The continental deep drilling project (KTB) in Germany: Overview and major result on the geochemistry of crustal fluids and gases

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INTRODUCTION

The German Continental Deep Drilling Program (KTB) was designed to study the properties and processes of the deeper continental crust by means of a superdeep borehole in the Oberpfalz (Bavaria, Germany) near the town of Windischeschenbach. Major research themes were (1) the nature of geophysical structures and phenomena, (2) the crustal stress field and the brittle-ductile transition, (3) the thermal structure of the crust, (4) crustal fluids and transport processes, and (5) structure and evolution of the central European Variscan basement. The project was conducted in distinct phases: a preparatory phase (1982-1984), a phase of site selection (1985-1986), and a pilot phase (1987-1990), which included drilling of a pilot borehole (KTB-VB) to 4000 m and a 1-year experimentation program. The main phase (1990-1994) comprised drilling of a superdeep borehole (KTB-HB) which reached a final depth of 9101 m at a temperature of ~265 °C, and three subsequent large-scale experiments in the uncased-bottom hole section (Emmermann & Lauterjung, 1997).

GENERAL RESULTS

This internationally conducted project has revealed a wealth of geoscientific data and new results of unreached quality and broadness such like (i) A continuous profile of the complete stress tensor was obtained. (ii) Several lines of evidence indicate that KTB reached the present-day brittle-ductile transition. (iii) The drilled crustal segment is distinguished by large amounts of free fluids down to midcrustal levels. (iv) The role of postorogenic brittle deformation had been grossly underestimated. (v) Steep-angle seismic reflection surveys depict the deformation pattern of the upper crust. (vi) High-resolution seismic images of the crust can be obtained with a newly developed technique of true-amplitude, prestack depth migration. (vii) The electrical behavior of the crust is determined by secondary graphite (±sulfides) in shear zones (for details see full text and references in Emmermann & Lauterjung, 1997).

REAL-TIME GAS MONITORING DURING DRILLING - THE KTB EXAMPLE -

Fluids are responsible for almost all chemical, physical, mechanical and dynamical processes within the earth's crust. They influence, for example, the rheological behaviour of rocks, seismicity, melting and crystallization processes, metamorphic reactions as well as the transport of matter and heat within the earth's crust. A major problem in modern geochemistry is, however, the quantification of fluid flow in the earth's crust.

KTB offered the unique opportunity to draw direct samples of deep-seated formation fluids. It was thus possible to determine the volatiles of almost "fresh" rocks just drilled and to examine intensively the gas phase of formation fluids transported with the drilling mud to the surface in the KTB pilot and main holes. Our major goal was to obtain information on the amount of gases in the continental crust as well as their composition and depth distribution. In the KTB field laboratory, established at the drill site, on-line analysis of the gases dissolved in the drilling fluids was carried out. An interpretation of these data and the following mass balances required information on the gas contents of the rocks and the amounts of gases, which could migrate on fissures.

Technical Description and Sampling Methods

The gases dissolved in the drilling fluid have been analyzed qualitatively and quantitatively in real-time during drilling of the KTB-VB and -HB. For the extraction of gases dissolved in the drilling fluid a gas-mud separator (degaser) at the mud outlet flow line was used in the KTB pilot hole and in the KTB main hole down to 3003 m (Fig. 1). With this gas trap assembly only the volumetric portion of each gas could be determined but not the amount of gas entering the borehole. Below 3003 m a newly developed closed by-pass system was installed at the KTB-HB. A constant portion (about 80 l/min) of gas-bearing drilling mud was pumped through a by-pass line and ran directly into an air-tight twirl gas separator. The gases were led from this degaser into the nearby automatic gas mass spectrometer, where they are quantitatively analyzed for N_2, O_2, Ar, He, CO_2 and CH_4. In addition, C_2H_6, C_3H_8 and C_4H_{10} were analyzed using a gas-chromatograph, and Radon was quantified with an alpha-spectrometer.

In order to quantify gases entering the borehole known quantities of pure gases and mixtures of gases were injected into the mud circulation system. While the drilling mud is equilibrated with atmospheric air before being pumped down into the borehole, the "outlet-mud" shows a corresponding atmospheric gas composition (with the exception of oxygen) if natural gases have not entered the borehole from the wall rocks.

