DEEP STRUCTURES OF THE SOULTZ-SOUS-FORETS HDR SITE (ALSACE, FRANCE)

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1. INTRODUCTION

The Soultz-sous-Forêts site in Alsace (France) is located within the extensive thermal anomaly of the Upper Rhine valley (fig. 1), on the eastern margin of the Pechelbronn oil field.

The site, which has been investigated since 1986 for its HDR potential, is currently being studied by scientists from France. Germany, and the United Kingdom, within the framework of a European programme supported by the CEC and coordinated by the European Hot Dry Rock Association.

The Soultz site corresponds lo a local horst structure within the Upper Rhine Graben, bounded by North-trending faults dipping respectively West and East. The objective of the HDR project is the development of an experimental deep thermal exchanger in the granite basement, which is covered by 1400 m of sediments of Triassic to Tertiary age (Kappelmeyer *et al.*, 1994).

Two deep reconnaissance drill holes, EPSl and GPKl, placed 500 m apart, have reached respective depths of 2200 and 3600 m in the granite basement. They are complemented by three refurbished oil wells used for scismic monitoring (Elsass *et al.,* 1994). Extensive single-well hydraulic injection and production experiments have been carried out between 1988 and 1994.

The next phase foresees the drilling of a second deep well down to 3600-4300 m (GPK2) and double-well circulation tests It is expected that natural fractures present in the basement will play a major role in these experiments

2. STRUCTURE OF THE SOULTZ SITE

2.1. Lithology

In the Soultz-sous-Forêts area, the porphyritic granite basement, of probable Visean age, is directly overlain by the sedimentary aquifers of the Buntsandstein sandstone and the Muschelkalk limestone, below a thick pile of sedimentary formations (Keuper, Jurassic, Oligocene) of generally poor permeability. The Triassic aquifers are captive artesian aquifers, because of their impervious sedimentary cover. The overlying Oligocene Pechelbronn formation in particular comprises mostly sandy marls interspersed with oil-bearing sand channels, with a very poor vertical permeability. it is further known from underground workings in the Pechelbronn formation that faults are sealed by clays near surface (Schnacbele, 1948).

2.2. Major faults

The whole series is offset by North-South-trending faults defining kilometer-wide horsts and grabens, which have been well delineated by scismic reflection profiles carried out by the Total oil company in the course of exploration for oil up to 1984 (unpublished reports, courtesy of Total Exploration).

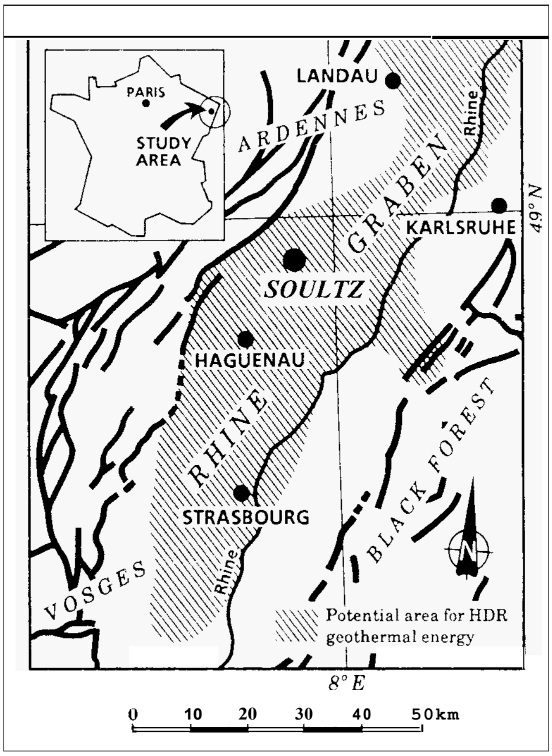

Figure 1: Location map ofthe Soultz-sous-Forêts site (France).

A general characteristic of these major faults is their shallow dip near surface (50 *to* 60") and the tendency to become steeper near the basement. Seismic reflection does not give any image within the granite basement and the attitude of the faults at greater depth is no? known. Ancient faults present within the granite but without any noticeable throw in the sediments are bound to be missed. Since most seismic profiles were carried out along East-West directions, a number of major N110°-striking faults, known from surface geological mapping, may also have been missed.

