Continental Drilling Heading Deeper

As scientific continental drilling here and abroad inches deeper into the crust, an ambitious U.S. superdeep borehole is being proposed

Geology can be a frustrating endeavor. Instead of studying whatever rocks they want, geologists must spend much of their time inferring what lies deep beneath their feet from what they can pick up off the ground. Erosion, a river, or road construction may reveal parts of the puzzle, but such processes are notoriously haphazard.

The oil and gas industry drills more than 10,000 wells a year in the United States, but many are in the wrong place or drilled to the wrong depth for scientific use. Besides, the results are generally not available to workers outside the oil company that drilled the hole. Lately, geophysicists have come to the aid of geologists with tools that probe the third, subterranean dimension of geology with acoustic or electromagnetic waves, producing three-dimensional albeit fuzzy and often controversial pictures of what lies beneath.

Increasingly, geologists are getting their hands on the rocks they need—and testing the conclusions of geophysical surveys—by drilling. Scientific drilling to modest depths of a kilometer or two is revealing what lies beneath the nearly complete sediment cover of the central United States and is helping to show how magma drives explosive eruptions. If a 10-kilometer-deep borehole proposed for the southern Appalachians becomes reality, American scientific drilling will surpass the deepest well ever drilled for oil or gas and penetrate several times deeper than any purely scientific borehole in North America. But this ambitious effort, the magnitude of which makes many American scientists uneasy, would not even catch up with the Soviet superdeep hole on the Kola Peninsula, where 14 years of drilling have pushed the hole past 12 kilometers toward the goal of 15 kilometers.

Although not prominent on the program, the southern Appalachian superdeep hole was on many researchers' minds last month at the International Symposium on Observation of the Continental Crust Through Drilling held at Tarrytown, New York.* The hole is being proposed by a group of researchers† to test, among other things, the hypothesis that a sheet of crystalline rock about 10 kilometers thick was shoved 225 kilometers westward over underlying sedimentary rock by a continental collision. In 1979, despite the seeming improbability that such a thin sheet would hold together like that, deep seismic reflection profiling revealed a layer that is presumably the previously proposed boundary between the crystalline sheet and the underlying sedimentary rock. The hole would penetrate this reflector of seismic waves at a depth of about 8 or 9 kilometers and return samples to verify its nature. The price being informally discussed—$45 million over a 3-year period, if all goes reasonably well.

> Many researchers are a bit apprehensive about putting all their eggs in one costly basket.

The 10-kilometer southern Appalachian hole would be almost twice as deep as any drilled through hard, crystalline rock, other than the Kola hole, but the American drilling industry is taking a can-do attitude. When asked to speak on the challenge and constraints of deep drilling, Frank Schuh of Arco Oil and Gas in Dallas had a well designed for purposes of discussion, a 15-kilometer well just for good measure. Aside from a couple of difficult areas, even this hole would be "not really much of a problem," according to Schuh. Two areas of drilling performance would have to be improved. The drilling rig would have to lower and raise a 15-kilometer-long, 450,000-kilogram pipe and its attached drilling bit (oil and gas drill strings are a third that weight at most). And the drilling would have to be straighter than ever before—deviations of less than a few degrees per 100 meters—or abrasion at the slightest of bends would wear out the drill string.

The drillers' optimism is based on what Schuh called the "rather benign" drilling environment at the bottom of even a 15-kilometer borehole in the southern Appalachians. It would be a cool 165°C, not the 250°C of a deep gas well; the walls of all but the uppermost section of the borehole would be strong enough to forgo the lining required in most wells; and fluid pressures would not be so great as to threaten to blow the drill string out the top, as can happen in gas exploration. To the oil and gas driller, the southern Appalachians are "a really great place to drill," as Schuh said. Still, the immensity of the task left many listeners uneasy. Recalling his own experience with the seemingly innumerable ways that a hole can go wrong, one researcher noted privately that "Murphy was a driller."

What little deep drilling experience in hard rock Americans have seems to support some optimism about the practicality of superdeep drilling. Two boreholes of about 4 kilometers were sunk at Fenton Hill near Valles Caldera in New Mexico as part of the hot dry rock geothermal project of Los Alamos National Laboratory (LANL). As William Laughlin of LANL explained at the meeting, the major drilling problems there resulted from the temperatures of 275°C to 325°C and the need to incline the hole at an angle of 35°. The deepest hard-rock hole in North America was an accident, drilled by Phillips Petroleum Company in a search for oil and gas in Arizona. Hoping that a seismic reflector marked another thin-skin overthrust like the one thought to underlie the southern Appalachians, Phillips drilled 5.5 kilometers down but found no overthrust or sediments, leaving a well entirely through crystalline rock.

