The KTB Borehole—Germany's Superdeep Telescope into the Earth's Crust

The drill bit has stopped turning and the KTB project is winding down. Germany's superdeep borehole is complete. How and why was it drilled? And what have the scientists achieved so far?

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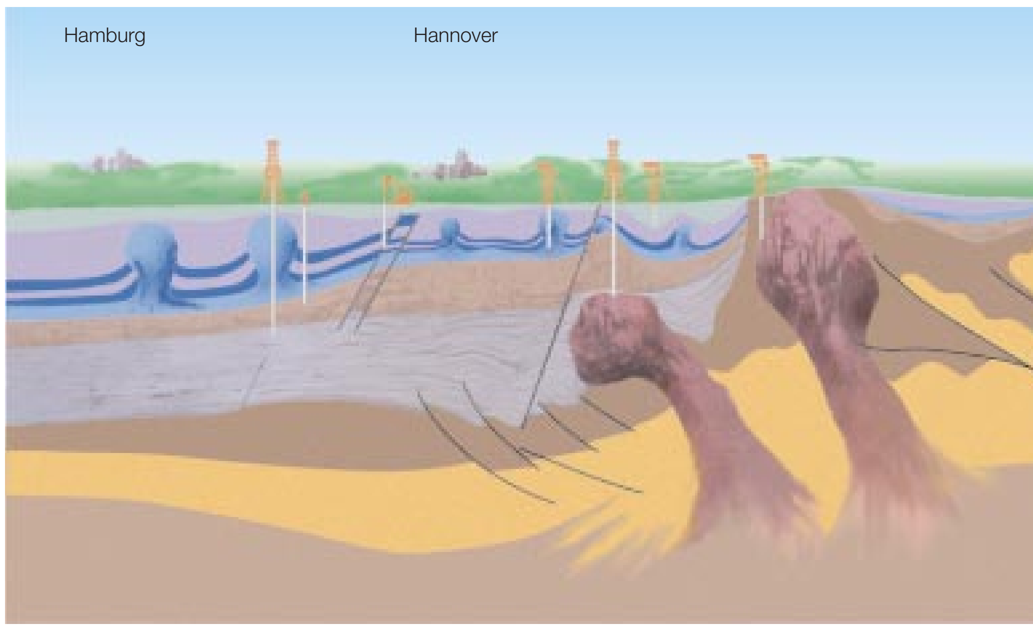

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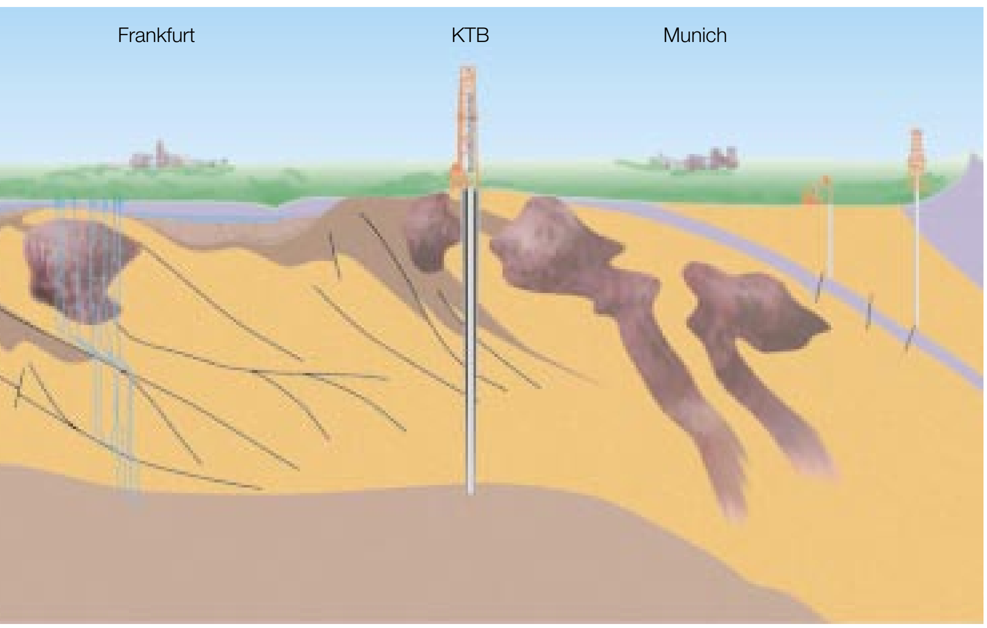
Thermal gradients, heat production, stress fields, fluid transport, deep seismics and deep resistivity are all of great interest to earth scientists. Studying these fundamental topics helps them unravel the mysteries of weather fluctuations, the distribution of mineral resources, and natural disasters such as earthquakes, volcanoes and floods. Rock outcrops, river gorges and cliff faces provide visual evidence to interpret deep probing measurements such as seismics, magnetics and gravimetrics. Commercial mining and drilling have also guided scientists, giving tangible connections to surface observations (*above*). However, drilling has been used specifically for scientific research only within the last thirty years.

The internationally funded Ocean Drilling Program (ODP) was started as part of a worldwide effort to research the hard outer layer of the Earth's crust called the lithosphere.[1] Results from this project have been dramatic, providing real evidence of continental drift and plate tectonics. The lithosphere is made up of six major and several minor rigid moving plates. New oceanic crust is formed and spreads out at mid-ocean ridges and is consumed at active plate margins—subduction zones—where it sinks back into the Earth's mantle. This process takes up to a few hundred million years.

Continents are different. They are made of lighter rock and are not easily recycled,



The lithosphere beneath Germany. Without superdeep boreholes earth scientists rely on surface observations to paint a picture of the structure of the lithosphere.

allowing them to achieve ages of 4 billion years.[2] They also provide the vast majority of the world's resources, so it is vital to understand their structure and development. One way of doing this is to extend the work started by ODP to the continent. KTB—which stands for Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland, or German Continental Deep Drilling Program—is drilling one of a handful of boreholes specifically for continental scientific research. This article looks at the major drilling achievements of KTB, at the Schlumberger wireline logging contribution and at some of the main areas of research.

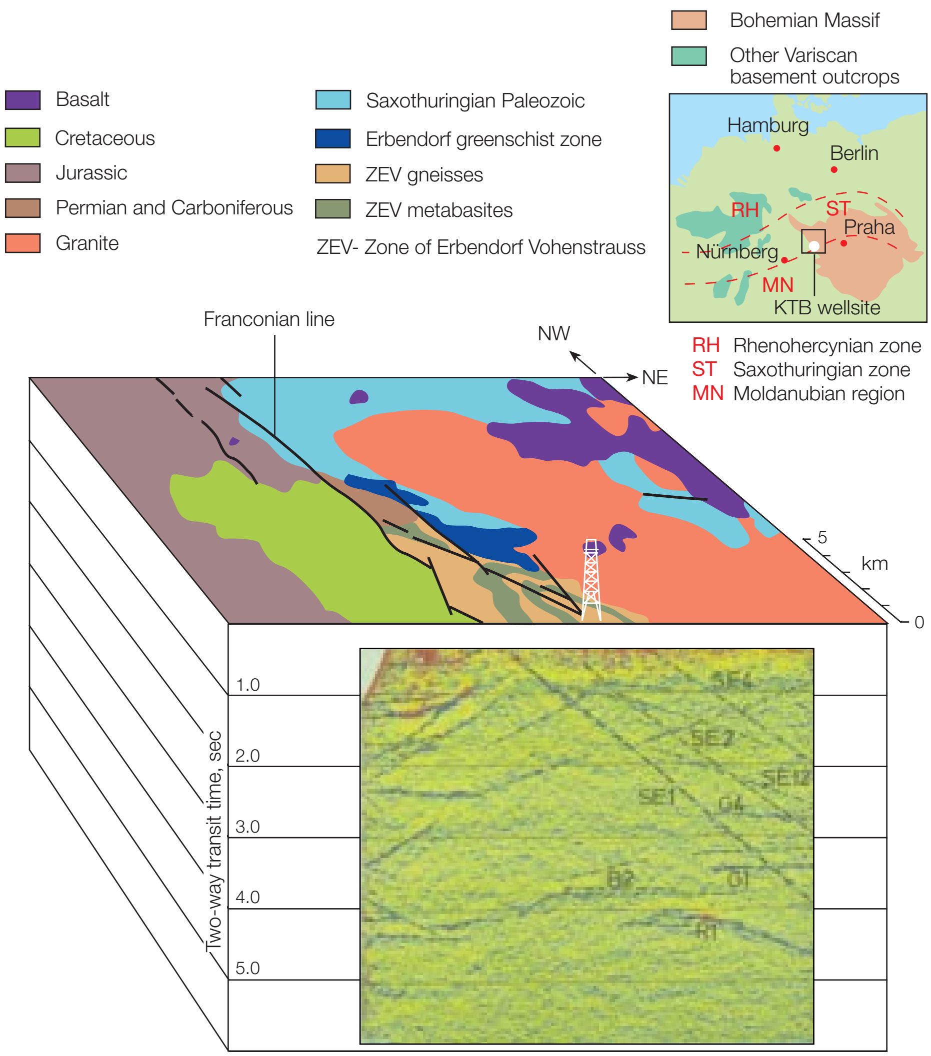
The project was initiated in 1978 by a working group of the German Geoscientific Commission of the German Science Foundation. The group discussed more than 40 possible drillsites in Germany, eliminating all but those with the broadest possible research potential. Two sites were chosen for further studies: Haslach in the Black Forest region of South Germany and Windischeschenbach 80 km [50 miles] east of Nürnberg in Bavaria, southeast Germany. In 1985, the Federal Ministry for Research and Technology gave the final approval for the KTB deep drilling program and both sites were comprehensively surveyed.

Both geology and the expectation of a lower formation temperature gradient favored the Windischeschenbach site. The site is located on the western flank of the Bohemian Massif about 4 km [2.5 miles]

1. Anderson RN, Jarrard R, Pezard P, Williams C and Dove R: "Logging for Science," *The Technical Review* 36, no. 4 (October 1988): 4-11.

   The lithosphere forms the hard outer layer of the earth. The rocks below are hot enough to deform freely and comprise the asthenosphere. The lithosphere slides over the asthenosphere with little resistance. As the rocks of the lithosphere cool, they thermally contract, increasing their density. At some stage the lithosphere becomes denser than the asthenosphere and starts to bend and sink back into the Earth's interior. A subduction zone occurs where the descending lithosphere meets an adjacent overlying lithosphere.

2. Turcotte DL and Schubert G: *Geodynamics: Applications of Continuum Physics to Geologic Problems.* New York, New York, USA: John Wiley & Sons, 1982.



Location of KTB wellsite. The site is located on the western flank of the Bohemian Massif about 4 km east of the Franconian line. The local surface geology is shown along with the three-dimensional (3D) surface seismic time slice beneath the KTB site. This was generated from data recorded after drilling the pilot hole (KTB-VB). Labeled are major seismic reflectors—SE1 corresponds to a major fault zone associated with the Franconian line. This was crossed by the superdeep hole (KTB-HB) at the interval 6850 to 7300 m [22,575 to 23,950 ft]. The inset shows Variscan basement outcrops in Middle Europe, including the Saxothuringian and Moldanubian units, and the position of the KTB site in the southeast corner of Germany close to the Czechoslovakian border.

east of a major fault system—the Franconian line (*left*).[3] Scientists also believe it lies at the boundary of two major tectono-stratigraphic units in Central Europe—the Saxothuringian and Moldanubian.[4] This boundary—which they hoped to cross—is regarded as a suture zone formed by the closure of a former oceanic basin 320 million years ago. This process gave rise to a continent-continent collision—forming a mountain chain and the present-day Eurasian plate. The mountains have long since eroded away, exposing rocks that were once deeply buried. Therefore, this area is ideal for the study of deep-seated crustal processes. In addition, geophysical surface experiments have shown that the area around the drillsite has unusually high electrical conductivity and strong gravimetric and magnetic anomalies, which deserve closer investigation.

The scientific challenges for the KTB project all contribute towards understanding the fundamental processes that occur in continental crust. Among these are earthquake activities and the formation of ore deposits. The primary objectives, therefore, were to gather basic data about the geophysical structure below the KTB site, such as the magnitude and direction of stresses, so that the evolution of the continental crust might be modeled. Information about thermal structure—temperature distribution, heat sources and heat flow—was also needed to understand chemical processes such as the transformation to metamorphic rock and the mineralization of ores. Fluids also play an important role in temperature distribution, heat flow and the various chemical processes, so measurements of pressure, permeability and recovery of fluids found were also important.