2.3. Fracturing in granite

About the only source of structural information available within granite comes from the study of drill cores (from well EPSl) and from borehole-wall imagery. Natural fractures observed in granite on drill cores and with borehole imagery appear to belong to two major structural sets, trending N010° with a westerly dip of 80° and N170° with an easterly dip of

70° respectively. The first set parallels the Soultz Fault, and the second set is almost a conjugate set to the first (Genter and Traineau, 1993).

Among the 3000-odd individual natural fractures observed in granite on the cores of well EPS1, about 1% could be considered as open fractures: either fractures not yet sealed by minerals, or veins of drusic quartz thought to retain some permeability (Genter and Traineau, 1992). The distribution of these open fractures shows a great dispersion (fig. 2a) but indicates that they belong to the two main North-trending sets plus to a NW-SE trending set. This latter transverse trend is known from surface mapping and is interpreted as reactivated pre-Rhine Graben faulting (Villemin, 1986).

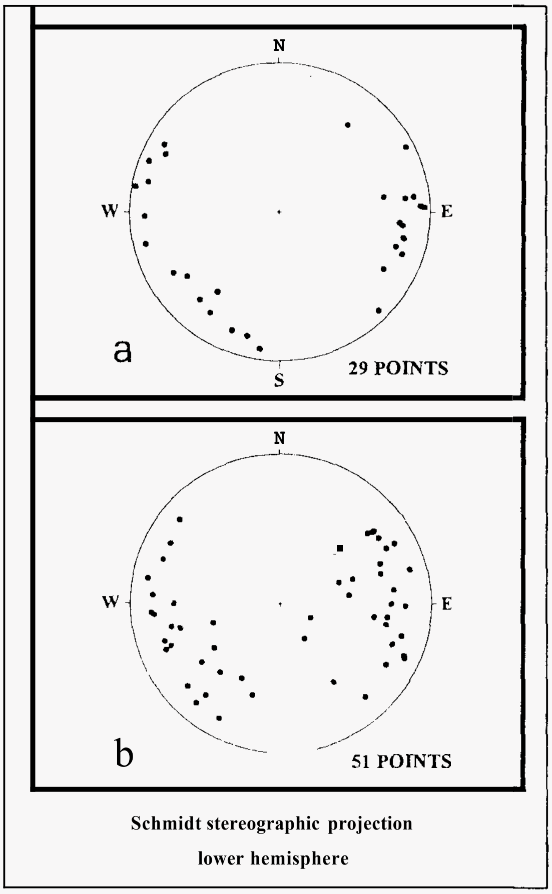

Figure 2: Distribution of fractures in Soultz granite:
a - Open fractures (well EPS 1);
b - Fracture zones (wells EPS 1 and GPK 1)

Geological studies of granite cores and borehole imagery have shown that fractures are not evenly distributed through the granite but are grouped in distinct zones, characterized by an argillitic wallrock alteration (Traineau *et al.*, 1991). This is interpreted as meaning that the granite is affected by a network of fracture zones with sufficient interconnections to enable hydrothermal brines to percolate.

The general attitude of these fracture zones can be estimated from the direction and dip of their wallrock alteration halo, as seen on borehole wall resistivity images obtained with the FMI tool by Schlumberger and, less reliably, ultrasonic images obtained by the BHTV tools by DMT or BLM (Genter *et al.*, in press). This is of course a local estimation and its validity away from the borehole is questionable. Nevertheless the distribution of the attitude of zones, estimated in this way, is similar to the distribution of individual open fractures, albeit with shallower dips (fig. 2b).

