KTB Deep Crustal Lab of the GFZ
A Brief Retrospective: 1996 - 2006

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Overview

Deep drilling into Earth's crust offers a unique chance for geoscientists to examine the chemical and physical processes in the crust and the Earth's interior. The 9.1 km deep main borehole of the German Continental Deep Drilling Program (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland - KTB) is the only operable super deep borehole in crystalline rock, and will remain so for many years ahead.

This borehole and the 200 m distant 4 km deep KTB pilot borehole were used for large-scale hydrogeological, geochemical and diverse geophysical experiments of significant scientific interest and potential for resolving problems relevant to geosciences. The complex dynamic behavior of continental fault systems can ideally be studied and quantified through controlled geoscientific experiments at the KTB site.

Within the first phase of the KTB-Tiefenlabor, KTB-TL, (1996 - 2001) experiments were carried out on seven main research areas: temperature field, gravity field, tidal effects, magnetic field/electrical conductivity, seismic imaging in crystalline rocks, seismology and rheology of the earth's crust. The duration of the experiments varied between a few weeks to at maximum of six months. With 233 wireline operations, including 70 logging runs deeper than 6000 m, deploying diverse sonde types more than 1000 km of logging were run, thereof 790 km in the ultra deep KTB-HB. This equals the amount of logging done during the entire seven-year active KTB drilling phase (1987-1994). More than 165 scientists and technicians from eleven institutes and companies worked in the KTB-TL and the surrounding area during the first phase. The participating research institutes were: GFZ Potsdam, GGA-Hannover, Universities of Bochum, Bonn, Braunschweig, Göttingen, Karlsruhe, Kiel, Leoben, München and Potsdam. Companies involved were: Antares, Createch, DMT, Edcon, GeCo-Prakla, LogIn, Magnitude, MeSy, Schlumberger, and Thor.

The second phase of the KTB-TL began in 2002. The research program 'Energy- and Fluid Transport in Continental Fault Systems' utilized the unique constellation of two close adjacent deep boreholes in crystalline rock of KTB for large-scale hydrogeological, geochemical and geophysical experiments of significant scientific interest. From the experimental point of view, key objectives were (a) the withdrawal and analysis of significant amounts of uncontaminated fluids from fault systems, (b) controlled tests to generate and tune the occurrence of micro seismicity at great depths, and (c) the geophysical imaging of changes induced by extensive pumping out and followed by massive water injection. The central open question was the nature of fluid transport in crystalline crust and how it affects the mechanical stability of the earth's crust. The project based on the concept of a brittle and fluid filled continental crust, in a critical tectonic state of stress.

Activities in the second phase included preparation, set-up and support of the active hydraulic & seismic long-term experiments, as well as more than 50 wireline runs.

All planned experiments required the extensive borehole logging equipment of the KTB-TL. The operation and maintenance of the complex logging infrastructure by a logging specialist was an essential prerequisite for the successful execution of measurements and experiments in the KTB-TL at minimum risk and with respect to the demands of the mining regulations. It was possible to allocate a position for a specialist who has long-years of experience with the available logging infrastructure and the unique instrumental and borehole conditions at the KTB site.

Introduction

In 1996, the GeoForschungsZentrum Potsdam, now Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum – GFZ, took over the scientific-operative and also the mining law responsibilities for the KTB location to run the so-called KTB Deep Crustal Lab (KTB-TL). This includes the KTB main hole KTB-HB, 9101 m deep, the pilot hole KTB-VB, 4000 m deep and all downhole logging facilities of the KTB project. The establishment of a deep laboratory was an indispensable part of the overall KTB concept from the very beginning as only long-term observations (months to years) allow investigating the close to equilibrium underground state and temporal variations.

All experiments carried out in the KTB-TL between 1996 and 2006 relied on the availability of the equipment of the KTB-TL. Only because of the KTB logging infrastructure wireline operations in the pilot and main well were possible at reasonable costs. In many ways the logging conditions at KTB are by no means normal (super great depth with very high pressure and very high temperature). Operation and maintenance of the extensive and complex logging infrastructure by an experienced logging specialist was a must for the successful performance of measurements and experiments in the KTB-TL at minimum risk and in view of the demands of the mining regulations. Of course one specialist alone could not run the KTB wireline operations. During the entire time of the KTB-TL an additional logging expert was permanently based at the KTB site. This was from 1996 to 2002 Jochem Kück, GFZ, and from 2002 to 2006 Miel Kühr. Repeatedly additional GFZ logging personnel supported those experiments with a higher demand for manpower.

