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The German Continental Deep Drilling Program KTB: Overview and major results

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Abstract. 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. 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 sinking of a pilot borehole to 4000 m and a 1-year experimentation program. The main phase (1990-1994) comprised drilling of a superdeep borehole which reached a final depth of 9101 m and a temperature of ~265°C, and three subsequent large-scale experiments in the uncased-bottom hole section. Among the outstanding results are the following (1) A continuous profile of the complete stress tensor was obtained. (2) Several lines of evidence indicate that KTB reached the present-day brittle-ductile transition. (3) The drilled crustal segment is distinguished by large amounts of free fluids down to midcrustal levels. (4) The role of postorogenic brittle deformation had been grossly underestimated. (5) Steep-angle seismic reflection surveys depict the deformation pattern of the upper crust. (6) High-resolution seismic images of the crust can be obtained with a newly developed technique of true-amplitude, prestack depth migration. (7) The electrical behavior of the crust is determined by secondary graphite (±sulfides) in shear zones.

Introduction

In October 1994, after 1468 days of drilling, the superdeep borehole of the German Continental Deep Drilling Program KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) reached its final depth of 9101 m at a temperature of ~265°C. The main phase of the KTB was then concluded with three major experiments in the uncased bottom section of the hole: a dipole-dipole experiment, a draw-down test and a combined hydrofracturing and fluid injection experiment. With this climax to the scientific program, the main phase of the KTB was terminated as scheduled on December 31, 1994.

The KTB was the largest and most expensive research program in the geosciences ever undertaken in Germany. The Federal Ministry for Research and Technology committed a total of 528 million DM (~$350,000,000 U.S.) to the project, from the planning phase in 1982 through to completion in 1994. A KTB project group, established at the Geological Survey of Lower Saxony, Hannover, was responsible for the technical and operational realization of the program. The Deutsche Forschungsgemeinschaft (DFG) oversaw and coordinated all KTB-related scientific activities. At one time or another during this period, more than 700 scientists and technicians were employed in KTB-related work.

KTB fully deserves the term "superdeep adventure" because it advanced the frontiers of many geoscientific and technical fields. It was clear from the very beginning that success would require close cooperation between geoscientists and engineers, a prerequisite which developed into a fruitful symbiosis. Like any expedition to uncharted regions, the KTB project was meticulously planned to foresee and minimize potential risks. Thus the project proceeded in distinct phases, after each of which a fundamental reevaluation was made and strategies were redefined. After a preparatory phase (1982-1984) and a phase of presite investigations and site selection (1985-1986), the KTB pilot phase began in 1987. This involved sinking a pilot hole to 4000 m (the "Vorbohrung", KTB-VB) and a subsequent 1-year logging, testing and experimentation program (until April 1990). The results of the pilot phase had a major impact on scientific and technical planning of the superdeep hole ("Hauptbohrung", KTB-HB), and provided the basis for the official go-ahead for the main phase. Approval was given to the design and construction of a specialized drill rig with a maximum capacity of 12 km, the target depth was set at the temperature level of 300°C (expected at about 10 km), a budget was determined, and a time frame for the main phase was limited to December 31, 1994. The year 1995 was committed for site shut-down and final data evaluation, and on January 1, 1996, the GeoForschungsZentrum Potsdam (GFZ) took over responsibility for the final phase. In this phase, the two drill holes, which are some 200 m apart, will be used over a 5-year period as a deep crustal laboratory for in situ scientific and technical experiments.

Realization of an Idea

In 1977 the Senate Commission on Geoscientific Research of the Deutsche Forschungsgemeinschaft first discussed the idea of investigating the continental crust by means of a superdeep

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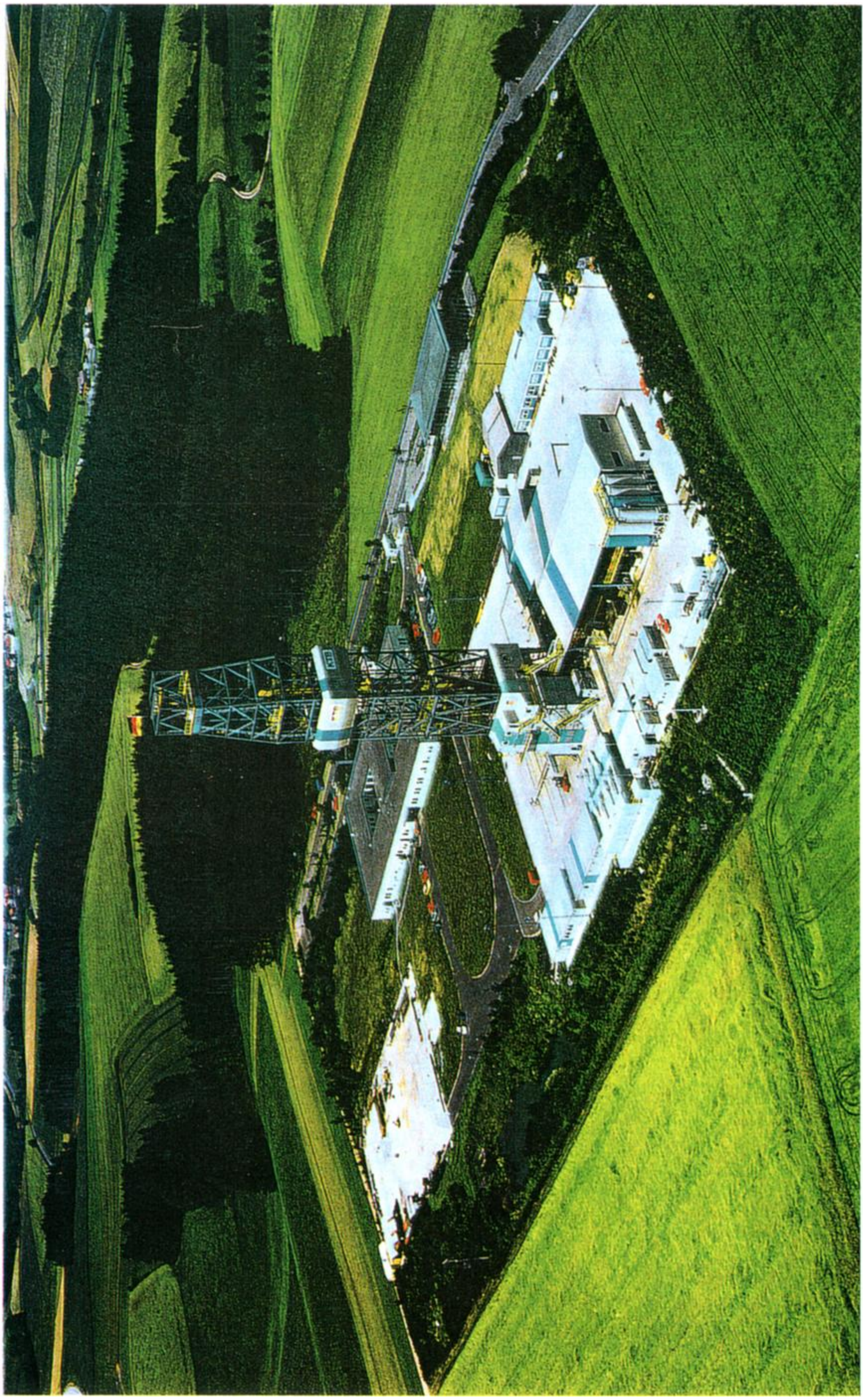

Plate 1. Aerial view of the KTB drill site with the drill rig of the superdeep hole in the foreground. The site of the pilot hole is to the left, 200 m from the drill rig. The field laboratory occupies the main building in the background.

borehole. At that time, conceptual models of the makeup and evolution of the continental crust were primarily based on interpretation of the geological record, interpretation of geophysical images obtained from various deep-sounding methods, and application of laboratory data from experimental petrology and geochemistry to real rocks. The commission felt that further progress required "ground truth" that could only be obtained by direct observation through drilling. From the beginning, therefore, two fundamental goals of global relevance were singled out: (1) calibration of crustal geophysics, and (2) study of the crustal stress field and the rheological behavior of the crust. In the ensuing years, discussions within the whole geoscience community led to a much broader definition of the concept of continental superdeep drilling. In 1984 the official proposal to establish the KTB was submitted and five priority areas were defined: (1) the nature of geophysical structures and phenomena: seismic reflectors and electrical, magnetic and gravimetric anomalies; (2) the crustal stress field and the brittle-ductile transition: orientation and magnitude of stresses as a function of depth; (3) the thermal structure of the continental crust: temperature distribution, heat flow, heat production, and heat transport; (4) crustal fluids and transport processes: fluid systems, fluid sources, and fluid movements; and (5) structure and evolution of the central European Variscan basement: properties, deformation mechanisms, and geodynamics of a multiply reactivated continental crustal environment.

From technical considerations, and based on the expectation of important changes in rheology and reaction kinetics above about 250°C, the target was set at the 250°-300°C temperature window. This temperature target was combined with the objective of penetrating at least 8000 m into the continental crust.

From its inception, close ties were established between KTB and the German Continental Seismic Reflection Program (DEKORP), which started in 1983 and was also funded by the Federal Ministry for Research and Technology. Together, these projects were intended to provide a major German contribution to understanding the architecture, composition, and evolution of the central European crust. Perhaps because of its relatively young age (typically < 500 Ma), this crustal type differs fundamentally from that sampled by the Russian superdeep borehole Kola SG3. Nevertheless, central European crust has a complex history and has been repeatedly affected by major compressional and tensional processes. It was largely formed or reshaped during the Variscan orogeny (~400-300 Ma), which was an important step toward the assembly of Pangea (at ~300 Ma).

The Variscan belt represents a collage of arcs and microcontinents resulting from collision of the Old Red Continent (Laurentia + Baltica + East Avalonia) with Armorica and Gondwana. An important rifting phase in Cambrian and Ordovician times (~500 Ma) first separated the microplates of East Avalonia and Armorica from mainland Gondwana and created large areas of thinned continental or even oceanic crust. The crustal blocks involved began to converge in Ordovician time (by ~450 Ma) and were finally welded together during a prolonged stage of collision in the Devonian and Carboniferous (400-300 Ma) to form the present-day Variscides. Incorporation of magmatic arcs and back arc basins, long-distance nappe transport, a final stage of low-pressure, high-temperature metamorphism, and voluminous intrusion of late to postorogenic granites have done much to obscure the record of oceans opening and closing.

Collapse of the Variscan orogen started in the late Carboniferous (~300 Ma) and was enhanced by mantle-induced crustal extension and magmatic activity which heralded the break-up of the newly assembled Pangea. This episode created a multitude of Permian (300-250 Ma) bimodal volcanic suites, intramontane basins and graben structures, many of which are wrench-related. During the Alpine orogeny (~100-30 Ma) the region was affected by compressional and transpressional tectonics which were followed by yet another stage of rifting and graben formation in the Tertiary (since ~25 Ma). Many of these events were accompanied by magmatism and enhanced hydrothermal activity, causing the formation of widespread mineralization.

This multiply reworked central European crust is relatively thin (~30 km) and extremely heterogeneous, both laterally and vertically. It is distinguished by regionally variable but generally high heat flow values, complex gravimetric and magnetic patterns, pronounced seismic reflectivity, the occurrence of high- and low-velocity layers, and zones of high electrical conductivity at different depths.

Site Selection: A Difficult Decision

Altogether, more than 40 potential drill sites were initially suggested, but only four survived the final definition of project objectives, and the first main selection conference in 1983 narrowed the choice to two final candidates, the Schwarzwald and Oberpfalz regions. As existing knowledge was inadequate to decide between the two, a 2-year program of geological, petrological, and geophysical studies was started in each region. The results were discussed at a final selection conference in September 1986, attended by over 200 geoscientists of all disciplines.

At that meeting it was acknowledged that each region offered highly attractive targets for solving a range of pressing geoscientific problems and preference for one site over the other became a partisan issue among the various disciplines. The deadlock was broken by focusing on the expected geothermal gradient. Extrapolation of geothermal data obtained from shallow-drilling studies carried out in both regions especially for this purpose indicated that the target temperature of 250°-300°C might be encountered at 7 km depth in the Schwarzwald, whereas it could lie about 5 km deeper in the Oberpfalz. Therefore, taking the original depth criterion into account, the Deutsche Forschungsgemeinschaft selected the Oberpfalz site for the superdeep borehole [*Emmermann and Behr*, 1987]. The specific scientific attractions of this site were seen to be (1) its location in the suture zone between two first-order units of the Variscan orogen; (2) the existence of an appealing and testable geologic model which had far-reaching implications for crustal architecture and geodynamics; (3) the occurrence of marked gravity, magnetic, and electrical self-potential anomalies; (4) the expected presence of seismic reflectors at drillable depths and of an electrical high-conductivity zone at 10 ± 1 km; and (5) the chance to test for thermal and geochemical influences from the nearby Tertiary Eger rift.

Two-Step Drilling Concept

Since the geological boundary conditions and their impact on the technical requirements for reaching the envisaged depth target were not known sufficiently, the KTB concept was based on drilling two holes, first a pilot hole as a sort of "fact-finding mission" and then the superdeep hole itself.

Main objectives of the pilot phase were to acquire a comprehensive set of geoscientific data from core investigations, cuttings analyses, and borehole measurements with which to develop the methodology required for optimal evaluation of the superdeep hole and to test the geological prognoses. Moreover, the pilot hole would reduce the need for sampling and logging in the upper, large caliber section of the superdeep hole and would provide the information on rock properties and drillability, borehole stability, potential gain and loss zones, temperature profile, etc., critically needed for the technical planning.

The KTB pilot hole was spudded on September 27, 1987. The concept developed by the KTB engineers, which was to modify a conventional drill rig from industry and to combine rotary drilling and wire line coring techniques, turned out to be very successful. With a high-speed topdrive rotating system and using an internal and external flush-jointed 5 ½ inch mining drill string with 6 inch thin-kerfed diamond corebits, 560 days of drilling and logging were needed to achieve a basement penetration of 4000 m, and a total of 3564 m of excellent quality cores was recovered. By applying straight vertical drilling capabilities this technique has a depth potential of 5 to 6 km and thus may be of special importance for future continental research drilling to intermediate depths.