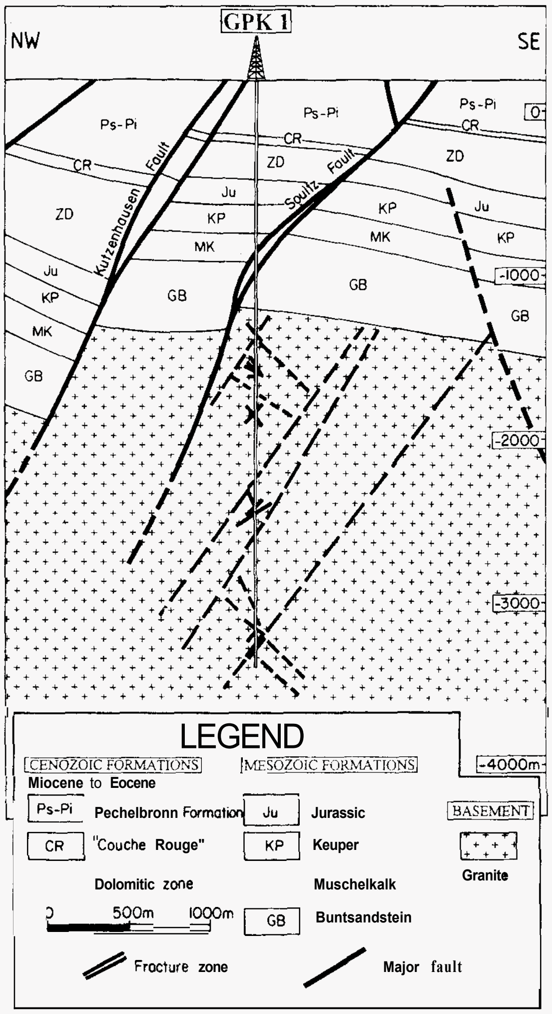

Figure 3: West-East interpretative vertical geological section through GPK1 borehole.

When these fracture zones are plotted on a section, they appear to belong to three main groups which could represent strands of major faults (fig. 3). A conjectural interpretation of these faults is given in figure 3: NW-SE-trending fault zones. being ancient reactivated sets, would be offset by North-trending Rhine Graben faults, determining a three-dimensional block structure within the Soultz horst.

3. DEEP FLUIDS IN THE RHINE GRABEN

3.1. The geothermal field

The Soultz area is a particularly anomalous zone within the general geothermal anomaly of the Upper Rhine Graben (fig. 1). Geothermal gradients reach 10°C per 100 m down to 1000 m depth but decrease in the basement (Schellschmidt and Schulz, 1991).

Several authors have tried to explain the origin of the thermal anomaly at Soultz, and more generally within the Rhine Graben, since the original discovery by geologists working on the Pechelbronn oil field (Haas and Hoffmann, 1929). After first hypotheses of an anomalously low thermal conductivity of the sediments and of volcanic rocks at depth, most hypotheses are now based on the convective circulation of hot water, horizontally by matrix permeability through the aquifers of the sedimentary cover (and sometimes weathered granite), or vertically by fracture permeability through basement faults, or by a combination of both mechanisms (Benderitter and Elsass, in press).

We can add that the deep seismic profile of the ECORS programme has demonstrated that there is no crustal thinning under the Rhine Graben which could explain an anomalous geothermal heat flow (Rousset *et al.*, 1992).

One of the most recent work on 2 D numerical modelling of transverse circulation across the Graben, based on multi-layered matrix permeability flow, shows that the observed temperature field can be reproduced by flow in the sedimentary aquifers with velocities of about 1 m/year. Circulation within the granite is a critical parameter for the model and local convective cells could occur where the aquifers are offset by major faults (Flores-Marquez. 1992).

These local convective cells may be linked to the circulation loops in the fracture zones of the granite basement.

3.2. Chemistry of fluids in the Rhine Graben

Reconnaissance drill holes EPSl and GPK1 have encountered chloride-rich 100 mg/l brines in three fractured zones in granite, at depths of 1800, 2000, and 3500 m (Vuataz *et al.*, 1990, Aquilina *et al.*, 1993). Hydraulic tests carried out in 1993 and 1994 have demonstrated that these hydraulically active zones, with artesian flows of 1 to 2 m³/h, are not directly interconnected.

These formation fluids in granite are very similar in composition to the brines circulating in the Buntsandstein and Muschelkalk aquifers. Geochemical and isotopic studies of deep brines encountered at Soultz and in other boreholes in the Upper Rhine Graben, in sediments as well as in granite, indicate that these saline fluids have a common origin. Fluids sampled at shallower depths in sediments around the Soultz anomaly are interpreted as a mixture of surface waters with deep brines (Pauwels *et al.*, 1991, 1993).

The interpretation of geothermometers further indicates that Soultz granite brines may have been subjected to higher temperatures than those at which they have been collected (150-160°C). This would imply that the fluids had circulated through hotter (and deeper?) levels, reaching temperatures of 200 to 250°C.

