Leibniz-Institut für Angewandte Geophysik

spp icdp

Freie Universität Berlin

Time-lapse Seismics in Crystalline Crust - Lessons Learned at the Continental Deep Drilling Site (KTB)

Beilecke, T. (LIAG, Hannover), Bram, K. (LIAG, Hannover), & Buske, S. (Freie Universität Berlin)

Contact: thies.beilecke@liag-hannover.de

Summary: We conducted an active seismic experiment with the aim to measure seismic reflection amplitudes changes as a result of fresh water injection and corresponding pressure changes in a reservoir. The water was injected into the so-called SE2 fault zone in crystalline rock units at the German Continental Deep Drilling site (KTB) (Beilecke et al., 2009). Prior to the experiment, theoretical calculations had indicated a possible increase of the compressional wave reflection coefficient of about 15% for vertical incidence, as a result of an injection-induced reduction of the seismic velocities within the fault zone (Kaselow, 2004). The experiment was not successful. We believe that the main cause is the effect of near-surface elastic variations on the signals, the impact of which we were not able to quantify.

1. Prediction

In theory and in the laboratory variations of the hydraulic pressure can be detected with seismic methods: A lowering of the hydraulic pressure leads to the closure of micro-cracks within the rock (increase of the differential or effective pressure). Subsequently, the seismic velocities increase locally (Fig. 1.1 left, Kaselow, 2004). Thus, seismic impedance contrasts vary behind a propagating fluid pressure front in a shear zone. The largest changes can be expected at vertical ray inclination (0° in Fig. 1.1 right, Kaselow, 2004). The expected changes are about 15 % on the SE 2 shear zone plane at the KTB site, if the pressure level is distributed across the first Fresnel zone as indicated in Fig. 1.2.

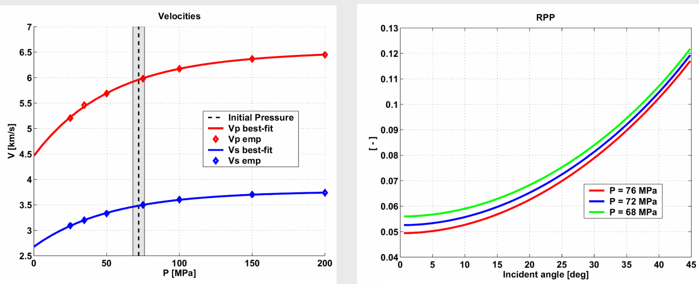

Figure 1.1 left: Laboratory velocity changes depending on effective pressure, typical for the KTB pilot hole at about 4000 m depth. Right: Reflection coefficients (PP) depen-ding on pressure values in Fig. 1.1 left and incident angle.

The model calculations by Kaselow, 2004 in Fig. 1.1 are based on the following assumptions:

Mean Confining Stress at 4000 m depth was determined from **Stress Tensor** *(Brudy et al., 1997 and Ito & Zoback, 2000)*:
$\sigma_{vertical}$ = 109 MPa, $\sigma_{HORIZONTAL}$ = 176 MPa, $\sigma_{horizontal}$ = 78 MPa
σ_{mean} = 120 MPa

Effective Pressure = Mean Confining Stress – Pore Fluid Pressure
if rock in Gassmann limit and/or porosity is low (Kaselow, 2004):
120 MPa – 45 MPa = 75 MPa

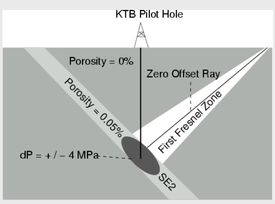

Figure 1.2: Non-scaled sketch, illustrating the model for estimating SE2 reflectivity changes due to an artificial pore pressure variation around the open hole section of the KTB pilot hole. We assume that the pore pressure can be changed by ±4 MPa in a volume covering at least the first Fresnel-Zone of the zero offset ray. A crack porosity of 0.05 % is assumed only within the fault zone (after Kaselow 2004).