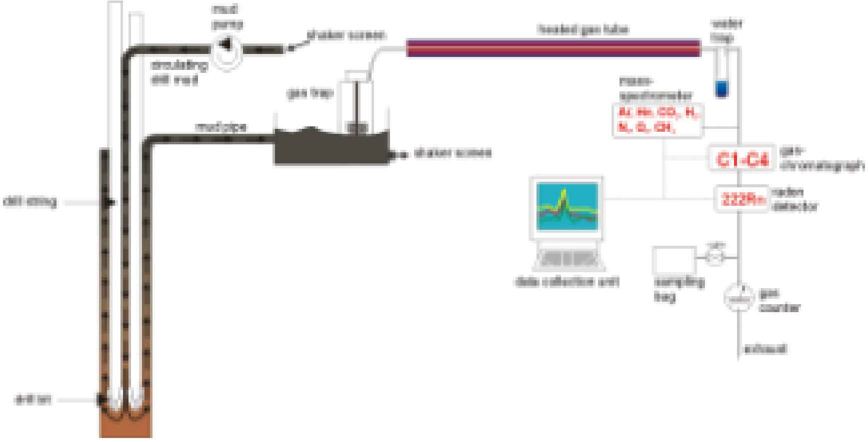

Figure 1:Real-time mud gas monitoring set-up

Results

The continuous drilling fluid analysis in the KTB-HB indicated several significant fluid inflow zones with high concentrations of methane and helium. From 1980 - 2200 m in the KTB-VB a cataclastic shear zone with graphite-rich paragneisses was drilled. Even though the largest part of the methane penetrated via fissures into the borehole, the rocks of this zone, which were investigated using high-vacuum degassing techniques, are very rich in gas. The cataclastic zone was characterized by long-lasting degassing features, hence the drilling fluid was enriched with methane down to about 2500 m. Below 3400 m (KTB-VB) several fluid inflows with high methane concentrations could be observed. In contrast to the graphite-rich cataclastic zone (1980 - 2200 m), in this case, the fluids entered the borehole abruptly via fissures of some centimeters in width, which manifests itself in the gas-logs as short sharply limited concentration maxima. A longer-lasting degassing did not seem to have taken place.

In the KTB-HB two different types of gas-bearing horizons could also be generally distinguished. The first type included "dry" inflows (i.e. mainly gas, less brines) from graphite-bearing cataclastic shear zones, at 1445 m, 1530 m, 1960 m and 2416 m. The second type included "liquid" or "brine" inflows, was frequently related to open fissures within a prehnit-mineralized section and appeared below 3000 m.

In the KTB-VB and KTB-HB the "dry" inflows are characterized by high hydrocarbon contents, whereas helium was enriched in brine-bearing inflows (second type). In addition the composition of gaseous hydrocarbons from the cataclastic zones differ significantly with relatively high ethane contents ($CH_4/C_2H_6=14$) from those of the fissure systems with lower C_2H_6 concentrations ($CH_4/C_2H_6=40$). Apart from methane and ethane, propane and butane as well as traces of unsaturated hydrocarbons such as ethene and propene could also be detected down hole in the drilling mud.

In the KTB-HB the amount of gases entering the borehole through specific borehole fractures increased with depth while the methane/helium ratios remained relatively constant. In amphibolite and gneiss sections the methane/helium ratio was about 40 and 25 respectively, probably due to the higher radiogenic helium production rate in the gneisses (see also Zimmer & Erzinger, 1995).

Conclusions

The main geoscientific goal of this study was to work out background information on gas contents in continental crustal rocks, their composition, origin and depth distribution. The new concept for on-line determination of gases dissolved in the drilling fluid has proved successful. Using this method, applied for the first time in a borehole, almost complete depth profiles could be surveyed for methane and helium. Most of helium and methane in the drilling fluid entered the borehole through fissures and fractures from the surrounding rocks, only a small portion was released during drilling by crushing of the rocks. It turned out that methane and helium are very sensitive indicators for formation fluids entering the borehole during drilling. The helium/argon ratio in the "4000 m fluid" corresponds to typical ratios for U-, Th- and K-decay in average magmatic rocks. Furthermore, hydrogen in the drilling fluid was mainly artificially created during the drilling process itself. The nitrogen isotopic composition did not differ significantly from that of the atmosphere, thus we were not able to state on the origin of nitrogen.

