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Stress regime in the Rhinegraben basement and in the surrounding tectonic units

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ABSTRACT

In-situ stresses are key parameters in the design of a bot-dry-rock operation for the extraction and economic use of geothermal energy. In-situ stresses control the pressure to initiate and activate fractures and joint systems, determine the underground fluid flow path, or influence the stability of un-cased borehole sections. Therefore, since the early days of the European HDR - project at Soultz-sous-Forets, the tectonic situation in the Upper Rhine-valley has been extensively investigated by hydraulic-fracturing stress measurements, so far at depth down to approximately 3.5 km. The results of the measurements yield

- the orientation of the acting maximum horizontal compression of N - S to NNW - SSE in accordance with both the spatial distribution of the seismic events induced during the stimulation experiments and the existing stress data for Central Europe,

- the stress-regime with notably low horizontal stresses, typical for the normal faulting tectonics in the Upper Rhine-valley.

The comparison with existing stress data of the surrounding tectonic units and the extrapolation of the stresses to the proposed reservoir depth at 5 km yield important data for both the technical planning of the drilling and casing cementation operation and the design of future circulation tests at the Soultz test-site.

KEYWORDS

Stress regime, Upper Rhine-valley, HDR

1. Introduction

The concept of hot-dry-rock geothermal energy extraction requires fluid circulation between two deep boreholes through artificially induced hydraulic fractures or/and through the pre-existing joint network in the crystalline rock-mass. However, the efficiency of the heat exchange strongly depends upon the hydraulic impedance of the fluid flow path. Besides rock-mass permeability, downhole 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 field. Therefore, both parameters were extensively investigated as part of the feasibility study at the European HDR - project site at Soultz - sous - Forêts.

This paper summarizes the results of in-situ experiments for the determination of the stress regime, presents a comparison with existing stress data in the surrounding tectonic units and derives an extrapolation of the data to future reservoir depth at about 5 km including consequences for the HDR project at Soultz-sous-Forêts.

2. Tectonic setting of the Soultz HDR-site

The European HDR-site at Soultz-sous-Forêts is located about 50 km north of Strasbourg near the western margin of the Upper Rhine-valley, the most active present-day tectonic unit in Central Europe north of the Alps. 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 100 mW/m^2.

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 (MÜLLER et al. 1992).

Earthquake focal mechanism data for the Upper Rhine-valley indicate mainly both, strike-slip faulting 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 (BLÜMLING 1986, RUMMEL 1987, MÜLLER et al. 1992).

3. In-situ stress regime at Soultz

Since no direct stress data from in-situ measurements were available in the immediate vicinity of the Soultz HDR project-site, the tectonic situation in the Upper Rhine-valley has been extensively investigated by various hydraulic fracturing stress measurements down to appromiately 3.5 km depth (RUMMEL & BAUMGÄRTNER 1991, KLEE & 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 1458 m and 2000 m depth in conjunction with the conventional hydraulic test program.

- Two hydrofrac tests were conducted in borehole EPS-1 at about 2200 m depth in late 1991.
- **After** deepening of borehole GPK-1 to almost 3.6 km depth, two further tests were carried out at 3315 m and 3506 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 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 aluminum packers as part of a wireline hydrofrac system (KLEE & HEGEMANN 1995). Since then, the metal-packer technology has been investigated with promising results for permanent borehole sealing in nuclear waste storage projects. Presently, the technology is being used for the design of new casing-cementation packers for the planned deepening of borehole GPK-2 (HEGEMANN et al. 1999).

The results of the stress measurements yield

- the orientation of the acting major horizontal stress S_H of N - S to NNW - SSE which is in accordance with both the spatial distribution of the seismic events induced during the stimulation experiments and existing stress data for Central Europe (Figure 1)
- a stress-regime with notably low horizontal stresses, typical for the graben tectonics:

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

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

  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):

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

The stress profiles are shown in Figure 2. **As** demonstrated by the initial stimulations in the boreholes GPK-1 and GPK-2 (95JUN16, 96SEP18), the pressure for massive fluid injection into favorable oriented joints is controlled mainly by the minimum horizontal stress component S_h. Therefore a reliable estimation of the stress magnitudes at 5 km depth yield important data for the technical planning of future injection tests at great depth.