In-between the experiments at KTB-TL the infrastructure was again and again used for tests of downhole instruments and equipment of the GFZ, German universities and institutes and cooperating downhole logging companies.

Successful completion of many experiments was possible only because the GFZ Potsdam invested more than 350,000 € in development and purchase of special logging equipment for the extreme KTB conditions (hi-temp mud parameter sonde, 2 hi-temp borehole geophones, stainless steel logging cable).

The time span from 1996 to 2006 can be separated into two phases. The first phase comprised mainly time consuming measurements and experiments that could be realized only after completion of the active drilling phase with its very high daily costs. In the second phase starting in 2002 the DFG research program 'Energy- and Fluid Transport in Continental Fault Systems' utilized the two closely adjacent deep boreholes in crystalline rock for large-scale hydrogeologic, geochemical and geophysical experiments.

KTB-TL – First Phase – 1996 to 2001

Within the first phase of the KTB-TL (1996 - 2001) experiments were carried out on seven main research areas: temperature field, gravity field, tidal effects, magnetic field/electrical conductivity, seismic imaging in crystalline rocks, seismology and rheology of the earth's crust. The duration of the experiments varied between a few weeks to at maximum of six months. With 233 wireline operations, 70 logging runs deeper than 6000 m, deploying diverse sonde types more than 1000 km of logging were run, 790 km in the ultra deep KTB-HB. This equals the amount of logging done during the entire seven-year active KTB drilling phase. More than 165 scientists and technicians from eleven institutes and companies worked in the KTB-TL and the surrounding area during the first phase. The participating research institutes were: GFZ Potsdam, GGA-Hannover, Universities of Bochum, Bonn, Braunschweig, Göttingen, Karlsruhe, Kiel, Leoben, München, Potsdam, Memphis, USA. Companies involved were: Antares, Createch, DMT, Edcon, GeCo-Prakla, LogIn, Magnitude, MeSy, Schlumberger, and Thor.

A new method to run electromagnetic measurements in a cased borehole was developed and used during a more than 100 days lasting experiment in the main borehole by the university of Göttingen. The highly sensitive gradient magnetometer was able to resolve the extremely weak effects in depths down to 3300 m caused by variations of the earth’s magnetic field. For interpretation of these unique data special methods of processing were developed at Göttingen University [Barckhausen 1997 & 1998].

In a 25 hours long survey with a special ultra-high temperature borehole gravity meter sonde the gravimetric profile at 69 positions and 10 m spacing within the 500 m thick SE1 seismic reflector of the KTB main hole was extended to a world record depth of 8400 m [Casten 1997], giving density values that integrate over large rock volumes incorporating several tens of meters surrounding the borehole.

The KTB-TL offers the rare opportunity to observe long time variations with repeated measurements, like alterations of the borehole shape due to the stress field. The altering of the borehole wall at 3850 to 4000 m in the pilot hole was examined by comparison of acoustic caliper measurements (borehole televiewer) from 1996 and old measurements from 1989, showing surprisingly no changes. In fact, the two images are so much alike that some structures formerly interpreted as artifacts of the recording method are exactly reproduced in the new logs. These image structures are now interpreted as real structures of the borehole wall.

As hydraulic experiments did not begin before 1999 the equilibration of an ultra deep temperature profile in the KTB-HB could be investigated by repeated measurements over five years. Two to five years after the last massive thermal disturbance by drilling operations in January 1995, the temperature profile still had not completely reached the equilibrium temperature. Nonetheless the temperature at bottom hole (9101 m) could be extrapolated to be 265°C. Several pronounced temperature anomalies mark zones with higher heat input that were later identified as hydraulic active zones (leakages). Before hydraulic testing the most prominent one was the large shear zone referred to as SE1 from 6800 m to 7200 m. After the so-called Massive Injection (MI) experiment in 2000 the strongest anomalies were found at 5450 m. All subsequent mud parameter logs (mud temperature, resistivity and pressure) and downhole fluid sampling finally proved that the KTB-HB casing has a strong leakage at that depth, which was widened from a former small leakage by the high injection pressures during the MI experiment.

Permanently installed pressure transducers in both wells quasi-continuously observed the water level variations caused by opening and closing of fracture systems due to tidal forces (frac breathing) until the start of the hydraulic experiments in October 1999.

