CONTINENTAL GEOLOGY

Looking–Deeply–Into the Earth's Crust in Europe

Call it a wishing well for Earth scientists. If you cleared all the equipment from the drill hole near the Bavarian village of Windischeschenbach in southeastern Germany and tossed in a coin, you would have several minutes before a faint tinkle of coin hitting bottom reached you from 7.5 kilometers down. German geoscientists, though, are not stopping with a pfennig or two. During the next year and a half they will throw the last of a third of a billion dollars into their Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (KTB) hole, all the while wishing for geoscience riches: access to a region of Earth's crust whose nature has so far only been guessed at.

The hole, the second deepest ever drilled into hard basement rock after a Soviet project, still has another 2.5 kilometers to go to reach its target depth of 10 kilometers. After a kilometer of the most difficult drilling yet, money is short, and project managers have had to request an additional $20 million from the Federal Ministry of Research and Technology to fund the remaining drilling. Yet the hole has already yielded unexpected payoffs. Geologists had previously inferred a picture of the crust under the drill site by examining rocks brought to the surface by erosion and making electrical and seismic measurements that probe deep beneath the surface. Since drilling began in September 1987, however, they have had to redraw large parts of that picture. The subsurface faults and folds look quite different than predicted. An unexpected set of mineral "circuits" seems to open conductive pathways in the deep rock. And at depths once thought to be bone-dry, the drill is penetrating abundant reservoirs of hot brine.

These and other KTB findings are helping convince the geophysical community of the value of deep drilling. Many had wondered whether deep holes were worth the trouble and expense, especially after watching the Soviet Union's 15-year effort to drill the world's deepest hard-rock well, 12 kilometers deep on the Kola Peninsula near Murmansk. Its cost, though never disclosed, was thought to be astronomical, and western scientists were skeptical about some of the scientific results.

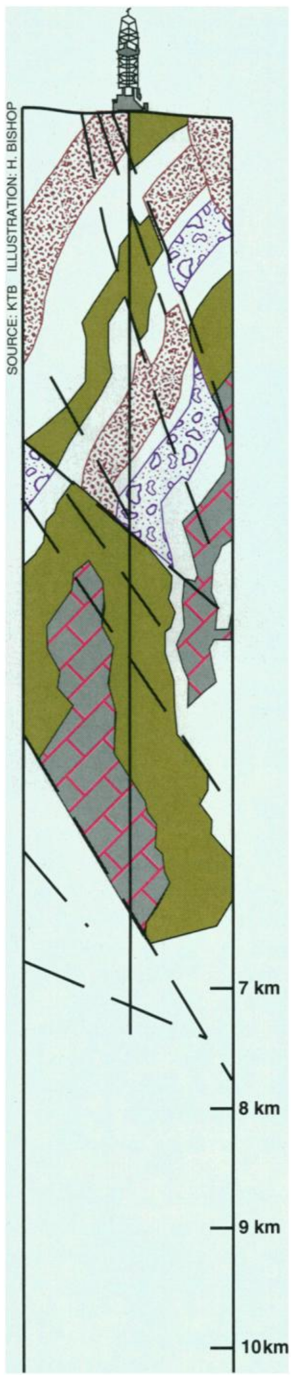
"I never was a big enthusiast for drilling," says Alfred Duba of Lawrence Livermore National Laboratory, who has studied samples from the KTB hole. "I thought the engineering costs were too large for the science you got. But the more we drill, the more we find out how little we know. There is a place for drilling." Yet Duba still adds, "I just wish it didn't cost so much." In spite of this caveat, the KTB hole has converted him and many of his colleagues to the idea of exploiting technology developed in the project for a broader international program of drilling (see sidebar).

In keeping with the well's tendency to deliver surprises, both of the features that initially drew the 300 KTB researchers to the Windischeschenbach site have turned out to be mirages. One was the expectation of moderate temperatures in the deep rock, which would have allowed drilling to a depth of 12 kilometers before heat overwhelmed the drilling equipment. But the first surprise from KTB—temperatures far higher than predicted—forced a retrenching to a target depth of 10 kilometers. The other attraction seemed to be an opportunity to drill through the buried boundary between two tectonic plates that collided 320 million years ago to help form the present Eurasian plate. But the suture, first predicted to slant under the KTB site at a depth of about 3 kilometers on the basis of surface geology, failed to show up at 3 kilometers, or at 5 kilometers as later hoped. And at 7.5 kilometers, researchers still "haven't seen any sign of a dramatic change" that would mark the boundary between the two plates, according to Jörg Lauterjung of the KTB project.