A prerequisite for the success of the drilling technique was the development of a new water-based drilling fluid system, which was undertaken in close cooperation between KTB engineers and geochemists. This system met all technical requirements, was environmentally safe and, for the first time, allowed a quantitative geoscientific monitoring of the drilled basement. The starting composition was a mixture of water with about 1.5 wt % DEHYDRIL-HT, a synthetic, hectorite-type, Li-bearing Na-Mg silicate which yielded a thixotropic, solid-free, highly lubricant mud system. Later, due to its electrolyte sensitivity, corrosive behavior, instability at high temperatures, and other factors, it was continuously modified by adding HOSTADRILL, an organic polymer, and NaOH plus Na_2CO_3 to fix a pH value of 10 to 11. With increasing temperature in the deeper parts of the KTB-HB (below 7100 m) and owing to continuing small influxes of saline formation waters, a steady deterioration in rheological properties and water-binding capacity required a partial replacement by adding a mixture of different commercial polymers (KEMSEAL, MILTEMP, PYROTROL). Furthermore, in order to reduce borehole instabilities the mud weight was raised from 1.06 kg/L to 1.40 kg/L by adding barite (see Table 1 for a summary of fluid systems used at various stages).

Table 1. Drilling Fluid Systems Used in the KTB Main Hole

Borehole section	Drilling Fluid System	Properties
0 - 6760 m (1, side track)	0.7% Dehydril 1% Hostadrill NaOH, Na_2CO_3	plastic viscosity 9-22 mPa s density 1.06 g/cm^3 *p*H 10-11
6460 - 7220 m (2, correction)	1.5% Dehydril 1.5% Hostadrill NaOH, Barite	plastic viscosity 29-53 mPa s density 1.06 g/cm^3 *p*H 11
7140 - 8330 m (2, side track)	Bentonite Kemseal, Miltemp, Pyrotrol, NaOH Barite	plastic viscosity 35-91 mPa s density 1.25 g/cm^3 *p*H 10
7460 - 8730 m (3, side track)	Bentonite Kemseal, Miltemp, Pyrotrol, NaOH Barite	plastic viscosity 25-90 mPa s density 1.40 g/cm^3 *p*H 9-10
8630 - 9100 m	Bentonite Kemseal, Miltemp, Pyrotrol, NaOH Barite, Polyglycol	plastic viscosity 27-59 mPa s density 1.40 g/cm^3 *p*H 9-10

All drilling fluid systems are water-based. Dehydril is a synthetic clay mineral (Hectorite-type). Hostadrill, Kemseal, Milltemp and Pyrotrol are synthetic viscosifiers and organic additives. NaOH and Na_2CO_3 have been added to control the *p*H value. Barite controls the density.

After completion of the pilot hole, a 1-year measuring and experimentation program was conducted, which included a comprehensive logging program, 14 hydrofrac measurements and a large-scale three-dimensional (3D) seismic reflection survey, covering an area of 19 x 19 km around the drill site. In April 1990 the hole was cased down to 3850 m, leaving an openhole section of 150 m. The pilot phase was then completed with a first short-term pump test, which yielded 71 m^3 of basement brines with high amounts of N_2 and CH_4 from the uncased bottom zone.

The main results of the pilot phase [*Emmermann*, 1989], which determined the technical concept for the superdeep hole, were (1) the considerably higher than expected geothermal gradient, which led to a definition of the depth target at 10 km (corresponding to about 300°C); (2) the lithologic heterogeneity and the continuous steep inclination of rock units, which caused severe deviation of the hole out of the vertical and resulted in development of a vertical drilling strategy; and (3) the frequency of cataclastic shear zones and fluid inflow zones which, in combination with the high horizontal differential stresses, led to the expectation that borehole instabilities would become a major problem at depth. This resulted in a slim-clearance casing strategy and development of water-based, high-temperature drilling mud systems described above.

Plate 1 shows the drill rig of the superdeep borehole KTB-HB, UTB 1, which, at a total height of 83 m, is the largest land-based drill rig in the world. The rig is fully electrically driven, and incorporates a number of technical innovations and improvements including, for example, an automatic pipe-handling system and remotely controlled gear-driven drawworks.

To ensure sufficient reserves, the drill string layout was made for a maximum depth of 12,000 m (diameter of 5 ½ inch, enhanced steel quality). By using 40 m stands of drill pipe instead of the standard 27 m stands, and in combination with the pipe-handling system, roundtrip time was reduced by about 30%. In order to achieve the targeted depth a vertical drilling system (VDS) was developed and deployed. The VDS is an actively self-steering system mounted directly above the downhole motor. It effectively minimized the friction between drill string and borehole wall and allowed a 50% reduction of the drilled rock volume by realization of the slim-clearance casing concept.

The VDS system was used to a depth of 7500 m at the maximum allowable temperature of 175°C for the electronics, whose data were pulsed through the mud to the surface. The horizontal displacement at this depth was only 12 m, which meant that the borehole was practically vertical. The hole then

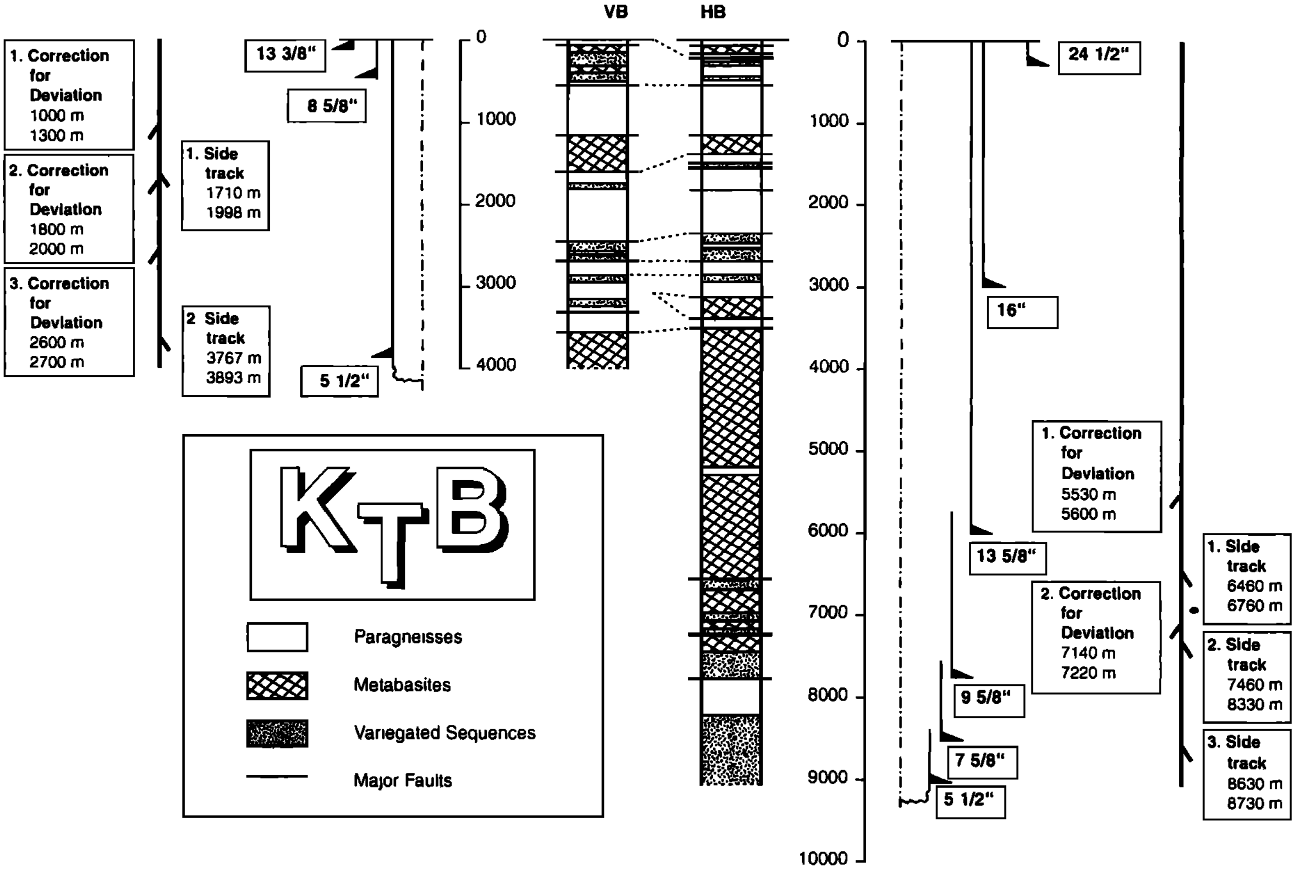

Figure 1. An outline of the final borehole configuration, showing the side tracks and corrections for deviation, casing scheme and lithological profile of (left) the pilothole and (right) the superdeep hole.

deviated toward the NE, almost perpendicular to the general dip of the foliation, and at 9069 m, where the final deviation survey was conducted, it showed a horizontal displacement of about 300 m. Down to a depth of 8120 m the superdeep hole was drilled almost exclusively with downhole motors, which could be used to maximum operating temperatures of about 190°C. The last step to the final depth was done with rotary drilling.

As coring is one of the most expensive drilling operations, maximizing core recovery and core quality was of special importance. The experience with the thin-kerfed diamond core bits in the pilot hole justified the decision to adapt this technology to the superdeep hole. A large diameter coring system (LDCS) was developed which, in the 12 ¼ inch phase, cut cores of 234 mm diameter and provided rock columns with a length of up to 5 m. In comparison to roller cone core bits, which were also used, the average core recovery with this system was increased from 41% to about 80%. Altogether, 35 core runs were performed in the superdeep hole with an overall recovery of 84 m. A large additional collection of partly oriented rock fragments, up to 10 cm in length, was provided by a junk basket, a simple, but very effective tool attached above the drill bit which was always used in non cored sections.

Figure 1 shows the KTB-HB in its final condition with the different side tracks and the casing scheme. Reasons for the side tracks were corrections for deviation, unsuccessful fishing operations, and borehole instabilities. Down to about 7500 m these instabilities mainly occurred in the form of breakouts and drilling-induced tensile fractures that produced localized borehole enlargements, preferentially related to shear zones. Below that depth, borehole convergence (i.e., reduction of the borehole diameter) first occurred and resulted in undergauge hole sections. Undergauge sections, with uniaxial narrowing in the direction of the maximum horizontal stress, developed within hours and became the major source of drilling problems [*Borm et al.*, this issue]. The drill string frequently got stuck, and side-tracking operations consumed over 1 year of total operation time. This type of instability, which caused a creep-like structural disintegration in the rock, resulted from the extremely unfavourable combination of high differential stresses, a preferred dip of planes of weakness in the direction of the minimum horizontal stress component, the presence of formation waters and the elevated temperatures. The instability eventually formed a technical barrier which could not be overcome within the strict limitations of budget and time. It was therefore decided to stop the drilling operations in October 1994 at a depth of 9101 m and a temperature of ~265°C in order to use the drill rig and the other technical facilities for three large-scale scientific experiments in the uncased open-hole bottom section.

Realization of the Scientific Program

The scientific program of KTB was carried out by an integrated evaluation and joint interpretation of data and results obtained from three sources: (1) the field laboratory established at the drill site, (2) borehole measurements and experiments, and (3) individual specialized research projects carried out at universities and other research institutions.

All KTB-related scientific activities were coordinated and reviewed by the Deutsche Forschungsgemeinschaft (DFG), which established a Priority Program "KTB" that was funded at an annual level of ~7 million DM. During the lifetime of the KTB, from 1982 to 1995, the DFG administered a total of 75 million DM (~$ 50 million US) to over 300 different research projects involving about 500 scientists. In addition, some 100 foreign scientists from 11 countries participated in KTB with a total of 70 research projects financed by their national funding agencies. Scientific communication within the DFG Priority Program, periodic discussion of the results and definition of major experiments were ensured by workshops, task group meetings, thematic sessions, and the annual KTB colloquium. As of 1995 a total of over 2000 publications have come out of the various research projects.

Establishment of a field laboratory at the drill site was a top priority from the time of the first discussions about a continental deep drilling program in Germany. The field laboratory became an indispensible component for the realization of the ambitious scientific program. Figure 2 summarizes the tasks of the field laboratory and its organizational structure. This lab, which was a modern and completely equipped research institute, was supported by nine university "mother institutes" (under the guidance of the Institute of Geosciences, University of Giessen), and staffed by up to 20 scientists and 18 technicians. Its primary purpose was to collect extensive geoscientific data on cores, cuttings, rock flour, drilling fluids and gases. Properties and characteristics (1) were measured which were necessary for operational decisions concerning drilling, sampling, and testing, (2) had to be determined on a quasi-continuous basis as a function of depth, (3) are time-dependent and therefore had to be recorded as soon as possible after sampling, and (4) were needed for calibration of borehole measurements and were required to guide sample selection and as basic information for all individual research projects.

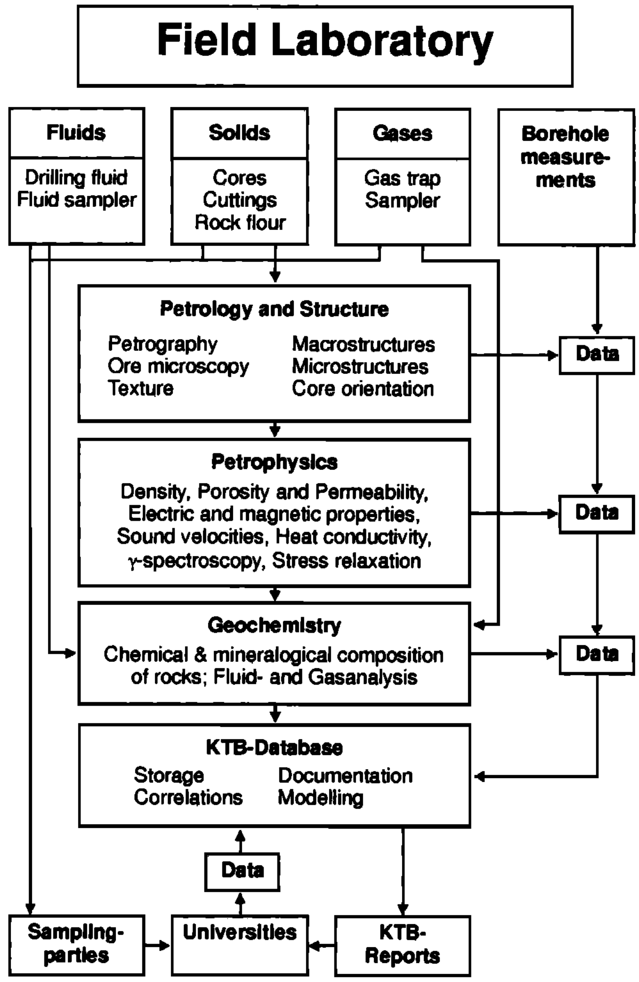

Figure 2. A flow chart showing the sampling and analysis scheme of the KTB field laboratory.