The set of deep seismic experiments was a time extensive project in the first KTB-TL phase in the years 1998 to 2000 over altogether more than 8 months. The ultra-high temperatures in the deeper borehole sections (T > 200°C) demanded for a hi-temp borehole geophone sonde. The KTB-TL crew together with a French company (CREATECH) developed a 3-component 15 Hz geophone sonde (BG-250) that can work at 250 °C for up to 10 hours. The sonde was manufactured two times to allow for alternating usage to minimize stand-by time and costs of the expensive seismic surface equipment and personnel. A long sequence of test runs and improvements by the KTB-TL crew and Createch had to be made before the sondes finally could serve as the heart of the deep Vertical Seismic Profiling (VSP), Moving Source Profiling (MSP) and Erbendorf-Körper Experiment (EKE). The execution of these three experiments took a total of 21 pure measurement days with 255 hours of sonde operations in the borehole. 511 depth positions were measured with the geophone sonde for 624 seismic shots and 279 vibrator truck positions [Rabbel et al. 2004]. The BG sondes were also used for the seismic monitoring during the massive injection experiment, see below.

A deep seismological laboratory (DSL) was launched in 1998 with a permanently installed borehole seismometer sonde in the KTB-VB at 3800 m. This BS-125 sonde was also co-developed by Createch (this company meanwhile was bought out by Sercel). The BS-125 was a triaxial 1 Hz seismometer with gimbal-mounted geophone sensors for permanent use at a maximum temperature of 125 °C. The BS-125 seismometer positioned at 3700 m in the KTB-VB permanently recorded local and worldwide seismic activity undisturbed from surface noise until the beginning of the massive injection experiment in August 2000. A triaxial seismometer (HTS) for long-term (months) operations under approx. 220 °C was developed by GFZ. Createch and the KTB-TL crew developed a sonde housing with a special anchoring system. This sonde also underwent a long sequence of test runs and modifications in depths mainly below 7000 m during 1998 to 2000. Despite the intensive efforts it unfortunately was not possible to qualify the anchoring mechanism to a field-reliable applicability.

Before the massive injection (MI) experiment could be performed from August to November 2000 the hydraulic condition of the KTB-HB (maximal possible pressure and flow rates) were estimated in a short pre-experiment in October 1999. A total of ≈ 38 m^3 of fresh water were injected with pumping rates between 10 – 100 liters/min. The maximum pressure reached was 24.6 MPa. This hi-pressure-test finally caused a ruptural widening of an already existing weak casing leakage at 5450 m represented in the pressure recording by a pressure drop of about 15 MPa. At that time the pressure drop was not recognized as a casing fracture but it was thought to be a rock fracture in the deepest part of the borehole (9040 – 9101 m). The design of the MI experiment about one year later considered the here estimated pressure/flow rate relations.

The aim of the MI experiment was to stimulate very small earthquakes (micro-seismicity) by injecting huge amounts of water under high pressure into the KTB-HB and to monitor these events by a vast array of seismic stations. A total of 4000 m^3 of fresh water was injected over a period of 60 days at flow rates ranging between 30 and 70 l/min. A temporary seismic network consisting of a borehole sonde in the pilot hole at 3827 m depth yielding an extremely low threshold of Mw = -2.5 and a surface network of 39 stations was installed. All stations were equipped with three-component seismometers. Seismicity was monitored continuously over 3 months including the injection period. 2799 events in total were detected with the borehole sonde. The 237 strongest events could be located using the borehole seismometer and the surface station recordings. In average, the location accuracy for these events is ±147 m, ±127 m, and ±26 m for eastern, northern and vertical directions, respectively [Baisch et al., 2002]. The events cluster at two depth levels of 5.0 – 6.0 km (81%) and 8.8 – 9.2 km (11%). No new tensile fractures could be generated by the injection, as the additional pressure did not reach the magnitude of the smallest principal stress. Consequently, the micro earthquakes represent pure shear failure on existing faults that were reactivated [Baisch and Harjes, 2003] [Bohnhoff et al., 2004].

KTB-TL – Second Phase – 2002 to 2005

In the second phase of the KTB-TL from January 2002 till January 2006 extensive and fastidious experiments were carried out within the general concept 'Energy- and Fluid Transport in Continental Fault Systems'. These large scale hydrogeologic, geochemical and geophysical experiments made even more use of the world-wide unique KTB constellation of two close adjacent KTB boreholes (distance 200 m at surface) by active long-term hydraulic manipulations in the pilot hole and monitoring in the KTB-HB.