As the KTB-HB was only partly cored, on-line gas analysis often represented the only possibility to gain continuous information on the gas contents of the drilled rocks. It was, in addition, an important help when the time arrived to decide if and to what depth rock or fluid samples should be taken. Furthermore, technically problematic horizons, for example the cataclastic zone at 1990 m, could been recognized by a significant increase in methane and helium concentrations before the drill bit reached those sections.

Whilst simultaneous sampling of drill mud fluids and solids as well as on-line gas analysis do not disturb drilling operation and allow immediate detection of fluid rich hole sections (help for quick operational decisions), drill mud analysis gives only a rough idea of formation fluid geochemistry.

Formation fluid sampling with down hole fluid sampler, draw down and packer testing, or continuous pumping has the advantage of less fluid contamination through drill mud and allows trace element and isotopes studies. However, these operations are expensive and need thorough planning in advance.

RESULTS FROM THE KTB-VB 4000M FLUID PRODUCTION TEST IN 1991

In order to collect less contaminated fluids and detailed information on the hydraulic nature of the fluid systems, a pumping test lasting about 4 months was performed after drilling of the KTB-VB in 1991. 460 m^3 of Ca-Na-Cl fluid, with about 70 g/l TDS (total dissolved solids) and 270 m^3 gas, were pumped to the surface. The following is a shortened and modified abstract from the paper of Möller et al, 1997 (for details see full text and references herein).

4000-m Fluid Chemistry

Concentrations of major and some minor elements as well as the gases were determined, whereas distinct difficulties arose for the exact determination of trace elements and isotopes of the brine. Particularly, heavy metals from abrasion of drilling pipes, core bits, and thread grease decreased continuously with time, but never reach natural values. At the end of the pumping test, the fluids were still contaminated with organic additives (1-5 mg/l), thus the $\delta^{13}C$ value of dissolved inorganic carbon of about -13‰ cannot be regarded as representative of the pure brine. The values of δD and $\delta^{18}O$ finally approached -32‰ and -6‰, respectively.

Concentrations of rare earth elements and Y (REY) in the KTB-VB fluid entering the pilot hole at depths between 3850 and 4000 m at the very end of the pumping test were found to be in the range 10^{-11} to 10^{-13} mol/kg. The shale-normalized REY patterns are crustal–like without any anomalous behavior of individual REE, however, the true contents in the uncontaminated brine might be less by one order of magnitude.

Under surface conditions, a *p*H value of 8.3 was measured. Assuming calcite saturation at the in-situ temperature of 119°C, *p*H values of 5.70 and 5.25 are calculated, respectively. Without the precondition of calcite saturation, a *p*H value of 7.04 is derived under formation temperature and a fluid pressure of 40 MPa.

The silica content did not change during the last 3 months of the pumping test and can be regarded as a true value of the pure brines. There is a good agreement between measured silica content and quartz saturation at 119°C.

The chemical composition of the KTB brine is typical for crystalline brines found worldwide. This is true above all for its Ca dominance, high Sr content, and Br/Cl ratio. In the Canadian Shield brines, Ca and Cl are positively correlated, which reflects dilution of brines by groundwater. Another positive correlation exists between Ca and Sr, suggesting a common source. The 4000-m fluid, without any recent meteoric water contribution, fits well on the regression lines of shield brines data.

The $^{87}Sr/^{86}Sr$ ratios of "free fluids" are rather constant, with a mean value of 0.7095, the Sr isotope ratio in the brine seems to be controlled by exchange reactions with plagioclase.

Several chemical geothermometers were calculated and compared with the sulfate geothermometer based on an equilibrium state of ^{18}O between H_2O and dissolved sulfate. According to the latter, the 4000-m fluid once experienced a temperature of about 160°C, although the in situ temperature was only 119°C. This temperature difference suggests an ascent of the fluid from about 5500 m depth.

Gas Composition

The gas phase released from the fluid of the KTB-VB pumping tests consists of 67.0 % N_2, 31.6 % CH_4, 0.52% He (10^5 times the He content of air-saturated water), 0.14 % Ar, and minor noble gas components, as well as traces of hydrogen, carbon dioxide (0.04 vol %), higher hydrocarbons, and about 2500 Bq/m^3 of ^{222}Rn. Similar gas compositions were found in KTB-HB fluids sampled at depths between 3063 and 6031 m. Gas samples relatively free of contaminants were only obtained from the 4000-m fluid.