Apart from established methods, a number of new techniques were developed and continuously improved. Among them were a computerized reorientation technique for cores, a new tool for high-quality density imaging of cores by gamma ray absorption and a four-component dilatometer for the measurement of the stress relaxion of cores. Because of the new drilling fluid system and a specially designed automatic sampling system, a real break-through was achieved in the evaluation of cuttings, rock flour, drilling fluid, and gases dissolved in the drilling fluid. The quantitative chemical and mineralogical composition of cuttings and rock flour was determined using a newly developed combination of X ray fluorescence and X ray diffraction, which allowed a reliable reconstruction of the drilled basement within 1 hour after sampling [*Emmermann and Lauterjung*, 1990]. Because the pilot hole was almost completely cored, it was possible to compare the lithological profile obtained from direct study of cores with that reconstructed from cuttings and rock flour analyses. It was demonstrated that the agreeement was excellent and that every rock type, even minor lithological changes, fault zones, and altered intervals, had been unequivocally identified.

In addition, quasi-online analyses of the drilling fluid, and the gases released from drilling fluid, were performed. These fluid logs turned out to be very sensitive indicators of cataclastic shear zones and fluid inflow zones. Even minor fluid influxes could be identified and localized, facilitating quick operational decisions concerning positioning of drill stem tests and downhole fluid sampling.

Together with the work in the field laboratory, downhole measurements played a central role in the reconstruction of the drilled basement and provided important information on the in situ properties of the rocks. Prior to KTB there was little experience in the integrated interpretation of logging data obtained from crystalline rocks [*Pechnig et al.*, this issue]. Therefore an extensive logging test program was conducted in the pilot hole using all available types of tools, and the borehole log responses were calibrated against core, cuttings and other data provided by the field laboratory.

During the drilling phase of the pilot hole, seven logging campaigns were performed at various intervals, mainly for data acquisition and technical purposes. After completion of the hole, 24 different experiments were conducted, and a total of 55 tools were deployed. On the basis of the results and experiences from these measurements, the combination of logging tools for the KTB superdeep hole was defined and, altogether, 266 logging runs were performed. Although there were some standard high-temperature logging tools available from industry, several tools were upgraded especially for KTB. Among these was a high-temperature formation microscanner (FMS) which could be used up to 260°C. Figure 3 presents an

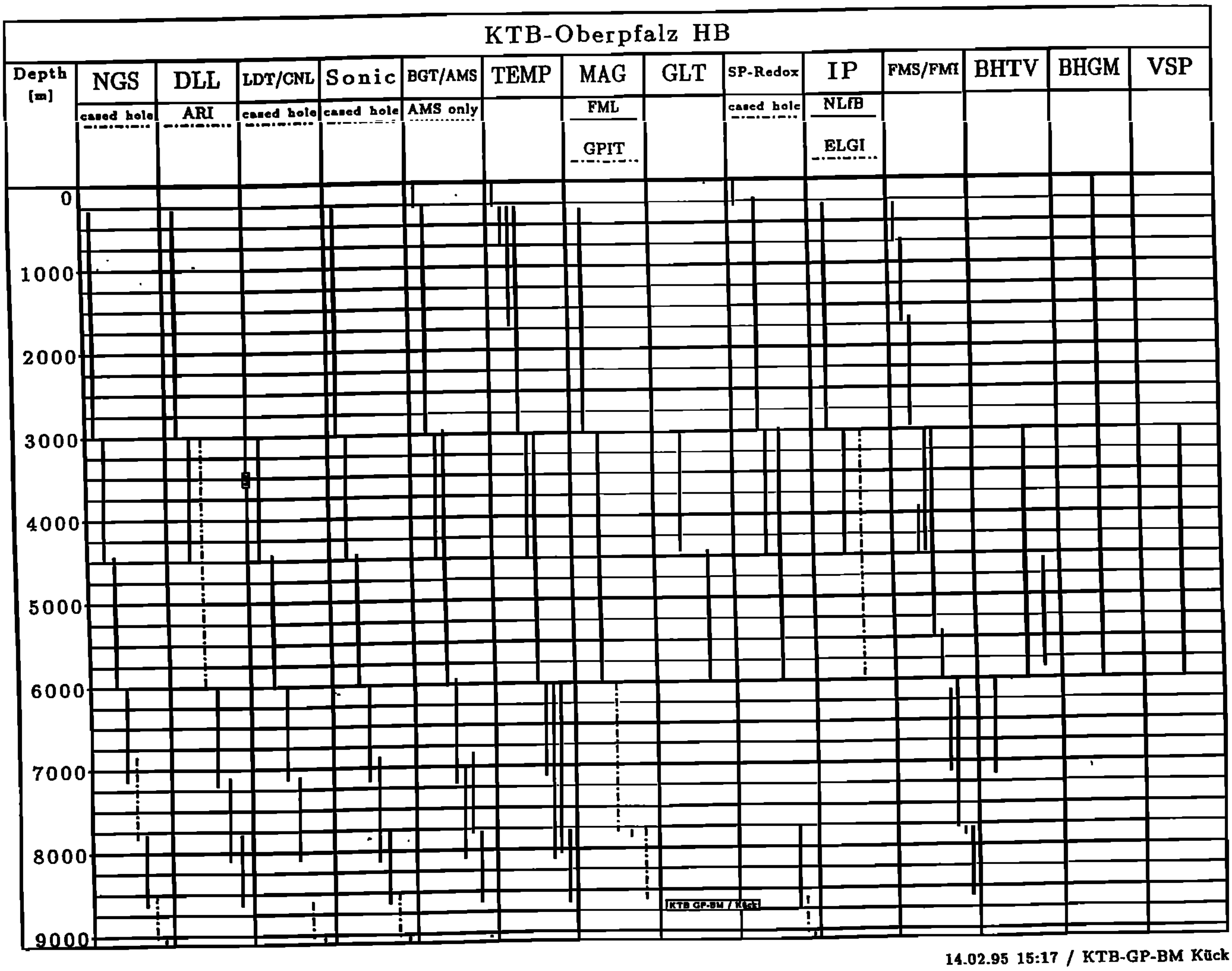

Figure 3. Summary of the major logging tools and their respective measuring interval in the superdeep hole. Abbreviations are NGS, natural gamma spectroscopy; DLL, electrical resistivity; sonic, seismic velocity; BGT, borehole geometry; TEMP, temperature log; MAG, magnetometer; GLT, geochemical logging tool; SP, self potential; IP, induction log; FMS/FMI, formation microscanner/formation microimager; BHTV, borehole televiewer; BHGM, borehole gravimeter; VSP, vertical seismic profiling.

overview of the major tools deployed and the measured depth sections.

A new and very precise method of lithologic evaluation of logging data with multivariate statistics was developed by the use of a broad spectrum of Schlumberger tools and the comparison and calibration with core, cuttings, and mud sample data. This method, which relies on discrimination of "electrofacies", is discussed by *Pechnig et al.* [this issue], and it contributed greatly to the refinement of the lithologic profile of the superdeep borehole.

The Information System KTBase: Access to KTB Data

KTB has produced an enormous amount of data of various kinds (descriptive versus quantitative numerical data) from different sources, including the field laboratory, borehole measurements, mud logging, technical monitoring, geophysical experiments, field investigations, and external scientific investigations.

Apart from archiving, the main task of data processing was to integrate all data into a single, accessible information system, which was achieved using the metadata concept. Metadata characterize data sets and include information on data sources and structure, experimental boundary conditions, experimental methods, literature, and, most important, the actual location of the data sets. The metadata concept is a basic requirement for the realization of an integrated, distributed database which can be accessed by any computer network.

The KTB database "KTBase" is a relational database: that is, it contains material such as tables of measured data and observational descriptions (e.g., thin section petrography) from the field laboratory, the downhole logging group, and the mud logging group, which are stored separately and can be retrieved and connected in any way by the user. KTBase is embedded in an application layer comprising interfaces for the presentation and application of KTB data in different ways. The applications cover administration tasks, telecommunication facilities, database management, and software modules developed especially for the scientific technical treatment of data from drilling projects, including numerical and graphical software packages. KTBase is now available at the GeoForschungsZentrum Potsdam. A hypertext link is installed on the home page of the GFZ WWW server (http://www.gfz-potsdam.de).

Scientific Results

Crustal Structure and Evolution

The Oberpfalz is situated at the western margin of the Bohemian Massif, the largest coherent surface exposure of basement rocks in central Europe, and it encompasses parts of three first-order tectonometamorphic units of the Variscan fold belt: the Saxothuringian, the Moldanubian, and the Tepla-Barrandian (Plate 2). This basement block is separated from Permo-Mesozoic foreland sediments (up to 3000 m thick) by the Franconian Lineament (FL), a NW-SE trending, deep-reaching and multiply reactivated system of reverse faults. The KTB location is about 4 km east of the FL and just south of the boundary between the Saxothuringian and Moldanubian units. This boundary has been regarded as a suture zone formed by closure of an early Paleozoic ocean basin during the Variscan collision in Devonian/Carboniferous times (~400-330 Ma).

The drill site was located in a small, isolated tectonometamorphic unit called the ZEV (Zone of Erbendorf-Vohenstrauß), which represents a variegated association of paragneisses and orthogneisses and metabasic rocks with minor metapegmatites. According to the results of presite studies, in particular lithologic-metamorphic comparisons with the Münchberg Massif in the north and preliminary interpretation of conventionally migrated DEKORP seismic profiles, the ZEV had been interpreted as a flat, bowl-shaped remnant of a supracrustal nappe complex straddling the Saxothuringian/Moldanubian boundary. In targeting the superdeep borehole, it was therefore expected to penetrate through a 3-5 km thick nappe complex and to drill into the postulated suture zone beneath it.

In fact, however, the KTB-HB encountered steeply inclined units belonging to the ZEV over the entire drilled section, and no evidence supporting the nappe concept was found. Figure 4 shows a schematic SW-NE profile through the ZEV down to about 10 km which summarizes all available geological information. The drilled crustal segment consists of an alternating sequence of three main lithologic units: paragneisses, metabasites and a "variegated" series of gneisses and amphibolites. Most rocks show a penetrative foliation which dips steeply between 50° and 80° to the SW or NE and is folded into large-scale open folds with NW-SE trending axes.

The paragneisses have a rather uniform composition and are made up essentially of plagioclase (oligoclase), quartz, biotite, muscovite, garnet, sillimanite, and/or kyanite; they commonly contain flakes of graphite. The protoliths of these rocks represent a turbidite sequence of graywackes and pelitic graywackes interlayered at a centimeter to meter scale which has preserved its original compositional features. Former graywackes show an equigranular quartz-feldspar fabric, whereas pelitic layers are coarser and richer in mica and typically display a biotite flaser texture. According to their chemical characteristics the protoliths were rather immature and contain a significant amount of basaltic material. They were probably deposited at an active continental margin.

The metabasic units comprise coarse- and fine-grained garnet-bearing amphibolites (plagioclase, hornblende, garnet and ilmenite), massive metagabbros with relict ophitic textures, and thin layers (up to 6 m thick) of mafic and ultramafic metacumulate rocks. Most rock types display chemical characteristics of enriched mid-ocean ridge basalts (MORB); however, normal MORB compositions also occur. These metabasic units perhaps represent slices of former ocean floor formed in a back arc environment or Red Sea type oceanic basin.

The variegated series consists of an alternation of massive garnet amphibolites, fine-grained banded amphibolites with layers of calcsilicates and marbles, hornblende-biotite gneisses, and paragneisses. Among the metabasic rocks, alkali basaltic compositions predominate with gradual transitions into trachyandesitic rocks (hornblende gneisses). These units constitute a metamorphosed volcano-sedimentary association with volcaniclastic material, thin lava flows, and pelites interbedded with minor marls and limestones. The combination of turbiditic material with volcanics and limestone indicates a marine depositional environment in a tectonically active setting.

All three of these lithologic units have suffered a pervasive Barrovian-type metamorphism at upper amphibolite facies conditions (6-8 kbar and 720°C at peak conditions in the paragneisses), connected with an intense ductile deformation that produced a penetrative foliation. Whereas the paragneisses seem to record prograde metamorphic evolution along the sillimanite-kyanite boundary and do not show any signs of earlier high-pressure events, the metabasic rocks contain relics which clearly display a multi stage evolution from an early high-pressure metamorphism under eclogite facies conditions ($P > 14$ kbar, $T >$ ~700°C) followed by a garnet granulite facies overprint (P=10-13 kbar, T=620-720°C) prior to the dominant amphibolite facies metamorphism [*O'Brien et al.*, this issue].

New age determinations using a broad spectrum of geochronologic methods confirm that the pre Variscan and early Variscan history of the ZEV is much more complex than previously thought and is distinguished by at least two separate metamorphic cycles[*O'Brien et al.*, this issue]. The formation ages of the metabasic rocks are about 485 Ma and nearly contemporaneous with the early Ordovician depositional age of the paragneiss protoliths. The earliest metamorphic event recorded in both the metabasic rocks and paragneisses has been dated at ~475 Ma, using U/Pb chronology on zircon and monazite, and it appears that the relict high-pressure mineral parageneses preserved in the metagabbros can be attributed to this Early Ordovician high-pressure metamorphism. Furthermore, the data imply that there was only a very short time span between formation of the rocks, their subduction to at least 40 km, and their subsequent rapid uplift into shallow (cool) crustal levels.

