Two Massive Hydraulic Tests Completed in Deep KTB Pilot Hole

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doi:10.2204/iodp.sd.3.05.2006

Introduction

The German Continental Deep Drilling Program (KTB) boreholes in Windischeschenbach, Bavaria, Germany have revealed a wealth of geoscientific data during the years of pre-drilling surveys (1984–1986), the drilling phase (1987–1994), and the subsequent deep-crustal laboratory phase (1995–2000, e.g. Emmermann & Lauterjung, 1997). In 2001, a new series of experiments were launched within and around the two KTB boreholes, the 4.0-km-deep pilot hole (KTB-VB), and the 9.1-km-deep main hole (KTB-HB; Fig. 1). These experiments address the spatial extension of fluid flow and fluid systems in the Earth’s crystalline crust, their impact on physical rock parameters, rheology, the dynamics and mechanical stability of the crust, and the transport of soluble matter. Studies of these parameters under in situ conditions are of fundamental geoscientific and societal interest in areas such as the optimal use of fluid and thermal reservoirs, the safe disposal of critical wastes, and understanding seismogenesis, particularly in connection with large lake reservoirs.

The use of the KTB site as a crustal laboratory addressing the role of rock fluids is supported by a wealth of exceptional surface and borehole data, two accessible boreholes in crystalline rock, at only 200 m apart, and the occurrence of two distinct, extended fault systems, named seismic reflectors SE1 and SE2, at roughly 7 and 4 km depths, respectively.

The new series of KTB experiments are part of a research program entitled “Energy and Fluid Transport in Continental Fault Systems”. The first phase of experiments involved massive hydraulic tests in KTB-VB to probe the SE2 fault system at a depth of 4 km and included a production test and an injection test, with subsequent recovery periods. A second phase of hydraulic tests is currently under planning and is intended to probe the more seismically reflective fault system SE1 at a depth of ~7.2 km.

One-Year Production Test

A production test within Phase I was conducted from June 2002 to June 2003. A submersible pump was lowered to a depth of 1284 m within hole KTB-VB, and 22,300 m³ of 119°C in situ saline fluids were produced from clefts in contact with the open-hole section, at 3850–4000 m depth. An initial production rate of 29 L·min⁻¹ (Table 1) resulted in a fluid-level draw down of only 280 m after the first four months, or less than one-third of the expected value. The production rate was therefore doubled for the rest of the test, and the fluid level reached a maximum draw down of 605 m in June 2003. Various geophysical, hydraulic, and geochemical parameters were monitored online at the site and were analyzed mostly in real time. Crustal fluids and gases were sampled regularly for detailed geochemical, geobiological, and isotopic investigations. The total volume of produced fluids was about fifty times larger than obtained by the largest previous study.

Table 1: Rough schedule of production and injection tests at KTB-VB (neglecting rate changes lasting 100 hours or less); negative rate: injection.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Rate (L·min⁻¹)</th>
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<tr>
<td>21 Jun 2002 – 2 Oct 2002</td>
<td>29</td>
</tr>
<tr>
<td>7 Jan 2003 – 27 Jun 2003</td>
<td>58</td>
</tr>
<tr>
<td>2 Sep 2004 – 30 Apr 2005</td>
<td>-185</td>
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Figure 1. Aerial view of KTB site with former drill tower atop main hole KTB-HB and pilot hole KTB-VB in center of second light, rectangular area (red circle).

Figure 2. Volume of water mobilized in hydraulic tests at KTB. Tests in 1994 and 2000 were applied to KTB-HB, tests in 2002–03 and 2004–05 to KTB-VB.
borehole geophone in the low-noise environment in KTB-HB, and 150 events were seen by the local seismic network at the surface (Fig. 3). Analysis of those data has revealed that seismicity induced by injecting fluid directly into a crustal fault remains guided by this fault and is triggered by pore-pressure perturbations as low as 0.01–1.00 bar at hypocenters (Shapiro et al., 2006). Most notable was the observation that seismicity started only after injecting a fluid volume approximately equivalent to the amount previously extracted by the pump test into the incompletely saturated formations. The crystalline crust at KTB site was mechanically stable when pore pressure was reduced from its natural level by the pump test, but became transiently destabilized when the reinjection of fluids created a positive pore-pressure perturbation. Pore pressure diffusion, therefore, appears to act as the dominant mechanism for triggering seismicity.

Given the rather large amount of water that was injected, seismicity generated by this test was much weaker than seismicity induced by the injection tests in 1994 and 2000 in KTB-HB, and 150 events were seen by the local seismic network at the surface (Fig. 3). Analysis of those data has revealed that seismicity induced by injecting fluid directly into a crustal fault remains guided by this fault and is triggered by pore-pressure perturbations as low as 0.01–1.00 bar at hypocenters (Shapiro et al., 2006). Most notable was the observation that seismicity started only after injecting a fluid volume approximately equivalent to the amount previously extracted by the pump test into the incompletely saturated formations. The crystalline crust at KTB site was mechanically stable when pore pressure was reduced from its natural level by the pump test, but became transiently destabilized when the re-injection of fluids created a positive pore-pressure perturbation. Pore pressure diffusion, therefore, appears to act as the dominant mechanism for triggering seismicity.
The fluid level in KTB-HB rose sharply several days after the injection started in KTB-VB (Gräsle et al., 2006). KTB-HB became artesian in October 2005 (Fig. 4), with an outflow of about 1 m³·day⁻¹ at the end of the injection test. Since then, both boreholes were kept mostly shut. One year after the injection ceased, the boreholes are still under excess fluid pressure. Hydraulic communication from KTB-VB into KTB-HB actually occurred through a previously identified leakage in the casing of KTB-HB at 5200–5600 m depth (Baisch et al., 2002).

**Ongoing and Future Research**

We continue to monitor the fluid pressure decay in both boreholes to assess the capability of the faults to recover from the fluid injection. Full recovery of the fluid pressure is not expected before 2008. Other ongoing experiments include push-pull tracer tests in KTB-VB, monitoring of the surface deformation field through borehole tiltmeters of nano-radian resolution (Jahr et al., 2006), and repeated reflection seismics and DC resistivity measurements to map induced changes in reflectivity and electrical conductivity of the SE2 fault system, respectively.

The successful completion of the Phase I hydraulic tests in KTB-VB can answer many of the questions we had in 2001. The plan to conduct hydraulic tests in the SE1 fault system at 7.2 km depth by perforating KTB-HB presents an experimental challenge yet to be overcome in Phase II of this program. Since the seismic signature of SE1 is much more pronounced than that of SE2, new findings are likely on transport properties and the mechanical stability of the crust; however, this would require stopping the leaks in the casing and clearing away equipment lost in the hole.

**Acknowledgements**

We are thankful for substantial financial support from the Deutsche Forschungsgemeinschaft and GeoForschungsZentrum Potsdam. The hydraulic tests were enabled by invaluable on-site support from Miel Kühr and Karl Bohn. About twenty scientists and ten students were involved in the various investigations.

**References**


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