The overriding goal of the KTB project was to provide scientists with a permanent, accessible, very deep hole for research. With a budget of 498 million Deutsche Marks [$319 million]—provided by the German government—the initial target was to drill until temperature reached about 300°C [572 °F]—expected at a depth of 10,000 m to 12,000 m [32,800 ft to 39,370 ft]—the estimated limit of borehole technology. This includes drilling hardware, drilling fluid chemistry, cementing as well as the downhole instrumentation required for the various scientific experiments. Many technical spin-offs developed from the project.

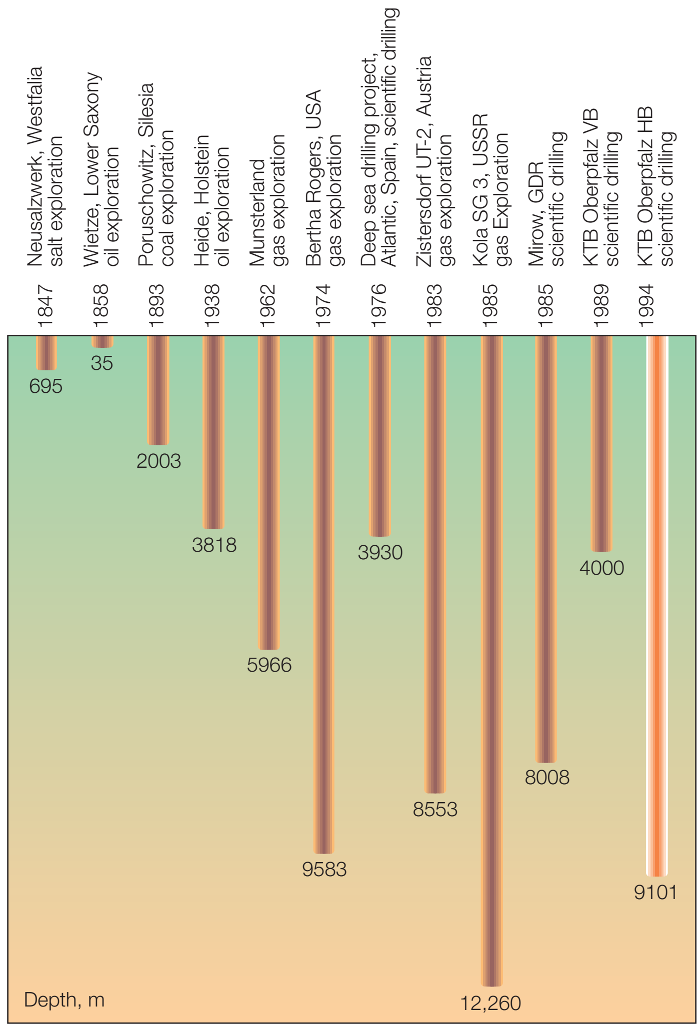
Drilling the Vorbohrung—Pilot Hole

It is not common to drill through surficial crystalline rock especially when the drilling conditions are unknown. Kola SG 3, on the Kola peninsula near Murmansk, Russia, is one exception. It is the world's deepest borehole, but not an ideal role model (*right*). After 15 years of drilling, at an untold cost, the borehole reached a depth of 12,066 m [39,587 ft]. Years later it was deepened to 12,260 m [40,200 ft].

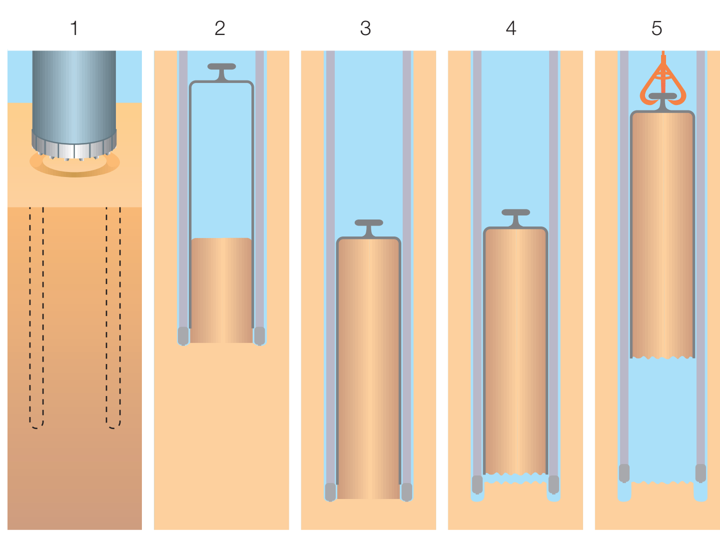
The project management team, having studied the Russian project, decided to first drill a pilot hole—KTB Vorbohrung (KTB-VB).[5] This was spudded on September 22, 1987. The objectives for the pilot hole were as follows:

- Acquire a maximum of geoscientific data, from coring and logging the entire borehole, at low cost and minimum risk before committing to an expensive heavy rig and superdeep hole.
- Minimize core runs and logging in the large-diameter, straight vertical upper section of the superdeep hole.
- Analyze the temperature profile for planning the superdeep hole.
- Obtain data about problem sections with inflow or lost circulation, wellbore instabilities and breakouts.
- Test drilling techniques and logging tools in preparation for the superdeep hole.

To accomplish these objectives, a new drilling technique was developed that combined rotary drilling and sandline core retrieval techniques (*right*). A modified land rig used a high-speed topdrive to rotate internal and external flush-jointed 5½-in. outside diameter mining drillstring in a 6-in. borehole. This drillstring provided enough clearance inside to allow 4-in. cores to be cut and pulled up to surface through the drillpipe by sandline—eliminating round trips to recover cores. A solids-free, highly



Depths of historically important boreholes in Germany and around the world.



Sandline coring technique. Four-in. cores are cut with high-performance, impregnated diamond core bits (1). As the cores are cut, they slide inside the core catcher barrel (2 and 3). When coring is complete, the drillstring is picked up off bottom to break free the core (4). A rig line and latching tool are run through the drillstring and latched onto the core barrel. The barrel is pulled out-of-hole through the internally flush mining drillstring (5). A new core barrel is run back into the drillstring and landed above the core bit to continue coring.

3. Massif is a block of the Earth's crust bounded by faults or flexures and displaced as a unit without internal change.
4. A tectono-stratigraphic unit is a mixture of lithostratigraphic units resulting from tectonic deformation. The Saxothurigian is a low pressure-high temperature unit still showing sedimentary structures. The Moldanubian is a low pressure-high temperature unit with relics of two older phases of higher pressure. The sedimentary structures have almost disappeared.
5. Rischmüller H: "Example for Advanced Drilling Technology," *Oil Gas* 16, no. 4 (1990): 16-20.

Schlumberger Logging Tools			
Tool	**KTB-VB**	**KTB-HB**	**High-Temp.**
Acoustic TeleScanner*	✓		
AIT* Array Induction Imager Tool		✓	
ARI* Azimuthal Resistivity Imager		✓	
Array-Sonic*	✓	✓	
Back Off	✓		
Casing Collar Locator	✓	✓	✓
Cement Bond Log	✓	✓	✓
CERT* Correlated Electromagnetic Retrieval Tool	✓		
CET* Cement Evaluation Tool	✓		
CNL* Compensated Neutron Log Tool	✓	✓	✓
DIL* Dual Induction Resistivity Log tool	✓		
DLL* Dual Laterolog Resistivity tool	✓	✓	✓
DSI* Dipole Shear Sonic Imager	✓	✓	
Eccentralized Dual Axis Caliper		✓	✓
FGT* Formation Gamma-Gamma Tool		✓	✓
FMI* Fullbore Formation MicroImager		✓	
Formation MicroScanner*	✓	✓	
FPIT* Free Point Indicator Tool	✓	✓	
GCT* Guidance Continuous Tool	✓	✓	
Germanium Detector Tool	✓		
GLT* Geochemical Logging Tool	✓	✓	
GPIT* inclinometry tool	✓	✓	
High Resolution Temperature	✓		
HLDT* Hostile Litho-Density Tool		✓	✓
Litho-Density*	✓	✓	
MicroSFL* tool	✓	✓	
Multifinger Caliper Tool	✓	✓	
NGS* Natural Gamma Ray Spectrometry tool	✓	✓	
RFT* Repeat Formation Tester	✓		
SAT* Seismic Acquisition Tool		✓	
Severing Tool		✓	
Sidewall CoreDriller*	✓	✓	
SLT* Sonic Logging Tool		✓	✓
Spontaneous Potential	✓	✓	✓
Stratigraphic High-Resolution Dipmeter	✓		
TDT* Thermal Decay Time	✓		
Variable Density*	✓	✓	✓
KTB Logging Tools			
Auxiliary Measurement Sonde[1]	✓	✓	✓
Borehole Geometry Tool[1]	✓	✓	✓
Colliding Detonation Drill Collar Cutter[2]		✓	✓
Fluid Sampler	✓	✓	✓
Formation MicroScanner*[1]		✓	✓
Gamma Ray[1]	✓	✓	✓
Self Potential		✓	✓
Single Shot	✓	✓	✓
Temperature Tool	✓	✓	✓
6-Arm Caliper	✓		

lubricating mud system had to be used, because of the small clearance between the flush external surface of the drillstring and the borehole wall. This coring method worked well until February 1989 when excessive corrosion in the pipe joints required replacing the mining string with conventional 3½-in. externally upset drillpipe and core barrels.

Coring operations had to be interrupted on other occasions—three times for directional drilling to bring the hole back to vertical and twice for sidetracking, because of lost bottomhole assemblies after unsuccessful fishing. However, a total depth (TD) of 4000 m [13,124 ft] was reached for KTB-VB on April 4, 1989, after 560 days of drilling and logging. More importantly, 3594 m [11,790 ft] of cores were recovered—a recovery rate comparable to those achieved worldwide in easier formations—and the hole was extensively logged with many different instruments (*left and next page*).

The drilling experience in KTB-VB proved invaluable to the planners of the superdeep borehole. For example, they encountered areas of borehole instability across fault zones; they had to modify the mud system to account for water influx and water-sensitive rock; they had numerous breakouts caused by the relaxation of stressed rock; and the formation dipped more steeply than predicted making it difficult to keep the hole anywhere near vertical. In total, the pilot hole presented a greater challenge for drillers than expected.

For the next year, many experiments and measurements—such as hydrofracs, production tests and extensive seismic work—were carried out in and around KTB-VB. In April 1990, the hole was finally cased and cemented. Meanwhile, plans continued for construction of a new rig to drill the superdeep borehole about 200 m [656 ft] away.

□ ***Logging tools used by KTB. The logging tools listed in the tables were run in the pilot hole (KTB-VB) and the superdeep hole (KTB-HB) and were provided by various logging companies, universities and institutes. KTB bought several tools, some of which were developed for the project.***

* Mark of Schlumberger
1 Bought from or developed by Schlumberger for KTB
2 Developed by SwETech (Bofors) for KTB

Other Companies' Logging Tools				
Company	**Tool**	**KTB-VB**	**KTB-HB**	**High Temp.**
EDCON	Borehole Gravity Meter	✓	✓	
Prakla-Seismos[3]	Geophone Survey	✓		
	Moving Source Profile	✓		
	Vertical Seismic Profile	✓	✓	
Leutert	Fluid Sampler		✓	
	High Temperature Fluid Sampler		✓	
PREUSSAG	Fluid Sampler	✓	✓	
	Gyroscope	✓	✓	
	Steering Tool	✓	✓	
Scientific Directional Drilling Company	Gyroscope		✓	
	Multi Shot		✓	
Western Atlas	Multiparameter Spectroscopy Instrument - Carbon/Oxygen Tool	✓		
	Pulsed Neutron Decay Time	✓		
	Segmented Bond Tool		✓	
	Z-Density Tool	✓		

3 Now part of Schlumberger Geco-Prakla

University and Institute Logging Tools				
University or Institute	**Tool**	**KTB-VB**	**KTB-HB**	**High-Temp.**
Berlin University, Berlin, Germany	Heat Conductivity Logging Sonde	✓		
Braunschweig University, Braunschweig, Germany	Fluxgate Magnetometer	✓	✓	
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany	3D Magnetometer		✓	
Deutsche Montan Technologie (DMT), Bochum, Germany	Borehole Televiewer	✓	✓	
Eötvös Lorant Geophysical Institute, Budapest, Hungary	Induced Polarization	✓	✓	
Frankfurt University, Frankfurt, Germany	Dipole-Dipole	✓	✓	
	Redox Potential	✓	✓	✓
Geostock, Malmaison, France	Geophone	✓		
Göttingen University, Göttingen, Germany	Gradient Magnetometer	✓		
Lawrence Livermore National Laboratory, Livermore, California, USA	Geophone	✓		
Los Alamos National Laboratory, Los Alamos, New Mexico, USA	Fluid Sampler	✓		
Munich University, Munich, Germany	Magnetic Susceptibility	✓	✓	
Niedersächsisches Landesamt für Bodenforschung (NLfB), Hannover, Germany	Induced Polarization	✓	✓	
Petrodata, Zürich, Switzerland	Variable Amplitude Logging	✓		
Scientific Academy, Swerdlowsk, Russia	Magnetometer	✓		