The high N_2 contents of about 560 ml (STP) per liter fluid exceed the solubility of N_2 in water by orders of magnitude and N_2/Ar ratios (about 480) are far above the atmospheric ratio of 84 and the seawater ratio of 38. The value of $\delta^{15}N$ is about +0.3‰. The N_2 originates probably (1) from the release of NH_4-fixed N_2 from paragneisses, which have $\delta^{15}N$ values of +6‰ and (2) from thermal decomposition of organic material together with CH_4.

The $\delta^{13}C$ values of the CH_4 dominated hydrocarbon fraction (32 vol%) of the 4000-m fluid indicate a low-maturity source rock. CH_4 clearly plots into the field characteristic for thermal origin in agreement with the $\delta^{13}C$ values of ethane and propane. For such low-maturity hydrocarbons, the concentrations of ethane to butane are unexpectedly low. However, different solubilities of the individual hydrocarbons in the mud and fluid system might account for the decreasing concentrations of the components with increasing carbon numbers. A thermal origin is much more likely than any other such as hydrothermal or crystalline sources.

Ne-corrected, He isotope ratios indicate small amounts of primordial He which reveal a maximum of 3 % "mantle He" contribution. No significant excess of fissiogenic ^{134}Xe and ^{136}Xe could be detected. The $^{40}Ar/^{36}Ar$ ratios range between 800 and 1770, which are higher than the atmospheric value of 295.5. Later pumping test gas samples also show excesses in ^{21}Ne of about 10 %. In situ production of ^{4}He, ^{21}Ne, and ^{40}Ar in host rocks and release to the fluid is the most evident source of these radiogenic (nucleogenic) components. Presumably, the origin of the high He concentrations is the surrounding rock, as supported by the combination of high loss rates from rocks and the similarity in composition of He in free fluids and fluid inclusions (Bach et al, 1999).

The apparent accumulation times yield 15-80 and 30-300 Ma for ^{4}He and ^{40}Ar, respectively. Although the ^{21}Ne excess data are in agreement with these results and the very similar ^{3}He/^{4}He ratios of rock and fluid samples indicate local origin, it has to be emphasized that parameters and conditions of these accumulation time calculations are covered by a wide range of potential uncertainties. Nonetheless, these accumulation times support a fluid exchange after the Cretaceous denudation, which is in agreement with the results of He and Ar loss rate determinations (Bach et al., 1999).

Geo-hydraulics

The KTB rocks are characterized by two different ranges of permeabilities, the fracture and the matrix porosity. Among other fluid flow stimulating tests in the KTB-VB and –HB, at the end of the pumping test in the pilot hole, a weak hydraulic communication with the fluid column in the KTB main hole was observed. All hydraulic tests indicate that fluids were collected from a range of about hundred meters around the uncased section of the borehole. During the period of the pumping tests the 4000-m fluid, chemical and isotope data did not indicate any communication with the present groundwater.

The KTB-HB cuts two main fault elements obviously belonging to the NW trending, large-scale, Franconian lineament. This deep-seated fault zone is more than 260 km long and about 25 km in width. The steep reflector element SE1 of the seismic profile KTB 8502 is cut at a depth interval between 6850 and 7300 m; the second main fault element (SE2) is cut between 3240 and 4000 m. Changes in fabrics, mineralization, and fluid content create the contrasts of the seismic impedance between the fault zone and the wall rock which are the reasons for the highly reflective zones of SE1 and SE2. The depths of these fault zones correspond to the depths of the most important fluid inflows of saline fluids. Hydraulic tests in the deepest zone in the KTB-VB and analysis of the hydraulic communication between KTB-VB and KTB-HB yield permeabilities between 10^{-16} and 10^{-15} m^{2}.