The second metamorphic cycle, that occurred under Barrovian conditions, can be bracketed between about 405 Ma (U-Pb ages of zircons and Rb-Sr, K-Ar and ^{40}Ar-^{39}Ar ages of muscovites) and 375 Ma (Rb-Sr ages of muscovite from shear zones, probably dating the regional deformation). Numerous K-Ar, ^{40}Ar-^{39}Ar and Rb-Sr dates on minerals indicate that the drilled basement segment, after cooling to 350-300°C in the Late Devonian (~360 Ma), stayed in the upper crust and, even more important, remained there for a long time period within a narrow depth and temperature interval. Only marginal and deeper parts of the ZEV were affected by the Carboniferous deformation and low-pressure, high-temperature metamorphism

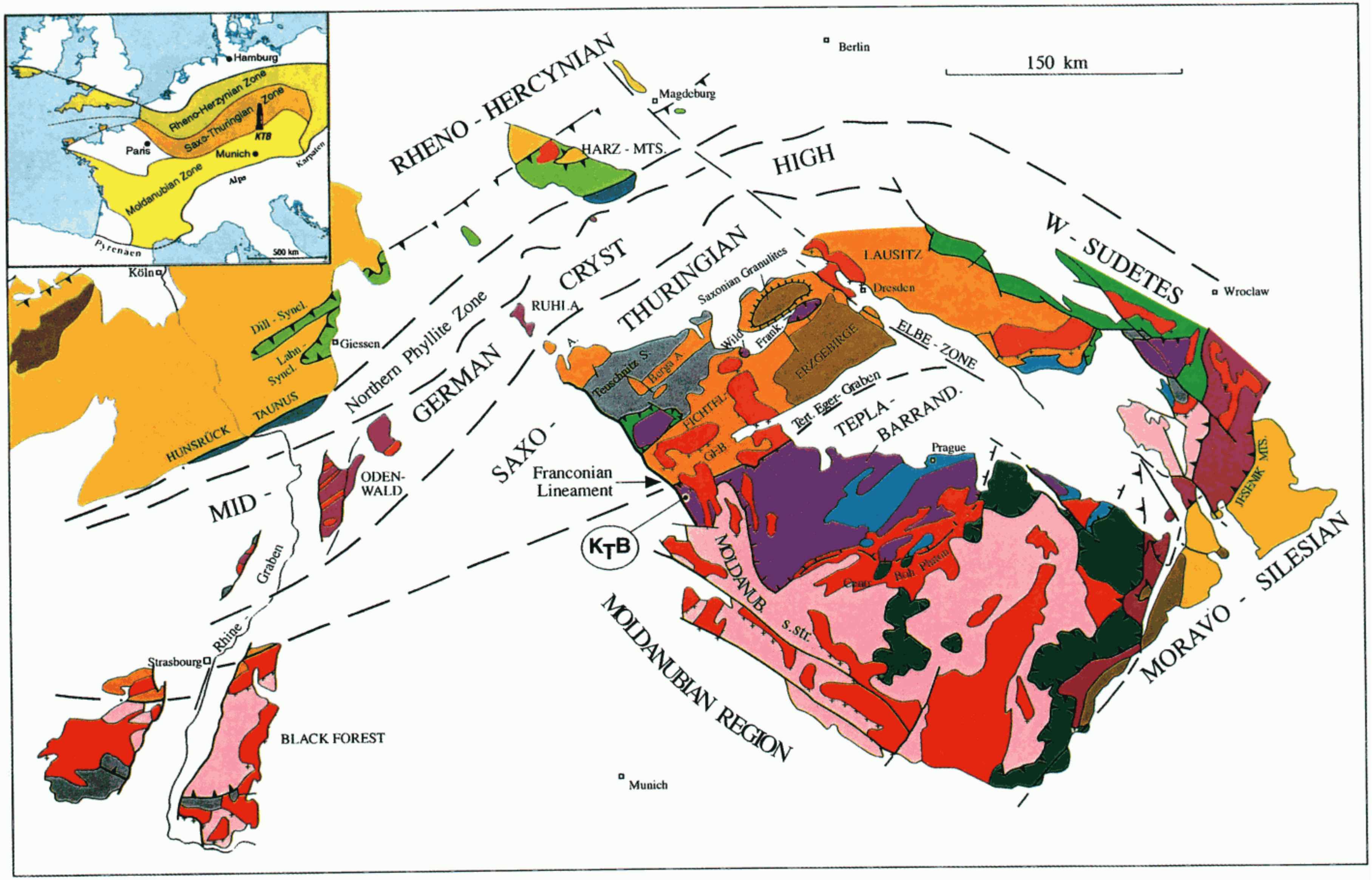

Plate 2. Simplified geological map showing the extent and internal makeup of the central European Variscides [after *Dallmeyer et al.*, 1995]. The KTB site is in a small tectonometamorphic unit (Zone Erbendorf-Vohenstrauss or ZEV) at the boundary between the Moldanubian and the Saxothuringian units. See text for explanations.

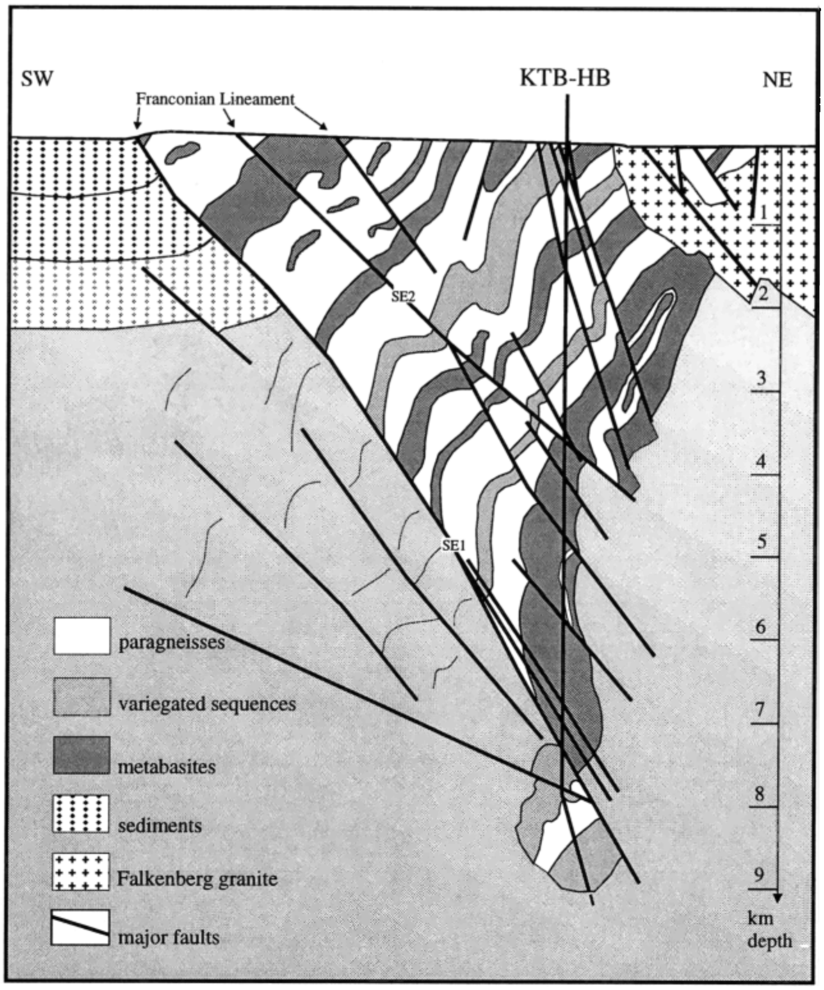

Figure 4. Schematic SW-NE profile through the ZEV in the surroundings of the KTB site (no vertical exaggeration). The metamorphic sequence of the ZEV has a polyphase history, with early high-pressure metamorphism at about 475 Ma, and later, Barrovian-type metamorphism at about 400-375 Ma. The Falkenberg granite, to the NE, intruded at about 310 Ma. To the SW are foreland sedimentary sequences of Upper Cretaceous, Triassic, and Permo-Carboniferous ages.

(335-325 Ma) which strongly overprinted the neighboring basement units.

The first evidence for a common history of the ZEV and the Moldanubian/Saxothuringian zones is the emplacement into all these units of late Carboniferous granites which occurred in two major "pulses", a late tectonic phase at 335-325 Ma and a posttectonic phase at 315-305 Ma. The Falkenberg granite, which borders the ZEV on the NE, has an age of 311 ± 8 Ma (Figure 4). The intrusion of dikes of aplites, calcalkaline lamprophyres (dated by ^{40}Ar-^{39}Ar at ~306 Ma) and monzodiorites, which crosscut the metamorphic rocks down to depths of about 7800 m, is closely related to the granitic magmatism.

The post-Variscan history of the ZEV is distinguished by unexpectedly intense, polyphase deformation under brittle conditions [*Wagner et al.*, this issue]. Major deformation phases include intense reverse faulting during the late Variscan (~300 Ma) and Cretaceous (~130-65Ma) followed by normal faulting during the Neogene (<22 Ma). The most widespread brittle elements in both boreholes are graphite-bearing late Variscan reverse faults. They occur preferentially in paragneisses and rocks of the variegated sequence and are connected with a local greenschist facies retrograde overprint. These faults are displaced by reverse faults of possible Cretaceous age, which formed under prehnite-actinolite facies conditions. The youngest structural elements are steep normal faults probably related to a phase of graben formation (Eger Rift) during the late Oligocene/Miocene (~25-20 Ma).

Figure 4 depicts the major faults encountered by the superdeep borehole. The most prominent fault system was penetrated between 6850 m to 7260 m and consists of a broad bundle of individual fault planes. Fission track data on sphene indicate that a vertical displacement of more than 3 km took place along this fault system in Cretaceous time. A second major system occurs between 7820 m and 7950 m, and vertical displacement there was at least 500 m. Both systems dip steeply to the NE and can be directly correlated with the Franconian Lineament at the surface.

Fission track studies on apatite, zircon and sphene, in combination with investigations of the Permo-Mesozoic sedimentary record in the western foreland of the ZEV, provide a detailed picture of the uplift and cooling history of this basement block and indicate that a rock pile of about 15 km has been eroded since the intrusion of the granites. Major phases of uplift and denudation occurred during the late Carboniferous and Permian (> 4000 m), lower Triassic (>1500 m), and during the Cretaceous (> 3000 m). All are connected to prominent stages of crustal shortening.

A highly unexpected result, confirmed by a number of independent observations, is the lack of any P-T gradients down to at least 8000 m and the uniformity of radiometric ages. This finding, together with the enormous amount of post-Variscan uplift and crustal thickening, requires a process of thrusting and stacking. Hence it appears that the superdeep hole penetrated a pile of steeply inclined thrust slices with the Franconian Lineament acting as the frontal ramp. Furthermore, the data suggest that the slices were detached from a decollement horizon coinciding with the Mesozoic brittle-ductile transition zone.

The geologic starting model proved to be inaccurate, and the new insights from the KTB results will have a strong impact on ongoing discussions of the structure and geodynamics of the Central European basement. It appears that the ZEV, because of its high-level crustal position since Devonian times, has been shielded from the Carboniferous deformation and high heat flow event and thereby preserved important structural and evolutionary information on the pre Variscan and early Variscan history. This history is characterized by a double P-T loop, with a first, high-pressure loop as early as Lower Ordovician and a second, Barrovian-type loop in the Devonian. The integration of these findings into the general geodynamic puzzle of reconstructing the Variscan consolidation of central Europe is still a matter for further work. Likewise unexpected, and of considerable consequence with respect to geologic models based on surface mapping, is the intense brittle deformation and the enormous amount of thrust faulting which hitherto had been regarded as impossible for an "anorogenic" intraplate setting, about 200 km north of the Alps.

Paleofluids and Recent Fluids

Fluids in the Earth's crust form one of the most important topics of contemporary geoscience, and the superdeep drill hole offers many new and surprising insights into fluid processes in the past and at present. One of the surprises for interpreting metamorphic rocks is that, despite the polymetamorphic history of the various metamorphic units and the strong Devonian medium-pressure overprint, the primary oxygen and sulfur isotopic patterns of the protoliths have been preserved. This implies that metamorphism took place under nearly closed-system conditions at low water/rock ratios and was not, as has often been postulated, accompanied by pervasive fluid flow.

The inventory of paleofluids from the ZEV rocks encompasses gases and aqueous solutions trapped in nanogram quantities as fluid inclusions mainly in quartz [*Möller et al.*, this issue]. Several generations and types of inclusions can be distinguished and related to distinct geodynamic processes. The oldest fluid generation preserved probably represents gaseous remnants from the Devonian metamorphism and consists of water-free N_2-bearing inclusions (with CH_4 or CO_2) which have the highest densities (about 750 kg/m^3). Moderately saline NaCl-KCl-$MgCl_2$ aqueous inclusions (4-8 wt % $NaCl_{eq}$), which are conspicuously enriched in the upper section of the borehole (above 4500 m), represent a fluid system that accompanied the late Carboniferous granitic intrusions (~330 Ma). CO_2-dominant gaseous inclusions with admixtures of CH_4 and N_2, and often containing graphite, formed in connection with the late Variscan cataclastic deformation (~300 Ma) and are associated with the graphite-containing shear zones.

The dominant type of fluid inclusions are highly saline Ca-Na(± K, Mg)-Cl aqueous solutions whose abundance, as well as salinity (up to 48 wt % NaCl-$CaCl_{2\,eq}$) and Ca-content, increase significantly with depth. These inclusions represent a young (<60 Ma) fluid system that probably infiltrated in connection with the Cretaceous phase of uplift and faulting. Subrecent fluid activity is reflected in low salinity Ca-Na-Cl inclusions only found in the upper section of the borehole.

Secondary minerals deposited in faults, veins, and veinlets document fluid activity related to the brittle deformation of the basement. Their chemical composition and parageneses mirror the evolution of the respective hydrothermal systems and constrain the PT conditions of each major deformation stage. A sequence with decreasing age can be established from actinolite through clinozoisite, epidote and prehnite to laumontite which reflects a decrease in temperature from about 350°C to 160°C (for laumontite).

The ZEV rocks contain a surprisingly large amount of free fluids, either in the form of hydrocarbon-rich "dry" gases or as formation waters. Dry gases were only detected in the gas logs and could not be sampled directly. They mainly consist of methane with minor helium and radon and are invariably associated with graphitized faults. Formation waters were first encountered at 400 m depth, and they occur very commonly from 3200 m down to the final depth in numerous distinct zones of up to several tens of meters in vertical thickness. Below 2000 m the first saline peaks were detected, and at 3200 m the first open fissures and porous alteration zones containing highly saline fluids were penetrated. Significant fluid inflow (up to 30 m^3) occurred at various depth levels associated with major fault zones or were stimulated by draw down tests [*Huenges et al.*, this issue].

The most promising fluid-containing sections were studied by in situ fluid sampling; and encouraged by a first successful pumping test in the pilot hole, a second, long-term pumping experiment (from August until December, 1991) was conducted in the open-hole section of the KTB-VB. 460 m^3 of brines with about 70 g/L TDS and 270 m^3 of gases were pumped to the surface and continuously analyzed (the "4000 m fluid"). Simultaneous monitoring of the KTB-HB showed that fluids of the two boreholes communicated through a network of fractures which connected the open-hole section of the pilot hole with the interval between 3000 m and 6000 m of the superdeep hole.

The composition of the formation waters changed systematically with depth, and the following general vertical sequence was established: (1) an upper zone of normal groundwater extending down to at least 650 m, (2) an intermediate zone of low-salinity, NaCl-dominated formation waters down to about 3200 m, and (3) moderately to highly saline Ca-Na-Cl basement brines with a pronounced increase in salinity and Ca content with depth. Type 2 probably represents a formation water which is evolving into type 3 by water/rock interaction.