□*UTB 1. This is the largest land rig in the world, capable of drilling to 12,000 m [39,500 ft] and of handling extra-length drillpipe racked in stands of 40 m [130 ft]. The rig has many advanced features, meets high environmental standards, including full electric drive, a large degree of automation and soundproofing.*

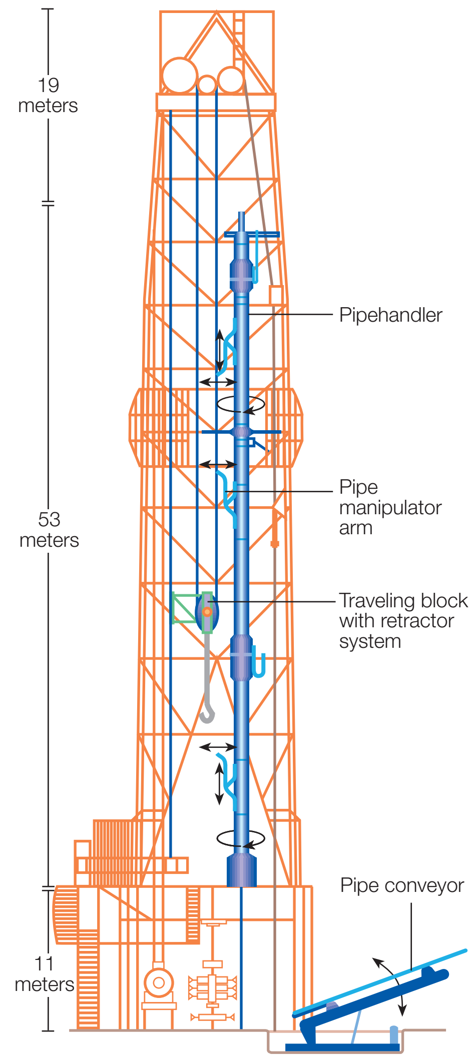
Drilling the Hauptbohrung

The superdeep hole—KTB Hauptbohrung (KTB-HB)—was spudded on October 6, 1990, and reached a TD of 9101 m [29,859 ft] on October 21, 1994. To drill to this depth in only four years required the design and construction of the largest land rig in the world—UTB 1 (*left*).[6] This rig could handle 12,000 m of drillpipe that required a maximum hook load of 8000 kN [1,800,000 lbf]—more than three times that of the rig used to drill KTB-VB. Mechanical wear and tear was expected to correspond to drilling 30 deep conventional wells, with over 600 round trips. Reducing trip time called for radical rig design. Using 40-m [130-ft] stands of drillpipe instead of the standard 27-m [90-ft] stands saved 30% of the time. However, long drillpipe stands meant the rig had to be 83 m [272 ft] high.

To further increase trip efficiency, an automated pipe handling system was installed (*right*). This consisted of a 53-m [174-ft] high pipehandler that grasped and lifted stands of drillpipe between the rotary table and star-shaped fingerboard for stacking in the derrick. Pipe connections were made by an iron roughneck that replaced traditional pipe-spinners and make-up tongs. Automatic slips gripped the pipe in the rotary table as connections were made and hydraulically operated elevator clamps did the derrick man's job. More time was saved as pipes were connected or disconnected by retracting the traveling block out of the way as it traveled up or down the derrick. This allowed the pipehandler to operate while the traveling block was moving.

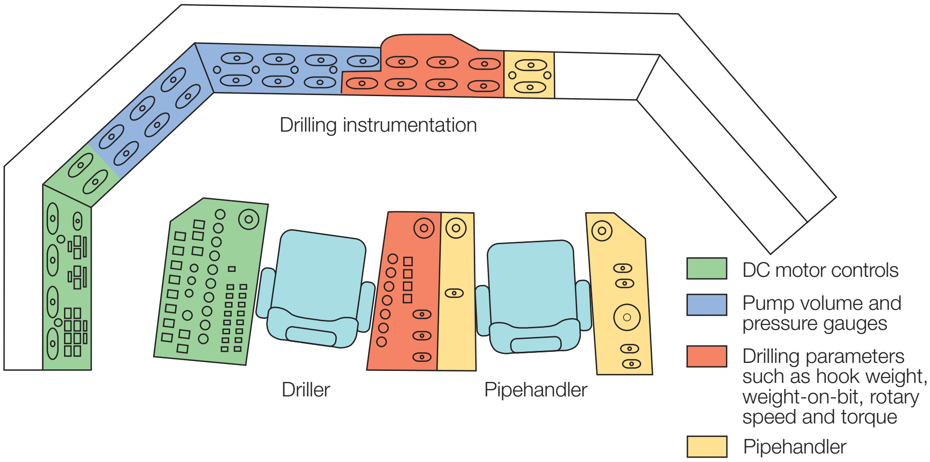
The entire operation was controlled by a driller, pipehandler operator and two floormen. Only the floormen worked outside on the rig floor—the other two sat inside a control room at consoles equipped with video screens and gauges (*next page, top*). Computers controlled many of the operations of the pipehandler. Using a pipe conveyor to lift single pipes between rig floor and pipe racks saved additional time.

Borehole torque and drag as well as the strength of the drillpipe are decisive factors when it comes to reaching great depths quickly and safely. Torque while drilling and excessive hook loads when pulling the string are caused by lateral forces and friction between drillstring and borehole wall. These two factors are increased by the weight of drillstring, borehole inclination and severity of any doglegs. Borehole trajectory influences not only drillstring design, but also any proposed casing scheme. A slim-clearance casing scheme cuts down on rock volume drilled, but also requires a near vertical borehole to minimize friction.[7] Without active steering the borehole would start to build angle as was proved in KTB-VB. So KTB commissioned Eastman Christensen—now Baker Hughes Inteq—to develop a self-steering vertical drilling system (VDS) (*next page, bottom*).[8]

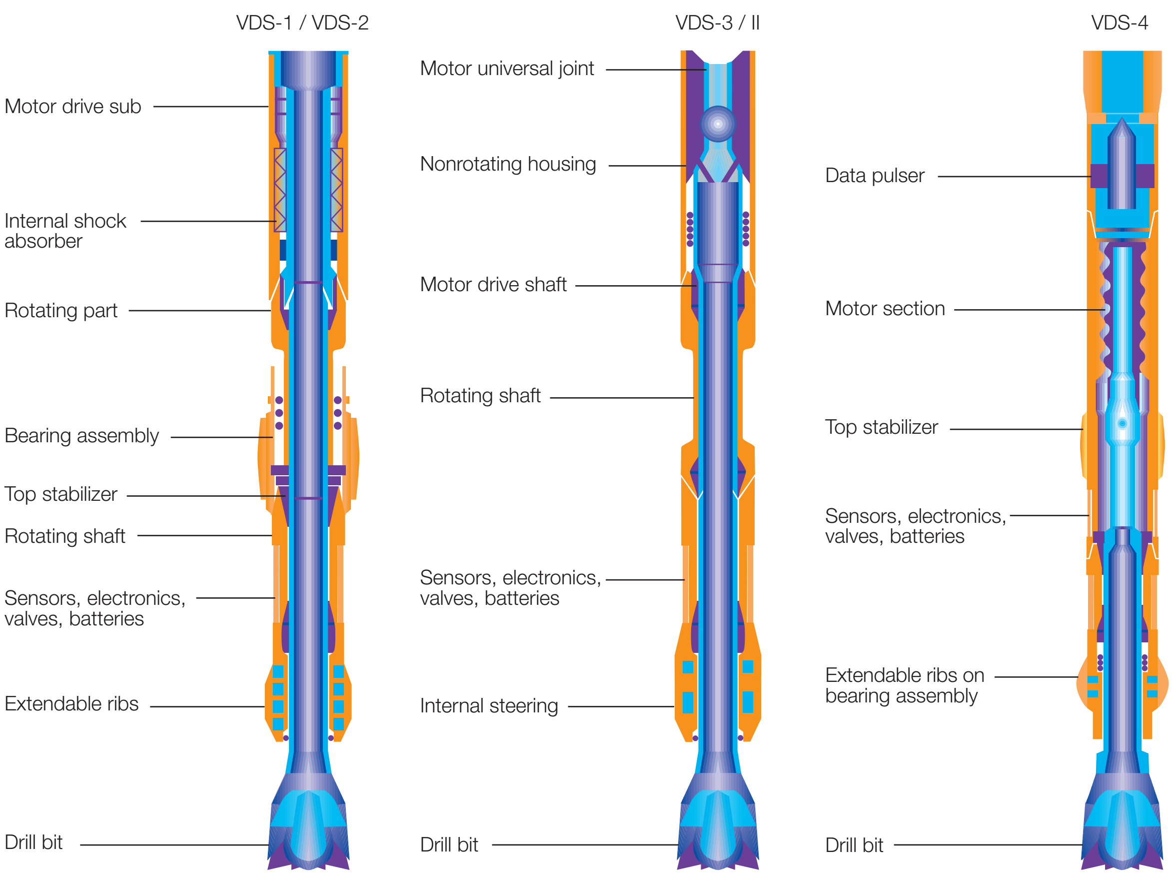


□*Pipehandling. Fast round-trip operation was one of the main specifications for UTB 1. Three mechanical aids helped. First, the 53-m [174-ft] high pipehandler takes stands of drillpipe and stacks them in the derrick. Second, to allow continuous pipehandler operation during round trips, the traveling block is retracted out of the way as it moved up or down the derrick. Third, a pipe conveyor picks up and lays down single joints of drillpipe between rig floor and pipe racks.*

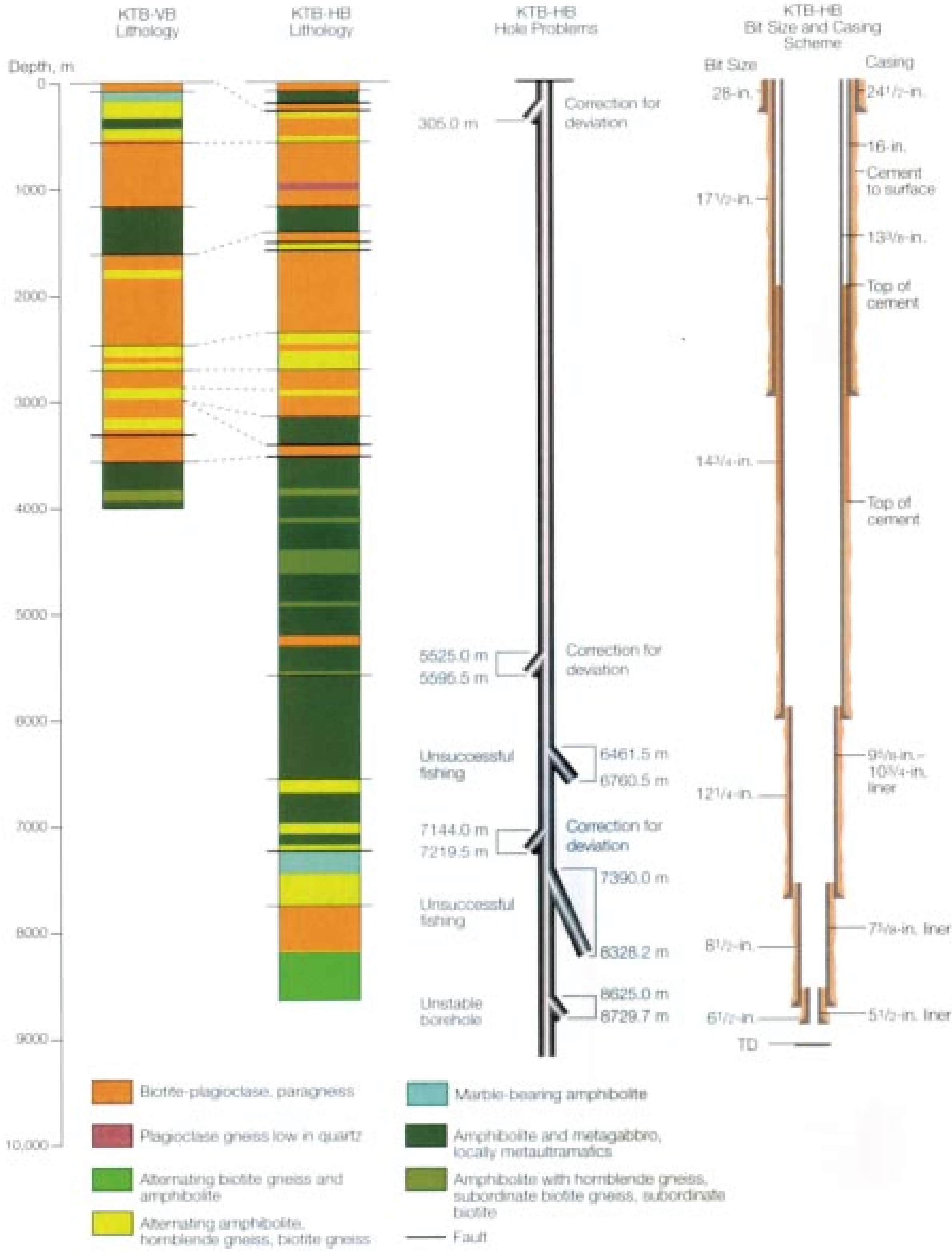
6. Wohlgemuth L and Chur C: "The KTB Drilling Rig," *Oil Gas* 16, no. 4 (1990): 42-46.
7. Sperber A: "The Casing Concept for the Main Well," *Oil Gas* 16, no. 4 (1990): 21-23.
8. Chur C, Engeser B and Oppelt J: " Vertical Drilling Concept for the Main Well," *Oil Gas* 16, no. 4 (1990): 26-29.