Fluid migration depends on the hydraulic potential, which is created by gradients of fluid density, temperature, and pressure. Assuming two differently structured and communicating reservoirs the morphology too dominates the flow direction of groundwater. For the Oberpfalz region in the surroundings of the KTB location, a plausible hydrogeological model is the following: At greater depths, saline fluids from an assumed sedimentary basin (reservoir 1 with basinal brines) penetrate the crystalline rocks (reservoir 2), where they evolve to basement brines. Even low-pressure difference between the two reservoirs can lead to significant field velocities. With a fracture width of 5 µm, a field velocity of about 30 m/yr results at a pressure gradient of 0.1 MPa/km [Kessels and Kück, 1995]. This fast transport system can be explained by a fracture porosity of 2 x 10^{-4} m^{2}. For the transport of chemical components and isotopes, a coupled system of matrix flow and fracture flow has to be considered; that is, the system is characterized by a double porosity. Fluid flow along microfractures and pores will be minor, rather resembling “closed system conditions”, whereas larger microcracks and cataclastic shear zones will experience more dynamic conditions, fitting the demands of the proposed double porosity system.

An analysis of the spatio-temporal evolution of the fluid injection induced microseismicity of the 1994 injection experiment also provides the permeability estimates of the same order (see Shapiro et al, 1997). Moreover, recent results show strong anisotropy of the permeability tensor. This indicates a fracturing and fault system related nature of the large spatial scale permeability of the rocks.

For KTB-HB and –VB, fluid level changes have been monitored, recorded and analyzed during several years (Schulze et al., 2000), which allows assessments of the rock-fluid interactions along the open parts of the boreholes. The data reveal that hydraulic equilibrium has not been attained in KTB-HB, possibly because of obstacles in the open part of the borehole (9025 m to 9101 m depth), and that the water column in KTB-VB sensitively responds to tidal and barometric forcing. Accordingly, the hydraulic situation in the lowermost part of the HB is not yet well understood. The open section of the VB (3850 m to 4000 m) is connected to formations of type “fluid saturated rocks”, capable of indicating slight changes in the regional stress regime (similar to a high-resolution strain meter).

KTB RESEARCH INITIATIVE “ENERGY AND FLUID TRANSPORT IN CONTINENTAL FAULT SYSTEMS”

Yet, several of the main objectives have only been marginally investigated, and by no means using the full potential of the two KTB boreholes. On one hand, these objectives are to deepen our knowledge on the spatial extension of fluid flow and fluid systems in the Earth's crust as well as on their impact on physical rock parameters, rheology, crustal dynamics, seismicity and the transport of solubles. On the other hand, they include the deepening of insight into crustal stress, its fluctuations in time and space, its alterations into strain and seismic energy, as well as the mechanical stability of the crust.

So far, on the scale of hundreds of meters to kilometer, the transmissivity of the crust for energy and substances and the influence of pore fluids and fluid systems on the stability of the Earth's crust have nowhere sufficiently been determined. Both these properties have gained particular attention through KTB. It has been shown that free mobile fluids exist too much greater extent than previously expected (Huenges et al., 1997; Möller et al., 1997). Also, stability of the Earth's crust was demonstrated to depend strongly on pore fluid pressure as was seen through the stimulation of a seismic swarm by a moderate increase in fluid pressure at 9 km depth (Zoback & Harjes, 1997). These two findings are among the most surprising and spectacular results of the whole drilling project.

More profound studies of these properties under in-situ conditions are of far more than of fundamental geoscientific interest. In view of urging socio-economic requirements like the optimal use of fluid and thermal reservoirs, the safe disposal of critical wastes, a better understanding of earthquake mechanics, particularly in the surroundings of large lake reservoirs, such investigations are of substantial concern for the society. As flow velocities of fluids are low in the subsurface, meaningful experiments dedicated to the change of associated parameters will last years. Clearly, the representative character and thus the value of new results in this domain will increase with the duration of respective experiments.

Ongoing use of the KTB boreholes as a crustal laboratory for a research initiative with special experiments on the multifarious role of mobile pore fluids as well as on the mechanical stability of the crust will benefit from a unique combination of mainly three factors. (1) The database obtained by already completed investigations which is exceptional in quantity and quality; (2) two accessible boreholes of 4,000 m and 9,101 m depth, respectively, at only 200 m distance from each other; (3) and the existence of two distinct, extended fault systems that have been drilled at roughly 4 and 7 km depths.

