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The European Hot-Dry-Rock Project in the Tectonic Regime of the Upper Rhine Graben

Gerd Klee

ABSTRACT

Deep hot crustal rocks offer an almost unexhaustible energy resource. In 1970, physicists of the US Los Alamos Scientific Laboratory (LASL) proposed a concept, the so-called Hot-Dry-Rock (HDR) concept, to tap this geothermal energy source, by circulating water through an artificially created heat exchanger between adjacent deep boreholes. This concept was studied by various geoscience groups in Europe at different locations during the 80s. In 1987 the European HDR research efforts merged into the Scientific European HDR project at the location Soultz-sous-Foret in the Upper Rhine Graben near the boundary between France and Germany. It was possible to create a large heat exchanger between two 3.5 km deep boreholes approximate 500 m apart from each other by high pressure water injection (hydraulic fracturing). In 1997, a four-month circulation test demonstrated a geothermal energy capacity of approximately 10 MW at a downhole rock temperature of 160°C. The test, in particular, showed that the tectonic graben-type stress field is the controlling factor for water circulation on induced and stimulated fractures within the granitic basement rock. Since 2000, the system was deepened to a depth of 5 km

with a rock temperature of 200°C. This system consisting of two production and one re-injection wells, operated by a European Industrial Consortium (EIEG), will be developed into a first HDR pilot plant to produce 5 to 10 MW electricity in 2006.

10.1 INTRODUCTION

The use of geothermal energy today is limited to hot water or steam deposits located in areas with specific geological and tectonic conditions which generally exist along plate boundaries (e.g. California, Japan, and in Mediterranean countries). By far the largest heat resource, however, exists in the hot basement of the continental crust, which could be tapped almost everywhere and anytime. This was first recognized by scientists from the Los Alamos Scientific Laboratory, New Mexico, USA, and led to the formulation of the Hot-Dry-Rock concept in 1970. Other countries like Germany, France, England, Sweden, and Japan contributed to the LASL project, but also developed their own national HDR research within their countries (e.g. Rummel and Kappelmeyer, 1993).

In 1986-87, scientists from Germany, France, and England combined their research efforts, agreed on a common test site in the Upper Rhine valley, and started the European HDR-project. The selected research site is situated at Soultz-sous-Forêts, about 50 km north of Strasbourg (Alsace, France) near the western margin of the Upper Rhine Graben, the most prominent present-day tectonic unit in Europe, north of the Alps (Fig. 10.1). The area is characterized by moderate seismicity, a thin continental crust (less than 25 km) and a well-known geothermal anomaly, with high heat flow of about 150 mW/m^2 and geothermal gradients of up to 100°C/km in the uppermost sediments to about 1.4 km depth and about 30°C/km in the underlying granitic basement. The anomaly is a result of deep water convection through a dense fracture network in the sediments and was identified from numerous measurements in the former local Pechelbronn oil-field.

The process of the Upper Rhine valley development was controlled by the opening of a pre-existing fault zone under compression parallel to the NNE-SSW orientation of the graben (parallel to the paleo-stress direction), crustal rifting due to the development of a mantle diapir in the southern graben and the evolution of the present-day stress regime. The earthquake focal mechanism data for the Upper Rhine valley indicate mainly both, strike-slip and normal faulting stress conditions with a consistent maximum horizontal stress direction of NW-SE, which is in agreement with borehole breakout and hydrofrac stress data from boreholes in the central part of the Rhine valley and in the Black Forest (Müller et al., 1992).