Armchair drilling. The driller, surrounded by instruments and video monitors, controls drilling operations from the comfort of a control room overlooking the rig floor. The driller is joined by the pipehandler operator when pipe is tripped in or out of the borehole.



Vertical Drilling Systems (VDS). The VDS systems consist of positive-displacement motors to drive the drill bits, battery-powered inclinometers to measure deviation, and hydraulic systems to steer the drill bit. Any drift away from vertical is measured by the inclinometer and fed back to the hydraulic system. Two steering systems were developed. The first holds extendable ribs against the formation using mud pressure *(left)*. ***Deviation corrections are made by releasing pressure in one rib, causing the whole assembly to move towards that rib. The second system is steered internally*** *(center)*. ***Pistons move the gimbal-mounted rotating shaft, which is connected to the bit, to make any deviation adjustments. Another variation, VDS-4, reverted back to extendable ribs*** *(right)*. *(Courtesy Baker Hughes Inteq.)*



Lithology comparison between KTB-VB and KTB-HB and an overview of drilling and casing KTB-HB. The differences in lithology between the two boreholes—which are only 200 m apart—highlight the complex structure being drilled *(left)*. ***Drilling difficulties required cement plugs to be set to correct for deviation and for sidetracks to be drilled after unsuccessful fishing operations*** *(middle)*. ***Extra casing strings had to be run to protect crumbling borehole*** *(right)*.

The VDS system consisted of a positive-displacement motor to drive the drill bit, a battery-powered inclinometer to measure deviation and a hydraulic system to adjust the angle of the drill bit to correct for deviation. Two hydraulic systems were used: the first system operated external stabilizer ribs that pushed against the borehole wall moving the whole VDS assembly back to the vertical; the second system used internal rams to move the shaft driving the drill bit back to vertical. As long as battery power was maintained to the inclinometer, both systems operated automatically. Inclination, and other parameters such as temperature, voltage and systems pressure, were transmitted to surface by a mud pulser to monitor progress.

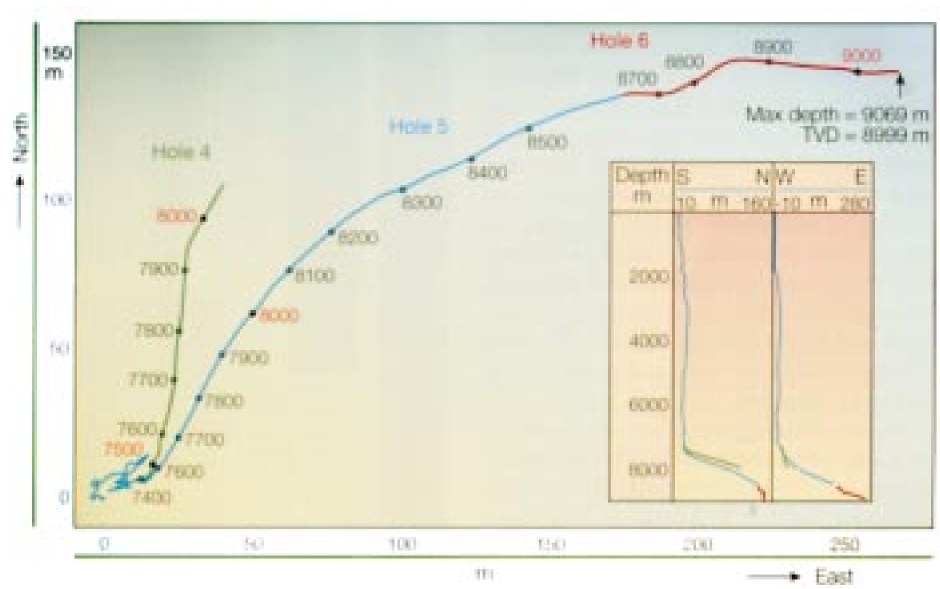
The first 292 m [958 ft] of KTB-HB were drilled with a $17\frac{1}{2}$-in. bit and opened up to 28 in. before setting the $24\frac{1}{2}$-in. casing (*previous page*). To meet the requirements of a vertical hole, a 2.5° correction to deviation was made as the hole was widened. The next section was drilled with a $17\frac{1}{2}$-in. VDS system to 3000 m [9840 ft] and completed at the end of May 1991. Teething problems with prototype VDS systems meant using packed-hole assemblies (PHAs) during maintenance and repair. Even so, average deviation for this section was less than 0.5°.

The same strategy was used for the $14\frac{3}{4}$-in. hole—alternating between the improving VDS systems and PHAs. A high deviation buildup from 5519 to 5596 m [18,107 to 18,360 ft] during one PHA run led to the borehole being pulled back and a correction made for deviation. The hole continued on course to 6013 m [19,728 ft] where $13\frac{3}{8}$-in. casing was set in April 1992—horizontal displacement at this stage was less than 10 m [33 ft].

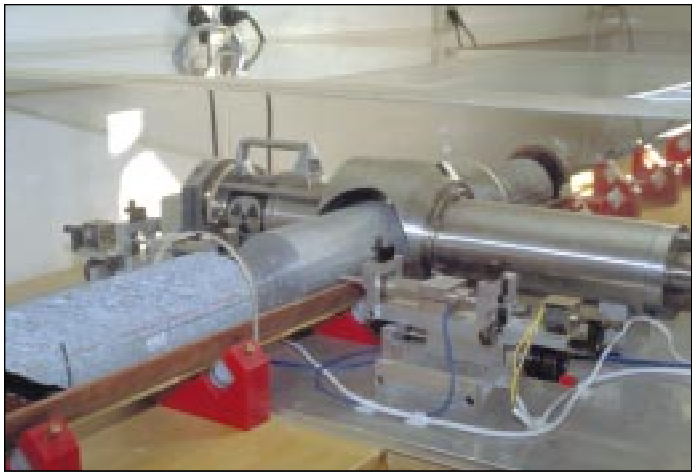
Drilling continued with VDS systems and PHAs and $12\frac{1}{4}$-in. bits. Within this section 45.7 m [150 ft] were cored, including 20.7 m [68 ft] with a newly developed, large-diameter coring system that gave $9\frac{1}{4}$-in. diameter cores. However, in July 1992 at 6760 m [22,179 ft], the bit became stuck. Eventually, after an unsuccessful fishing operation, the hole had to be plugged back to 6461 m [21,198 ft] and sidetracked. In March 1993, over an interval of 6850 to 7300 m [22,474 to 23,950 ft], a major fault system was crossed. The VDS system could not control deviation over this interval and another correction had to be made. This system was thought to be an extension of the main fault that lies along the boundary between sediments to the west and metamorphic rocks to the east—the Franconian line. Along this fault system a displacement of more than 3000 m occurred, showing a repetition of drilled rock sequences. This signaled the start of the most difficult drilling yet and additional funds had to be provided by the German government to complete the project—bringing the total cost to DM 528 million [$338 million].

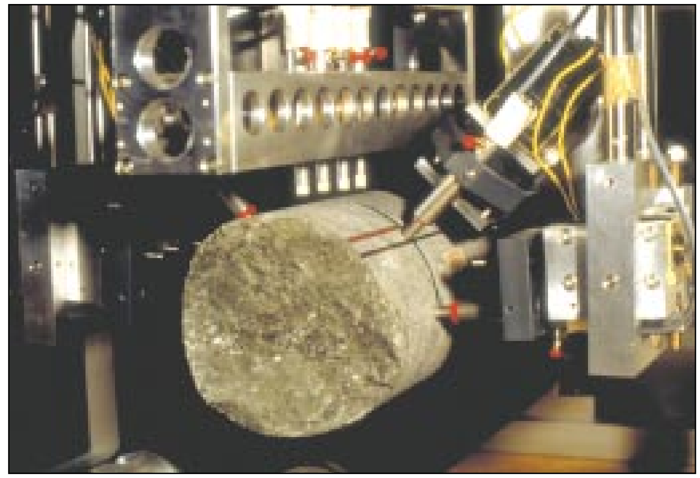
At 7490 m [24,573 ft], when the horizontal displacement was only 12 m [39 ft], the VDS system was abandoned, as borehole temperatures became too high for the electronics. The hole then started to deviate north (*below*). Within the main fault system the borehole became unstable and more breakouts occurred. While tripping out-of-hole from 8328 m [27,323 ft], the drillpipe became stuck at 7523 m [24,682 ft]. Jarring eventually broke the downhole motor housing allowing the pipe to be pulled out but leaving behind a complicated fish. Several attempts to retrieve the fish failed and the hole was finally plugged back to the vertical section—at 7390 m [24,245 ft]—and sidetracked. Drilling again proved difficult and so a $9\frac{5}{8}$-in. liner was set at 7785 m [25,541 ft] in December 1993 to protect this hard-won section of hole.

Difficult drilling continued with a $8\frac{1}{2}$-in. bit down to 8730 m [28,642 ft]. Borehole instability prevented further progress and a $7\frac{5}{8}$-in. liner was set in May 1994. To bypass the unstable section, a sidetrack was made at 8625 m [28,297 ft] through a precut window in the liner. Funds to continue drilling were now running low and a decision was made to stop 476 m [1561 ft] later on October 12, 1994. More than four years after spudding, the hole had reached 9101 m with a final bit size of $6\frac{1}{2}$ in. However, the borehole had not finished with the drillers yet. Attempts to lower logging tools into the open hole failed. The last section had to be re-drilled and a $5\frac{1}{2}$-in. liner set, leaving only 70 m [230 ft] of open hole for the wireline loggers and other scientific experiments.



Superdeep borehole projection. The main graph shows the horizontal projection of the final three openhole sections drilled to complete KTB-HB—inset are the vertical projections. Down to 7490 m [24,573 ft], the horizontal projection wanders around the origin, indicating that the hole is nearly vertical. At this depth, the borehole temperature became too high to continue with the VDS drilling system and deviation built up rapidly. The hole followed a course labeled Hole 4 until drilling difficulties caused it to be abandoned. A new hole was started in the vertical section—Hole 5. After the casing was set, the last openhole section was drilled—Hole 6. The final directional survey, conducted at 9069 m [29,754 ft], showed a horizontal displacement of only 300 m [1000 ft].