4. Extrapolation of stress data and discussion

For a prediction of the stress regime at **5** km depth, dimensionless stress - depth relations for the Soultz-site are compared with both the existing stress data for Central Europe and the average relations suggested by **RUMMEL** et al. (1986) for continental areas (Figure 3):

$$k_h = \frac{S_h}{S_v} = \frac{0.15}{z} + 0.65 \qquad k_H = \frac{S_H}{S_v} = \frac{0.27}{z} + 0.98$$

where z is the depth (km).

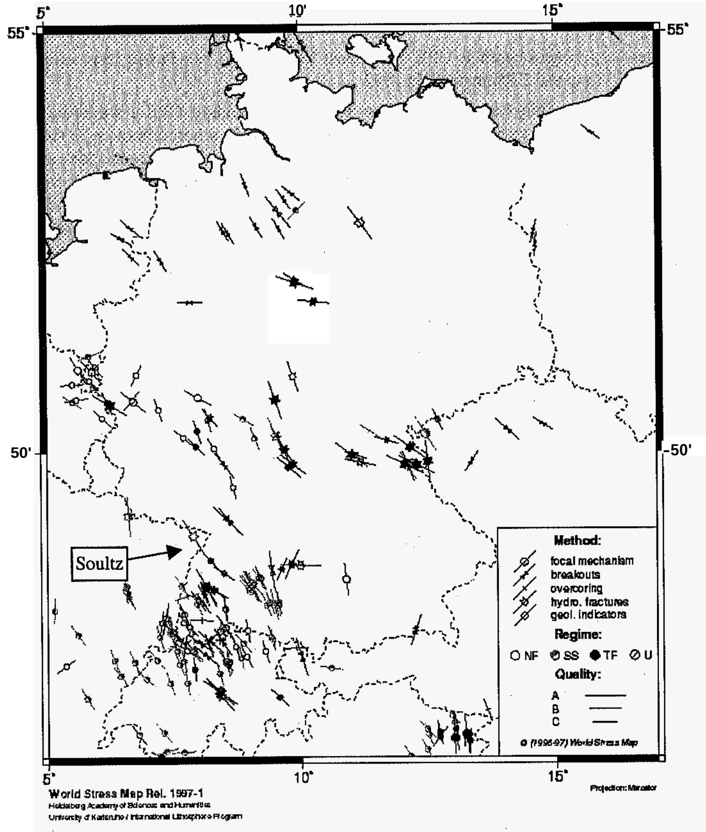

Figure 1: Orientation of the maximum horizontal stress S_H in Central Europe (released by the World Stress Map Project, 1997).

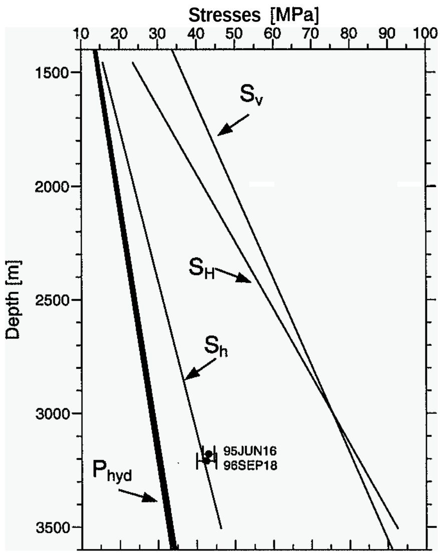

Figure 2: Stress-field at the HDR test-site Soultz in relation to the hydrostatic pressure P_{hyd}. 95JUN16 and 96SEP18 marks the injection pressure for massive fluid injection in borehole GPK-1 and GPK-2.

The comparison demonstrates that the average relations yield an upper bound estimation of the minimum horizontal stress of $S_h \approx$ **87** MPa and a lower bound estimation of the maximum horizontal stress of S_H = **132** MPa, while the linear extrapolation of the stress - depth relations for the Soultz-site to 5 km depth yields minimum and maximum horizontal stresses of S_h = **68.5** MPa and S_H = **143** MPa, respectively. Assuming a hydrostatic pressure of **45** MPa to **48** MPa at **5** km depth (depending on the temperature and the salinity of the injection fluid) the stimulation and future fluid circulation will require a differential pressure of at least **20** MPa.

