments of GPK-3 and GPK-4 were performed subsequently. A total of 209,000 m^3 of hot brine was produced by buoyancy drive at a cumulative flow rate of 15 l/s from the lateral boreholes GPK-2 (160 °C) and GPK-4 (120 °C) without any downhole production pumps (Gérard et al., 2006). The produced fluid was re-injected into the central well GPK-3 at a wellhead pressure which increased from 4 to 7 MPa. Tracer tests conducted during the circulation showed that ~25% of the injected tracer was recovered from GPK-2 but only 2% from GPK-4 (Sanjuan et al., 2006a,b). This asymmetrical response reflects the complex organisation of fracture zones or faults describing different underground fluid circulation loops, the hydraulic connections between GPK-3 and GPK-2 being much more direct and faster than those between GPK-3 and GPK-4 (Sanjuan et al., 2006a,b). During this circulation, and all production tests conducted in the lower reservoir, tracer tests and geochemical data invariably showed the presence of the native geothermal brine in the discharged fluids, even after large amounts of external water had been injected into the wells (Sanjuan et al., 2006a,b). This again points to the conclusion that the exchanger is connected to a deep natural reservoir. Some 600 microseismic events were recorded in the 6 months during and immediately following the circulation. Several exceeded magnitude 2.0 and some of these were felt (Cuenot et al., 2008b).

In 2008, the lower reservoir was again circulated during the power-plant commissioning phase. This time, a line-shaft production pump was operational at 350 m depth in GPK-2, with GPK-4 remaining shut-in (Table 1). Since the earlier circulation in 2005, injection well GPK-3 had been subject to a further acid stimulation in 2007, which had little effect on injectivity (Nami et al., 2008), whilst well GPK-4 had been subject to three different types of acidization treatments with considerable success (Table 2). Circulation began at the end of June 2008 and lasted until mid-August 2008. During this period, the pump-assisted production from GPK-2 was around 25 l/s at a temperature of 155 °C. The production fluid at the surface was maintained at a pressure of 2 MPa before passing through a pump for injection into GPK-3. Wellhead injection pressure began at 6 MPa and increased continuously albeit progressively more slowly to stabilize at 7 MPa for last week of the test. Approximately 190 microearthquakes were associated with the circulation, which gives an event rate comparable to that observed in the 2005 circulation (Cuenot et al., 2008b). They also occurred in much the same locations as the earlier events, but the magnitude did not exceed 1.4, in contrast to the earlier events, several of which exceeded 2.0 (Cuenot et al., 2006b).

The lower magnitudes may reflect several differences between the two tests: the duration in 2005 was 6 months as compared to 2 months in 2008; a larger volume of water was circulated in 2005; and the use of a down-hole production pump in 2008 induced higher production flow rates and lower net reservoir pressure compared to the artesian production from two production wells in 2005. Additionally, between 2005 and 2008, the wells were chemically stimulated (Nami et al., 2008). Moreover most of the larger magnitude earthquakes in 2005 occurred after a sudden increase of injection flow rate and pressure. This behaviour is quite similar to the tendency of large events to occur during the shut in phase of stimulation tests (Cuenot et al., 2006a), although the underlying mechanisms are not necessarily identical.

6. The Soultz reservoir: a channel network poorly connected through hydrothermally altered and fractured zones

By drilling into the Soultz granite to 5 km depth, several depth sections containing permeable fractures were observed (Dezayes et al., 2010). This vertical zonation is organized in three main sections from the top of the basement to TD. The main HAFZs are located: (1) in a highly fractured and altered granite interval between 1.4 and 2.2 km (GPK-1, 1820 m; EPS-1, 2180 m; GPK-2, 2120 m); (2) in the upper reservoir between 3.5 and 3.9 km depth (GPK-1, 3490 m; GPK-2, 3900 m); and (3) in the lower reservoir below 4.5 km depth (GPK-3, 4770 m). This vertical zonation corresponds to the geometrical intersection of the drillholes with major nearly vertical fracture zones. As all the wells are roughly aligned along the N170°E striking direction and as the major HAFZs range azimuthally between N150°E and N170°E, they appear in cross-section in 3 main depth sections. The presence of additional fracture zones which do not intersect the wells but are near them is indicated from microseismic imaging (Evans et al., 2005b; Moriya et al., 2002; Phillips, 2000) and Vertical Seismic Profiling (VSP) studies (Place et al., 2007). Moreover, there are several major fracture zones that are not strongly hydraulically active. For example, the fracture zone in GPK-1 at 3.5 km, whilst transmissive, is not the principal hydraulically-active HAFZ in the well after stimulation, even though it was the principal hydro-geologic structure in the open hole section prior to stimulation (Evans et al., 2005b).