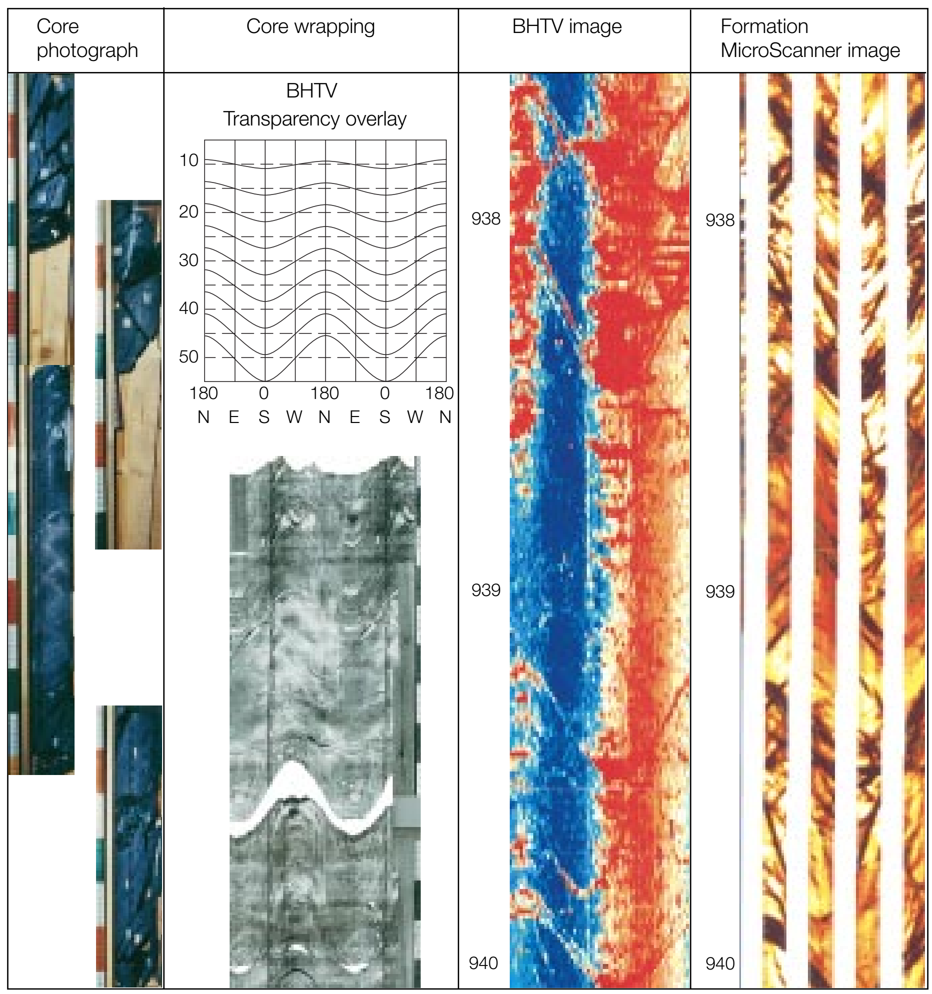
***Field laboratory core measurements—detailed density profile** (left) **and electrical conductivity measurements** (right).*

Data Collection and Analysis

The main center of scientific activity at KTB was the field laboratory with a staff of 40 including resident scientists and technicians (*see "KTB Logging Center," page 16*). Here, experiments were performed on cores—mainly from the KTB-VB—drill cuttings and gas traces from the shale shakers, sidewall cores from the Schlumberger Sidewall CoreDriller tool, rock fragments from the drillpipe-conveyed cutting sampler and fluid samples collected during pump tests and downhole. The field laboratory provided cataloging and storage facilities and a data base of basic information such as petrophysical properties, mineralogy and lithology needed for further experiments (*above*).[9] More detailed long-term experiments were conducted at universities and research centers in 12 countries.

Nearly 400 logging runs were made in KTB-VB—the pilot hole—with every available borehole instrument (*page 8*). And 266 runs were made in KTB-HB—the superdeep hole.[10] The wealth of data acquired in the field lab allowed a rare opportunity to calibrate borehole log responses to core data in crystalline rocks—as opposed to sedimentary environments where their response is well known—satisfying one of the main objectives of KTB-VB.

The formations that were cored and drilled consisted of metamorphic basement rocks—principally gneisses and amphibolites.[11] Initially cores and rock fragments—from cuttings—were photographed and cataloged according to depth recovered. Microscopic analysis of thin sections assisted recognition of mineralogy and microstruc-



Post-orientation of cores. The cores are released from the core barrels on the catwalk, reassembled in storage boxes and marked by a black solid line and a red dashed line to show which end is top. They are then photographed in the field laboratory** (far left). **A photocopy is then taken by rolling the cores over the copier** (left). **This photocopy may then be compared to borehole images recorded by the Borehole Televiewer (BHTV)** (right) **or the Formation MicroScanner tool** (far right) **and the orientation of the black line, drawn on the core, calculated.

ture and assignment of rock type.[12] By mapping the macroscopic structure and orienting it with borehole logs such as the FMI Fullbore Formation MicroImager image or Borehole Televiewer (BHTV) image, a structural picture of the borehole was gradually built up (*previous page, bottom*).

Petrophysical parameters, such as thermal conductivity, density, electrical conductivity, acoustic impedance, natural radioactivity, natural remanent magnetism and magnetic susceptibility were also routinely measured. In addition to determining the strength of rock samples, scientists made highly sensitive measurements of expansion of the cores as they relaxed to atmospheric pressure.

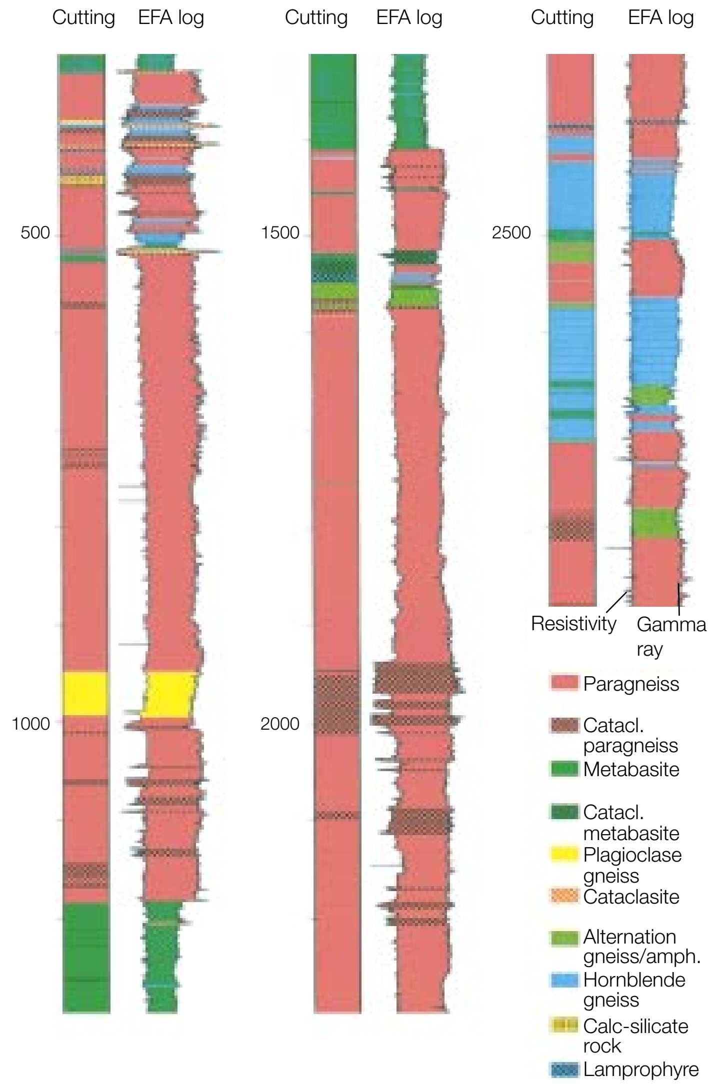
Geochemists at the field laboratory performed detailed core analysis using X-ray fluorescence for rock chemical composition and X-ray diffraction for mineralogy.[13] This analysis allowed a reliable reconstruction of the lithology.

After comparing logs with cores, scientists at the Geophysical Institute at the University of Aachen were able to distinguish 32 distinct electrofacies corresponding to 32 minerals. This enabled borehole logs to contribute to and refine the lithological profile of the superdeep borehole, established from cutting samples and the limited cores available (*right*).

One contributor to the success of the logging operation was the GLT Geochemical Logging Tool. This provided concentrations of 10 elements present in rock: silicon, calcium, iron, titanium, gadolinium, sulfur, aluminum, potassium, uranium and thorium. Another tool with a semiconductor detector—germanium—was also used, which gave a higher sensitivity and provided the additional elemental concentrations of sodium, magnesium, manganese, chromium and vanadium.[14] By combining the GLT results with other measurements, minerals such as pyrite, pyrrhotite, magnetite and hematite could be quantified.

Older logging techniques also proved invaluable. Abnormal Spontaneous Potential (SP) deflections occurred across mineralized fault systems. Other SP deflections combined with low mud resistivity readings from the Auxiliary Measurement Sonde (AMS) occurred at zones of water influx. When the AMS resistivity showed only mud and the SP showed a deflection, this was regarded as an indicator for mineralization. Uranium tends to concentrate at graphite accumulations so the uranium reading from the NGS Natural Gamma Ray Spectrometry tool was used as a graphite indicator.

(continued on page 19)



Comparison of Electro-Facies Analysis (EFA) log and lithology from cuttings. The EFA log was developed by scientists at the University of Aachen by comparing core data with logs from KTB-VB. They were able to distinguish 32 electrofacies corresponding to 32 rock types. The EFA log—produced from logs from KTB-HB—compares well with the lithology profile from cuttings.

9. Emmermann R, Lauterjung J and Umsonst T: *KTB Report 93-2: Contributions to the 6th Annual KTB-Colloquium. Geoscientific Results.* Stuttgart, Germany: Schweitzerbart, 1993.
10. Bram K and Draxler JK: *KTB Report 93-1: Basic Research and Borehole Geophysics (Report 14).* Stuttgart, Germany: Schweitzerbart, 1993.
11. Gneisses are banded rocks formed during high-grade regional metamorphism. Included in this group are a number of rock types having different origins. Gneissose banding consists of the more-or-less regular alteration of schistose and granulose bands. The schistose layers consist of micas and/or amphiboles. The granulose bands are essentially quartzofeldspathic and may vary from 1 mm up to several centimeters in thickness. There are various types of gneiss depending on the rock origin. Paragneiss is from a sedimentary parent and orthogneiss from an igneous parent. Amphibolite is a metamorphic rock composed mainly of feldspars and amphibole, a group of inosilicates.
12. For more detail: Emmermann et al, reference 9: 67-87.
13. Emmermann et al, reference 9: 529-534.
14. Grau JA, Schweitzer JS, Draxler JK, Gatto H and Lauterjung J: “Elemental Logging in the KTB Pilot Hole—I. NaI-based Spectrometry,” *Nuclear Geophysics* 7, no. 2 (1993): 173-187.

    Schweitzer JS, Peterson CA and Draxler JK: “Elemental Logging with a Germanium Spectrometer in the Continental Deep Drilling Project,” *IEEE Transactions on Nuclear Science* 40, no. 4 (August 1993): 920-923.

KTB Logging Center

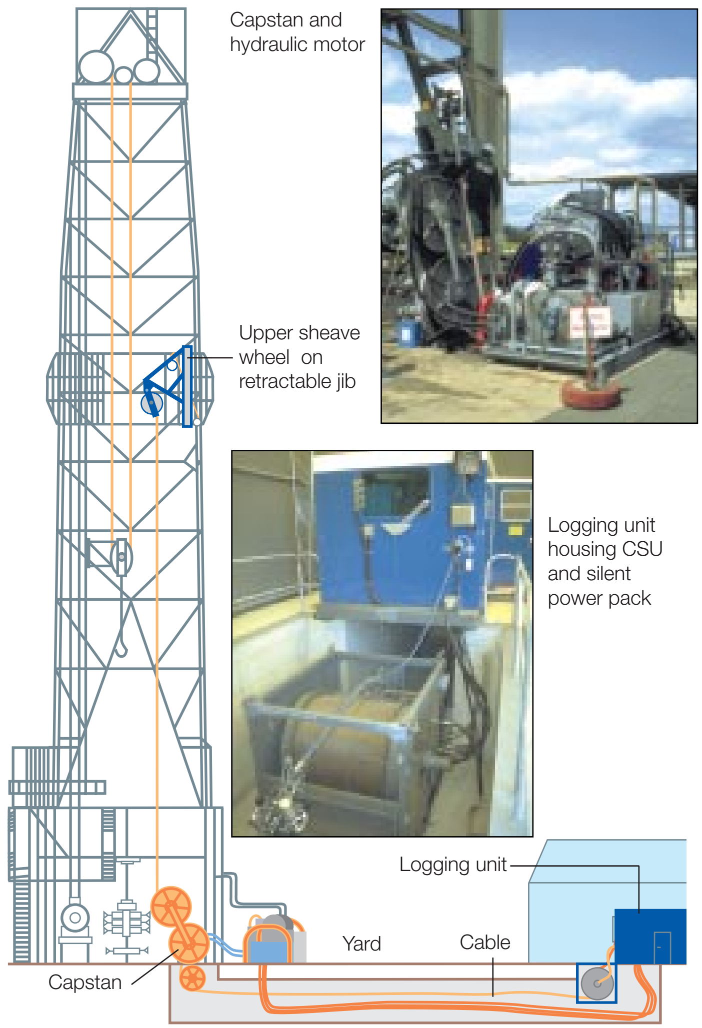
□KTB logging center and Schlumberger crew. The logging center *(top left)* comprises an enclosed area—housing the logging unit—numerous offices for KTB, guests and Schlumberger personnel, a computer room and various workshops, including a well-equipped electronics laboratory *(bottom left)* and sonde laboratory *(bottom right)*. Schlumberger Engineer Miel Kühr, Operator Karl Bohn and Electronics Engineer Ignaz de Grefte were assigned to KTB operations for the entire seven-year project *(top right)*.