Ground truth. Other predicted boundaries in the rock have proven equally elusive. One object of the hole was to provide a kind of ground truth for seismic reflection profiling, the radar-like technique that creates images of subsurface structures from the manmade seismic waves that they reflect. "You see all kinds of [seismic] reflectors around the world," says KTB operations leader Peter Kehrer, "but we don't know what they are." Distinguishing among faults, changes in rock type, fluid-filled cracks, or other possibilities has been largely guesswork—and the KTB hole suggests an extra measure of caution. Seismic profiles predicted the position of some—but not all—of the structures encountered so far, and even those that showed up where expected were often different from what researchers had assumed they were.

Many surprises, however, have been more positive. Duba, for example, prizes the evidence that "a rock we get at the surface is not a very good indicator of what goes on at depth," at least in his specialty of subsurface electrical conductivity. Like seismic profiling, conductivity surveys can reveal aspects of the deep crust without the need for expensive drilling. When researchers inject electric current into the ground at the KTB site, the Earth's electrical response points to regions of high conductivity deep beneath the surface. From experience in other regions, Duba had expected the conductivity to reflect a high proportion of conductive graphite in the deep rocks. Rocks exposed at the surface by erosion didn't conduct well enough to account for the observations, but Duba guessed that chemical alteration and weathering of deep rocks as they gradually worked their way to the surface must have disrupted their continuous graphite "circuits."

If so, rocks extracted from the depths of the well should have intact graphite films that, at least under deep-Earth pressures, should readily conduct electricity. When Duba compressed KTB samples in a press and passed an electric current through them, they conducted as well as he'd hoped. So far, so good. But he couldn't find the expected amounts of graphite in the deep rocks. The samples' conductivity instead seemed to come from an unexpected source: the mineral ilmenite, an iron titanium oxide. To Duba, that implies that variations in subsurface conductivity, at the KTB site and elsewhere, may reflect a far more complex web of circuits than had been assumed: not just graphite but also ilmenite and other oxide minerals, and even the brines that the drilling has been turning up.



Getting there. A complex and difficult route down.

Water from the stone. The brines are another surprise that is opening researchers' eyes to the merit of deep drilling. "When I started 25 years ago, the idea was that the deeper you go into the crust, the drier it gets," says Kehrer. Conventional wisdom had it that kilometers of overlying rock squeeze shut any cracks, cutting off the fluid flows that deposit ores and chemically alter the rock at shallower depths. But after the drill bit had penetrated more than 3 kilometers of dry rock, it broke into water aplenty. Core samples retrieved from 3.4 kilometers were veined with open cracks more than a centimeter wide that had presumably carried fluids. That was only a hint of what was to come at 4 kilometers, where more than half a million liters of a gas-rich, calcium-sodium-chloride brine twice as concentrated as seawater poured into the well. Abundant fluids gushed from depths as great as 6 kilometers. "This has been a real sensation," says Kehrer. "The surprise is that there are fluids of *that* amount."

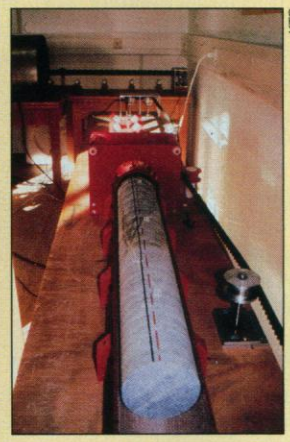
Geophysicists had had some earlier hints from the Kola hole, where drilling "mud" pumped into the hole to lubricate and cool the bit returned to the surface with its chemistry subtly altered. The Soviets took the changes as evidence that brines were flowing into the hole from surrounding rock, but western scientists remained unconvinced. Now the obvious inflows in the KTB hole

The Gang That Drilled Straight

American drillers are the world's top dogs in the search for oil and gas, and the Soviets have drilled the deepest hole in the world, reaching a depth of 12 kilometers. But in sophistication, the KTB project in southeastern Germany outdoes them all. Thanks to high technology and the money freely flowing from the German government, this Cadillac of continental scientific drilling projects has managed to push through treacherous rock to a depth of 7.5 kilometers, on the way toward its goal of 10 kilometers, and is producing plenty of scientific surprises (see main story). In the process, it has attracted fans who would like to see the engineering innovations of the KTB drilling put to work in a broader program of deep scientific drilling.