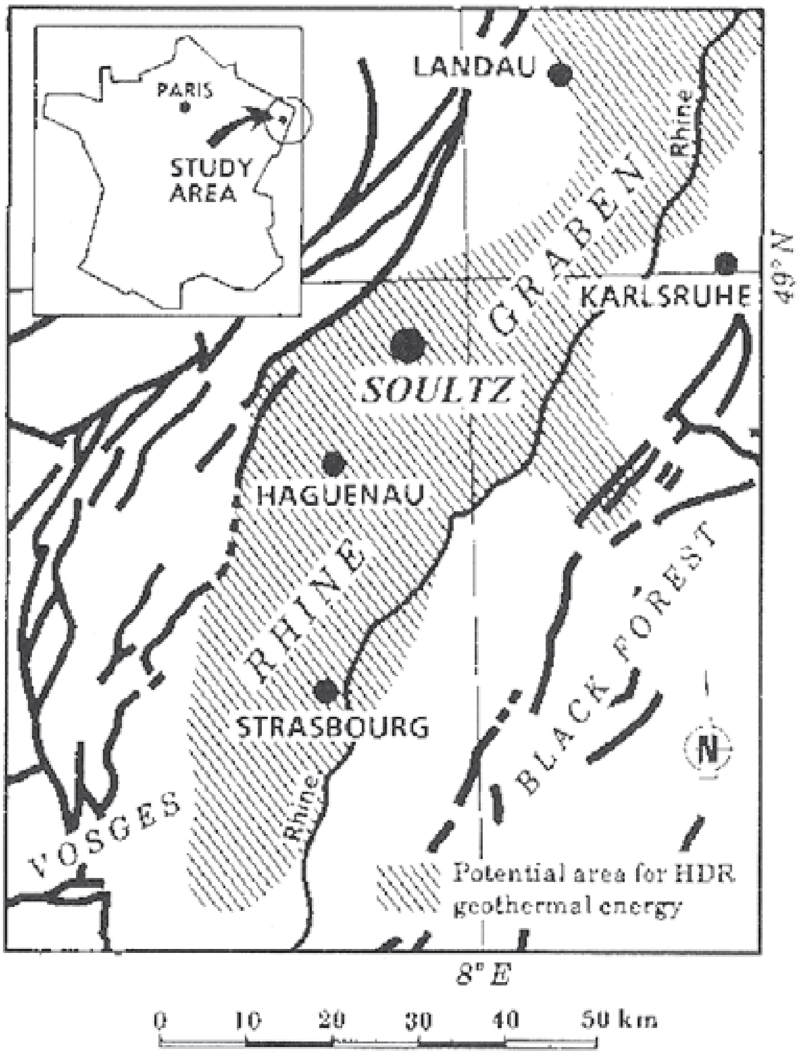


Fig. 10.1 Location of the European HDR project at Soultz-sous-Forêts, France

10.2 PROJECT DEVELOPMENT DURING 1987-2000

Due to regulations of the funding agencies (European Commission, France, Germany) the project was developed in steps of 2-3 years duration since 1987. During this time the project has been continuously reinforced in terms of infrastructure at the site, a borehole network, and massive stimulation operations.

During the initial project phase between 1987 and 1988, borehole GPK-1 (Fig. 10.2) was drilled to 2,000 m depth with a bottom hole temperature of 140°C. A number of small-scale hydraulic tests and geophysical measurements were conducted to investigate the rock mass conditions to 2 km depth (Bresee, 1992).

During 1989-1991, the first seismic network was installed in three recovered old oil wells (Fig. 10.2, borehole nos. 4550, 4601, and 4616). Borehole GPK-1 was stimulated with 7 and 15 l/s to connect the bottom section of the borehole with a permeable fault system. These tests already

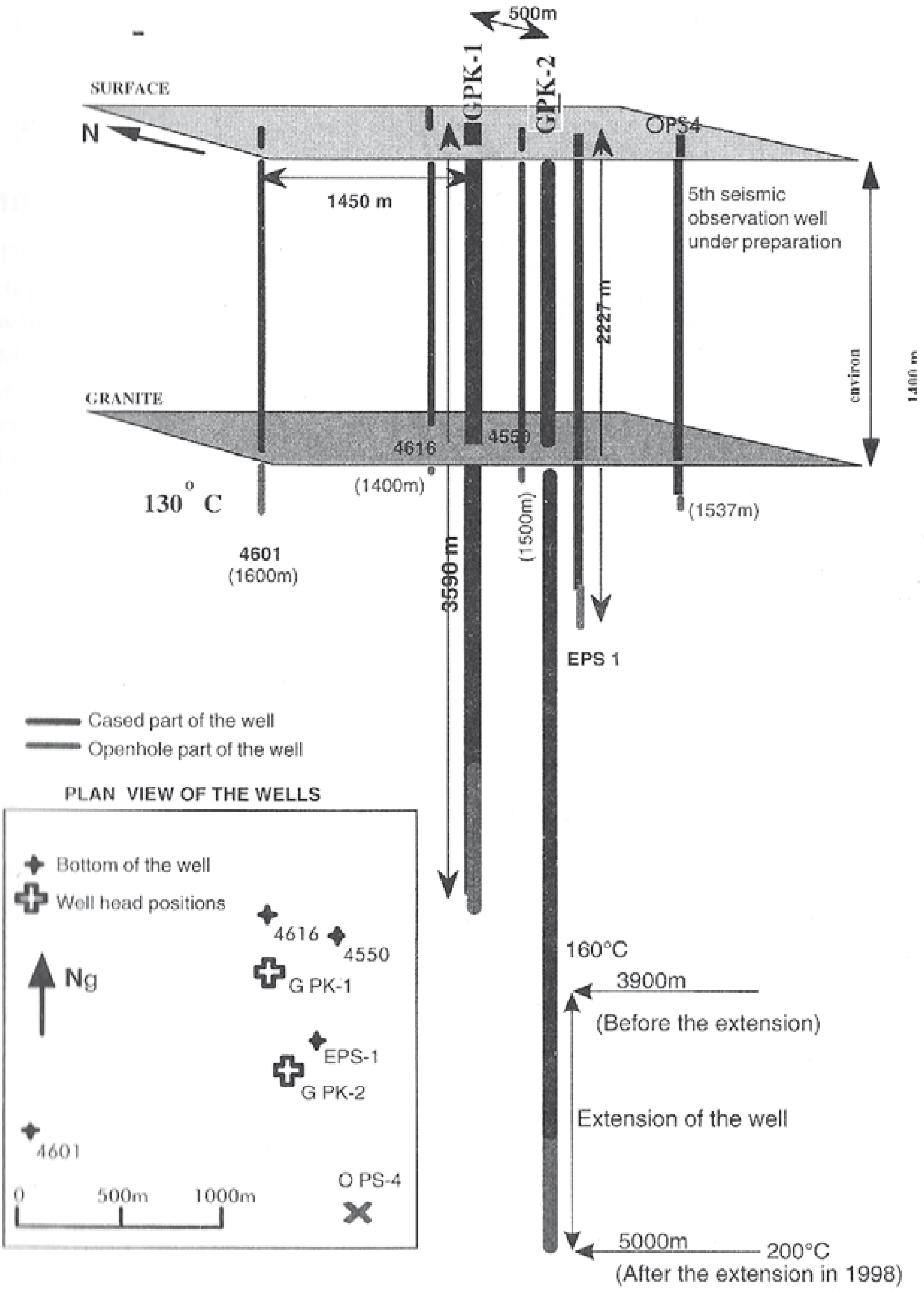


Fig. 10.2 Borehole network at the European HDR project site Soultz-sous-Forêt

showed a proportionality between stimulation flow rate and production rate, one of the major findings of the project which contributed to the planning of subsequent stimulation operations. An attempt was also made to drill the continuous cored borehole EPS-1 to 3,500 m depth. However, the well was terminated at 2,227 m due to drilling problems. Nevertheless, extensive investigations on core samples and cuttings of the borehole yield important data on the mechanics, joint network, and mineralogy, and provided the basis for subsequent interpretations of geophysical logs. Today, borehole EPS-1 is also used for micro-seismic monitoring (Fig. 10.2).