Table 2 summarizes the major analytical data of the "4000 m fluid" (representative of types) which, at atmospheric pressure, released about 0.8 L/L gases that were dissolved under in-situ conditions. The gas phase consists of 67.0% N_2, 31.6% CH_4, 0.52% He, 0.14% Ar, and 0.04% CO_2. Chemical and isotopic data show that nitrogen and methane were derived by thermal

Table 2. The "4000 m Fluid"

Brine Data				Gas Data	
Element	mg/L	Element	mg/L	Element	vol %
Na	7160	Al	<0.015	N_2	67.0
K	231	Fe	0.3	CH_4	31.6
Li	2.4	SiO_2	54.0	He	0.52
				Ar	0.14
Ca	15700	Cl	44100	CO_2	0.04
Mg	2.2	Br	417		
Sr	244	F	3.8		
Ba	1.5				
		SO_4	307		
Mn	0.13	PO_4	0.5		
Zn	0.01	HCO_3	45		
Cu	0.02				
		TDS	68260		
$^{87}Sr/^{86}Sr$	0.7095	pH	8.3 (in-situ 5.3-5.8)	$\delta^{15}N$	+0.3‰
$\delta^{18}O$	-5‰	Eh	-150 (mV)	$^3He/^4He$	$6x10^{-6}$
δD	-10‰				

decomposition of organic material of a marine sedimentary source (paragneiss protoliths). The He-isotopic signature is dominated by radiogenic crustal helium, with less than 3% of mantle component which probably originates from the metabasic rocks [*Möller et al.*, this issue].

The chemical composition of the 4000 m fluid, and especially its Ca dominance, high Sr content and Br/Cl ratio resembles that of other basement brines (e.g., in the Canadian shield, [see *Frape and Fritz*, 1982]). Various lines of evidence suggest that this brine was originally rich in NaCl and that its high contents of Ca and Sr were derived from exchange with wallrock feldspars at 250°C-300°C. There are no indications of contamination by recent meteoric waters.

Application of several independent chemical geothermometers suggests that the 4000 m brine has experienced a temperature of about 160°C (equilibrium temperature), although its in situ temperature is only 119°C. This fluid probably came from a deeper level (~5500 m, corresponding to 160°C) and was "pumped" by tectonic processes into its present position. Altogether, the existing data support the contention of *Möller et al.* [this issue] that the precursor fluids of this brine were ultimately derived from (evaporitic) Permo-Mesozoic sediments in the western foreland of the ZEV and migrated into their present position in connection with Cretaceous uplift and deformation by infiltration along the deep reaching fault systems of the Franconian Lineament.

Information on in situ permeabilities and hydraulic properties of the basement, which are critically needed for understanding and modeling hydrodynamic processes, come from a number of borehole experiments. These include drawdown, drill stem and injection tests conducted at different depth levels and two very successful key experiments: a drill stem test and a combined fluid injection and hydraulic experiment, carried out in the open-hole bottom section of the superdeep borehole. The results obtained reveal the existence of a number of distinct, hydraulically connected zones that are related to major fault systems and extend down to at least 9 km. In situ permeabilities within these zones are between $10^{-17} m^2$ and $10^{-15} m^2$, which are several orders of magnitude higher than the matrix permeabilities of the rocks as measured in the laboratory under simulated in situ conditions [*Huenges et al.*, this issue].

The formation pressures determined for the brine-containing zones at different intervals show a progressive increase with depth to a maximum value of 105 MPa for the fluids at 9 km. The gradient of mean formation pressure is about 11 MPa/km and is non linear, probably because of a stepwise increase in salinity with depth. Inflow behavior during the tests and other evidence indicates that the brine-containing zones represent a hydraulically open system which is under hydrostatic conditions.

Geophysical Structures and Phenomena

Crustal seismic structure. Calibration of crustal seismic structure and understanding of the nature of reflectors was one of the foremost objectives of the KTB program. To achieve this, a combination of different geophysical experiments was carried out to define the position and spatial distribution of reflective elements and to unravel their message by directly probing their petrophysical, compositional and structural properties. With this information, and by comparing the observed and modeled dynamic wave field, constraints on the decisive elements of the seismic response function were derived.

The KTB drill hole was sited at the intersection of two seismic profiles, DEKORP-4 and KTB 8502, where presite investigations had indicated a number of reflectors at accessible depths [*Harjes et al.*, this issue]. To obtain a more detailed seismic image of the KTB surroundings a 3-D seismic experiment (ISO89) was conducted in 1989, covering an area of 19 x 19 km centered on the drill site [*Harjes et al.*, this issue]. Analysis of the results from the ISO89 experiment led to an interpretive geologic-tectonic model of the crust, a cross section, shown in Figure 5. West of the ZEV block seismic images reflect structures of the foreland sediments, and within the basement, two main groups of reflectors are present. One group is planar, steeply inclined (steep elements, SE), and

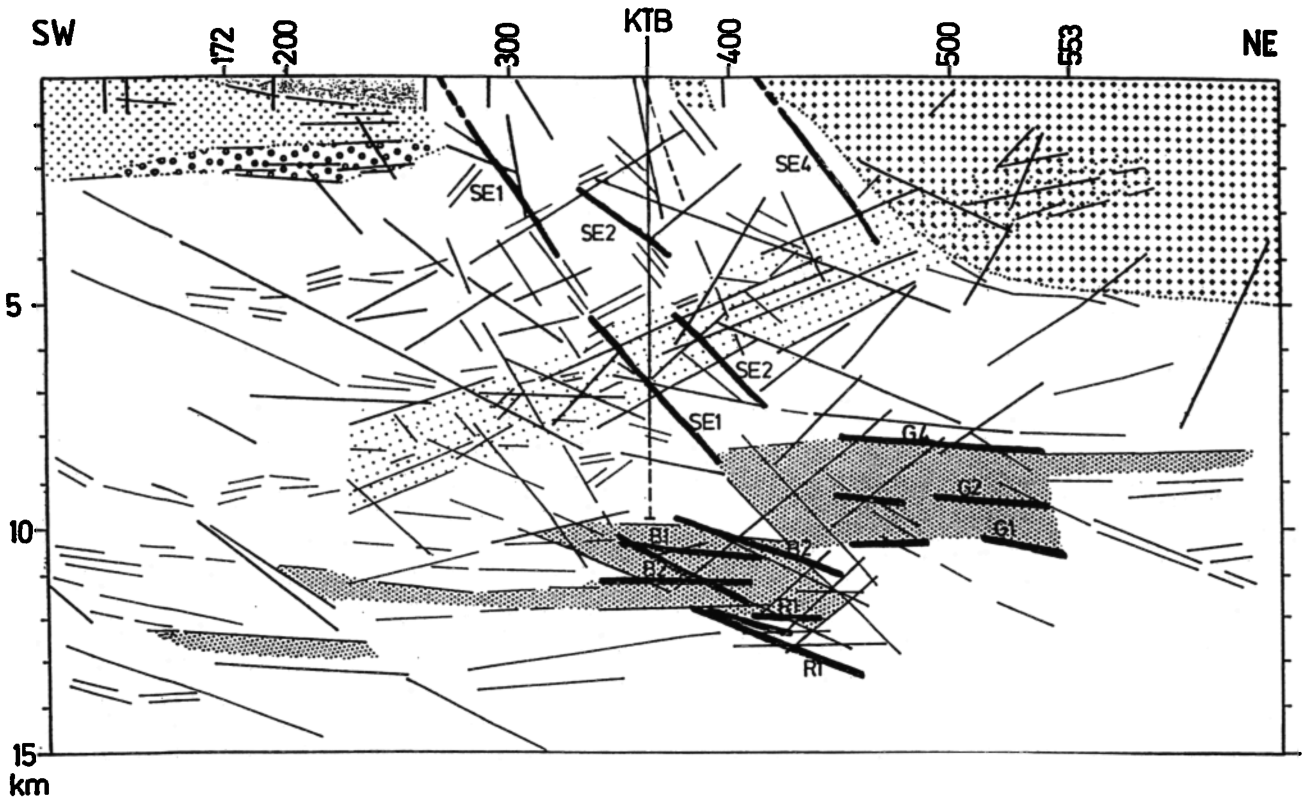

Figure 5. Interpretation of the seismic profile KTB 8502. Reflecting elements can be divided into two groups: steeply inclined reflectors (SE1-SE4) and subhorizontal reflectors (B, G, and R) The darkly shaded zone bounded by the subhorizontal reflectors is the "Erbendorf body."

extends down to about 10 km. The second group of reflectors is sub horizontal and is "bundled" in the depth interval >8.5 to 12 km. This latter group marks a zone of high seismic reflectivity which, based on wide-angle reflection seismics, is immediately underlain by a high-velocity zone (V_p > 7 km/s). This prominent mid crustal phenomenon, which combines high seismic reflectivity and high *P* wave velocity, is called the Erbendorf body (dark shading on Figure 5).

Most of the steeply inclined reflectors can be traced to the surface and related to known major fault systems. The strongest of these reflectors is the so-called SE1 reflector, which strikes SE-NW and dips 55° to the NE, has a considerable lateral extent, and crosscuts all lithologic boundaries. It can be correlated directly to the Franconian Lineament at the surface and clearly represents its depth continuation. The SE1 reflector was predicted to occur between 6600 and 7100 m in the borehole, and in fact, the most prominent cataclastic fault bundle of the KTB, consisting of at least four major fault planes, was drilled in the depth interval between 6850 and 7260 m. Calculations suggest that the contrast of seismic impedance between the wallrocks and the permeable, fluid-bearing, and mineralized fault zone can produce the observed reflectivity.

On the basis of these findings, a special seismic experiment was designed whose major goal was to quantitatively understand seismic reflectors in the crystalline basement [*Harjes et al.*, this issue]. The spatial orientation of the reflecting element SE1 was defined as precisely as possible, and the geometry of the seismic experiment was optimized in order to achieve maximum resolution. Then the seismic impedance of the rock section between 6500 and 7500 m was calculated from borehole measurements and transformed into synthetic seismograms. Comparison of these with the measured seismograms shows a fairly good agreement. On the other hand, synthetic seismograms calculated using seismic impedance values derived from compositional data measured on cuttings in the field laboratory yielded only very small amplitudes. This result proves that the seismic reflectivity of the SE1 is not due to lithologic contrast but is mainly caused by the effects of cataclastic deformation.

Altogether, the geophysical results combined with "ground truth" from the borehole have shown that steep-angle seismic reflection profiling, at least in this basement region, mainly depicts the effects of brittle faulting and images the young deformation pattern of the upper crust. Faulting is also obviously responsible for a 2-3 km vertical displacement of the subhorizontal reflectors belonging to the Erbendorf body (Figure 5). This body may well be a metabasic relict of a paleosubduction zone, or a sliver of dense rock emplaced tectonically during the Variscan collision. It is therefore a key element in the geodynamic interpretation of the entire basement region, but more interpretive work, and perhaps even additional experiments, will be needed to understand fully its nature.

In the course of the interpretive work summarized above, the KTB seismic group developed a promising new processing method of true-amplitude, prestack migration which represents an important general advance in seismic data processing. This method is based on a general diffraction concept instead of a reflection concept and provides a quantitative and geometrically correct reconstruction of the reflectivity distribution with depth. Plate 3 shows a section of the KTB 8502 profile which was reprocessed with this method. Comparison with Figure 5 shows the interpretive power of the new method.

Geoelectrics. In the last decade many electromagnetic surveys of continental basement regions have revealed deep-seated zones of high electrical conductivity whose nature is still enigmatic. Suggested causes of these features are the presence of saline fluids, interconnected films of graphite or sulfide mineralizations, or some combination of these. The European Geotraverse Project (EGT) proved the existence and large extent of such layers at midcrustal levels in the central European Variscan crust [*ERCEUGT Group*, 1992], and they were also found during KTB site selection studies in both the Schwarzwald and Oberpfalz regions.

Magnetotelluric surveys and long-period magnetic field variations indicated a zone of high electrical conductivity underlying the KTB drill site at about 10 km, which has a pronounced anisotropy with maximum conductivity values in the N-S direction. After completion of the superdeep borehole, a large-scale dipole-dipole experiment (Plate 4), the first of its kind, was carried out to investigate the extent and properties of this high-conductivity zone [*ELEKTB group*, this issue]. The result confirmed the expectation that the borehole reached this zone and that the electrode at 9065 m depth was indeed located within a layer of high conductivity. The position of this layer at 9 km roughly coincides with the postulated basal detachment horizon which is related to the post-Variscan crustal thrust stack.

Extensive suface measurements with a variety of electrical methods carried out in the KTB surroundings during the presite survey and the pilot phase revealed the existence of shallow low electrical resistivity anomalies and confirmed that the drill site was close to the centre of an unusually large surface anomaly of the electric self-potential (about -600 mV) extending NW-SE. That is, the drill site is situated on a "geobattery" which probably draws its energy from redox potential differences in the subsurface, with graphite-coated cataclastic shear zones acting as electron conducting bridges. The model presented by *Stoll et al.*, [1995] provides a general explanation of the nature and source of the observed anomalous electric fields. It is supported by downhole measurements of the self-potential and the redox potential obtained from specially developed logging tools.

Hence it appears that graphite is of special importance in producing the observed geoelectric phenomena. Among the ZEV rocks, the paragneisses contain primary graphite whose crystallinity indicates temperatures of about 700°C, in accord with the temperatures of peak metamorphism. This graphite represents original organic material in the protoliths and is finely dispersed so that it does not contribute to the overall electrical conductivity. More important for electrical conductivity is the secondary graphite, which is ubiquitous in cataclastic shear zones, where it is always associated with iron sulfides and chlorite. This graphite often forms a quasi-continuous coating along shear planes and is locally concentrated in millimeter-thick layers which constitute good electrical conductors over hundreds of meters.

All the evidence suggests that this graphite was precipitated from hydrocarbon-bearing fluids at about 400°C and 2 kbar. A possible mode of formation is described by the reaction $CH_4 + CO_2 \rightleftharpoons 2C + 2H_2O$. This reaction requires a relatively high activation energy, which could be provided by mechanical, tribochemical effects in connection with brittle deformation. Alternatively, since graphite is intimately associated with Fe sulfides, a reaction involving methane and sulfate in the system C-O-H-Fe-S could also be considered, which has a lower, more favorable free energy value at the relevant temperature: $3\ CH_4 + 2FeS + 2H_2SO_4 \rightleftharpoons 3C + 2FeS_2 + 8H_2O$.

In summary, the results obtained on core material and from various borehole measurements indicate that the basement section, despite the ubiquitous occurrence of saline brines, has, in general, a relatively high electric resistivity which increases downward from $10^3\ \Omega$ m at surface to $10^5\Omega$ m at 9 km depth. Intermediate discrete zones of low to very low resistivity (1 to 100 Ω m) are in most cases clearly related to graphite-containing shear zones. Graphite (±sulfides) therefore determines the electrical behavior of this crustal segment, and it appears that geoelectrical methods can image tectonic processes and can be used to trace paleoshear zones.