Another confirmation of hydraulic connections between sediments and granite basement has been found in the course of petrologic studies of hydrothermally altered zones in granite. Traces of organic matter of bitumen type (different from drilling lubricants) sealed in hydrothermal deposits, have been found in the filling material of a fracture intersected by borehole EPSl at 2160 m depth within granite (Ledesert, 1993). These are most probably particles which have been carried down from overlying sedimentary rocks by downward circulation of fluid and were then trapped in hydrothermal deposits.

4. DEEP NATURAL CIRCULATION AT SOULTZ

4.1. Natural circulation pathways

The natural circulation pathways in a network of fractured zones such as the one we envision in the granite basement at Soultz are bound to be complex. However an analogy with vein-type mineral deposits may be attempted, if we consider that mineral lodes represent fossilized circulation pathways of hydrothermal solutions.

A common representation of vein-type deposits is as a series of parallel subvertical "columns" within a main fault zone. This columnar habit may be interpreted as due to the filling of voids generated by displacement of the fault, such as strike-slip under shearing conditions.

The Upper Rhine Graben, which originated in a distensive regime, is now subjected to a compressive regime with a major horizontal stress direction of 140° to 150° (Baumann, 1981). Under such conditions, NNE-trending faults such as the Soultz and Kutzenhausen Faults (fig. 2) react with a sinistral strike-slip displacement, such as during the 1952 local earthquake in the Soultz area (Illies, 1981).

We can therefore postulate that natural circulation will tend to follow subvertical channels within NNE-trending fault zones. In order to test this hypothesis, we have mapped temperature data recorded in oil exploration boreholes at the top of the Muschelkalk aquifer, in order to try to identify temperature anomalies indicative of discharge points of upflowing hydrothermal channels in the granite basement.

The unsmoothed temperature map obtained, however imperfect because of the irregular density of data points and the poor quality of the measurements, does indicate the existence of a number of "hot spots" along the Soultz Fault (fig. 4). These "hot spots" are areas where recorded temperatures are 20 to 30°C higher than the general background temperature. Numerical modelling of hydrothermal circulation in a vertical channel indicates a thermal effect consistent with the temperature map (Benderittcr *et al*, submitted).

4.2. Hydraulic injection tests

Seismic monitoring during hydraulic injection tests is the main geophysical method used to evaluate the growth of the "reservoir" and identify circulation pathways. Microseismic events identify the location of fractures generated or reactivated by the injection. In favorable cases, when the array of seismic sondes or ground stations recording the events is sufficiently large and adequately located, fault plane solutions can be computed for each event.

Clouds of microseismic events have been recorded during all injection tests at Soultz (Beauce *et al.*, 1991, 1992, in press). During the latest massive hydraulic injection tests in 1993, a large, well-structured, and elongated cloud was recorded, extending over 1 km in the NNW-SSE direction (Fabriol *et al.*, in press).

This cloud reflects in part the hydraulic fracturing of the rock near the well but mostly the tectonic adjustment of the granite mass under the local modification of the stress field. It does not necessarily represent a map of all actual flowpaths of injected water. Free-flowing channels can be invisible to seismic monitoring, as has been demonstrated at the Mayet-de-Montagne granite site in France (Cornet and Yin, 1992).

Single-well hydraulic injection experiments carried out in 1991 at 2000 m depth in GPK1 are indeed interpreted as having connected the borehole to an aseismic natural fracture system by means of hydraulic fracturing (Jung, 1991. 1992). The turbulent flow observed during these tests is an argument in favor of the connection to a natural channel system versus a network of planar fractures.

5. CONCLUSIONS

The fracture network in the granite basement of the Soultz site is known mostly from conjecture. We do have an image of major faults dissecting the sedimentary cover in kilometer-wide horsts and grabens from seismic reflection profiles, but the inner structure of the basement in three-dimensional blocks bounded by fractured and altered zones is inferred only from borehole wall imagery. We lack a reliable geophysical tool capable of imaging fracture zones at a