During 1992-1993, the existing borehole GPK-1 was deepened from 2,000 m to 3,590 m depth with a bottom hole temperature of 159°C. Various geophysical measurements were conducted during and after drilling. Following the drilling of the well, two massive stimulation tests with a maximum flow rate of 50 l/s were carried out in the open-hole section of borehole GPK-1 below 2,850 m depth. During these tests, a 2 km^2 large fracture system was stimulated which was well connected with a highly permeable fault system (Baria et al., 1995). Subsequently, the fracture system was extensively investigated with the highlight of the first production test in June 1994 (Jung et al., 1995).

The large body of existing information on in-situ stress, temperature, joint network, and seismicity was than used to target the drilling of the second deep borehole GPK-2 to 3,890 m depth, located approximately 450 m south of borehole GPK-1 (Fig. 10.2). After the well was completed in early 1995 with a bottom hole temperature of 175°C, a massive stimulation test was conducted in borehole GPK-2 below 3,200 m depth, where a fracture system of approximately 1 km^2 was created and connected to the stimulated reservoir of borehole GPK-1. At the end of this phase, a 10-days circulation test between the two deep boreholes was carried out. Since several hydraulic tests showed that the fracture system at Soultz is hydraulically open at its periphery, it was concluded that the circulation could not be operated at a fluid pressure above hydrostatic as this would cause high fluid losses. Therefore, a downhole pump was used with great success in the production borehole GPK-1. The test showed a stable equilibrated flow of 20 l/s at a temperature of 135°C and a thermal power of 8 MW (th). Since the produced fluid was re-injected, no fluid losses occurred (Baumgärtner et al., 1996).

In order to demonstrate that such a circulation can be maintained over a longer period, a circulation test of 4 months duration was conducted during summer and autumn 1997. Prior to this test, borehole GPK-2 was re-stimulated with flow rates up to 78 l/s to reduce the flow resistance at the fracture inlet which increased during the first circulation test (Gérard et al., 1997). The set-up of the circulation experiment is shown in Fig. 10.3, where the produced brine is kept within a fully closed loop on surface to prevent scaling and corrosion. A submersible pump was installed in the