2. Field Experiment

The practical utilization of active seismics for the detection of pressure changes in hard rock was studied at the Continental Deep Drilling Site (KTB, Figs. 2.1 and 2.2). The injection of water (200 l/min) in a depth of about 4000 m into the so-called SE2 shear zone in the KTB pilot hole was monitored with active seismics between the springs of 2004 and 2005. Source and receiver points are close to the location of former deep seismic experiments acting as reference (Figs. 2.4, 3.1, and 3.2). The core of the monitoring experiment was a fixed 5-arm geophone array consisting of 24 3C-geophones, buried at about 70 cm depth (Fig. 2.3 and 2.4). Each channel was recorded separately to allow spatial post-processing. Water pressure and temperature were monitored in the borehole (Fig. 2.5).

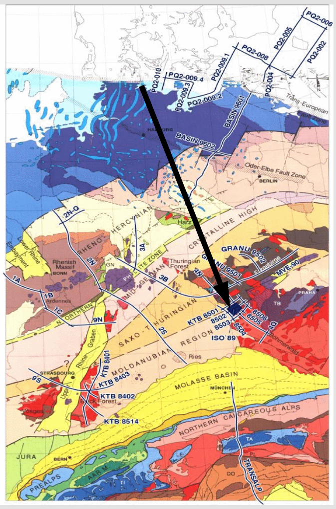

Figure 2.1: The KTB site within the tectonic map of central Europe. Deep seismic profiles are indicated (GFZ Potsdam after Burollet et al., 1992).

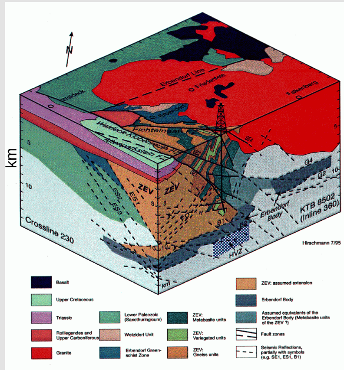

Figure 2.2: 3D model of the crustal structure at the KTB (Harjes et al., 1997).

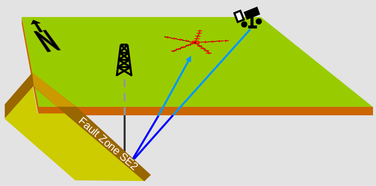

Figure 2.3: Experiment geometry: Vertical vibrator signal source and receiver array. Injection was through borehole into the fault zone SE2.

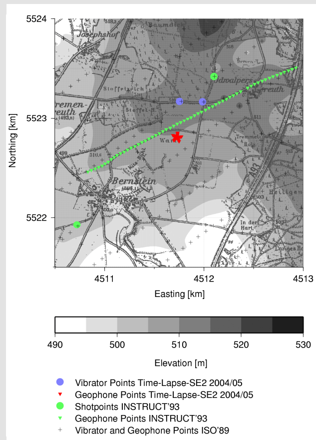

Figure 2.4: Topography and indicated locations of sources and receivers.

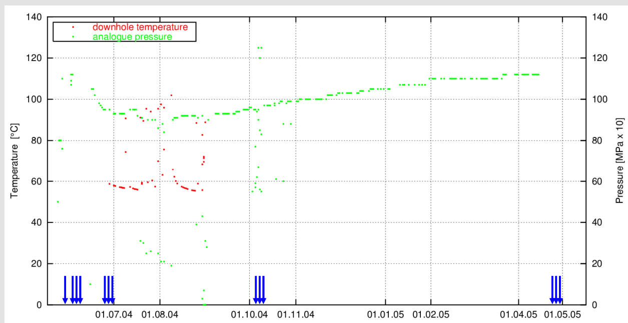

Figure 2.5: Fresh water injection: Pressure evolution at the well head and temperature at a depth of 3856 m in the KTB pilot hole. Blue arrows indicate days of active seismic measurements at the geophone array.

Leibniz-Institut für Angewandte Geophysik

spp | icdp

Freie Universität Berlin

3. Reference Data

Different fault zones at the KTB site, including the SE2 zone had been imaged before with target-oriented seismic investigations.

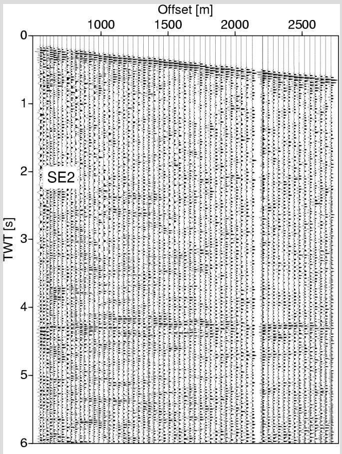

Figure 3.1 Seismic reflections of shot point 7 of the INSTRUCT'93 experiment (Wenzel et al. 1995).