The research program was based on the concept of a continental crust with fault systems composed of fluid-filled fissures and cracks. Elements of these fault systems are locally close to the critical state of stress. The complex dynamic behavior of continental fault systems can ideally be studied and quantified through controlled geoscientific experiments at the KTB site. Key objectives of the program were (a) the withdrawal and analysis of significant amounts of uncontaminated fluids from fault systems, (b) controlled tests to generate and tune the occurrence of micro seismicity at great depths, and (c) the geophysical imaging of changes induced by extensive pumping and fluid injection. The target question was the nature of fluid transport in crystalline crust and how it affects the mechanical stability of the earth's crust.

KTB-TL crew activities in the second phase included preparation, set-up and support of the long-term experiments, as well as wireline measurements. The experiments required for the extensive borehole logging equipment of the KTB-TL. In this second phase, like in the five years before, operation and maintenance of the complex logging infrastructure by a logging specialist is an essential prerequisite for the successful execution. Additionally since April 2002 a new expert (Miel Kühr) was employed in the KTB-TL who was in charge especially for all operations associated with the pumping test and sampling. He replaced the former on-site head of the KTB-TL crew, Jochem Kück, who moved to GFZ Potsdam at the end of 2002. The substantial operational requests of the long-term experiment required a minimum of a permanent crew of two persons on-site.

The second KTB-TL phase began in January 2002 with a small injection and withdrawal experiment (push-pull test) in the KTB-VB using the conductivity contrast of rock fluid and fresh water as a natural tracer [Gräsle, 2003]. The experiment consisted of two stages and lasted all in all three and a half months, from January till mid April. All downhole observations were carried out with the GFZ mud parameter sonde MP. It was used for multiple logging of the entire borehole and also kept stationary at positions in the open hole section from 3850 m to 3975 m. The test included several stages of injection and withdrawal of water in the borehole (push/pull). Due to the equilibrium water level of approximately 16 m below surface, injection could easily be achieved by permanently filling up the well with fresh water. For water withdrawal a small pump was installed alongside the logging cable at different depths (20 - 78 m). The test showed that unexpected high flow rates could be stimulated. For one week during the push-pull test the University of Leipzig carried out an experiment with their multi electrode sonde (VEL).

With the installation of the downhole pump in the KTB-VB and the respective surface installations a one-year fluid pumping test (FPT) began in June 2002. After preparations since April the major part of the installations was done during the first weeks of July 2002. The permanent maintenance and improvement of the pumping, sampling and measuring equipment at the pilot hole took up a lot of the working time. The strong winters in the Oberpfalz demanded for installation of a reliable protection against freezing of the many hydraulic lines. Pumping began in July 2002 and was only interrupted for very short times because of power outs or other minor technical problems. The longest interruption of three weeks took place over the Christmas holiday season 2002/2003. As already the push-pull test also the pumping test showed a much higher fluid production rate as expected after all previous studies in the KTB-VB. Besides the online gas analysis (GFZ) an extensive sampling by several associated institutes was part of the fluid pumping test.

Parallel to the hydraulic part of the test an array of seismic stations recorded seismic activities due to changes in the stress field induced by the water level changes (GFZ, TU Berlin). A very important role had the borehole geophone sonde (BG-250) in the KTB-HB at 3875 m. During installation of the GFZ owned BG sonde the main cable for the KTB-HB broke and both BG sonde and 4200 m of cable were lost in the borehole. As the highest priority was to maintain a geophone sonde in the KTB-HB at 3875 m, all investigations of the fish (BG sonde & cable) and fishing operations were postponed to a later time when the well was not required for active experiments (after 2005). A second BG sonde was installed at 3875 m. It monitored seismic signals during and after the active pilot hole pumping. After a long operation time of 458 days it failed on 17-June-2004. When attempting to retrieve the sonde from the well it turned out that not the sonde was defect but the cable was broken at a depth of 3204 m and also the second BG sonde with 670 m of logging cable was lost in the borehole. At the end of the retrieved 3204 m cable evidence was found for strong hydrogen corrosion of the armor wires. Hydrogen is generated in the well in only very small amounts but could act on the cable over the very long installation time of far more than a year. When the second BG was lost it was 'anchored', that means its clamping arm was pressed against the casing wall. With the opened clamping arm it could not slip deeper than 5900 m, the depth of the head of the next liner casing. During several measurements and successful fishing operations between 2006 and 2008 the second lost BG sonde with 670 m of cable was fished successfully. Further it was identified that the first lost BG sonde had sunken to the deepest accessible depth of 8630 m in the KTB-HB and the top of the cable was found at 6760 m.