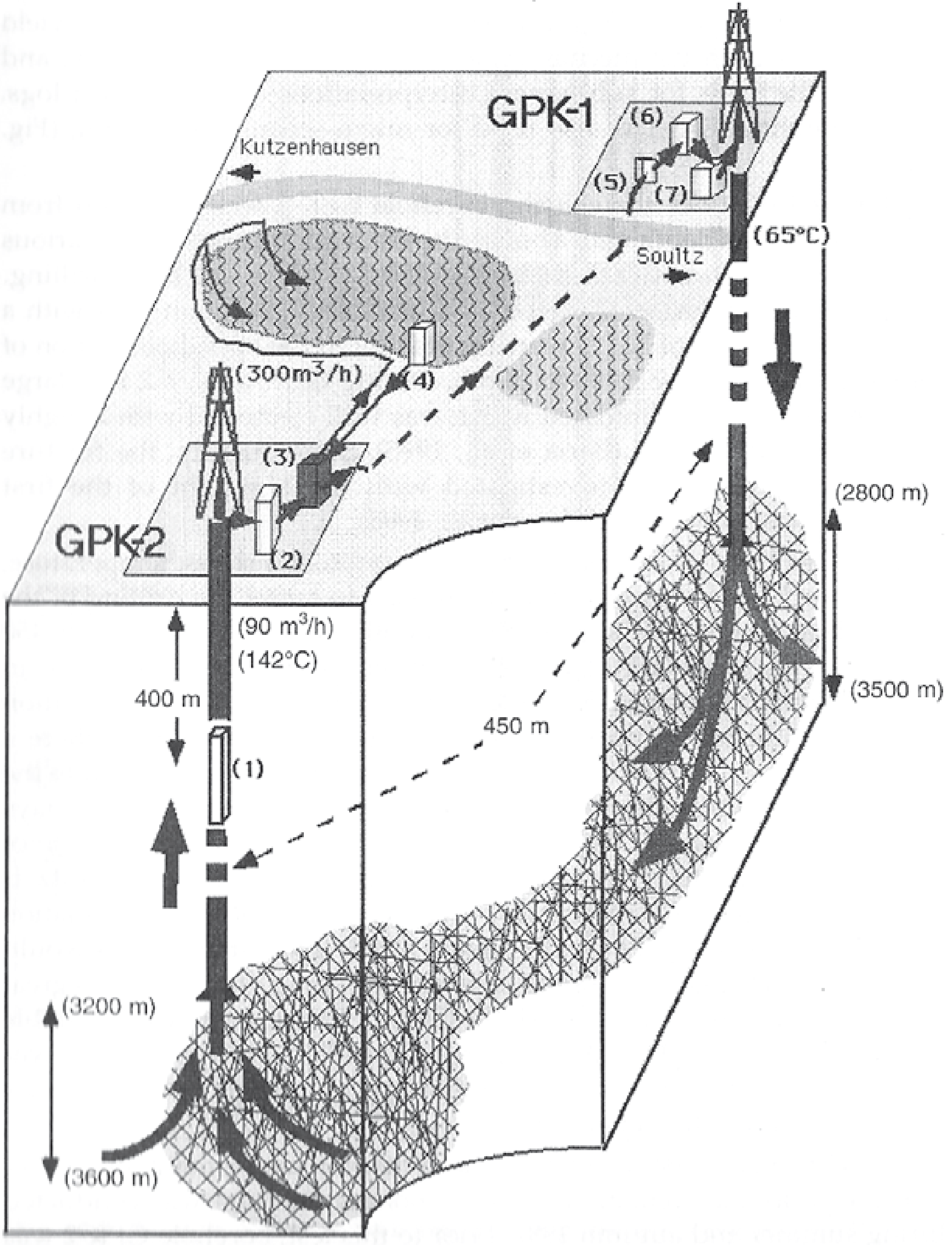


Fig. 10.3 Circulation tests between borehole GPK-1 and GPK-2 in 1997 (Gérard et al., 1999). (1) Submersible pump, (2) Pre-filter, (3) Heat-exchanger, (4) Pumps for cooling loop,

production borehole GPK-2 at about 400 m depth. The produced brine was pre-filtered before entering the cooling loop consisting of a heat-exchanger to extract a large portion of the recovered heat and an artificial lagoon. The cooled water was then transmitted via a composite line to the platform of borehole GPK-1. Before re-injection, the brine was again filtered. The circulation-system infrastructure installed was automated and fully instrumented with online data monitoring.

Neglecting some initial problems due to unexpected power failures and short interruptions for equipment maintenance and cleaning, the experiment was continued for four months without major technical problems and noticeable environmental impact (Fig. 10.4). The circulation was maintained without adding any additional fluid, production and re-injection were fully balanced. The produced flow increased stepwise from 21 l/s to 25 l/s (90 tons/hour). By the end of the test, 244,000 tons of brine were recovered with a temperature of 142°C. The re-injection pressure in borehole GPK-1 decreased from about 4.5 MPa to 2 MPa after the injection of an anti-scaling agent was cancelled (the anti-scaling agent may have caused some skin effect in the near well-bore area). The thermal energy available at the heat exchanger was in the order of 10-11 MW (th) (based on a re-injection temperature of 40°C for space heating installations). On the other hand, the electric energy necessary to maintain the circulation was only about 250 kW (Baumgärtner et al., 1998).

In the later stage of the project during 1998-2000, the accuracy of the micro-seismic monitoring system has been improved by drilling the additional observation borehole OPS-4 located in the south of the network (Fig. 10.2). In order to investigate the conditions in the temperature region of 200°C (sufficient for electricity generation), borehole GPK-2 was deepened to 5,084 m depth. The operation was accompanied by the development of new casing packer elements based on inflatable metal shells which were successfully integrated into the completion of the well (Hegemann et al., 1999). Finally, the new reservoir below the casing shoe at 4,430 m depth was stimulated with flow rates up to 50 l/s. Presently, two further deep boreholes to 5,000 m depth were completed to develop a first HDR pilot plant for electrical power generation of approximately 5 MW_{el}.

10.3 IN-SITU HYDROFRAC TESTS AND STRESS REGIME

The efficiency of the heat exchange by fluid circulation between deep boreholes strongly depends upon the hydraulic impedance of the fluid flow path. Besides permeability, temperature, and chemical reactions between the circulating fluid and the crystalline rock-mass, the hydraulic properties at depth are mainly controlled by the in-situ stress regime.