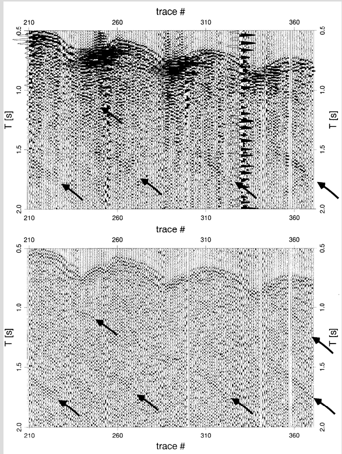

Figure 3.2 Shot record of ISO89-3D experiment (Buske, 1999) showing several clear reflections from fault zones marked by arrows. Top: raw shot record, bottom: AGC (1 s) applied.

4. Source Repeatability

The seismic source was a mobile vertical vibrator (mass = 2.6 t, peak force of 27 kN) (Buness & Wiederhold, 1999). The source signal was a vertical vibrator sweep of 30 s (30-120 Hz) emitted 32 times during each measurement cycle. For QC it was recorded with accelerometers on the vibrator unit and a 3C-geophone at about 10 m distance (Fig. 4.1), the center accelerometer on the vibrator mass. Its deviation is below 10% for both source points, i.e., below the expected reflection amplitude change.

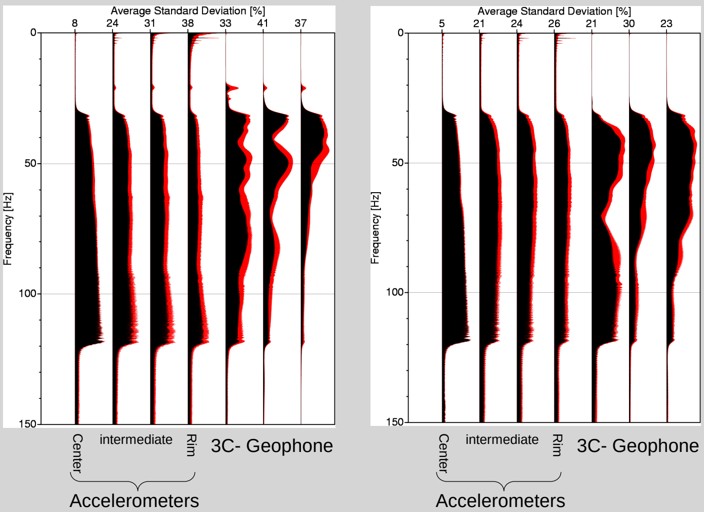

Figure 4.1 left: Average amplitude spectrum of different sensors close to the vibrator source (black) and indicated standard deviation (red). Input are all the sweeps of all measurement cycles between June 1st, 2004 and April 29th, 2005 at vibrator point 1 (blue arrows in Fig. 2.5). Numbers above the traces show the average of the standard deviation values along the frequency axis of each trace.

Right: Like Fig. 4.1 left but of vibrator point 2.

5. Observations

A resulting seismogram of the experiment is depicted in Fig. 5.1. Main surprise: In some cases, traces within the same time cluster differ more than traces from different time clusters (cp. Fig. 2.5). The amplitudes do not seem to be strictly pressure-related, compared with the indicated well head pressure values. Error bars can't explain all amplitude variations within the year (Fig. 5.2). We believe short-term near-surface variations of elastic properties (we could not quantify with this setting) spoiled the signals.