walls of the hole repeatedly broke off, jamming the drill bit with debris and at some places widening the hole to more than 3 times its normal 31-centimeter width. In the widened hole, the vertical drilling system can't keep the hole straight. On three occasions, such hole instabilities required drillers to backtrack, fill in as much as 300 meters of hole, and redrill a straighter hole. And during one maneuver last February, the drill pipe broke, sending 7 kilometers of pipe to the bottom, where it had to be fished out. The resulting delays and other expenses due to the difficult drilling have cut back on the recovery of rock cores for analysis. Researchers had hoped to extract core samples from 25% of the hole below 4 kilometers, but coring is running at about 6%.



KTB

Tapping into the deep crust. Left to right: The 83-meter-high KTB drill rig, the drill pipe, a tungsten carbide bit, and a "mega-core" of deep rock extracted from the hole.

The technological innovations range from a scheme for continuous analysis of rock powder drilled from the hole to equipment that makes it possible to recover rock "megacores," cylinders of rock up to 24.5 centimeters thick that provide researchers with abundant material for analysis. But the primary KTB engineering achievement may be the ability to drill straight. That's critical in deep drilling, because after every 70 meters or so, a drill crew has to withdraw the entire length of drill pipe from the hole to replace worn bits and do other chores. If the hole is crooked, hauling the drill pipe out quickly becomes impossible. The Soviet drillers did make it to 12 kilometers with a crooked hole, but they paid a terrible price: 15 years, untold rubles, and a hole that is still a nightmare to work in.

The KTB drillers have avoided most such pitfalls with the help of a "vertical drilling system" mounted just above the bit. The system senses any departure from the vertical and nudges the bit back on track. So far, the KTB hole is more than straight enough. At a depth of 7000 meters the bottom of the hole was less than 5 meters away from being perfectly plumb.

Technology hasn't smoothed out all the obstacles, though. As the bit passed through a fault zone at 7 kilometers, the brittle

Even so, scientific drillers around the world are eager to get their hands on the German technology, and the Germans seem willing to cooperate. The German Federal Ministry of Research and Technology, the agency that funds KTB drilling, has shown an interest in developing the KTB project into an international drilling program. An international meeting is scheduled for the end of August in Potsdam to discuss the possibility.

As most potential participants envision it, a worldwide program of continental drilling would be organized along the lines of the current Ocean Drilling Program. With Germany providing the technology and know how, one lead country would come up with the largest block of funding while others joined up with smaller shares. Specific drill sites will not be discussed in Potsdam, but according to Mark Zoback of Stanford University, a meeting coordinator, the program would include shallow and intermediate-depth holes as well as a few super-deep holes.

Zoback, though, has a favorite hole in mind. He and his colleagues would like to drill 10 kilometers into the San Andreas fault, site of so many earthquakes, to look at the deep workings of the fault. And only the KTB gear looks up to the job.

–R.A.K.

give more weight to the Kola claims. "The Kola well and our own have shown that a deep crust of dense, hot rock is definitely not the case," says Kehrer. "There are large amounts of highly saline brine in the crust that migrate, carrying metals around and depositing them as minerals."

A minority of geophysicists, including Lawrence Cathles of Cornell University, had suspected that at least some permeability would remain at great depths, enough to allow fluids to circulate. But the large volumes flowing into the KTB hole are welcome confirmation. "It's beginning to look like the lower parts of the crust can be fairly permeable," Cathles says, making room at relatively great depths for ore formation.

The hole shows the potential for settling another debate about the lower crust—specifically, about the role it plays in transmitting the forces that shift tectonic plates. Theory and experiments on rocks in the lab suggested that down to about 10 kilometers, increasing pressures strengthen rock. At greater depths, the weakening effects of increasing temperatures should overwhelm the effect of pressure. Thus, the thinking went, the strong top 10 kilometers of crust should carry most of the stress that moves the entire 100-kilometer thickness of a plate. In recent years, however, some investigators have argued that the upper crust weakens so rapidly with depth that the lower crust and the mantle beneath drive plate motions. If so, surface motions, including earthquakes, would simply reflect whatever the underlying rock was doing. As Mark Zoback of Stanford University puts it: "Does the top drive the bottom or the bottom the top?"