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, a 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 favorable faults or joints might occur. **k** is the pore-pressure ratio with respect to hydrostatic conditions (k = 0: no pore - pressure, **k** > 1:

over-hydrostatic conditions). In Figure 4, a comparison of calculated critical differential stresses with the experimental and linearly extrapolated results is shown. The calculations were carried out by using a friction coefficient of μ = 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) will induce microseismicity and will reduce the stored elastic energy within the reservoir.

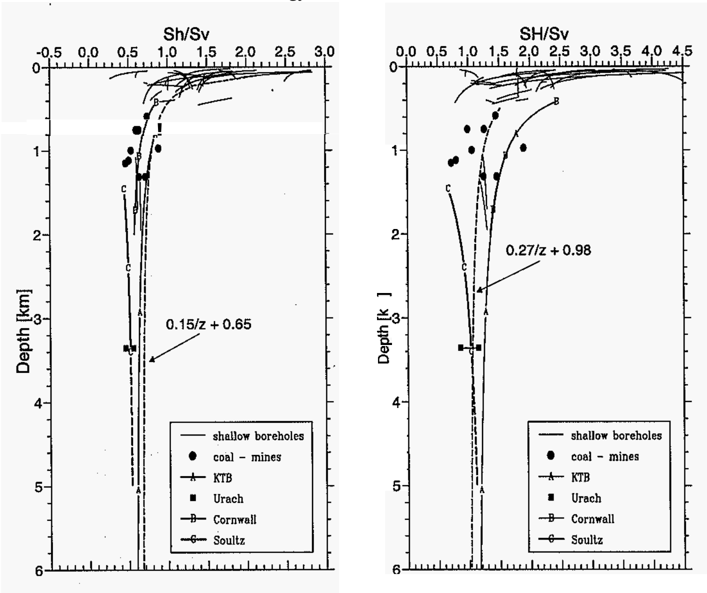

Figure 3: Dimensionless stress ratios $k_h=S_h/S_v$ and $k_H=S_H/S_v$ derived from various hydrofrac stress measurements in Central Europe. Average relations after RUMMEL et al. (1986).

5. Summary and conclusions

In designing an HDR operation for the extraction and use of geothermal energy it is necessary to have knowledge on the magnitude and the direction of the in-situ stresses at depth of the geothermal reservoir. Therefore, since the early beginning of the project, numerous hydraulic fracturing stress measurements were carried out at the European HDR research test-site at Soultz-sous- Forêts.

The results of the in-situ tests yield a stress regime with considerable low horizontal stresses, typical for the normal faulting stress regime in the Upper Rhine-valley. The derived orientation of the maximum horizontal compression is in agreement with existing stress data for Central Europe.

Extrapolation and comparison with existing stress data for the surrounding tectonic units yield an estimation of the stresses at future reservoir depth at 5 km. The derived differential pressure of about 20 MPa is presently used for the technical planning of future operations (e. g. design of metal casing-cementation packers). However, due to the uncertainties, a reliable estimation of in-situ stresses requires further deep hydraulic fracturing tests, which will be carried out after deepening of borehole GPK-2 to about 5 km.

As demonstrated by a stability analysis on the basis of a simple friction law, critical differential stresses can be expected at **5** km depth for pore pressure ratios slightly higher than the hydrostatic conditions. Therefore small reservoir fluid pressure changes will cause sliding along favourable orientated fractures associated with microseismicity.

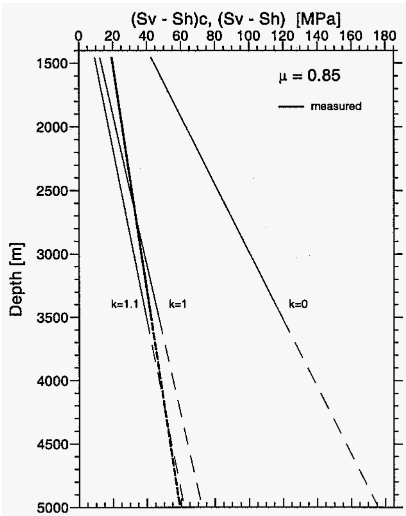

Figure 4: Comparison between critical differential stresses calculated for different pore pressure ratios, a friction coefficient of 0.85 and a normal faulting stress regime with in-situ measured and extrapolated stress data.

Acknowledgments

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