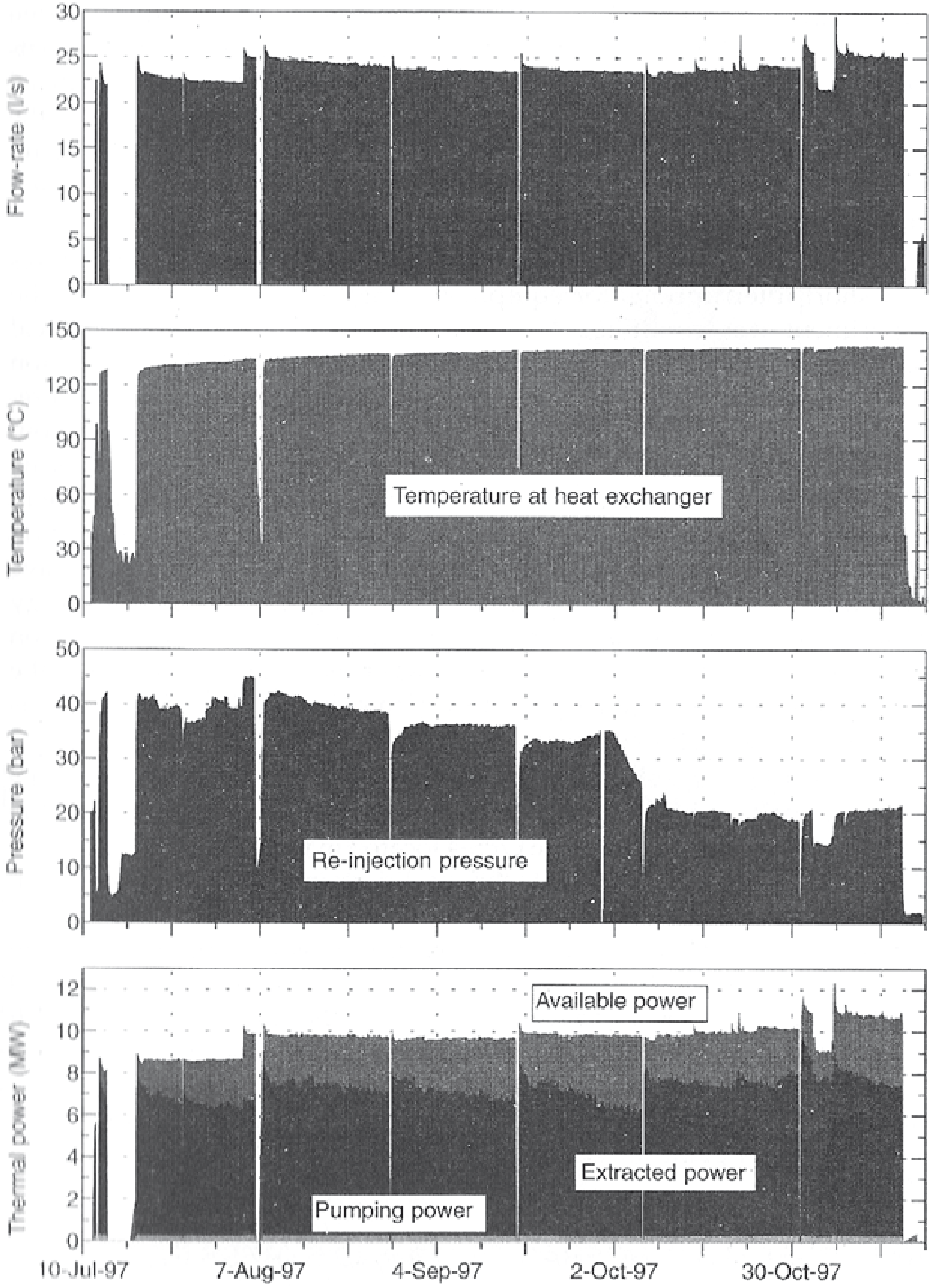


Fig. 10.4 Major parameters of the 1997 circulation experiment (Baumgärtner et al., 1998)

Therefore, since the early beginning of the Soultz HDR project, the tectonic situation in the Upper Rhine valley has been extensively investigated by various hydraulic fracturing stress measurements down to 3.5 km depth (Rummel and Baumgärtner, 1991; Klee and Rummel, 1993).

- During the first project phase in late 1988, a total of eight hydrofrac/hydraulic injection tests were carried out in borehole GPK-1 between 1,458 m and 2,000 m depth in conjunction with the small-scale hydraulic test program.
- Two hydrofrac tests were conducted in borehole EPS-1 at about 2,200 m depth in late 1991.
- After deepening of borehole GPK-1 to almost 3.6 km depth, two further tests were carried out at 3,315 m and 3,506 m depth in 1992.

Although successfully completed, the first test series in borehole GPK-1 was characterized by several technical problems caused by using conventional (rubber-based) packer technology in the hostile downhole environment (temperatures up to 140°C and high gas and salt content of the borehole fluid). Therefore, the later tests in borehole EPS-1 and GPK-1 were conducted using ductile metallic packers as part of a wireline hydrofrac system (Klee and Rummel, 1993).

10.3.1 Aluminium Straddle Packer Tool

For the first approach, aluminium was selected as packer material on account of its high ductility, good machining properties, the low cost. After several tests with laboratory models, aluminium straddle packer tools for borehole diameter of 4, 5-7/8, 6-1/4, and 8-1/2 inch were designed. A schematic view showing the essential details of the system is given in Fig. 10.5. The major characteristics are as follows.

The packer elements consist of pure (soft) aluminium (Al 99.5 %) which allows a maximum deformation of 25 % at room temperature. However, the outer diameters and the wall thickness are designed in such a way to accommodate the borehole diameter by approximately 15 % of lateral deformation and differential pressures of about 25 MPa. To guarantee sealing, the outer surface of the aluminium packers is furnished with high temperature O-ring seals. The two soft aluminium packer elements are connected with threads to the injection interval part and the end pieces, both made from high strength aluminium alloy (ERGAL 55).

For separate pressurization of both, the packer elements and the injection interval, an inner stainless steel mandrel is used. This mandrel contains high temperature O-rings as seals against the aluminium shells and deep borings for hydraulic connection to the packer inflation sections and the injection interval. The aluminium parts of the arrangement are