1st Phase: Fluid Production Test in the KTB Pilot Hole

The first major experiment is a fluid production test over a period of 12 months in the KTB-VB. The test started on June 10, 2002 with the installation of an electrical submersible pump, a type-400 pump system with 306 stages, at 1283 m below surface. The motor of the pump has a performance of 21.3 H.P. at 650 volts and 24.5 amps; it is operated with a frequency controller. A LEUTERT pressure gauge (0 – 350 bars) is mounted below the motor at depth 1284 m. The crustal fluids produced from the open hole section (3850 m – 4000 m, approx. 120°C) are led through a 2 3/8“ tubing to the surface. The installation was finished on June 18th.

Fluid outlet temperature, variation in water pressure at the pump, fluid yield as well as pH and redox values, electrical conductivity and the amount of dissolved gases are monitored and recorded in real-time. After being degassed in a water-gas separator, the produced waters are pumped into the nearby Fichtelnaab creek. The separated gas phase is analyzed in real-time with a quadrupole gas mass spectrometer for N_2, CH_4, He, H_2, O_2, Ar, and CO_2. ^{222}Radon is measured by alpha-spectrometry using a Lucas cell detector (Fig. 2). So-called bio-reactors are mounted into the flow line in order to collect bacteria and other forms of living species from the deep biosphere. Several working groups are taking water and gas samples on a regular basis for further detailed investigations.

In addition to this, the KTB main hole is equipped with (1) a borehole seismometer (BG 250 from Createch S.A., Paris) which is permanently installed at 3900 m depth and (2) with two or three water level sensors at shallow depths. These tools monitor seismic and hydraulic signals that might be caused by the draw down in the KTB-VB, 200 m away from KTB-HB (distance at surface).

From June 18 until June 24, 2002 a test phase was conducted to optimize the submersible pump system and the monitoring equipment.

