Hydrofrac Stress Profile in the KTB Boreholes VB and HB

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Despite all we know about plate tectonics, our knowledge on lithospheric dynamics still is rudimentary. This includes crustal faulting, the physics of earthquake processes, or deformation and fluid transport within the crust. The lack of knowledge is mainly based on the fact that we know little on the sources and magnitudes of plate driving forces, how forces are transmitted from plate boundaries over large distances, or how to balance forces and model lithosphere dynamics. Consequently, we cannot encounter the arguments for a low strength or high strength upper continental crust, or speculate on the depth of the brittle-ductile transition due to strength decrease in the "crustal asthenosphere."

These are just some aspects why the scientific community put strong emphasis on crustal stress probing in the KTB project. It was obvious that the main information on stress magnitudes had to come from hydraulic fracturing tests if possible conducted as a quasi continuous stress log. The hydrofrac stress data then could be used for calibrating stress information from other sources such as borehole break-outs or core relaxation experiments.

In Phase I during February 1990 14 hydrofrac tests were conducted in the KTB pilot hole between 800 and 23000 m. Most of the tests were carried out by the wireline hydrofrac technique developed at the Institute of Geophysics, Ruhr-University Bochum, with lowering an inflatable double straddle packer system. A typical downhole pressure record is given in Fig. 1 showing hydrofrac breakdown at 38 MPa and 3 refrac cycles. It should be noted that the average pumping rate was in the order of 4 liters per minute only.

Unfortunately, a deeper test in the KTB main borehole at 4.2 km depth (September 1991) using a wireline aluminum straddle packer system (high temperature!) in a 4 inch pilot hole was not possible since the pilot hole drilling was not successful. Subsequently, this technique was successfully applied in the HDR-geothermal drillhole GPK1 to a depth of 3.4 km at 180°C.
The presently final test in the KTB main hole could be carried out at a depth of 6 km in May 1992 after cementing the 13 3/8" ID casing. A mechanical casing single packer was set at depth and the 12 1/4" open-hole section between 6013 and 6031 m was pressurized. The pressure record of the experiment is given in Fig. 2 (well-head pressures).

The experiment can be divided into three stages:

- high flow rate injections with about 50 liters per minute and higher at the beginning
- low flow rate injection of about 20 liters per minute (the lowest injection rate technically possible)
- pressure pulse tests at the end to observe the pressure decline at different pressure values.

After careful interpretation at the pressure records, the stress profile including the tests in the pilot hole is shown in Fig. 3 in comparison with the vertical stress calculated for reasonable rock densities. The data are shown in a shear stress vs. normal stress plot in Fig. 4. For hydrostatic pore pressure and friction on favourable slip planes the friction coefficient is about 0.6 which is in agreement with our present understanding of friction processes.

Finally, we present the stress data in the form of maximum shear stress with respect to critical shear stresses for dry (zero pore pressure) and wet conditions (hydrostatic pore pressure) in Fig. 5.

The present data base to 6 km depth suggests the following:
- Assuming hydrostatic pressure on fractures, the upper crust seems to be in a quasi-stable equilibrium for both strike-slip and normal faulting.

- The stress data support the hypothesis for a strong upper crust with a shear strength of about 100 MPa at 6 km depth.

- Despite the uncertainty of the depth of the brittle-ductile transition and the strength of the lower crust, the stress levels observed in the upper crust seem to characterize the ability of the crust to support and transmit plate driving forces in the order of 2 to $3 \cdot 10^{12}$ N/m, i.e. the upper crust acts as a "stress guide."

The data base is poor. Hopefully, further tests can be conducted in the KTB borehole to final depth.
Fig. 1: Typical hydrofrac pressure and flow-rate versus time record, observed for a sealed-off injection interval at 1270 m depth in the KTB-VB.

Fig. 2: Pressure and flow-rate versus time plot of the hydrofrac experiment at 6 km in the KTB-HB.
Fig. 3: Principal stress profiles to 6 km depth derived from hydrofrac tests in the KTB boreholes VB and HB (S₃ and S₂ minor and major horizontal stresses, Sᵥ vertical overburden stress) for average rock densities between 2.8 and 2.9 g/cm³.

Fig. 4: Acting shear and normal stresses, and frictional strength for different friction coefficients for strike-slip faulting.

Fig. 5: Acting differential stresses (data points) and critical stress condition for strike-slip faulting (S₈−Sᵥ) at zero (k=0) and hydrostatic pore pressure (k=1).