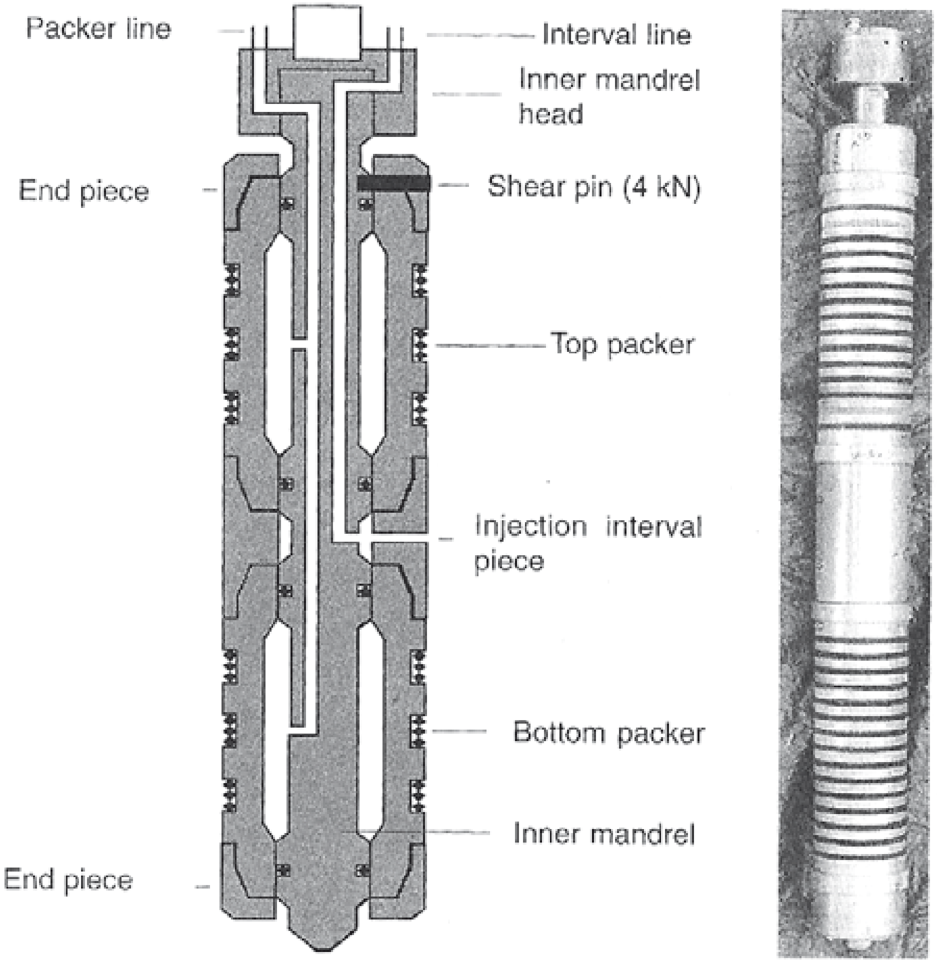


Fig. 10.5 Schematic diagram and photograph of the aluminium straddle packer tool

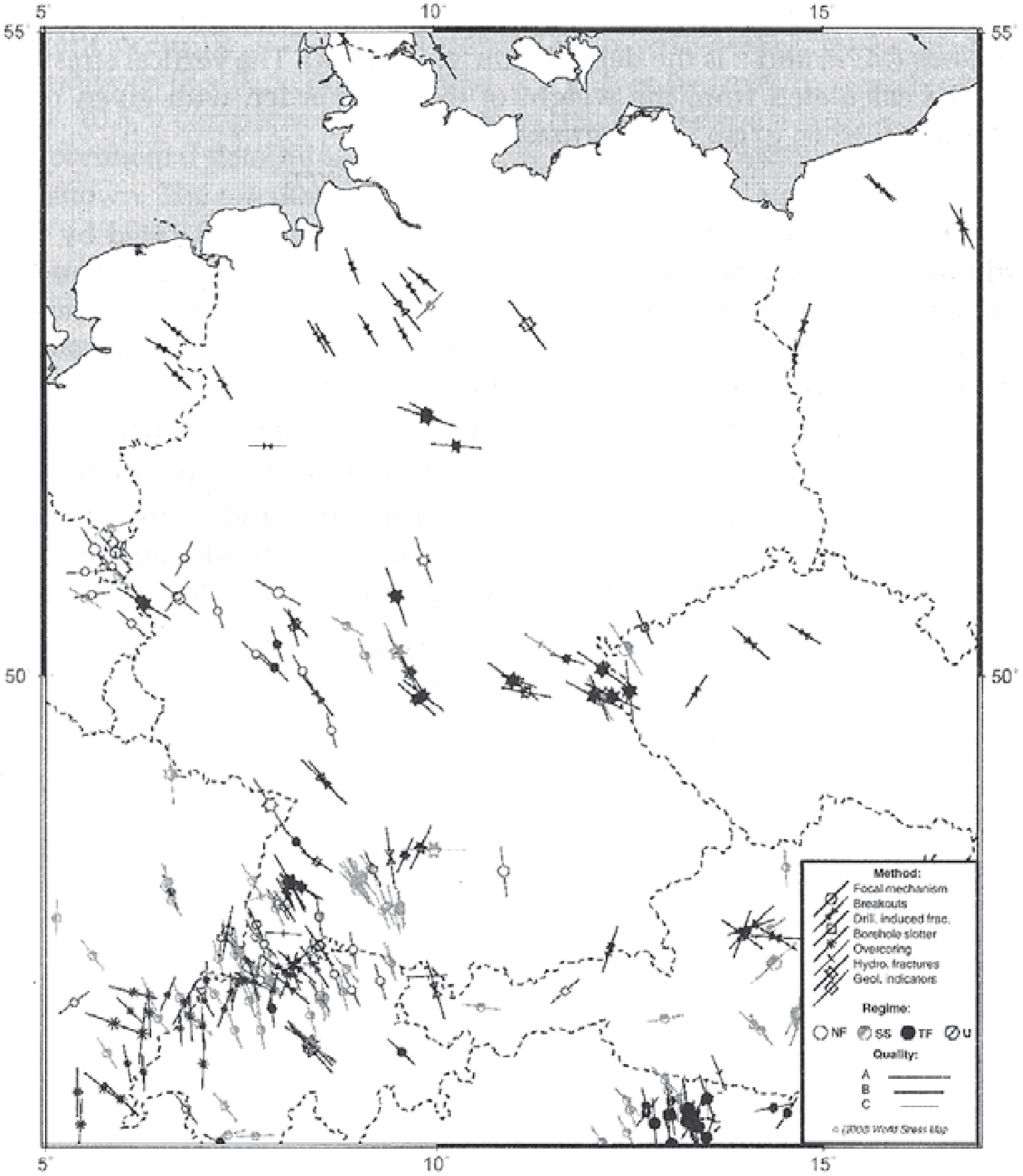
fixed on the inner mandrel with a 4 kN shear pin. This design enables all steel parts of the tool to be recovered after completion of the test, while the aluminium parts remain in the borehole. The aluminium can be drilled out by adequate drilling procedures.