Gravimetry and Magnetics. The KTB superdeep borehole was sited on a strong magnetic anomaly and gravity high, and it was expected that borehole geophysics and laboratory measurements of rock samples obtained during drilling would give important new insights into interpretation of such anomalies. Plate 5 shows a new, high-resolution 3-D gravity map of the KTB surroundings which portrays the density distribution. The pronounced gravity low in the NE corresponds to the Falkenberg granite, and the strong positive anomalies at the KTB site are due to metabasic bodies. However, despite a relatively large density contrast between the major rock types of the ZEV (paragneisses 2740 kg/m^3 and metabasites 2890 kg/m^3), their steep dips, interlayering and complex structure make lithologic interpretation of the gravity pattern very difficult. A partial solution to this problem can be achieved by a combination of gravity data with results of geomagnetics [*Bosum et al.*, this issue].

The magnetic data give independent information about lithology (inventory of ferri-magnetic minerals) and can also portray tectonic features, like mineralized shear zones. The KTB superdeep hole penetrated many magnetic anomalies, which have a vertical extent of some meters up to about hundred meters. One of the most important of these anomalies, with a strong decrease of the magnetic field intensity, occurs near the surface. Below about 1200 m the total magnetic field intensity increases systematically with depth with a gradient of up to 200 nT/km, which is much higher than the undisturbed Earth's magnetic field would produce (about 22 nT/km). This result requires a magnetic body at depth, the exact nature of which, however, remains unknown. Unfortunately, the deep section of the superdeep hole was cased before a high-temperature modification of the magnetometer tool was developed. Therefore the interval between 6000 m and 8600 m was only measured by a Schlumberger GPIT inclinometer tool, whose resolution is about 100 times poorer than the magnetometer tool. Nevertheless, the deep magnetic data obtained with this tool document that the strongest magnetic anomaly encountered in the borehole occurs between 7300 m and 7900 m.

Surprisingly, pyrrhotite turned out to be the main carrier of rock magnetism in the drilled sequence and is responsible for most of the observed downhole magnetic anomalies. Magnetite plays only a very subordinate role and is restricted to a few distinct intervals. It is particularly enriched in some parts of the variegated series (marble and calcsilicate-bearing amphibolites) between 7320 and 7800 m, where it produces the magnetic anomaly mentioned above, which is about 2 orders of magnitude higher than any of those generated by pyrrhotite.

The pyrrhotite content in paragneisses and metabasic rocks is very similar and mostly below 1 wt %. Enrichments up to

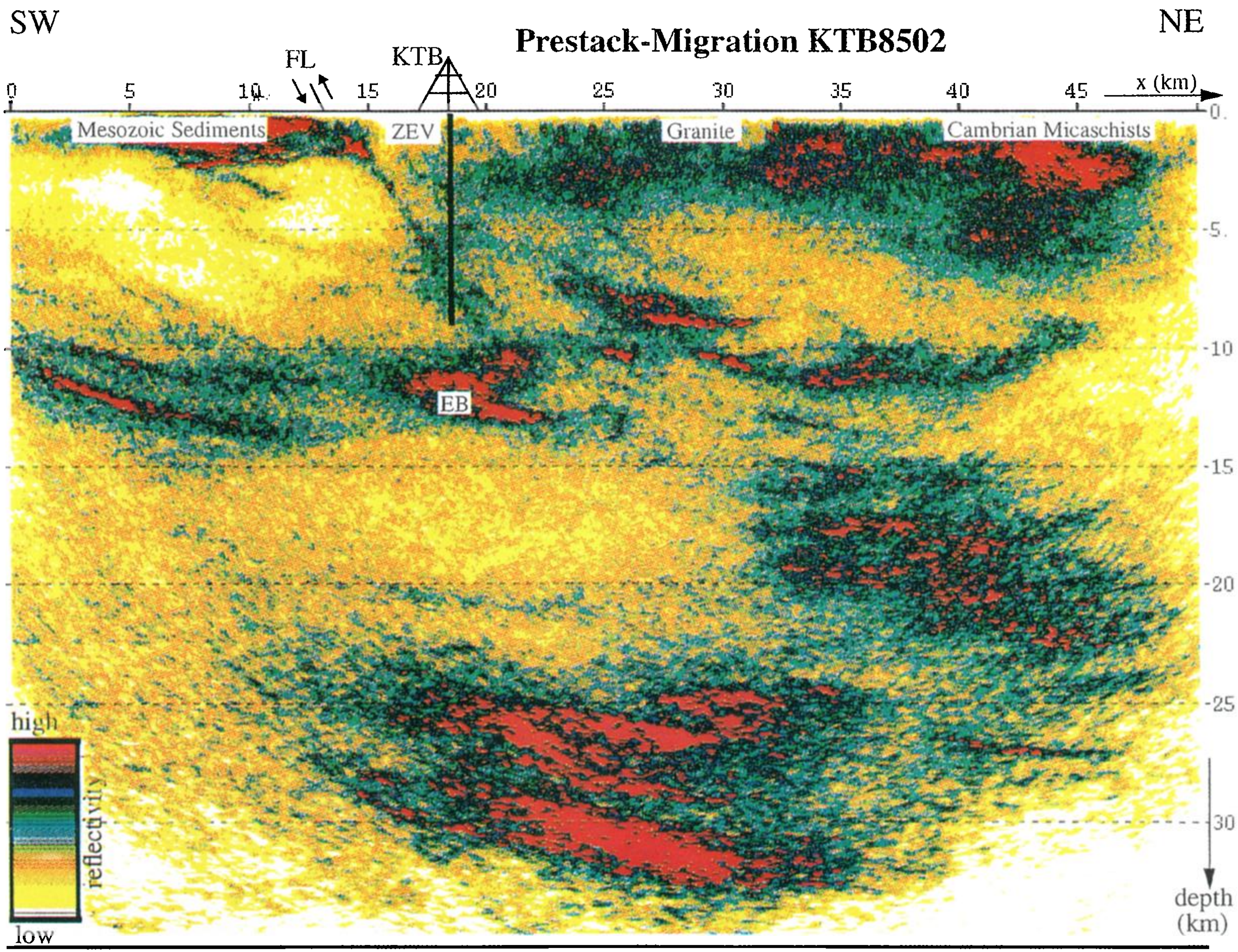

Plate 3. Reinterpretation of the seismic profile KTB 8502 using the newly developed method of true amplitude, prestack migration (compare with Figure 5). Reflectivity increases in the sequence: white, yellow, blue, green, red. FL, Franconian lineament; EB, Erbendorf body.

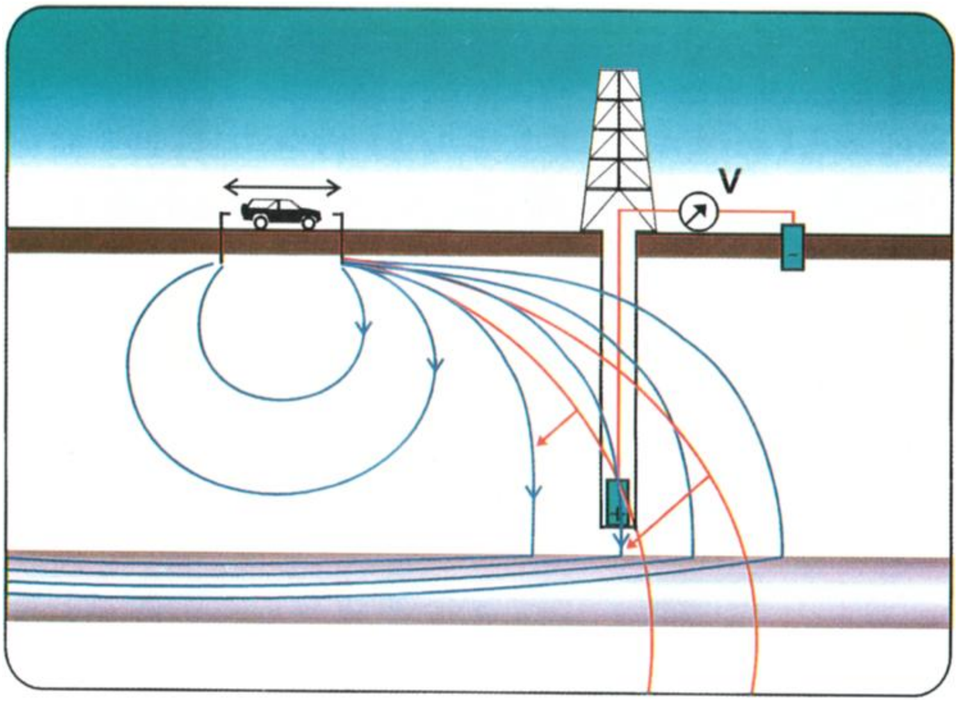

Plate 4. Schematic setup of the dipole-dipole experiment carried out at the final depth of 9101 m. Electric current was injected at variable distances from the drill site on two perpendicular profiles. The electrical field was measured by two probes at the bottons of the superdeep hole and the pilot hole. The first results confirm that the superdeep hole penetrated into the high-conductivity layer predicted to lie at 10±1 km (shaded band).

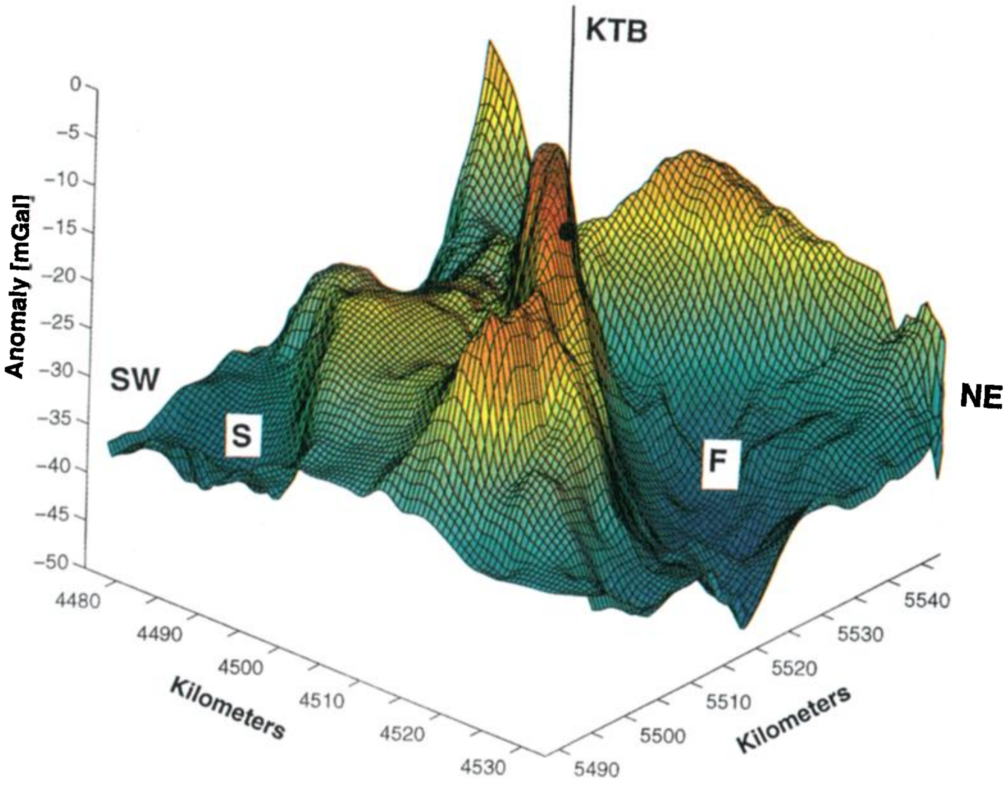

Plate 5. Three-dimensional gravity map of the KTB surroundings, showing the gravity high at the drill site caused by metabasites of the ZEV, and the pronounced gravity lows related to the Falkenberg granite (F) to the NE and the foreland sediments (S) to the SW:

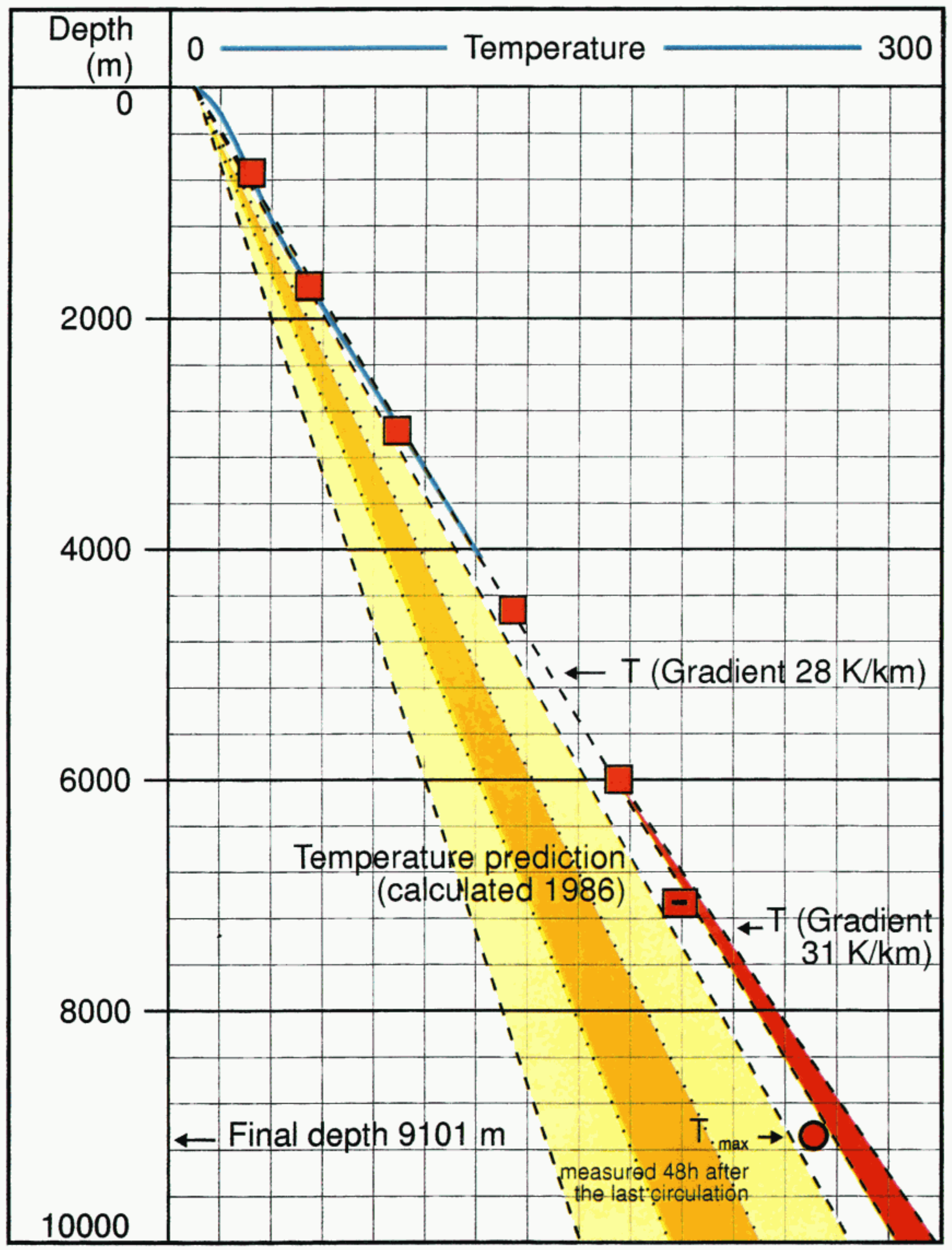

Plate 6. Diagram showing the predicted and measured temperatures at depth in the KTB site. The curves outlined in yellow show the predicted thermal gradient from presite studies (with 1σ and 2σ envelopes). This prediction turned out to be much too low. The blue line from surface to 4000 m shows the measured temperature profile in the pilot hole. Bottom hole temperatures (BHT) at different stages of drilling the superdeep hole are shown by red squares and these correspond to a constant gradient of 28 K/km. The temperature at final depth (red dot) was measured 48 hours after drilling ceased. The red shaded field shows the temperature profile predicted from the 6000 m BHT and based on 31 K/km and 28 K/km.

several weight percent are typical for hornblende gneisses and all major shear zones. Since it was known from laboratory experiments that pyrrhotite occurs in at least two low-temperature polymorphs, a monoclinic ferrimagnetic and a hexagonal antiferromagnetic modification, and that the Curie temperature of this mineral is around 300°C the superdeep borehole offered an ideal opportunity to study the in situ magnetomineralogical properties of this hitherto poorly investigated mineral [*Kontny et al.*, this issue].