The KTB logging center is every wireline engineer's dream come true. Situated 60 m [200 ft] from the rig, the logging unit is housed in a covered enclosure, providing space for calibration and operation checks of logging tools (above)**. Portable units off the enclosure provide maintenance workshops for electronics and hydraulic sondes. Several offices are provided for the KTB logging staff and Schlumberger personnel as well as a computer room equipped with a micro-VAX III for interpretation and presentation of results. The offices also provide workplaces for scientists from universities who run their own logging tools into the borehole using the logging unit.**

The winch unit houses the CSU wellsite surface instrumentation computer and a silent power pack, which provides hydraulic power for the winch and electrical power for the instruments (next page)**. The winch is extensively modified to cope with the high cable tensions encountered during logging. A high-strength drum holds around 9500 m [31,200 ft] of cable, and a capstan at the foot of the rig reduces cable tension from a maximum of 90,000 N [20,000 lbf] to a normal spooling tension of 4500 N [1000 lbf]. Other modifications allow additional tensiometers and depth measuring systems to monitor the cable at different points of the rig-up.**

The logging cable is permanently suspended in the derrick to save as much rig-up time as possible. The winch is housed in a cellar in front of the logging unit allowing logging cable and ancillary wiring to run through a tunnel below the rig yard exiting at the capstan unit. The cable passes around the capstan before going up the outside of the rig. Here it passes over the upper sheave wheel attached to a retractable jib. When logging is required, the jib is extended out over the rig floor so that logging tools may be connected to the cable and lowered into the borehole. Built into the rig floor is a series of tool magazines. These contain logging tools in a state of readiness to run into the borehole.

Logging at depths of 9100 m [30,000 ft] and temperatures approaching 260 °C requires special hardware—cable, logging head and logging tools—to withstand ultrahigh temperatures and pressures. The cable also has to have the



□Permanent logging rig-up. The logging cable is rigged up permanently to allow logging at short notice and save rig time. The cable drum is in a cellar below ground level, so that the logging cable and ancillary cables can pass through a tunnel to the rig. At the side of the rig, the cable passes around a capstan—to reduce cable tension—and then up the outside of the derrick to a retractable jib holding the upper sheave wheel. Logging tools are pulled up to the rig floor during other rig operations and lowered into tool magazines. When the rig is ready for logging, the jib is lowered, aligning the logging cable with the borehole. Then logging tools are connected to the cable and winched out of the magazines before entering the borehole.

strength to pull the logging tools back to surface. At 9100 m, the normal logging tension is 67,000 N [15,000 lbf], right on the maximum safe pull for the special high-strength cable used. This cable has high-tensile steel armor wires and is thicker than standard to provide the strength. It has special insulating materials at the business end that allow logging at temperatures up to 260 °C for short periods of time.

If the borehole had gone any deeper, a two-cable approach to logging would have been used. At 10,000 m, the high-strength logging cable would be in danger of breaking under its own weight—even accounting for the buoyancy effect of the mud. To reduce cable weight, a smaller diameter, lighter, high-temperature cable hooked up to a second winch would have been used to lower logging tools into the borehole for the first 3200 m [10,500 ft]. At this depth, the small-diameter cable would be connected to the high-strength cable of the main winch and the journey into the hole continued. With this tapered cable configuration, the overall weight of cable is decreased, reducing the tension, and the high-strength cable is at the top of the hole where the tension is greatest. This technique was used twice, but only with 1500 m [4921 ft] of small-diameter cable. This approach was taken by Russian well loggers to log the 12-km [7.4-mile] Kola borehole using a three-conductor cable.

A special oil-filled logging head was developed by Schlumberger for the KTB project. This had high-temperature feed-throughs and special O-rings, and provided the connection between cable and logging tool.

Although there are several standard high-temperature logging tools available, tools were upgraded especially for KTB. One example is the high-temperature Formation MicroScanner tool, which was upgraded to 260 °C (next page, left). The first task in modifying this tool was to produce a list of components to upgrade. Several components, such as the pads containing the button electrodes, were not changed, but could be used only once. Other components, such as the hydraulic motor that opens and closes the sonde calipers, could still be used more than once. Mechanical maintenance of such high-temperature tools has to be meticulous—using even one component that should have been changed could result not only in a malfunction but also in destruction of expensive equipment.

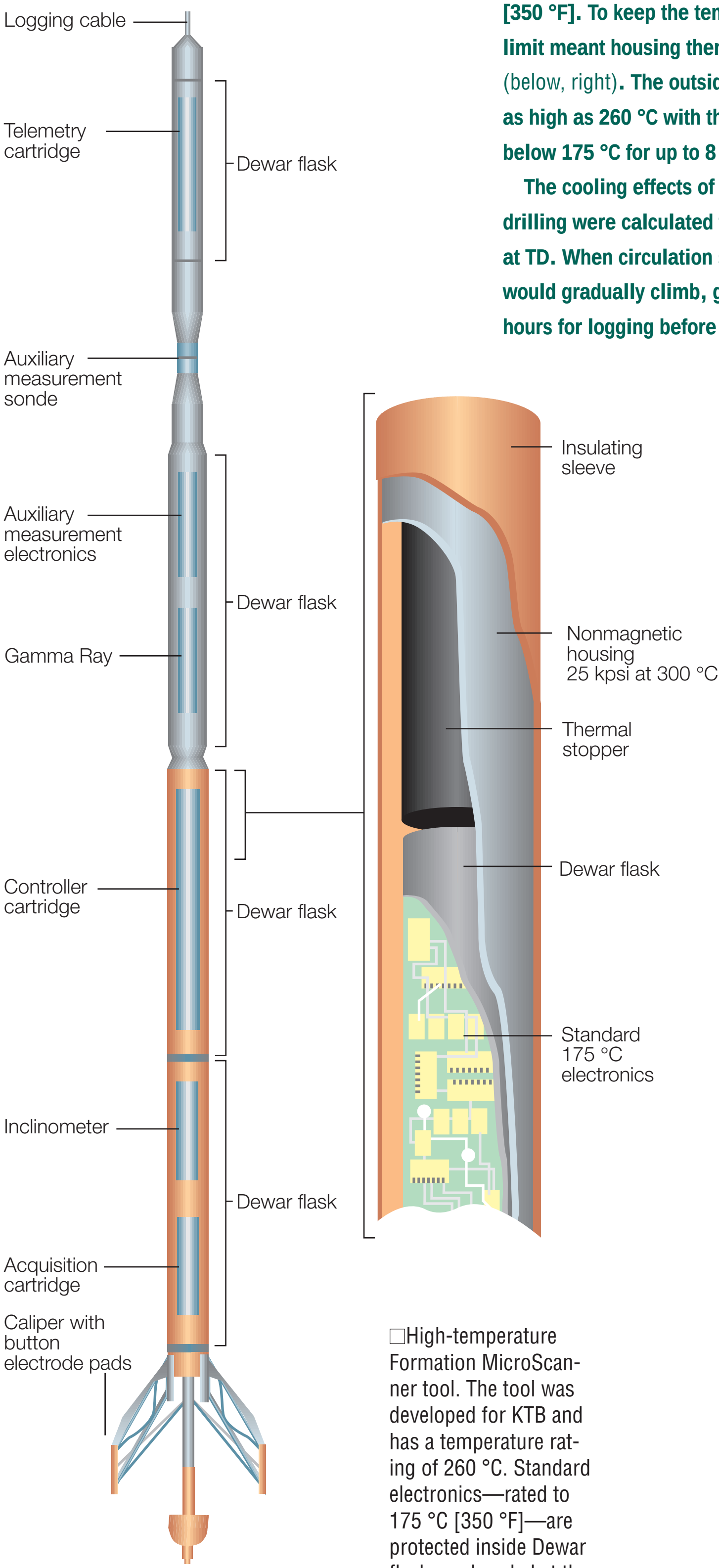
Temperature limits on the mechanical aspects of the tool were relatively straightforward to overcome. However, the electronics were of major concern. Normally these operate up to 175 °C

[350 °F]. To keep the temperature within this limit meant housing them inside a Dewar flask (below, right). The outside temperature could be as high as 260 °C with the inside remaining below 175 °C for up to 8 hours.

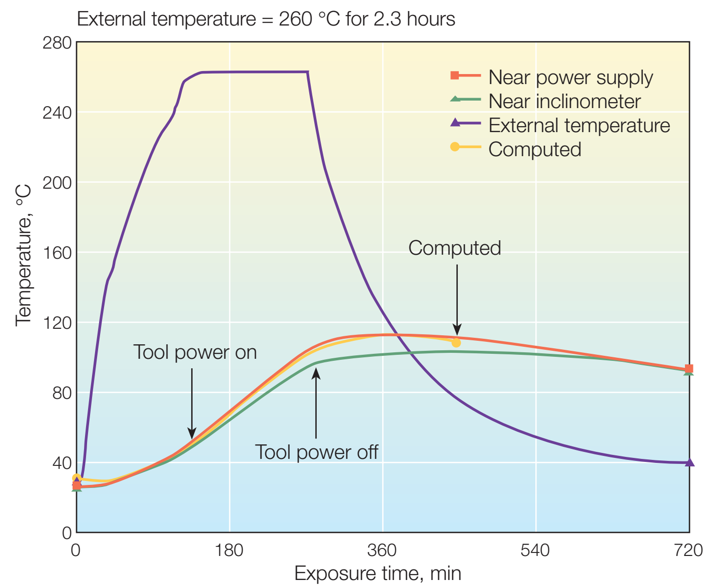
The cooling effects of mud circulation during drilling were calculated to be about 50 °C [90 °F] at TD. When circulation stopped, the temperature would gradually climb, giving a window of 36 hours for logging before it exceeded tool ratings.

On the first logging run at TD, the maximum temperature recorded was 240 °C [464 °F] and on the last run, this reached 250.5 °C [483 °F]—confirming earlier calculations. At the end of each logging run the Dewar flasks were cooled down slowly by blowing air through to avoid thermal shock.

Apart from Schlumberger logging tools, several universities developed equipment for their own experiments in the borehole (see page 9).



□High-temperature Formation MicroScanner tool. The tool was developed for KTB and has a temperature rating of 260 °C. Standard electronics—rated to 175 °C [350 °F]—are protected inside Dewar flasks and sealed at the ends by thermal stoppers. Standard mechanical components may withstand this temperature, but the button electrode pads are changed after each logging run.

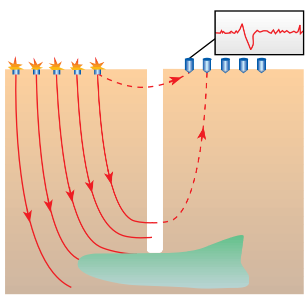


□Temperature profile inside Dewar flask. Logging tools are heat-tested in ovens. With the oven temperature maintained at 260 °C for 2.3 hours, the temperature remained below 120 °C [248 °F] inside the Dewar flask.

Surprises—Some Welcome, Some Not

Both boreholes yielded unexpected results for the scientists. Geologists had formed a picture of the crust at the Windischeschenbach site by examining rock outcrops and two-dimensional (2D) seismic measurements. At a depth of about 7000 m [22,966 ft] they had expected to drill through the boundary between two tectonic plates that collided 320 million years ago, forming the Eurasian plate. However, this boundary was never crossed, and the geologists have had to redraw most of the subsurface picture.