Stress measurements in shallower wells down to 3 kilometers had showed that, at least to that depth, the strength of the upper crust increases with depth, supporting Zoback's expectations, but he saw an opportunity for a more convincing test at KTB. With colleagues at the University of Karlsruhe and the KTB project, Zoback measured the stress at the bottom of the hole when it was 6 kilometers deep—halfway through the upper crust—and found that the strength of the rock was still increasing, just as he predicted.

The KTB drillers are hoping that the hole starts defying predictions again as it approaches 8 kilometers. If not, the drilling may end prematurely. The reason: A seismic reflector at about that depth, which Ewald Lüschen and his colleagues at the University of Karlsruhe suspect could be a reservoir of fluids, might spell trouble. If the fluids are voluminous and highly pressurized, the drill rig could find them hard to contain—and the resulting delays might be enough to end the money-strapped project. KTB officials find all this highly speculative, but any sort of problem could fatal. "If all goes well, we will reach 10 kilometers in October of next year," says Kehrer. "If any larger unknown things happen, this could be the end of it." Making one more wish at his deep, deep well, he adds, "We have to have luck from now to the end."

–Richard A. Kerr

PALEOANTHROPOLOGY

'Java Man' Gains (and Loses) a Consort

All fields of science are moving very quickly these days, but in few fields are remarkable claims made and retracted within 2 weeks. But that's just what happened recently in paleoanthropology, where a skull from Java made its scientific debut at a conference in the Netherlands. The skull, its two discoverers claimed, was a female specimen of *Homo erectus*, the immediate ancestor of Homo sapiens. At 1.4 million years old, it could definitively push the timing of African migrations into East Asia by human ancestors back by about half a million years.

Ten days later, after one of the researchers had threatened to withdraw his name from the paper presented at the conference, both authors agreed that the skull was a relative stripling of 500,000 to 700,000 years. And others were doubting that the skull really had the "African" features that had initially made it of such interest.

Yet interest in the skull is still high, for the specimen is more complete than most other fossils from the region. "This has opened a real window for us," physical anthropologist C. Loring Brace of the University of Michigan noted after the latest round in this dating game.

But that's only a pale shadow of the interest that the skull initially aroused because it seemed to throw light on the first migrations of *Homo erectus*. The hominid was moving out of Africa around 1.5 million years ago, according to its fossil trail, yet the oldest *erectus* fossils from East Asia were in the 500,000 to 800,000 range, leaving a sizable gap to be explained.

That was one reason so much excitement arose on 16 May, when peasants found the new skull near the village of Sangiran on Central Java. They alerted Donald Tyler, a physical anthropologist from the University of Idaho, who was nearby conducting an archeological survey with some students of geologist Sastrohamijoyo Sartono of the the Institute of Technology in Bandung, Indonesia. Coincidentally, the skull surfaced exactly 100 years after Dutch physician Eugene Dubois discovered the first *Homo erectus* remains, also in Java, a find known as "Java Man."

The University of Leiden was holding a conference to commemorate Dubois' discovery from 26 June to 1 July, which gave Tyler and Sartono just enough time to write a paper introducing the new find. The paper, presented by Tyler in Leiden, reported that the skull was from a layer "approximately 1.2 to 1.5 million years old". And as it came from the lower part of the layer, Tyler was confident that the skull was about 1.4 million years old.

What is more, said Tyler, the skull showed a marked similarity to two *Homo erectus* specimens from east Lake Turkana in Kenya, which are about 1.6 million years old. The "African" features and the antiquity of the Java skull pointed to an earlier migration of *Homo erectus* to Asia, filling in that large gap.

But a week after the meeting, Sartono, back home in Bandung, faxed organizers in Leiden stating that he wished to withdraw as co-author of the paper. The date of the skull, he insisted, was wrong. The true age of the sediment layer that held the fossil was between 500,000 and 700,000 years. One of his students had misdated the layer, said Sartono. Tyler retorts that Sartono never pointed out the mistake, though he had ample opportunity to do so. Nevertheless, after a round of phone calls, Tyler revised the date.

DON E. TYLER

A woman of a certain age? Anthropologists had trouble dating Java Woman.

The revisionism hasn't stopped there. Brace has doubts about the skull's African morphology. "I'm not sure it does look more African," he says. Tyler, however, still maintains that it does. And if he is correct, then he's created another puzzle for his colleagues: How can a skull so young still have such pronounced African features?

–Felix Eijgenraam

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