The single southern Appalachian superdeep hole is the most ambitious and costly drilling by far ever seriously proposed outside the Soviet Union, but the project has gained considerable momentum in recent months as it has become the centerpiece—indeed the sole goal for the time being—of a nascent national continental drilling program. Modest efforts toward organizing and coordinating drilling received a boost in the 1983 National Academy of Sciences report *Opportunities for Research in the Geological Sciences*, which recommended immediate funding of $4 million per year to take advantage of wells drilled for other purposes and opportunities to

*Organized by a committee headed by Barry Raleigh of Lamont-Doherty Geological Observatory, Palisades, New York 10964.
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deepen existing wells. The drilling of deep boreholes dedicated to scientific research—of unspecified depth—should be funded at a level of $20 million dollars by 1990, the report said.

Continental scientific drilling received its most crucial support to date, as well as a change of direction, when the White House's Office of Science and Technology Policy (OSTP) was briefed by a National Academy of Sciences solid earth sciences panel as to where fiscal year 1985 funding increases might yield the greatest return. From the five suggested areas, OSTP picked drilling. More important for the nature of the drilling to be done, OSTP urged the Continental Scientific Drilling Committee (CSDC), a broad-based Academy panel formed in 1978 to encourage the development of a national drilling program, to designate a single project as the first target. OSTP also made it clear that the recommended target should excite other scientists, the general public, and Congress. The competitive spirit engendered by the outdistancing of American drillers by their Soviet colleagues also seems to have influenced OSTP's interest in a single exciting objective.

The CSDC considered site recommendations from its panels studying drilling into faults, hot rock and hydrothermal systems, mineral systems, and crustal structures. Last November, it handed up what one committee member called the "pound of flesh" requested by OSTP—the first and, for some years, only target of a national drilling program would be a 10-kilometer hole in the southern Appalachians. Among the technical considerations that swayed the CSDC were those presented to the symposium by Robert Hatcher of the University of South Carolina—a fundamental question requiring drilling would be attacked, as well as problems of regional geology; failure to achieve the 10-kilometer objective would still allow the study of intermediate-depth objectives, such as the thrusting along the Brevard Zone; and, if it is there, the thrust boundary is so broad that drilling could not miss it.

With the new priority in hand, OSTP then encouraged the National Science Foundation (NSF) to include $2 million in its fiscal year 1985 budget request for site selection and preliminary studies. The southern Appalachian hole proposal will be resubmitted shortly to NSF along with a proposed management structure for drilling patterned after the highly successful Deep-Sea Drilling Program model. The management group is a consortium of eight academic institutions, headed by Barry Raleigh of Lamont-Doherty Geological Observatory, that is called Deep Observation and Sampling of the Earth's Continental Crust.

U.S. deep scientific drilling seems to be getting a quick start, but many researchers attending the Tarrytown symposium, including some CSDC members, are a bit apprehensive about putting all their eggs in one basket, especially such a costly one. The intended broad program for simultaneous deep drilling into a variety of rocks seems to have narrowed to a single superdeep hole. In order to sell a program of drilling, researchers find themselves pushing a single hole.

In contrast to the proposed American deep hole, other drilling programs are targeting one or more shallower, less costly holes. J. Bouckaert of the Belgian Geological Survey reported that their drilling has brought them within a few hundred meters of an anticipated Appalachian-like overthrust boundary at a depth of 5.7 kilometers in the south of Belgium. French researchers have chosen two sites in their Deep Geology of France program, according to C. Weber of the Bureau of Geologic Research and Mines. Near Echassières in central France, a 2-kilometer, continuously cored borehole will penetrate granite that produced metal-rich deposits.