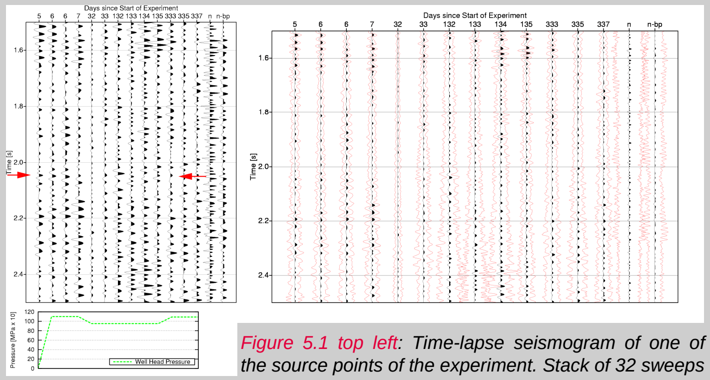

Figure 5.1 top left: Time-lapse seismogram of one of the source points of the experiment. Stack of 32 sweeps and 24 vertical components of array, spherical divergence correction and bandpass filter. Trace "n" denotes a stack of noise recordings without amplitude correction, "n-bp" represents its bandpass-filtered version. The arrows indicate the expected onset times of the target reflections. Right: Representation of the top left figure with included error bars. Bottom left: approximate well head pressure.

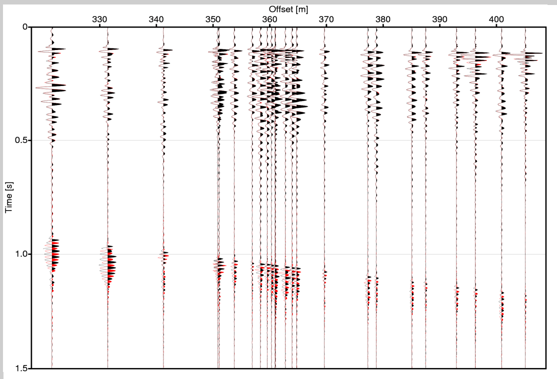

Figure 5.2: Signals of the vertical components of the geophone array, plotted according to offset. Red: Recording of the measurement cycle during the morning of June 2, 2004. Black: Recording of the measurement cycle during the afternoon of June 2, 2004. Note the time delay of the surface waves starting at about 0.9 s travel time as opposed to the signatures of the first break.

Conclusions: Despite good repeatability of the emitted source signals, the experiment suffered from missing the clear reflections expected from the fault zone with regard to seismic data from past experiments and the signal-to-noise ratio remains smaller than the effects under observation. Therefore, we conclude that the experiment was not successful in seismically measuring pressure variations. We believe that the near-surface variations of elastic properties influenced the seismic monitoring negatively. Burring geophones is not enough to suppress this influence. Quantifying this seems to be the key problem in this experiment and requires additional effort.

Acknowledgments: Authors thank Deutsche Forschungsgemeinschaft (DFG) for support through grants BR 606/7-1 and BR 606/7-2.

References

BEILECKE, T., BRAM, K., and BUSKE, S., 2009. Pressure-dependent seismic reflection amplitude changes in crystalline crust: lessons learned at the Continental Deep Drilling Site (KTB). Geophys. J. Int., 180, 311–326, doi: 10.1111/j.1365-246X.2009.04405.x.

BRUDY, M., ZOBACK, M. D., FUCHS, K., RUMMEL, F., & BAUMGÄRTNER, J., 1997. Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength. J. Geophys. Res., 102(B8), 18453-18475.

BUNESS, H. and WIEDERHOLD, H., 1999. Experience with a vibrator system: a high frequency tool, in Proceedings of the 61st EAGE Conference, Expanded Abstracts, p. session 4042, European Association of Geoscientists & Engineers.

BUROLLET, P., DAL PIAZ, G.V., FRANKE, W. & TRÜMPY, R., 1992. The European Geotraverse, Atlas Map 1, Tectonics. In: Blundel, D., Freeman, R., Mueller, St. (eds), A Continent Revealed: The European Geotraverse.

BUSKE, S., 1999. Three-dimensional pre-stack Kirchhoff migration of deep seismic reflection data, Geophys. J. Int., 137(1), 243–260.

HARJES, H. P., et al., 1997. Origin and nature of crustal reflections: Result from integrated seismic measurements at the KTB superdeep drilling site. Journal of Geophysical Research, 102(B8), 18,267–18,288.

ITO, T. & ZOBACK, M.D., 2000. Fracture permeability and in situ stress to 7 km depth in the KTB Scientific Drillhole. Geophys. Res. Letters, 27(7), 1048-1051.

KASELOW, A., 2004. The stress sensitivity approach: theory and application, PhD thesis, Freie Universität Berlin.

WENZEL, F., BRAM, K., and REICHERT, C., 1995. Physical insight in a crustal reflector at the KTB, Technical Report, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany, unpublished.