The drilling of numerous wells at Soultz has provided a good description of structures present within the rock mass to 5 km depth. As noted earlier, these can be broadly viewed as falling into two categories: small-scale fractures (meter-scale) that are widely distributed in the massive granite but are not hydraulically significant; and more localized, large-scale (i.e. $>$ 100 m) hydrothermally-altered fracture zone (HAFZ) structures created or reactivated by the Rhine graben tectonics. Both networks are steeply dipping and show a strong orientation anisotropy with similar strikes of N170°E $\pm$ 30°. Numerous HAFZs are intersected by the wells, and these are often found to be naturally permeable, although usually only slightly so. However, several of the HAFZs are clearly major structures in both a geological and hydrological sense. Structures recognised as major in both senses are listed in Table 1 of reference (Dezayes et al., 2010). These major structures will be expected to have significant influence on the pattern of forced fluid flow within reservoirs developed in their vicinity, although they may not be dominant since other sub-vertical major HAFZ structures may be present that are not intersected by any well. High-resolution microseismic imaging of the microseismic cloud generated during the stimulation of the upper reservoir demonstrates that many conductive features that do not intersect the wellbore are activated during stimulation (Moriya et al., 2002; Phillips, 2000). Most likely, almost all primary flow is confined to HAFZs, both before, during and after stimulation (Evans et al., 2005b). Within a given HAFZ, the natural permeability structure is probably channelled with a rather complex 3D organization (Caine et al., 1996).

Exploration and testing of the Soultz granite has shown that it differs significantly from the original concept of a HDR reservoir (Smith, 1983). The presence of the HAFZs, which together form a connected system of large hydraulic capacity (i.e. storage), means that the Soultz reservoirs share many facets of conventional geothermal reservoirs that benefit from re-injection. It is probable that the elements of the natural reservoirs govern the flow field that develops under forced flow conditions within the reservoirs.

7. The Soultz power plant

Based on the results of the circulation test performed in 2005, and the subsequent improvement of the hydraulic performance of the three deep wells, it was decided to build a 1.5 MWe geothermal power plant. In view of the highly saline geothermal fluid which prohibits direct vaporization in a turbine, and the expected production temperature, it was decided to use an Organic Rankine Cycle (ORC) system that used a low boiling-point working fluid (isobutane) in the heat-power conversion scheme. The turbine is radial and operates at around 13000 rpm. The generator is asynchronous, operates at around 1500 rpm, and has an 11 kV output, which is transformed up to feed into the 20 kV local power network. The geothermal fluid is cooled down to 80–90 °C in the heat exchangers of the binary unit before reinjection. The system is constructed to allow the production from either or both of the two wells to be used to feed the power production loop. The expected production flow rate from both wells together is about 35 l/s for a production temperature of 175 °C. As of September 2009, the power plant has been assembled and produced electrical power during the circulation in June–August 2008 when production came from GPK-2 with a Line-Shaft Pump (LSP). Since then, an Electro-Submersible Pump (ESP) has been deployed in the second production well GPK-4. The next phase of the project will involve the long-term circulation of the system with both production wells operational, in order to optimize the power plant operation and to progressively increase the generated electric power, which will be fed into the local network. This phase will begin shortly.

8. Future geothermal targets in the Rhine Graben

Exploration at the Soultz site has shown that the geothermal anomaly and the presence of oil in the Pechelbronn oil field are related, and that the heat distribution is mainly controlled by large-scale convection of high-salinity fluid occurring within fractured formations (sandstones, granite). The granite near the top of the basement (1.4 to 2.2 km depth) is a promising geothermal target because it is more naturally fractured and more permeable than the upper and the lower reservoirs.

The nature of the deeper fractured basement at Soultz is well documented along the boreholes, but the inter-well domain is poorly constrained because all holes are near-vertical or steeply inclined. This borehole geometry was driven by the fact that the orientation of the main fracture system was aligned with the maximum horizontal principal stress (Baumgaertner et al., 1998). Since it is difficult to image the fracture system in 3D prior to drilling, it might be more convenient for future geothermal projects in a similar geology/stress context to drill inclined holes perpendicular to the strike of the fracture system to maximise the likelihood of intersecting as many as possible. Such an approach has recently been successfully applied in a Soultz spin-off project near Landau, Rhineland Palatinate, Germany, some 40 km north of Soultz, where two shallow deviated wells were drilled into the lowermost sediments and the top of the basement (Baumgaertner et al., 2007).

Based on geological findings and drilling results, the Soultz adventure contributed significantly to improving our vision of the EGS potential and will contribute to the design of new projects in France and abroad (Ledru, 2008).

9. Conclusions

Some 20 years of EGS research at the Soultz geothermal site has produced numerous scientific results and advances related to drilling, surface exploration methods, basement geology, geochemical and geophysical monitoring, tracer testing, hydraulic and chemical stimulations, and general EGS know-how. A key finding of the drilling and testing to 5 km depth is that the rock mass contains numerous hydrothermally-altered fracture zones that host large volumes of brines and essentially constitute a significant natural hydraulic reservoir. These high-angle zones, which strike principally to the NNW, are seen on core and image logs and can be mapped as discrete structures at scales of up to several hundred meters on high-resolution images of the pattern of microseismicity and VSP surveys. The structures control the movement of fluids through the rock mass under natural and forced fluid flow conditions, and thus determine the behaviour of the reservoir. Flow between the wells during circulation of the two systems built at 3.5 km and 5 km depth in large part followed natural flow paths defined within these structures, leading to mixing of the circulation fluid with reservoir brines. The hydraulic and chemical stimulations served to enhance the transmissivity of these natural flow paths. The 3.5 km system was the first EGS to have attained a circulation impedance of 0.1 MPa/l/s. The long-term circulation of the 5 km system is about to begin. The future development of EGS projects in Soultz-like environments would benefit from improved exploration methods for imaging structures remote from the wells. It is also important to obtain a better understanding of the factors that promote stimulation/circulation-related microseisms large enough to be felt by local population, and to identify ways to mitigate the hazard.

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