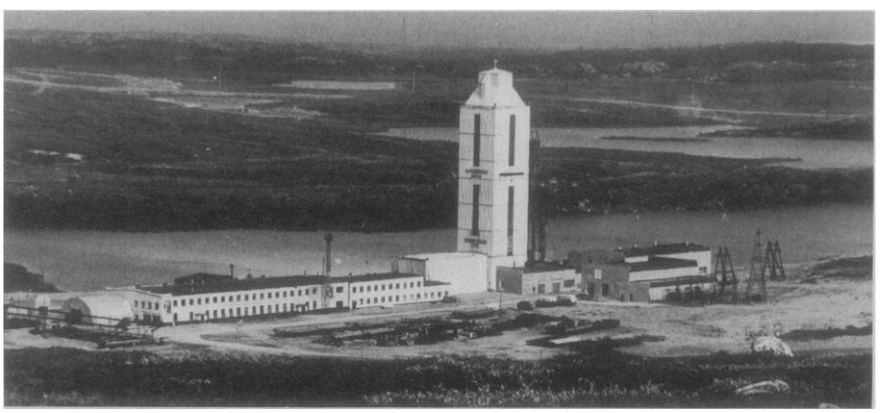
In the Federal Republic of Germany, formal planning has progressed to the selection of two sites—one in the Black Forest and one near the Bohemian Massif—for a possible deep hole. Eugen Seibold of the Deutsche Forschungsgemeinschaft told the gathering that he and some others favor an ultimate depth of 10 kilometers, although that decision has not been made.

Unexpected results are already in from scientific drilling of even more modest means and depth penetration. Paul Robinson and James Hall of Dalhousie University reported on drilling through ocean crust stranded on Cyprus. The drilling is being conducted by the International Crustal Research Drilling Group (ICRDG), an informal organization of 120 scientists from nine countries. With a budget of about $1.15 million for the drilling of several holes totaling 6 kilometers, ICRDG has found among other results that, contrary to earlier expectations, valuable copper deposits should be buried by lava at greater depths. If true, the finding could help lead to the first new deposit discoveries since Roman times.

This summer, one of the ICRDG holes will penetrate the Mohorovicic discontinuity or Moho, the boundary between the crust and the mantle that has been shoved up within easy reach on Cyprus. The Mohole Project, a fiasco in American scientific drilling, had as its single goal a deep ocean hole through the Moho, a task now seen as far more difficult than drilling the southern Appalachian hole.

If abundant science from drilling of modest cost is good, scientific drilling at little or no cost should be better. Although they have their own problems, holes of opportunity that are drilled by commercial concerns and made available to scientists have provided perhaps the highest return per dollar invested. As one example, M. E. Bickford and Randall Van Schmus of the University of Kansas reported the discovery of two adjacent provinces of crust in the midcontinent that had been unsuspected because they had broken through the blanket of overlying sediments at only three tiny areas.

To judge by the cores from the bottoms of holes of opportunity, the two provinces are composed of granite crys-



The Kola hole—the world's deepest

Here near the Arctic Circle a well over 12 kilometers deep sits beneath this 64-meter derrick. The Soviet drilling program includes a second superdeep hole now under way, as well as plans for three other superdeep and five deep holes. [*Courtesy* Espisodes]

The Deepest Hole in the World

They beat the world to Earth orbit in 1956. For several years now, Soviet researchers have also been leading the way in the opposite direction—toward the depths of Earth's crust. After 14 years and uncounted rubles, their drill bit sits at more than 12 kilometers below the surface of the Kola Peninsula not far from Murmansk. The trip down has been full of surprises of the sort that may await American drillers in the southern Appalachians.

The 12-kilometer Kola hole—deeper than the deepest ocean abyss—is more than 2 kilometers deeper than any hole drilled for oil or gas and runs through mostly hard crystalline rock rather than the softer sedimentary rock encountered in oil and gas exploration. The hole is being drilled by a turbodrill of Soviet design that, unlike conventional drills, drives only the drill bit, not the 12 kilometers of drill pipe connecting the bit to the surface. This saves wear and tear on the drill pipe. The drill pipe itself is unusual, being made of a lightweight aluminum alloy instead of steel. That keeps the weight that must be carried by the 20-story-high derrick to less than 250 tons. The hole itself starts at a diameter of about a meter and narrows to about 20 centimeters below 2 kilometers. Unlike oil and gas wells, only the upper 2 kilometers are lined with a protective pipe and that is protected from wear by a disposable liner.