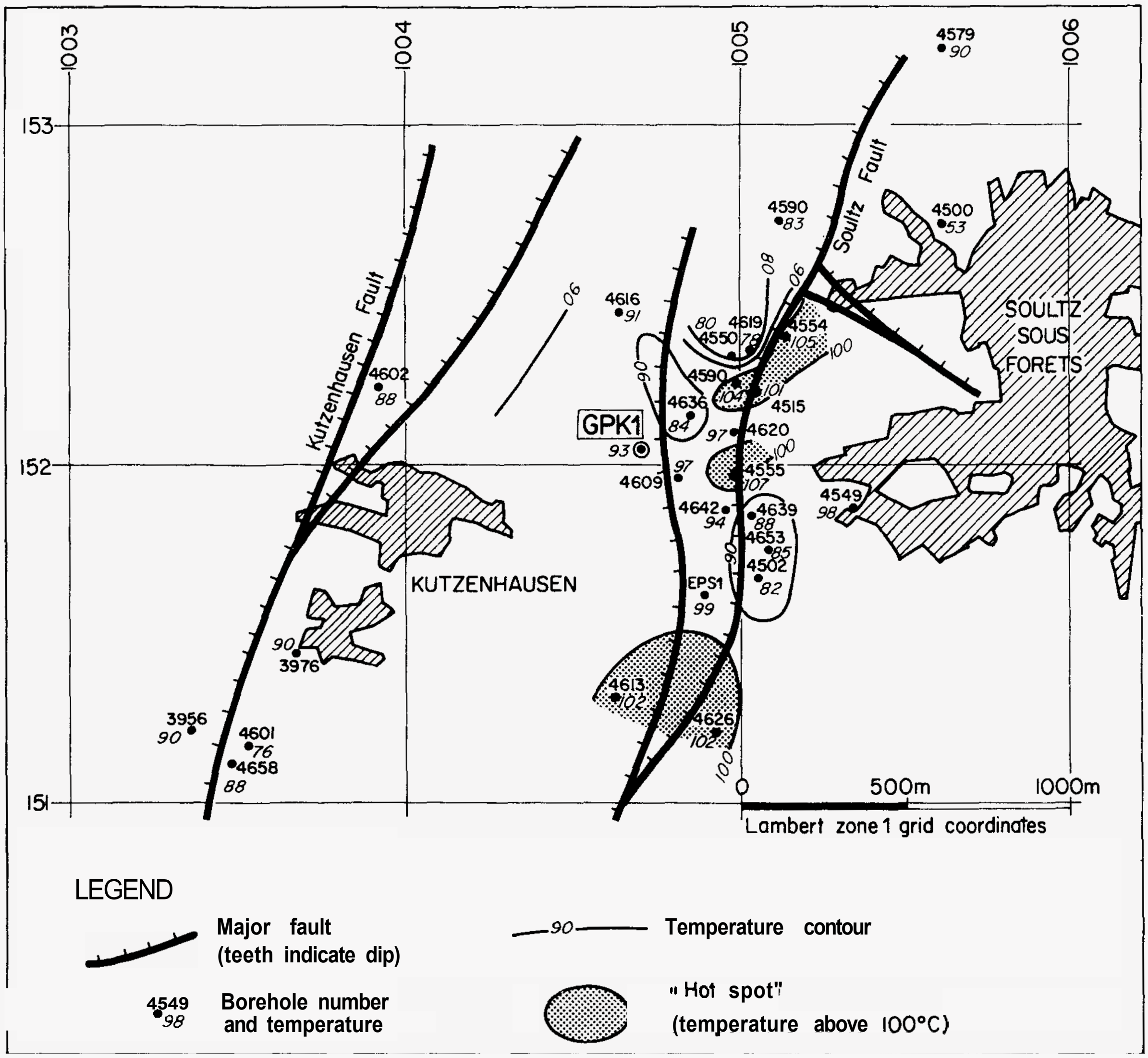

Figure 4 Temperature map at the top of the Muschelkalk formation in the Soultz-sous-Forêts area (France)

distance from the wells at the great depths and high temperatures of HDR sites.

The deep brines encountered at Soultz in granite clearly belong to a regional natural circulation system. This system comprises inflow points of meteoric waters, the Buntsandstein and Muschelkalk aquifers, and fault zones in these aquifers as well as in the granite basement down to at least 3500 m depth. The sytem is artesian because of the impervious Tertiary sedimentary cover.

Subvertical channels carrying hydrothermal fluids within fracture zones may link the basement to the sedimentary aquifers, creating "hot spots" at their outflow points. If this hypothesis holds true, future double-well circulation experiments at Soultz will be strongly influenced by such preferential connections to the overlying sedimentary aquifers.

6. ACKNOWLEDGMENTS

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