Other unexpected results include core and log evidence for a network of conductive pathways through highly resistive rock, and in rock devoid of matrix porosity, an ample supply of water. Look at these findings in more detail:

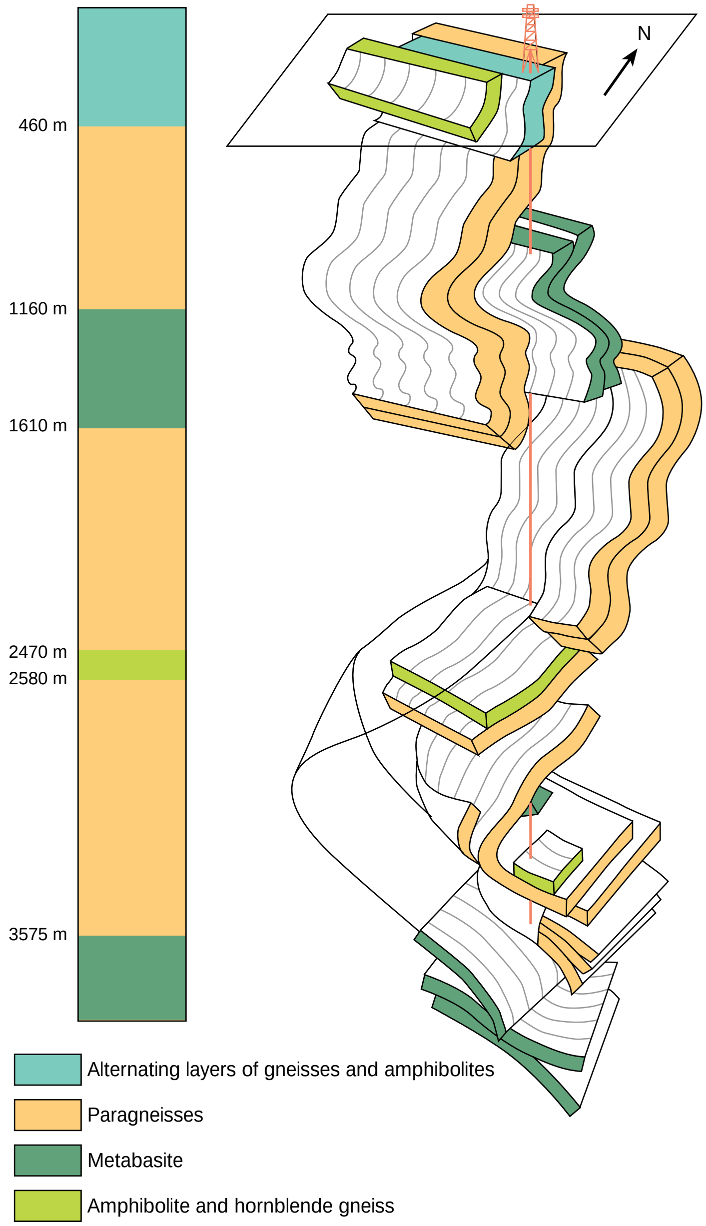


Seismic Investigations—During the project, surface and borehole seismic measurements helped visualize the structure below the KTB site. The original picture had been formed from 2D seismic work undertaken before drilling. But the structural profile of KTB-VB showed a more complicated subsurface. Instead of a nappe unit, the formation followed a more tortuous path (*right*).[15]

After KTB-VB was completed in April 1989, a year was spent on major seismic evaluation. The seismic work, under the joint responsibility of KTB and DEKORP—German Continental Reflection Seismic Profiling—was performed by Prakla-Seismos—now part of Geco-Prakla. This included a 3D survey over an area of 19 by 19 km [11.8 by 11.8 miles], vertical seismic profile (VSP) and moving source profile (MSP), using geophones in KTB-VB, and two wide-angle 2D seismic surveys with an offset of 30 km [18.6 miles] using vibrators and explosives as sources. The evaluation, conducted by a number of German universities and their geophysical institutes, utilized acoustic impedance calculated from borehole sonic and density measurements and the acoustic measurements made on cores in the field laboratory. The seismic processing was complicated by the tortuous structure and the large seismic anisotropy. The results, however, gave a much clearer picture than the earlier 2D work and accurately predicted the major fault system drilled through between 6850 to 7300 m (*page 6*).[16]

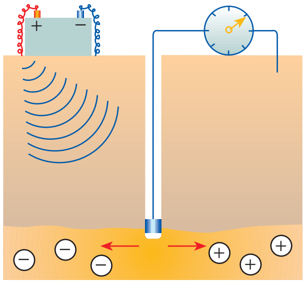
It is now known that the borehole remained inside the Zone of Erbendorf Vohenstrauss (ZEV), a small crystalline unit tectonically placed between the Saxothuringian and Moldanubian units. There are indications that these metamorphic units of the Bohemian Massif have been uplifted 10 km [6.2 miles] since Variscan time—about 300 million years ago—and eroded to the present day surface.[17]

Future experiments have been designed to measure seismic anisotropy at greater depths, the spatial extension of seismic reflectors—such as the "Erbendorf" structure at a depth of about 12 km [7.4 miles]—and the detailed velocity distribution between the two boreholes using seismic tomography. Seismologists will also take advantage of the superdeep borehole KTB-HB by recording downhole seismic waveforms emitted by earthquakes. In this way, surface noise will be reduced and the frequency content of the signal preserved.



n ***Lithology and structure revealed by KTB-VB. Simplified lithology of KTB-VB** (left) **shows the alternating layers of metamorphic rock. The structural model** (right) **shows formations dipping 50° to 75° south-southwest over the first 3000 m, followed by a rotation of the dip to the east with a much shallower dip of 25° in the fold hinge. These models were built from interpretation of core data and borehole images such as Formation MicroScanner images. The formation appears to have twisted and piled up.***

15. Wall H, Röckel T and Hirschmann G: "Structural Information from FMI in Crystalline Rocks. Results from the KTB Drilling Site," Document du BRGM 223 6th International Symposium—Continental Scientific Drilling Programs—Paris, France, April 1992.
    Nappe is a sheet-like rock unit emplaced by thrust faulting, recumbent folding or both.
16. Emmermann et al, reference 9: 137-164.
17. Indications come from the analysis, for example, of detrital muscovites from the sedimentary basin west of the Bohemian Massif and the study of eroded sediments. Typical techniques used in geochronology are the determination of cooling ages by radiometric dating.

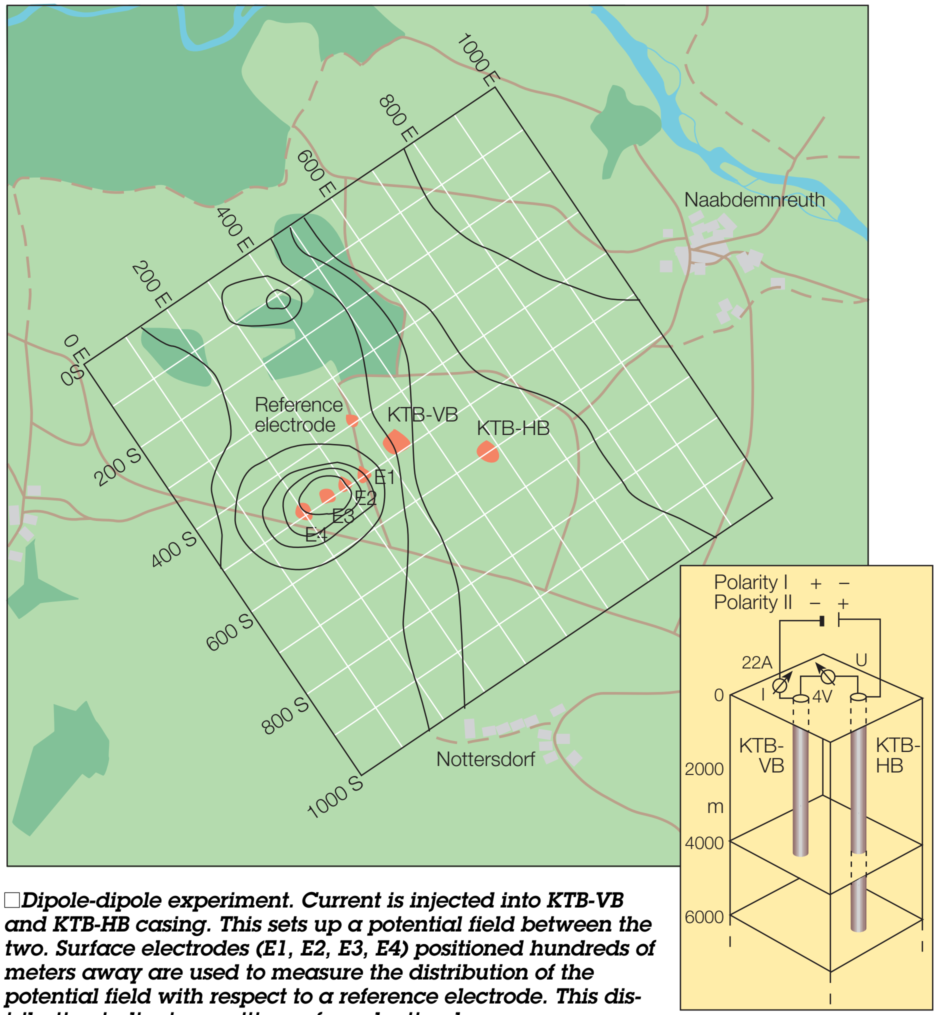


Electromagnetics—One of the reasons for choosing the Windischeschenbach site was to investigate the origin and nature of a low-resistivity layer recorded by surface measurements that appeared to be 10 km below the Earth's surface. This is not unique to southern Germany, as similar layers are found in many continents around the world.

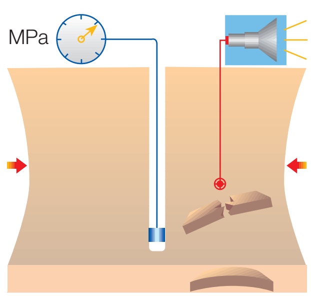
To unravel the mysteries of this conductive layer, scientists pursued many different angles. Conductivity measurements on cores from KTB-VB showed high resistivity as expected in crystalline rocks. But then highly conductive graphite-bearing faults and cataclastic zones were found at various depths up to 7000 m [22,970 ft].[18] These were also seen on borehole logs where abnormal SP deflections of more than 200 millivolts (mV) coincided with the graphite. Other logs, such as induced polarization—where the decay of a voltage applied at a surface electrode is measured downhole—showed conductive pathways potentially formed by veins of graphite and/or sulfides.

At a much larger scale, when the KTB-HB was at a depth of 6013 m [19,730 ft] a dipole-dipole experiment was carried out. This consisted of using the casing from both holes to inject current into the formation (*above, right*). The resulting potential field was measured around the borehole. Any changes in potential indicated a connection of an electric conductor to one of the casings, supporting the theory for a conducting layer extending over a distance of several hundred meters. The results showed that the conducting layer coincided with graphite deposits in a north-south striking fault system—the Nottersdorf fault zone. The faults from this system crossed KTB-VB at about 250 m [820 ft] and KTB-HB at about 1500 m [4921 ft].

Further experiments are planned to investigate the depth, thickness, electrical anisotropy and source of the high conductivity layer still believed to be at 10 km.



Dipole-dipole experiment. Current is injected into KTB-VB and KTB-HB casing. This sets up a potential field between the two. Surface electrodes (E1, E2, E3, E4) positioned hundreds of meters away are used to measure the distribution of the potential field with respect to a reference electrode. This distribution indicates positions of conducting layers.



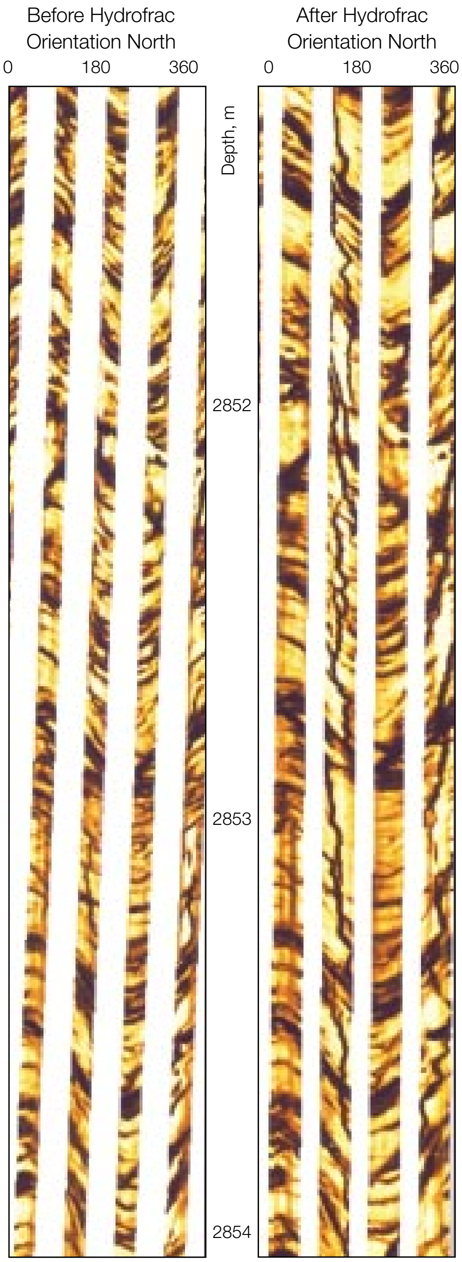
Stress and Deformation—One of the goals of earth science is earthquake prediction, and ultimately reduction in earthquake risk. The physics of earthquakes requires an understanding of the movement of tectonic plates, the forces involved and role the crust plays in transmitting those forces. Many scientists think that the top 10 km of crust is brittle and carries most of the stress that moves the entire 100-km [62-mile] thick continental plates. They also believe that, with increasing depth, the crust becomes ductile and cannot support the stress. KTB research may help clarify the transition from brittle to ductile.