After extensive study and the drilling of a number of 1- to 1.5-kilometer holes, Soviet researchers expected to find their three classic crustal layers—a "sedimentary-volcanogenic" layer down to a depth of 4.7 kilometers, a "granitic" layer to about 7 kilometers, and a "basaltic" layer below that. These had been defined according to the velocity of seismic waves refracted through the layers. During actual drilling, the granitic rock did not appear in the borehole until a depth of 6.8 kilometers. The "basaltic" layer has yet to be found. Missing also is any sign of the Conrad discontinuity, a change in seismic velocity that supposedly reflected the transition from granite to basalt. In 1981, the Soviet scientist I. A. Rezanov suggested that the mistaken identification of reflected seismic waves as refracted waves and the generation of a single seismic velocity by a variety of rock compositions might explain the apparent layering.

There were other unanticipated results. The expected warming of 1°C per 100 meters jumped to 2.5°C per 100 meters below 3 kilometers, pushing the temperature to 180°C at 10 kilometers instead of the expected 100°C. At that rate, a hole to 15 kilometers—the stated goal—would push the 300°C limit for drilling specified by Rezanov. Also contrary to expectations, there were signs of rock alteration and mineralization as deep as 7 kilometers. The hole actually intercepted a copper-nickel ore body almost 2 kilometers below the level at which ore bodies had seemed to disappear.

The most surprising discovery in the Kola hole is "circulating fluids" where none should be. "Throughout the Kola superdeep borehole," wrote Yevgeny Kozlovsky, Soviet minister of geology, in 1982, "gases and inflows of strongly mineralized waters have been encountered, circulating through broad deformed zones. This is so even near the present base [11.5 kilometers] of the borehole. . . ." The gases include "methane and other hydrocarbons." The presence of fractures open to fluid circulation at pressures of more than 3000 bars was unanticipated. Soviet scientists quoted in earlier press reports attributed similarly mineralized waters encountered at shallower depths to biological remains in ancient sediments, none of which are found at greater depths.

Soviet drillers are not content with a single superdeep hole. Another, the Saatly well near the Caspian Sea, is now at 8.5 kilometers in sedimentary rock, heading for 15 kilometers in crystalline basement. Other holes are planned that will incorporate the findings at the Kola hole. "Now that some experience has been accumulated with respect to ultradeep drilling," wrote Rezanov, "we approach the planning of a well with a depth of 10 kilometers or more with considerably more care."—**R.A.K.**

Additional Readings

1. Y. A. Kozlovsky, *Episodes* **5**, 9 (1982).
2. I. A. Rezanov, *Ultra-Deep Drilling* (Nauka, Moscow, 1981).

tallized from subsurface magma and rhyolite lavas extruded onto the ancient continent during two episodes of volcanic activity—1450 to 1480 and 1340 to 1400 million years ago. Together, the two provinces stretch 2000 kilometers from northern Ohio to the Texas Panhandle. From his own field studies, Leon Silver of the California Institute of Technology had found that the younger province extends into the Southwest and may have been one step in the process called cratonization that welded the young continent into a stable platform.

Other modest American drilling projects are about to get under way or are being planned without the assistance of a formal national drilling program. John Eichelberger of Sandia National Laboratories will be joining a consortium of researchers that this fall will continue his progressively deeper probing of volcanic plumbing systems. They will drill 1 kilometer beneath the Inyo Domes near Mammoth Lakes, California, which would be the first penetration of a magma feeder conduit, called a dike, that is so young that it has not cooled entirely.

In the geothermal fields near the Mexico-California border, the Salton Sea Scientific Drilling Project consortium has $5.9 million in Department of Energy funding to drill to depths where temperatures are about 300°C to study the interaction of hot brines and rock. And near the San Andreas fault at Pearlblossom, Mark Zoback of the U.S. Geological Survey in Menlo Park and his colleagues are considering deepening a well drilled for oil in order to investigate why the fault shows some signs of being weak and others of being strong. This deepening or another target identified by the CSDC would be a possible backup for the southern Appalachian hole, should it fail to receive immediate funding.

Funding a superdeep hole does remain a concern. Unsettling parallels with the ill-fated, narrowly focused Mohole Project are never far from mind. To calm such concerns, researchers are emphasizing that they really only want to buy a year's worth of drilling at a time, not an entire superdeep hole. That way, the prospect of a large cost overrun—not uncommon in industry—would leave them with part of a hole and some good science. Ralph DeVries of OSTP told the symposium banquet that would not work. To start a national drilling program under present funding conditions, scientists must not only designate an exciting hole as first priority, but they must also put a clear price on it. Still, "I'm optimistic about your chances," said DeVries.—**RICHARD A. KERR**