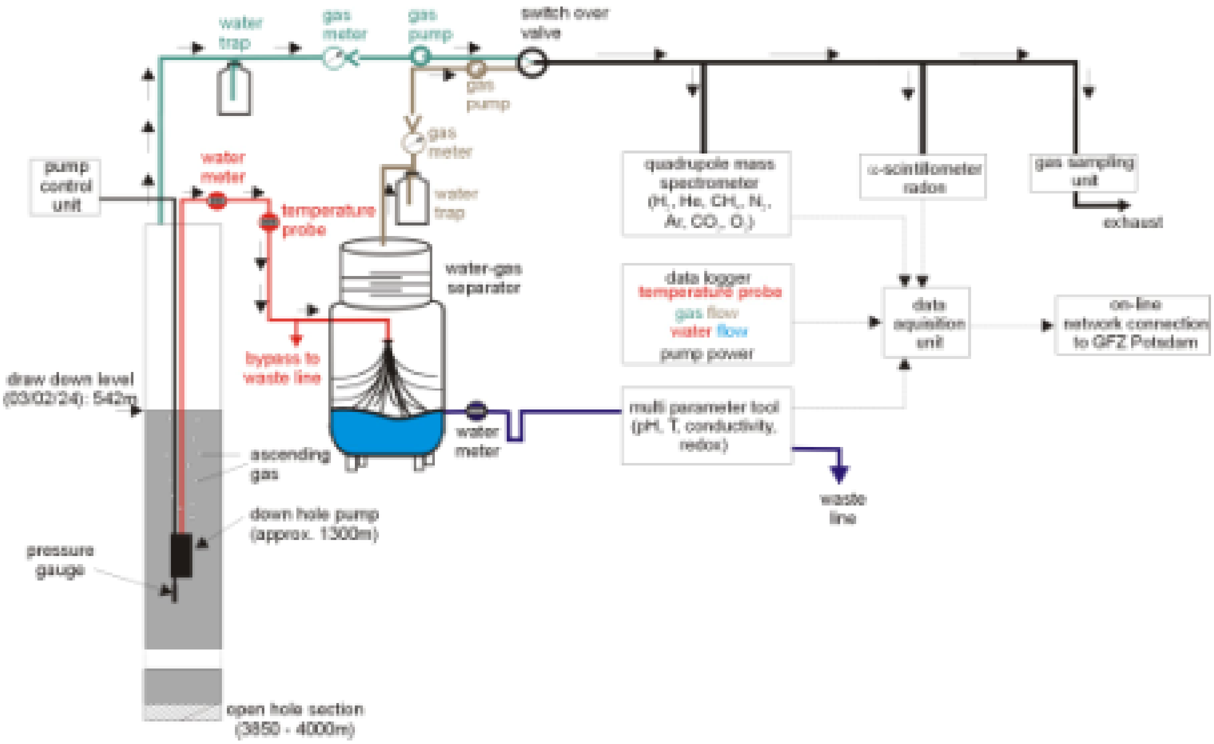

Figure 2: Real-time monitoring set-up used for fluid production tests

Operation and First Results

On June 24, the long-term fluid production test started with the pump operating at approx. 60% of its maximum power. This resulted in an average yield of crustal fluids of 29 liters per minute (surface water temperature 25°C). 30 l/min was the maximum amount we were allowed to discharge into the Fichtelnaab creek at that time. The draw down was some 280 m, only, or about 8 times less than was estimated on the basis of an earlier pump test in 1991 - one year after drilling of the KTB-VB was completed. We therefore asked for permission to discharge up to 60 l/min into the creek. When this was granted, we made necessary arrangements for the surface installations and increased the pump speed on October 2nd to its maximum performance. Since then, the fluid yield is 58 l/min at a final draw down of 620 m and at 42 °C outlet temperature.

The volume ratio of gas to water (surface conditions) is varying between 0.95 and 1.05. Electrical conductivity of the fluid is rather constant at 86 mS/cm as are the values for pH (7.4) and E_H (-430 mV). 99% of the gas phase is composed of nitrogen and methane; He, H_2, Ar and CO_2 are present in trace quantities, only. ^{222}Rn activity varies between 5000 and 6000 Bq/m^3 (see also Table 1).

Preliminary results of the Science Team are:

ÿ Analyses of two interim recovery tests in October and December 2002 appear to indicate that the reservoir is infinite; hydraulic transmissivity is around $3 \cdot 10^{-13} m^2$.

ÿ Hitherto, we did not observe any significant changes in the concentrations of dissolved fluid constituents including gases. Furthermore, isotope ratios of Helium

(He$^{3/4}$He = 5.7±0.2•10^{-7}; R/R_A=0.41), Neon (^{21}Ne/^{20}Ne = 0.0035), Argon (^{40}Ar/^{36}Ar = 900), CH_4 (δ^{13}C = - 52 ‰) and Sr were more or less constant throughout the production period.

- Rare earth element (REE) concentrations of the produced fluids are extremely low. Such low REE concentrations have never been reported before, neither for natural surface waters nor for crustal fluids.
- Surprisingly, up to now Radium and Radon are the only elements the concentrations of which depend on the production rate. Concentrations are 30% higher at 58 l/min yield than at 29 l/min. However, Ra and Rn are in radio-chemical equilibrium.
- The down-hole seismometer in the KTB-HB is working fine and has detected small seismic events in the near vicinity of the borehole, indicating that the events might be released by the production activities.
- Neither thermophile nor hyperthermophile organisms were detected until present, possibly because the inlet-temperature at the bottom of the pilot hole is too high (115° - 120°C).

The production test in KTB-VB will be pursued at maximum pumping rate up to July 2003. A water level recovery tests in the pilot and main holes lasting several weeks are planned before the submersible pump and the tubing will be pulled out. Thereafter, DC resistivity and alternating temperature and conductivity logging is scheduled until December 2003.

Tabelle 1: Composition of deep crustal fluids from the KTB long-term production test

Sodium (Na)	8.0	g/l	Calcium (Ca)	16.7	g/l
Potassium (K)	0.3	g/l	Magnesium (Mg)	1.7	mg/l
Strontium (Sr)	0.6	g/l	Lithium (Li)	10	mg/l
Aluminium (Al)	< 0.05	mg/l	Silicium (Si)	30	mg/l
Chloride (Cl)	43.5	g/l	Bromide (Br)	0.6	g/l
Fluoride (F)	4	mg/l	Sulfate (SO_4)	0.3	g/l
Iodine (I)	3	mg/l	Boron (B)	4.4	mg/l
HCO_3	34	mg/l	Ammonium (NH_4)	5	mg/l
Arsen (As)	<0.05	mg/l	Lead (Pb)	<0.005	mg/l
Zinc (Zn)	0.08	mg/l	Cadmium (Cd)	<0.005	mg/l
Total diss. solids (TDS)	70.5	g/l	^{129}I/I	1700 - 4400x10^{-15}	