Among the most important results of this study is that frequently, both monoclinic and hexagonal pyrrhotite occur together, mostly in intimate intergrowths, with the monoclinic polymorph being dominant in metabasic units. Hexagonal pyrrhotite is the stable phase at higher temperatures (above about 220°C) and it predominates below 8000 m. The observations of monoclinic pyrrhotite grains with relict hexagonal cores indicate low-temperature transformation from an originally hexagonal phase during uplift and cooling. According to experimental findings the Curie temperature of hexagonal pyrrhotite might be as low as 260°C. It is well known from laboratory measurements that the magnetic susceptibility increases strongly at temperatures just below the Curie temperature (the Hopkinson effect), and one of the open questions relevant to the borehole magnetic studies is whether the Hopkinson effect contributes significantly to the observed anomalous depth gradient in the magnetic field intensity, or whether the magnetite-containing layer is sufficient to produce this phenomenon.

The geopotential fields, electric, gravity, and magnetic, provide complementary information. Whereas geoelectrics mainly image tectonic features and gravity provides lithological information, geomagnetics carry information about both. The combined evaluation of data from the three sources, now underway, will contribute to a detailed 3-D geologic reconstruction of the KTB surroundings.

Geothermal studies. Evaluation of the geothermal data from the KTB pilot hole provided the highly unexpected result that the thermal gradient (21 K/km) and vertical heat flow density (55 mW/m^2) met the predicted values only in the upper 1000 m. Both parameters then increased rapidly to about 1500 m, after which almost constant gradients of 28 K/km and heat flow values of 85 mW/m^2 prevailed. The temperature in the pilot hole at 4000 m was 119°C and lay well above even the upper error limit calculated from the data obtained by the shallow-drilling geothermal studies (Plate 6).

The desire to explain the failed prognosis led to an ambitious research effort [*Clauser et al.*, this issue]. The KTB field lab carried out a large number of measurements on core material and cuttings to determine statistically sound values for thermal conductivity, heat diffusion, and heat production to be used in thermal modeling. An extensive geothermal logging program was also designed, which provided a wealth of new information about the thermal structure of the drilled segment and led to improved methods of handling downhole temperature measurements. Table 3 presents a summary of values for thermal conductivity and heat production. Rock foliation and microcracks are responsible for significant anisotropy in thermal conductivity (up to 20%), with highest values parallel to foliation. The distribution of heat production with depth reflects local lithologies. The data, in general, show a slight decrease but definitely do not confirm the widely cited law of an exponential decrease of heat production with depth (Figure 6).

Geothermal data from the superdeep borehole are consistent with the results and predictions from the pilot hole. Within the upper 1500 m the temperature gradient increased from 20 K/km to about 28 K/km at 1500 m and remained at that value down to the final depth. On that basis, the undisturbed equilibrium temperature at 9100 m is about 265°C. Within uncertainty, the vertical heat flow density, which is the product of temperature gradient and vertical thermal conductivity, is also constant below 1500 m, with a mean value of around 85 mW/m^2. Estimation of the contribution of the cumulative heat production rate to the vertical heat flow density shows that the upper 6 km of the penetrated basement only provide about 10% of the calculated heat flow density value of 85 mW/m^2 at 1.5 km. If this value is typical for the crust, then a shift in the thermal gradient to lower values must occur well below 10 km depth.

The results of thermal studies in the two boreholes raise a number of basic questions about the heat budget in the continental crust. One of the problems is how to explain the low thermal gradient in the uppermost 1500 m, and how to reconcile the ~25 mW/m^2 deficit in heat flow density between the upper and lower borehole sections. Three alternatives are currently discussed, which may work in concert: (1) topography-enhanced heat advection by groundwater flow; (2) paleoclimatic perturbation of the steady state temperature field due to changes of the mean surface temperature (e.g., in connection with the last ice age); and (3) disturbances of the steady state temperature field due to lateral refraction of heat flow in a compositionally and structurally very heterogeneous subsurface [*Clauser et al.*, this issue].

Modeling of available data prove that both groundwater advection and paleoclimatic effects are able to produce the measured near-surface thermal gradient and heat flow, but the exact contribution of each process cannot yet be quantified. In any case, the observations clearly demonstrate that external factors influence the near-surface temperature field in the crust, and this suggests that values of geothermal gradient and heat flow from shallow drill holes in crystalline terranes tend to be systematically too low.

Another set of problems is raised by the surprisingly high

Table 3. Parameters Used for Geothermal Calculations

	Paragneisses	Hornblende Gneisses	Amphibolites
Thermal conductivity, W/m K	1.50 ± 0.19	1.15 ± 0.11	0.53 ± 0.28
Heat production, μW/m³	51 ± 5	39 ± 5	23 ± 7
Natural gamma activity, c/s kg	3.4 ± 0.2	2.8 ± 0.2	2.6 ± 0.2
Potassium, wt %	2.24 ± 0.25	1.9 ± 0.22	0.88 ± 0.42
Uranium, ppm	2.8 ± 0.4	2.0 ± 0.2	1.0 ± 0.6
Thorium, ppm	7.9 ± 1.0	5.7 ± 0.8	2.5 ± 1.5

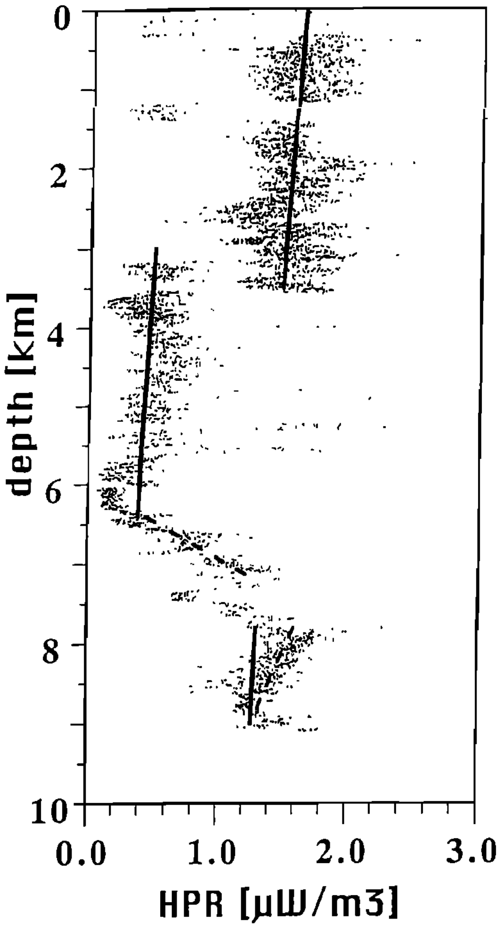

Figure 6. Diagram showing the changes in heat production values, as measured by laboratory experiments and downhole logging, with depth in the superdeep borehole. The commonly cited exponential decrease in heat production with depth is not confirmed by these data. Instead, one finds intervals of constant average heat production (vertical lines) which correlate with lithologic changes.

value of 85 mW/m^2 for the heat flow density at 8 km depth. Extrapolation of the temperature gradient measured in the superdeep hole using conventional models for the lower crust and assuming conductive heat flow leads to predicted temperatures well above 800°C and heat flow densities of 55 to 80 mW/m^2 at the crust/mantle boundary in 30 km depth. There is no evidence for partial melting at this depth from seismic data, and there are also other reasons to expect lower temperatures for the crust/mantle boundary. Therefore one must question the model assumptions. Is there an additional heat source in the crust below the drill site? Could the Erbendorf body be responsible for high heat production or are there even significant heat inputs from exothermal hydration reactions in the middle and lower crust? Is the assumption of conductive heat transport incorrect, and can fluid convection related to the Franconian Lineament explain the dilemma?

These and other ideas will be explored numerically and additional constraints are expected from planned geothermal experiments in the KTB "Deep Crustal Laboratory." The proposed idea that the thermal anomaly around the Tertiary Eger Rift, to the north of the drill site, is the cause of the high heat flow density can be discounted because the value measured at the KTB site well corresponds to the average background value of about 80 mW/m^2 in southern Germany.

Rheology and Stress Field. A key target of the KTB program from the very beginning was the study of the state of stress in the Earth's crust and the rheological behavior of rocks under_in situ conditions down to mid crustal levels. Current understanding of the rheology of the continental crust is based primarily on laboratory studies of rock strength under greatly simplified conditions. These studies indicate that two major processes control the mechanical behavior of crustal rocks: (1) In upper crustal levels, deformation causes brittle failure and rock strength is limited by frictional strength of preexisting faults. Because the frictional strength increases linearly with confining pressure, the strength of the crust correspondingly increases with depth. (2) At greater depth, beyond a certain temperature and at low strain rates, rock strength is determined by flow laws and decreases exponentially with further rise in temperature.

The change from brittle to ductile (plastic) behavior, commonly referred to as the brittle-ductile transition, depends on factors such as, among others, rock mineralogy, fluid content, and strain rate. Therefore, in nature a more or less broad transition zone can be expected. Most models of rheology are based on the mechanical properties of quartz because of its abundance in continental crustal rocks. According to the "quartz model" (Figure 7), there is a linear buildup of differential stress with depth in the crust to the brittle-ductile transition at about 300°C, after which rock strength, and thus the magnitude of "stored" stress, falls exponentially.

Obviously, there are shortcomings in such a simple model. Apart from uncertainties in the physical-mechanical properties of minerals and rocks, a more fundamental problem is that the threshold temperature for ductile flow is critically dependent on strain rate, and realistic strain rates (10^{-14} s^{-1} to 10^{-16} s^{-1}) are unattainable in the laboratory. On diagrams like Figure 7, the expected natural situation is therefore depicted as a continuous transition from the brittle to the ductile regime.

With a basal temperature of about 265°C, the KTB superdeep hole has penetrated into depths in which the brittle-ductile transition can be expected, and thus a unique opportunity is available to study this fundamental region in situ. The most important elements of these studies are the determination of the stress tensor with depth and the structural analysis of rocks from depth approaching the transition zone. From the beginning of the KTB program, geoscientists and engineers worked closely together to develop an integrated stress measurement strategy that involved a number of different methods and experiments whose common goal was to establish a continuous stress profile from the surface to the final depth. These include modified hydraulic fracturing tests and analysis of borehole breakouts and drilling-induced tensile fractures [*Brudy et al.*, this issue].

The magnitude of the least horizontal principal stress component (S_h) was determined by conventional hydraulic fracturing experiments in the pilot hole (14 experiments between 800 m and 3000 m), and by two modified hydraulic fracturing experiments at 6018 and 9070 m depth in the superdeep hole. These experiments yielded inprecise values for the maximum horizontal stress component (S_H), and therefore a new method was developed to estimate the magnitude of S_H from a combined analysis of borehole breakouts and drilling-induced tensile fractures of the borehole wall. Assuming that the vertical stress S_v, whose value was calculated from the

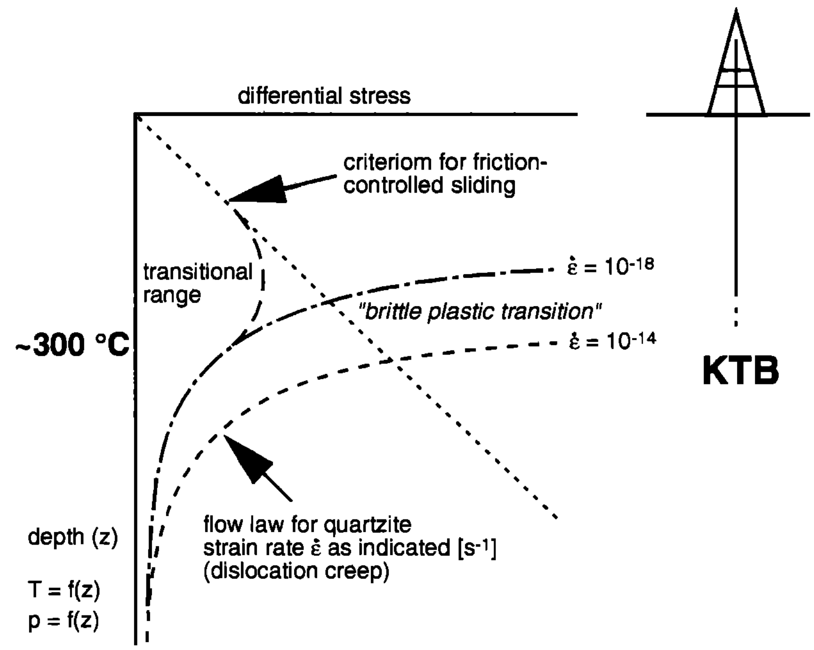

Figure 7. Schematic diagram showing the dependence of crustal rheology (based on the behavior of quartzite) on pressure (depth) and temperature and the magnitude of differential stress [*Stoeckhert*, 1994]. The final depth of the KTB borehole (9101) reached the zone of transitional brittle-ductile behavior.

lithology of the drilled section and density of the respective rock types, is a principal stress component, a continuous profile of the complete stress tensor down to about 9 km was established.