The complex and fragile installations demanded for permanent maintenance and improvement of the pumping, sampling and measuring equipment at the pilot hole by the KTB-TL crew. Pumping out fluids from the open KTB-VB borehole section (3850 – 4000 m) continued until 27-June-2003. Pumping rates varied between 28 l/min and 56 l/min resulting in a total of 23,000 m^3 of gained fluids. The temperature of the pumped out water reached 42 °C and its density was 1.03 – 1.07 kg/l. The electrical conductivity of the Ca–Na–Cl fluid (63 g/l TDS) was rather constant at 86 mS/cm as were the on-line values for pH (7.5) and Eh (430 mV). The 6 to 30 million years old crustal fluids probably originate from Mesozoic seawater or formation water from Permo-Carboniferous sedimentary rocks. After pumping was stopped the water level was monitored before the downhole pump was uninstalled on 7-11-August-2003. Until the beginning of September the well was left undisturbed for water level monitoring.

Within the following five months a series of five mud parameter logs (GFZ sonde) and four downhole measurements with the multi electrode sonde (VES) from the University of Leipzig were carried out with the KTB-GFZ logging facilities. The local KTB-TL personnel supported these GFZ Potsdam lead activities. The time plan of the logs and over-night stationary measurements followed a schedule with increasing time gaps between the log-runs. The measurements were analyzed at GGA Hannover and at the University of Leipzig respectively.

From February through April 2004 a hydraulic pre-experiment to the main long-term injection experiment, a push-pull test, was carried out in the pilot hole under the guidance of the University of Gottingen. During the first phase of that test water was injected into the KTB-VB over several weeks using a GFZ injection pump. A downhole pressure sensor was installed in the well at 3875 m. Several chemical tracers were introduced. The following second test phase was a short pumping test using a small electrical downhole pump. Samples of the extracted fluids were also taken.

Preparations for the main injection experiment began in December 2003. Originally it was planned to have the VES sonde (Univ. Leipzig) installed downhole throughout the 1-year injection time. After installation in the open hole section it turned out that this sonde was damaged and could not be repaired in time for the start of the injection. The sonde was uninstalled and replaced by a single temperature sensor at 3875 m in June 2004 to monitor the temperature development during the injection. For this purpose the logging cable was cut on surface and coupled mechanically and electrically inside the casing to the heavy well head blind flange. Special pressure tight electrical 'feed-throughs' connect the 7-conductors of the logging cable to the outside data acquisition system.

On 25-May-2004 the injection pump was switched on for the first time. Problems with the electrical power supply lead to several pumping stops. The large volume extracted during the 2002/2003 pumping test had to be refilled first before a strong underground pressure build-up became possible.

Flow rates varied around 200 l/min and a pressure of merely 9-10 MPa. Higher flow-rates are not achievable with the pump available. The temperature in the KTB-VB at 3875 m decreased from 118 °C to 57 °C after injection of nearly 7000 m^3 over less than two months. The injection was finished in May 2005 with the injection of a tracer pill. A total of 84,575 m^3 of fresh water were injected. Subsequently the free back-flow of water was monitored. Two months after stop of the injection the KTB-VB had an outflow rate of 100 liter/min, or a shut-in pressure of 1.9 MPa. The large volume of rock inflated by the KTB-VB injection also arrived at the KTB-HB. Its well head pressure was 0.3 MPa at end of the injection time. Pressure sensors mounted to the two well heads monitored the pressure decay in both boreholes. This continued until early 2009. Surface fluid samples were taken repeatedly from the outflowing water until the end of 2005. [Erzinger, 2006], [Gräsle 2006]. In June 2006 a final VES experiment was carried out in the KTB-VB as the last logging operation of the second KTB-TL phase.

When the well head was opened the KTB-HB was flowing and the fluid column slowly moved upward. This offered the chance to investigate the presumed casing leakages with repeated mud parameter logs and with several fluid samples (GFZ fluid sampler) from depths below and above the suspected leakage zones (5500 m, 5000 m and 3000 m). Only 20 to 30 % of the flow originates from below 5400 m. A leakage with a significant inflow was identified at 5400 m and another inflow/leakage at 3250 m cannot be excluded.

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