Besides the application of the metal packer technology for hydrofracturing at great depth and high temperature, the technology has been investigated with promising results for permanent borehole sealing in nuclear waste storage projects and for the reliable casing cementation/anchoring at severe downhole conditions (Hegemann et al., 1999).

10.3.2 In-Situ Stress Data

The results of the stress measurements yield:

- An orientation of the acting major horizontal stress S_H of N-S to NNW-SSE which is in accordance with existing stress data for Central Europe (Fig. 10.6). The stress direction was verified by the spatial distribution of thousands of induced seismic events during the massive stimulation tests in borehole GPK-1 and GPK-2.



World Stress Map Rel. 2000-1
Heidelberg Academy of Sciences and Humanities
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Projection: Mercator

Fig. 10.6 Orientation of the maximum horizontal stress S_H in Central Europe (Müller et al., 2000)

- A stress regime with notably low horizontal stresses, typical for the tectonic situation in the Upper Rhine graben (e.g. Klee and Rummel, 1999):

  $$S_h = 15.7 + 0.0149 \times (z - 1458)$$

  $$S_H = 23.5 + 0.0337 \times (z - 1458)$$

where S_h and S_H are the minimum and maximum horizontal principal stresses (MPa) and z is the depth below surface (m). The vertical stress S_v can be calculated from the weight of the overburden with given rock density ($\rho = 2.66\ g/cm^3$ in the granite):

$$S_v = 33.1 + 0.0261 \times (z - 1377)$$

The stress profiles are shown in Fig. 10.7. As demonstrated by the stimulation tests in borehole GPK-2 (95JUN16, 96SEP18), the pressure for massive fluid injection into favourable oriented joints is controlled mainly by the minimum horizontal stress component S_h. Therefore, reliable stress data can be used for the technical planning of injection tests at great depth.

A stability analysis on the basis of a simple friction law $|\tau_c| = \mu \cdot \bar{\sigma} = \mu \cdot (\sigma - k \cdot P_o)$ where τ_c is the critical shear stress, σ the effective normal stress, P_o the local hydrostatic pressure, and μ the friction coefficient and the stress-profile equations leads to an estimation of the critical differential stress at which sliding on favourable faults or joints

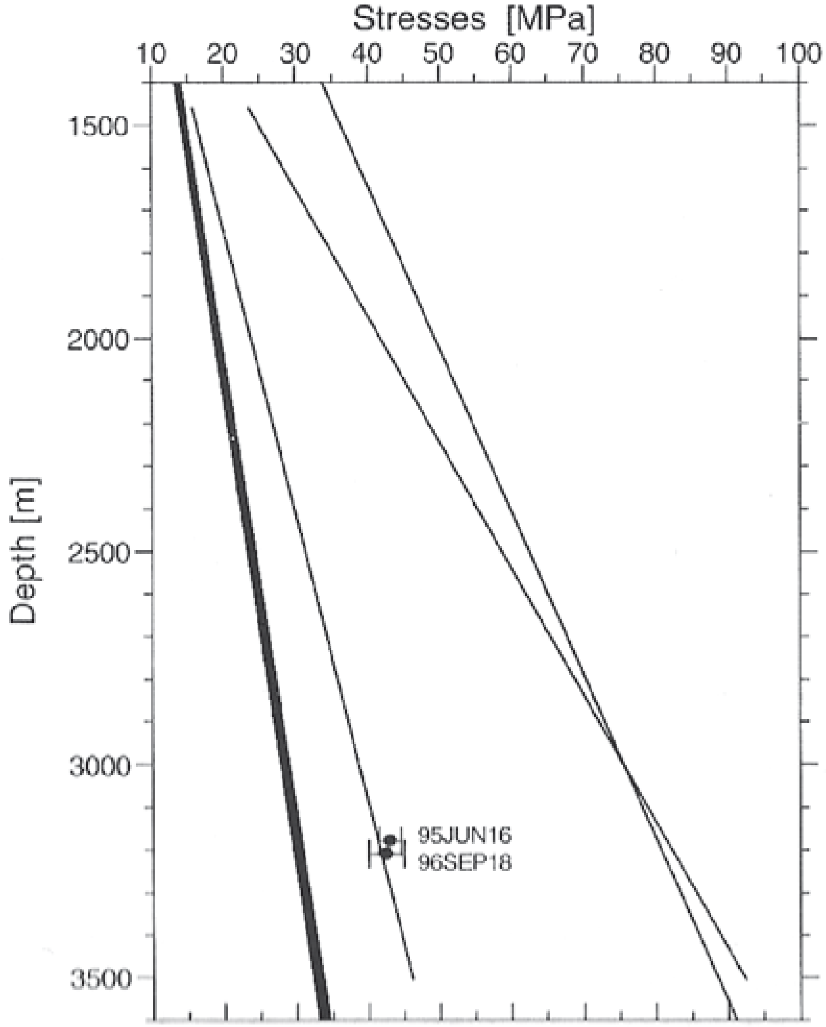

Fig. 10.7 Stress-filed at the Soultz site in relation to the hydrostatic pressure P_{hyd}. 95JUN16 and 96SEP18 marks the injection pressure for massive fluid injection in borehole GPK-2

might occur. k is the pore-pressure ratio with respect to hydrostatic conditions (k = 0: no pore pressure, k > 1: over-hydrostatic conditions). In Fig. 10.8, a comparison of calculated critical differential stresses with the experimental determined and linearly extrapolated results to 5 km depth is shown. The calculations were carried out by using a friction coefficient of $\mu = 0.85$ for a normal faulting stress regime (similar results were obtained for a strike-slip faulting stress regime below 3 km depth). The analysis demonstrates that minor reservoir fluid pressure variations (pore pressure values slightly higher than the hydrostatic pressure) already will induce micro-seismicity and will release the stored elastic energy within the reservoir.