N_2 = 66.2 $\%_{vol}$; CH_4 = 33 $\%_{vol}$; He = 0.59 $\%_{vol}$; Ar+H_2+CO_2 = 0.21 $\%_{vol}$;

^{3}He/^{4}He = 5.7*10^{-7} ≡ R/R_A = 0.41; ^{21}Ne/^{20}Ne = 0.0035; ^{40}Ar/^{36}Ar = 900; $\delta^{13}C_{CH4}$ = -52 ‰; δ^{15}N = +1.5 ‰

EXAMPLES OF APPLICATION

In recent years we applied the gas and fluid monitoring technique in various international project of the ICDP (International Continental Drilling Program) such like Chinese Continental Scientific Drilling Program at Donghai, China (CCSD), San Andreas Fault Observatory at Depth, U.S.A. (SAFOD), Gulf of Corinth Rift Laboratory, Greece (CRL), Gas Hydrates Drilling at Mallik, NW Canada, and Unzen Scientific Drilling Program, Japan (see also: www.icdp-online.org). Furthermore, we carried out fluid monitoring during crustal fluid production tests in Soultz-Sous-Forets, France and CRL as well as at commercial geothermal fluid production in Germany (Naumann, et al 2000 and 2001).

REFERENCES

Bach, W., Naumann, D. and Erzinger, J., (1999), A helium, argon, and nitrogen record of the upper continental crust (KTB drill holes, Oberpfalz, Germany): implications for crustal degassing, Chemical Geology 160, 81-101

Emmermann, R. and Lauterjung, J., (1997), The German Continental Deep Drilling Program KTB: Overview and major results. JGR, vol. 102, No. B8, 18,179-18,201

Huenges, E., Erzinger, J., Engeser, B., J., Kessels, W. and Kück, J., (1997), The permeable crust: Geohydraulic properties down to 9101 m depth, JGR, 18,255-18,265

Kessels, W. and Kück, J., (1995), Hydraulic communication in crystalline rocks between the two boreholes of the Continental Deep Drilling Programme in Germany, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 32, 37-47

Möller, P., Weise, S. M., Althaus, E., Bach, W., Behr, H. J., Borchardt, R., Bräuer, K., Drescher, J., Erzinger, J., Faber, E., Hansen, B. T., Horn, E. E., Huenges, E., Kämpf, H., Kessels, W., Kirsten, T., Landwehr, D., Lodemann, M., Machon, L., Pekdeger, A., Pielow, H.-U., Reutel, C., Simon, K., Walther, J., Weinlich, F. H. and Zimmer, M., (1997), Paleofluids and Recent fluids in the upper continental crust: Results from the German Continental Deep Drilling Program (KTB), JGR, 18,233-18,254

Naumann, D., (2000), Salinare Tiefenwässer in Norddeutschland: Gas- und isotopengeochemische Untersuchungen zur Herkunft und geothermischen Nutzung, Dissertation, Scientific Technical Report STR00/21, GFZ Potsdam, 116pp

Naumann, D., Zimmer, M., Erzinger, J and Wiersberg, T., (2001) Gas monitoring, fluid flux and fluid sampling at well GPK-2 (Soultz-sous-Forets, France) – First results from the 5000m production test, Scientific Technical Report STR00/23, GFZ Potsdam, 71-84 (Elektronic version: www.geothermie.de/oberflaechennahe/geothermie_report_2k1/gas_monitoring.htm

Schulze, K.C., Kümpel, H.-J., and Huenges, E., (2000), In-situ petrohydraulic parameters from tidal and barometric analysis of fluid level variations in deep wells: Some results from KTB, In:I. Stober and K. Bucher (eds), Hydrogeology of Crystalline Rocks, Kluwer Acad. Publ., 79-104

S. A. Shapiro, E. Huenges and G. Borm, (1997), Estimating the crust permeability from fluid-injection-induced seismic emission at the KTB site, Geophysical J. Int., 131, F15-F18, (see also Corrigendum, Geoph. J. Int., 1998, v.134, p.913)

Zimmer, M. and Erzinger, J., (1995) On the geochemistry of gases in formation and drilling fluids - results from the KTB, Scietific. Drilling, 5, 101-109.

Zoback, M. D. and Harjes, H.-P., (1997), Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany, JGR, 18,477- 18,491