The combined results of all stress measurements indicate that the direction of S_H is remarkably uniform at N160°E ±10° over almost the entire investigated depth range from 3 km to 9 km, and it corresponds well with the N146°E regional orientation of S_H in central Europe. The only significant change of S_H with depth is a shift of about 60°, to N220°W, at 7200 m which coincides with the lowermost fault plane of the SE1 fault bundle. Values of the magnitude of S_h at 6018 m and 9070 m depth in the superdeep hole are 111 MPa and 183 MPa, respectively, and the estimated differential stresses are between 180 MPa and 147 MPa. Apart from the uppermost section of the drill hole down to about 1000 m, where S_v appears to be the least principal stress, the stress magnitudes obtained from S_h, S_H and S_V (~240 MPa at 9100 m) indicate strike-slip conditions ($S_h < S_v < S_H$).

The data support the hypothesis that the state of stress in the brittle crust is limited by the frictional equilibrium on preexisting faults and that the continental upper crust acts as a stress guide and is capable of transmitting forces of hundreds of megapascals, comparable to those exerted by plate-driving processes.

The urgent question of whether the brittle-ductile transition was encountered in the KTB superdeep hole can be answered with a definite "maybe." One of the most important lines of evidence comes from a large-scale hydraulic fracturing and fluid injection experiment conducted in the uncased bottom hole section at the conclusion of drilling and was especially devoted to testing the brittle-ductile transition hypothesis. Within 25 hours, 200 m^3 of fluid were injected into the crust at about 9030 m and some 400 microearthquakes were triggered a few hundreds of meters from the injection zone in the depth range between 8 and 9 km [*Zoback and Harjes*, this issue].

The induced seismicity was recorded by a surface network of 70 stations and with a three-component geophone tool deployed at 4 km depth in the pilot hole. Cluster analysis showed that the events were concentrated at two different depth levels, both above the injection zone and extending about 1 km from the borehole. Fault plane solutions of the seismic events indicate a strike-slip character, and this documents that the crust at 8-9 km is still in a state of frictional equilibrium. However, the complete absence of induced earthquakes near 9030 m depth, coupled with the observation that the seismic events clustering at a depth of about 8.7 km, indicates an abrupt change of the stress state, and markedly lower shear stresses suggest that the bottom of the borehole may be near the brittle-ductile transition.

A different approach to identifying directly the current brittle-ductile transition zone comes from combining data on the present state of stress with the results of microscopic and submicroscopic textural studies of minerals, especially quartz, in the suspected depth range [*Dresen et al.*, this issue]. Because the rate of processes which control quartz textures increases exponentially with increasing temperature, it was expected that significant changes in textural features would appear on approaching the transition zone. Therefore quartz from cutting samples taken quasi-continuously below 7000 m was analyzed by optical microscopy and transmission electron microscopy. In general, the quartz microtextures are similar within the depth interval 7-9 km; however, there are systematic qualitative changes with depth. These include an improved spatial organization of dislocations, decrease of dislocation density, and submicroscopic fluid inclusions and indicate an increasing rate of thermally activated recovery processes. These findings, like those of the hydaulic fracturing and fluid injection experiments, indicate that the superdeep hole might have, in fact, reached the present-day brittle-ductile transition zone.

Deep Crustal Laboratory: A Telescope Into the Earth's Interior

A detailed picture of the crustal section and its properties has been assembled from the field experiments, laboratory investigations and borehole measurements of the KTB main phase. During the next 5 years of the final phase, supplementary experiments are planned using the globally unique association of two deep boreholes into the crystalline basement with a separation of 200 m.

Two main objectives of this so-called "Deep Crustal Laboratory" have been defined: (1) The discrimination of geophysical signals generated by deep-seated processes and by shallow events. Conventional deep-sounding methods can be interfered with by effects induced at the Earth-Atmosphere interface and disturbed by structures and processes at shallow depth. (2) Determination of equilibrium values of physical parameters and their long-period variations with time and depth. These objectives will be tackled by deployment of instruments at various depth and time intervals.

Altogether, three general types of experiments are planned: (1) Stationary registration of time-dependent variations of physical parameters at different depths under "natural" boundary conditions: planned investigations include long-term measurements of the seismicity, tidal effects, deformation, and natural electromagnetic events (in addition, depth profiles of equilibrium field values will be registered (e.g., temperature, heat production)), (2) experiments, unique or repeated, with defined changes in boundary conditions (e.g., downhole measurements of seismic surface vibrations and active electrical experiments or hydraulic/fluid tests), (3) cross-hole experiments (the use of two holes allows specific experiments to investigate hydraulic connectivity and fluid pathways as well as anisotropy of physical parameters (e.g., seismic wave-propagation) under natural conditions). A particular benefit of the close proximity of the two deep boreholes is the ability to perform seismic cross-hole experiments with higher frequencies and thus improved spatial resolution. This type of experiments will close the gap in scale factor between laboratory measurements (centimeter range), borehole measurements (dezimeter range), seismic field experiments (kilometer range) and seismology (100-1000 km range).

Finally, it is planned to expand into a 3-D triangular array by sinking a third hole down to about 1000 m and thereby create a greatly improved "telescope" into Earth's interior. With this configuration the Deep Crustal Lab will provide a platform for high-resolution investigations of anisotropy and transport properties in the vicinity of the site and will greatly improve the discrimination between deep-seated and near-surface effects and processes.

Conclusions

In this paper we attempted to summarize the scientific advances gained by the continental deep drilling program, the KTB, with respect to all of the major research themes. Some of the results will have their greatest impact in advancing regional studies, whereas others are of general significance. In this conclusion we pick out those aspects of the KTB scientific program which are principally of global importance and which could not have been obtained without drilling.

Stress field. A continuous profile of the complete stress tensor has been obtained from the surface down to midcrustal levels. This was done using a combination of hydraulic fracturing tests with analyses of compressional (breakouts) and tensile failures (drilling-induced fractures) of the borehole walls. The study has shown that the brittle upper crust is strong, "stress-loaded," and capable of sustaining and transmitting forces of plate-driving magnitude. The generation of hundreds of microearthquakes by extremely small increase in pore pressure (< 1 MPa) indicates that stress levels throughout the brittle crust are near its frictional strength and that only a small stress increase is necessary to induce failure. These findings prove the validity of experimentally derived theoretical stress profiles, and confirm that crustal strength in situ depends on the frictional strength on preexisting, favorably oriented fractures with coefficients of friction in the range of 0.6 to 1.0 [*Byerlee*, 1978].

The brittle-ductile transition. The lack of induced microearthquakes below about 9 km suggests that the bottom of the superdeep borehole is close to the present-day brittle-ductile transition. This has been confirmed by detailed study of quartz microstructures in gneisses, where strain is partitioned between brittle fracture, solution/precipitation creep, and plastic flow. Measurements of the dislocation density in quartz, which decreases toward the bottom of the borehole, yield differential stresses of about 140 MPa, which approximately equal the confining pressure at that depth. Thus the emprical Goetze criterion also indicates that plastic flow contributes to rock deformation at final depths [*Dresen et al.*, this issue].

Crustal fluids and rock permeability. Mixtures of aqueous and gaseous fluids are widespread in the upper 9 km of the continental crust sampled by the KTB. Fluids are mostly confined to faults and fractures, and these were encountered, even at bottom hole depths, in numerous distinct zones up to several tens of meters thick. The permeability of these zones is of the order of 10^{-15} to 10^{-17} m^2, which is several orders of magnitude higher than the matrix permeability of the rocks. Formation pressures determined in brine-containing zones show a nonlinear increase with depth, probably due to stepwise increases in salinity. The formation pressure of 103 MPa at 9 km is near-hydrostatic. This, and the fact that experiments proved a hydraulic connection between the pilot hole and the main hole, indicates that fluid pathways are highly interconnected.

The composition of the fluids varies systematically with depth: groundwater in the upper levels, NaCl-dominated fluids of low salinity at intermediate depths, and highly saline, Ca-Na-Cl basement brines below about 3200 m. The latter contain high amounts of dissolved gas (~0.8L/L of brine), mainly nitrogen and methane, which is derived by thermal decomposition of organic material in the paragneiss protoliths. Data suggest that Permo-Triassic evaporites in the sedimentary basin west of the drill site are the ultimate source of the brines, which have infiltrated the basement along deep-reaching fault systems down to at least 10 km depth.

Graphite and geoelectric anomalies. Despite the ubiquitous presence of saline brines, the electrical resistivity increases, in general, from 10^3 Ω m at surface to 10^5 Ω m at 9 km depths. Local anomalies, at various depths, with extremely low resistivity (1 to 100 Ω m) are clearly related to graphite-bearing shear zones. Graphite in such shear zones is interconnected over distances of hundreds of meters, and this phenomenon obviously determines the electrical response of the basement. Before drilling, a prominent low-resistivity layer of regional extent was postulated at about 10 ± 1 km depth. This zone was the target of a dipole-dipole experiment conducted in the borehole after cessation of drilling. It turns out that the bottom depth of the KTB is well within this major conductor, whose position coincides with a postulated basal detachment zone of the post-Variscan thrusts (Mesozoic brittle-ductile transition). An important implication of these findings is that geoelectric surveys could be used to map paleoshear zones and thus help in tectonic reconstructions.

Thermal structure of the crust. A major lesson of the KTB is that geothermal data obtained from shallow wells should be used with great caution in making geothermal prognoses. The thermal structure of the uppermost 1500 m of the crust is highly disturbed. In this interval the geothermal gradient is about 21 K/km and the heat flow reaches values of about 55 mW/m^2. Both parameters then increase rapidly to about 27.5 K/km and 85 mW/m^2, respectively, and remain close to those levels right responsible for the near-surface effects: heat advection by topographically induced groundwater flow and surface temperature fluctuations due to paleoclimate. The effect of paleoclimate is dominant. In particular, the last ice age is responsible for a perturbation of up to several degrees in the present-day temperature distribution of the upper 4 km. Below about 2000 m, advection is negligible and heat transport can be described by a purely conductive model.

The KTB has fostered a number of important advances in interpreting and modeling heat flow data. For example, the intimate alternation of gneiss and metabasite units with near-vertical contacts was ideal for studying the effects of lateral refraction of heat flow and for developing new models which take these effects into account. The large amount of data from logging and from laboratory measurements clearly refuted the widely held assumption that heat-producing elements are strongly concentrated in the upper crust and then decrease exponentially with depth. Instead, the data show that heat production is controlled by lithology, and there is only a very slight overall decrease with depth.

Seismic structure. The seismic program employed a broad spectrum of studies, which covered scale lengths from kilometers to a few centimeters. These included 2-D and 3-D, near-vertical and wide-angle seismic surveys, VSP measurements, and more sophisticated surface-to-borehole experiments. These were complemented by petrophysical laboratory studies under in situ conditions, drill core analyses, and a variety of borehole measurements.

The 3-D experiment, the first of its kind in crystalline basement, revealed a number of pronounced, steeply dipping reflectors in the upper crust. The most prominent of these was penetrated, as predicted, at a depth of about 7000 m. The reflector is a deep-reaching fault system consisting of a 400 m thick group of shear zones. The physical parameters responsible for the observed reflectivity were quantified by integrated modeling of data from surface experiments, borehole measurements and laboratory studies.

Altogether, the seismic program demonstrated that most of the reflections registered in the upper crust originate from fracture zones and faults and that lithologic boundaries are of little importance. This is due to the fact that impedance contrasts produced by faulting are much higher than those due to lithological variations. Furthermore, although the petrophysical studies and VSP data clearly indicated seismic anisotropy of the rocks, the anisotropy effect was found not to contribute significantly to the reflectivity of the crust.

The complexity of the drilled crustal structures inspired the development of a new seismic processing method (true amplitude, prestack migration) and demonstrated the need to consider 3-D aspects in seismic imaging. The new method provided high-resolution images of the midcrust and lower crust at the KTB site. It has been and will continue to be used for reprocessing and reinterpretation of existing seismic records, for example, the DEKORP data, and thus holds great promise for new insights into the deep structure of crystalline basement.

Looking Back

As this paper goes to press, we look back on 19 years of involvement in the KTB program, starting in the first planning stages in 1977, to the cessation of drilling in 1994, and on to the final phase of on-site experimentation in the Deep Crustal Laboratory. The success of the KTB program depended on close cooperation among diverse groups including ministries and agencies, management teams and engineering units from industry and academia, and not least the scientists, those assigned to the KTB field laboratory and scientists from universities and research insitutes. It might be useful to summarize, from our current perspective, what we believe were the key elements for the success of the German Continental Deep Drilling Program and what we would probably do differently a second time.

The single most important factor was the continuing support and participation from the geoscience community in Germany, both from the professional societies and steering committees and from the leading individuals in most branches of the solid earth sciences who participated in the program. This broad basis of support resulted from a long concept finding phase, which lasted nearly 7 years, and during which the fundamental aspects and general philosophy of the drilling program were discussed. The result of this phase was a rich and diverse research program which combined the key issues of the various geoscience disciplines involved. This hard won scientific consensus in the geoscience community helped to keep the debates on site selection at a professional level and to ensure that all disciplines were equally involved in the selection decision and in the ensuing research.

It was clear from the beginning that a superdeep drilling program would exceed the limits of existing technology. This technical challenge and the strong support from the German industry were prerequisites for KTB to be considered for funding as a large-scale national research initiative. From the total budget of $350 million US, 50 million were earmarked for scientific projects and an equal sum was allocated to the industry for R&D projects. The drilling industry was also funded for construction of a completely new drill rig, which involved a number of technical innovations. This greatly improved the competitive stance of the German drilling industry internationally.

Approval for a fully equipped modern field laboratory on site was hard fought in the planning stage but it proved to be indispensible and should be included in any future projects of this kind. The field laboratory staff carried out a broad spectrum of investigations which provided the necessary background data for the numerous research projects at universities and other institions. An information stream from quasi-continuous analysis of cuttings and drilling fluid (including dissolved gases), combined with data from borehole logging provided the basis for an optimum balance between logging and coring, and also gave the engineers rapid feedback in case of technical problems.

A lesson learned while drilling the pilot hole was that the project management must have a clearly defined chain of command and responsibility and that decision making must give equal weight to the concerns of the geoscientists and those of the engineering team. Therefore the go-ahead for the superdeep hole by the Ministry for Research and Technology was conditional on reorganization of the project management. The new, and ultimately successful, management scheme consisted of three directorates: geoscience, borehole logging and experimentation, and engineering. The final decisions were made by a project manager with experience in all three areas, and his responsibility was to weigh the often diverging interests of the three directorates. He was advised by an expert panel made up from leading scientists and industry representatives. This management structure integrated industry experience and geoscience concerns at the decision-making level, and it ensured a balanced distribution of finances and manpower for drilling, coring, logging, and the borehole experiments.

In retrospect, we believe that the time given for the planning phase (7 years) and the presite investigations (2 years) was necessary and sufficient. For the purpose of site selection, however, it would have been better to have drilled a technically simple, 2-3 km hole at each site instead of several shallow boreholes (< 500 m).

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