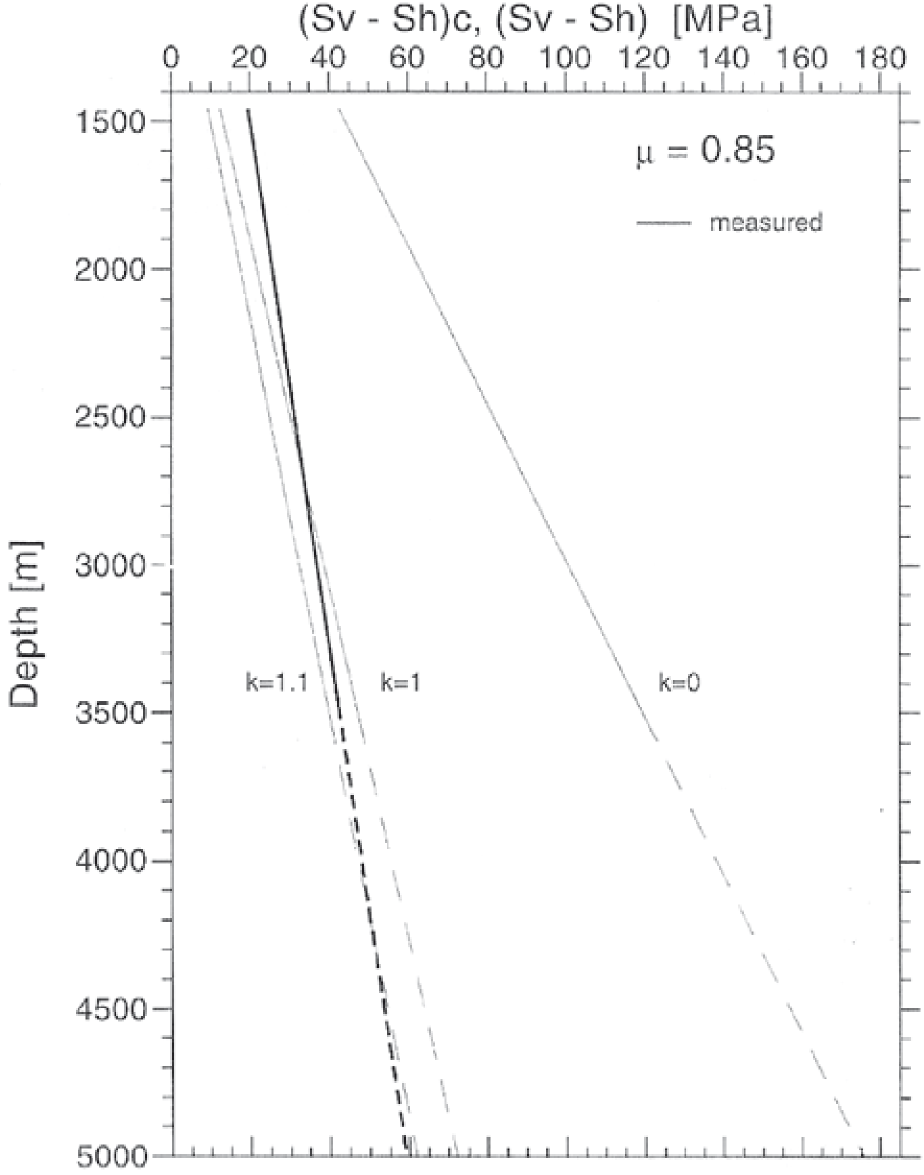

Fig. 10.8 Comparison between critical differential stresses calculated for different pore pressure ratios, a friction coefficient of 0.85 and a normal faulting stress regime with the in-situ measured and extrapolated data (dashed lines)

10.4 CONCLUSIONS

During 15 years of research within the European HDR project at Soultz-sous-Forêts, the fracture network in the Upper Rhine graben has been explored down to 5 km depth with a temperature of more than 200°C. Besides the large geothermal anomaly, one of the secrets for the successful project development was the detailed consideration of the tectonic stress situation at depth, measured by various hydraulic fracturing tests to a depth of 3.5 km using metallic packers suitable for the hot and chemically aggressive downhole environment in the Soultz boreholes. The results yield an in-situ stress direction of NWW-SEE in accordance with existing stress data for Central Europe, and an in-situ stress regime with notably low horizontal stresses, typical for the normal faulting graben tectonics which offers favourable conditions for massive fluid circulation tests.

Later, during various stimulation and hydraulic tests including a circulation experiment of four months duration, the favourable conditions in a graben structure were verified. The four-months circulation test demonstrated that a circulation loop can be maintained with flow rates up to 90 tons per hour and a fluid temperature of more than 140°C, between two boreholes of 450 m distance without any water losses and requiring only 250 kW_{el} pumping power compared to a thermal output of about 11 MW_{th}.

Future work will include the design and construction of a pre-industrial prototype enabling forced fluid circulation between a central injection borehole and two deviated productions wells at depth with temperatures of 200°C. Such a scientific pilot plant could produce approximately 50 MW_{th} over a period of several years and enables electric power generation of approximately 5 MW_{el}.

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