Preliminary work in the two KTB boreholes has already determined the orientation of the local stress field.[19] The four-arm caliper, resistivity imaging tools, such as the Formation MicroScanner tool, and acoustic imaging tools, such as the BHTV, were used to calculate the stress direction from analysis of two types of failure: shear failure of the borehole wall—called breakouts—and drilling-induced tensile failures. The former occur at an azimuth orthogonal to the orientation of the maximum horizontal stress. The latter are near-vertical fractures in the borehole wall in the direction of the maximum horizontal stress (*next page, left*). These fractures were easily identifiable on the cores cut in the KTB-VB and were oriented using Formation MicroScanner and BHTV images (*page 14, bottom*). The maximum horizontal stress is oriented to N 150° ± 10° E from surface down to 6000 m [19,685 ft].

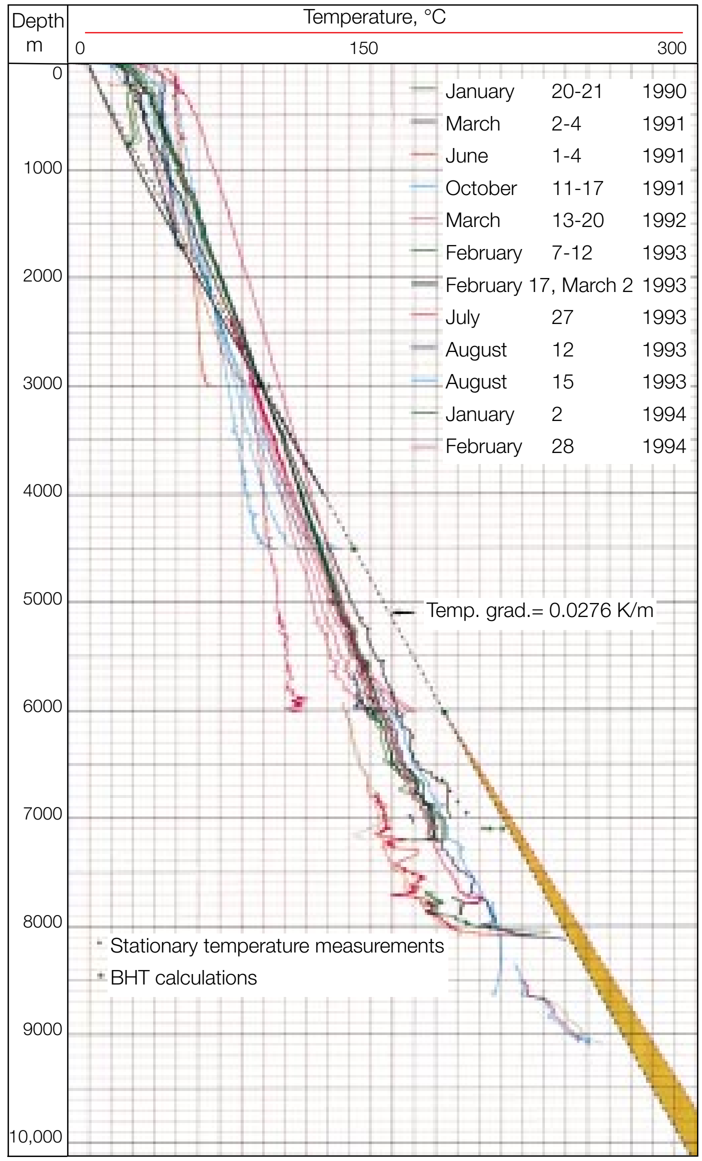
To obtain the stress magnitude, hydrofrac experiments were carried out in both boreholes at various depths in conjunction with geoscientists at the Universities of Bochum,

18. Cataclastic rock is rock that has undergone mechanical breakage usually by dynamic metamorphism or faulting.

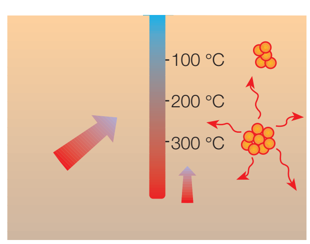
19. Emmermann et al, reference 9: 165-218.



□*Formation MicroScanner images before and after a hydrofrac in KTB-VB. The Formation MicroScanner image recorded after the hydrofrac clearly shows near-vertical induced fractures around an azimuth of about 150°.*



□*Temperature profiles recorded in KTB-HB. The dashed line shows the extrapolated formation temperature estimated from borehole temperature profiles. Estimated bottomhole temperature (BHT) is between 260 °C and 270 °C [500 °F and 518 °F] at 9101 m [29,859 ft]. BHT calculations at other depths are marked. The borehole was cooled by mud circulation in the lower part of the hole and heated up in the upper sections. Time-lapse profiles, such as those recorded in March 1992 when the hole was at 6013 m [19,728 ft], show temperature increasing.*



and Karlsruhe, Germany and at Stanford University, California, USA. By fracturing the formation, the minimum and maximum principle stresses were determined.

These and earlier tests in KTB-VB confirmed that the strength of the rock was increasing with depth, supporting the theory that the upper crust is strong enough to carry most of the stress of tectonic movement. Very recently, a hydrofrac experiment was carried out at 9000 m [29,528 ft] and is being evaluated.

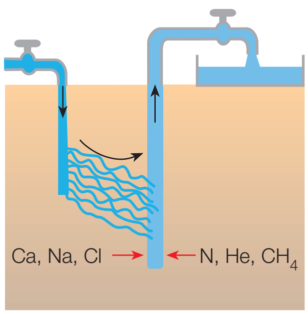
Thermal Studies—Of the many processes occurring within the continental crust, most are temperature dependent. Mapping the temperature distribution and measuring heat production, heat flow and thermal conductivity are therefore a vital part of understanding these processes. During the initial temperature mapping, KTB-VB held the unwelcome surprise that the formation temperature gradient was higher than anticipated. This disappointing result meant that 300 °C—the set limit of current technology—would be reached at about 10,000 m—much shallower than originally predicted.

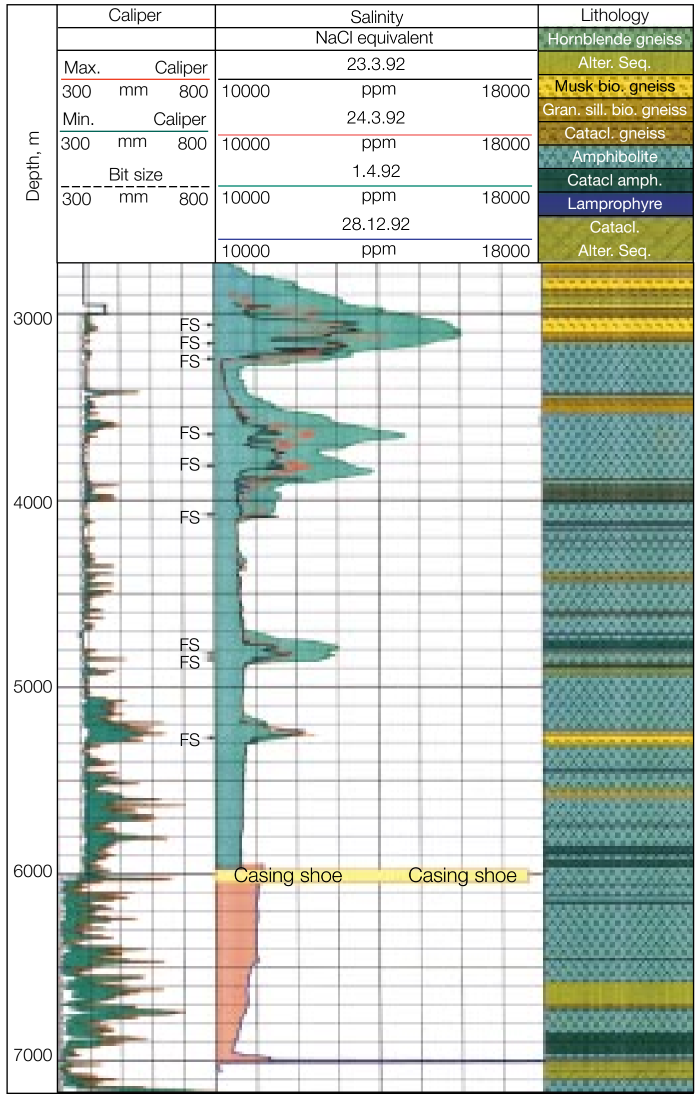
Temperature measurements were carried out in the two boreholes during regular logging campaigns (*above*). These were used to estimate true formation temperature. The borehole is cooled during drilling, by up to 70 °C [158 °F] in the deepest sections of KTB-HB. Formation temperature is obtained by recording several temperature profiles at preset time intervals as the hole heats up again and extrapolating these profiles to infinite time on a logarithmic plot.

Each temperature profile was recorded during the first wireline logging run. This helped avoid another complication, disturbing the mud temperature profile by the logging tools. A wireline tool was even modified at KTB with the temperature sensor mounted on the bottom of the tool to provide the least disturbance and give the best possible result.

Temperature data provided an opportunity to measure heat production and conductivity. In addition, thermal conductivity measurements were carried out in the field laboratory on cores cut from the boreholes. From the NGS and Litho-Density data, heat produced by radioactive decay was calculated—for metabasites the results were 0.5 micro-Watts per cubic meter (μW/m³) and for gneisses 1.6 μW/m³.

The final temperature profile has yet to be extrapolated from the data obtained so far. Experiments will continue to examine temperature distribution, heat production, heat flow and thermal conductivity.





☐ ***Fluid detection and sampling. Pulling the drillpipe out of hole without refilling the borehole decreased the hydrostatic head, provoking inflow from the formation. A fluid sampler (FS)—run in combination with the Auxiliary Measurement Sonde (AMS) tool—collected samples. The AMS tool was used to detect changes in mud resistivity** (track 2). **Where this occurred, a fluid sample was taken** (track 2). **Also displayed are hole size** (track 1) **and lithology** (track 3). **All curves displayed were acquired in open hole.***

Fluids—The scientists at KTB expected deep crystalline rock to be bone dry, but to their surprise, water influx occurred at several depths from open fractures.

Sonic, Formation MicroScanner and BHTV data were used to detect the fractures. As fresh mud was used for drilling, any saline water inflow would cause a decrease in mud resistivity. This could easily be seen from mud resistivity measurements made by the AMS tool (*above right*). These zones were allowed to produce by dropping the mud level, enabling a fluid sample to be collected by a wireline-conveyed sampler run in combination with the AMS tool. Tests showed the water had not leached down recently from surface. Further tests will be performed to ascertain the origin and composition and investigate fluid-rock interaction.

During a two-month pumping test 275 m³ [1730 bbl] of salt water were produced from an open fracture system at the bottom of KTB-VB. Further evidence showed the extent of the fluid network. During a production test at 6000 m in KTB-HB, the fluid level in KTB-VB dropped. When the 13³/₈-in. casing in KTB-HB was cemented, there was an increase in fluid level in KTB-VB. These two events confirmed hydraulic communication and allowed an estimate of permeability of the fracture system between the two boreholes.[20]

Natural causes of fluid movement became apparent when pressure sensors deployed in KTB-VB recorded changes in pressure due to earth tides caused by the gravitational pull of the moon.

Fluids play an important role in the chemical and physical processes in the Earth's crust, influencing mineral reactions, rheological properties of rocks and melting and crystallization processes. To aid further scientific research into these processes long-term pumping tests are planned between KTB-HB and KTB-VB to measure hydraulic communication, identify fluid pathways and collect additional fluid samples.

The Future for Superdeep Boreholes

In 1996, the KTB boreholes will be handed over to GeoForschungsZentrum (GFZ), a German government-sponsored geoscientific institute based in Potsdam, Germany. GFZ will continue the work started by KTB and the site will become a laboratory for deep measurements. Although the rig will be dismantled, the derrick will remain as a monument to KTB's achievements. These achievements have inspired scientists all over the world to look again at superdeep boreholes with renewed enthusiasm. Many potential sites whet the appetite: the San Andreas fault zone, California, tops the list for studying earthquake activity; for volcanic studies, the Novarupta Vent in Alaska, USA; subduction zones at the Izu peninsula, Japan or the Hellenic subduction zone, Crete; and there is no larger continental collision zone than the intracontinental thrust in the Nanga Parbat region of the Himalayas. It is now up to scientists to convince governments to support international continental scientific drilling with the necessary funding. —AM

20. Bram and Draxler, reference 10: 337-365.