GEOMICROBIOLOGY

Life Goes to Extremes in the Deep Earth—and Elsewhere?

Life underground has always been abundant in literature and folklore—dragons guarding their caves, fairy folk under the hill, dwarves mining precious metals in the depths. But when scientists have considered life's role in the subsurface, they have been a good deal less imaginative. Until recently, the conventional wisdom was that the rich life on the surface petered out to sterility not far beneath the soil, and occasional claims that some deep, ancient rock had yielded living microbes were greeted with extreme skepticism. No longer.

In recent years, microbiologists and geologists have teamed up to probe the deepest limits of life, and they have discovered just how lacking their imagination has been. They have found organisms trapped almost 3 kilometers beneath Virginia for millions of years, microbes living off bare rock and water a kilometer down in the Columbia Plateau, and signs of life subsisting on glass and mineral-rich water beneath the midocean ridges. It seems that wherever a source of energy exists, life is present. And although there are obvious limits to what life can endure, they are turning out to be far less restrictive than once assumed. "The only true limit on the depth of life is temperature," says hydrogeologist Tullis Onstott of Princeton University. At the moment, the most thermophilic, or heat-loving, organism known lives at temperatures up to 113 degrees Celsius—which would allow life down to perhaps 5 kilometers beneath the surface.

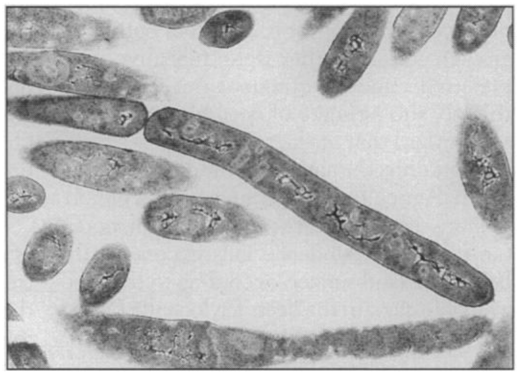
Isolated in the depths for millions of years, microbes have adapted with exotic metabolisms and very slow rates of reproduction. And they are shaping the deep Earth and its waters to a degree that researchers are only beginning to determine. "We have convinced people that there are microorganisms in the subsurface and that they are responsible for geochemical changes there," says microbiologist Thomas Kieft of the New Mexico Institute of Mining and Technology. Now, he says, the focus will be on gauging the extent of those changes—and judging whether life may await discovery below the inhospitable surfaces of other planets and moons.

Visitors from the past. Perhaps the most dramatic claim for deep life on Earth has come from a hole drilled in northeastern Virginia under the aegis of the Department of Energy's (DOE's) recently terminated Deep Subsurface Program. In 1992, Texaco and the Eastern Exploration Co. tapped into a pocket of life 2.8 kilometers down that may have persisted—out of touch with surface life—since the rise of the dinosaurs. The drillers were looking for oil in a 4-kilometer-deep rift called the Taylorsville Basin; the rock now filling this basin was laid down as lake and stream sediments starting 230 million years ago, and has since been buried by 500 meters more of sediment—heated, uplifted, cooled, and partially eroded.

After all that time and turmoil, cores retrieved from depths of about 2.75 kilometers—where temperatures ran up to 75°C—contained microbes that flourished in lab cultures, as the DOE team has reported in a string of reports. Some of the microbes apparently extract energy from ancient organic matter in nearby rock, using minerals such as iron or manganese (instead of oxygen) to oxidize the carbon. In 1994, John Parkes, of Bristol University in the United Kingdom, and his colleagues made the same claim for microbes retrieved from beneath more than 500 meters of Pacific Ocean sediment. And in 1995, Todd Stevens and James McKinley of Pacific Northwest National Laboratory (PNNL) in Richland, Washington, found microbes living 1.5 kilometers beneath the Columbia Plateau in bare basalt rock. Finally, in March, Lee Krumholz of the University of Oklahoma and his colleagues reported finding viable bacteria hundreds of meters down in New Mexico. They were living off 100-million-year-old organic matter; the water that might have carried these microbes to the depths left the surface 30,000 years ago.

All these spectacular reports had to overcome one key doubt: that the microbes really came from the depths and not from contamination, a problem that sank many previous claims of deep life. Ensuring cleanliness is no small task when working a kilometer or two down a 20-centimeter-wide hole flooded with the fluid "mud" needed for drilling. But potential contamination can now be spotted by looking for tracers—highly fluorescent dyes or other chemicals that are injected into the hole before coring. The ultimate tracers, however, are bacteria themselves. If those bear little resemblance to retrieved microbes in the likely sources of contamination, they are probably the "real McCoy." Such safeguards have convinced researchers that, in the recent studies, contamination is not masquerading as deep life. "It's really clear now that there are microbes in all these deep subsurface environments," says ground-water microbiologist Derek Lovley of the University of Massachusetts.

Thousands of leagues under the sea. The rocky depths beneath the continents aren't the only deep environments for life. Other researchers are finding evidence of microbial activity below the 60,000-kilometer-long system of volcanic midocean ridges that girdles the planet. Bacteria are an important part of the bizarre ecosystems found around midocean ridge hot springs, where microbes survive on sulfides leached from the ocean crust by deep-circulating seawater. But in recent years, the first oceanographers on the scene of volcanic disturbances along ridge crests have discovered great white billows of material, including much bacterial debris, spewing from the vents. This discovery immediately set researchers debating whether these microbes are living throughout the hundreds of meters of deep circulating fluids or just within the upper couple of meters of the crust. Now, two independent groups—Martin Fisk and Stephen Giovannoni of Oregon State University, and Terje Torsvik of the University of Bergen in Norway and his colleagues—have evidence that some bacteria, at least, come from deep down.



HENRY ALDRICH/UNIVERSITY OF FLORIDA

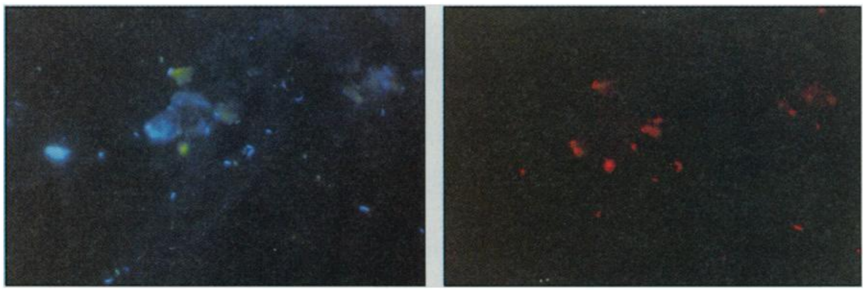
Hell's bacterium. *Bacillus infernus* dwells 2.7 kilometers down, at over 60°C, without oxygen.

About 5% of ocean crustal rock is glass, and "glass will weather on its own because it is unstable," notes Fisk, who presented his group's findings at a March workshop in Washington, D.C. But microbes are apparently accelerating the process to their own benefit. Both groups have seen signs that glass in rock drilled from deep within ocean crust has suffered such microbially enhanced weathering, including glass with deep pits and glass etched in feathery patterns suggestive of microbial activity. Fluorescent chemical tags that attach only to DNA light up the pits, presumably marking the responsible bacteria. Given that and the volume of vented bacterial debris, Fisk concludes that "you have a subsurface aquifer that is just humming with life."

A hidden biosphere? Just how much life is down there? It's hard to be sure; Fisk's notion of a richly populated subsurface needs to substantiated by drilling. And Onstott calculates that deep life accounts for just 0.1% of the world's total biosphere. But he's being conservative: He is only counting bacteria that can be cultured in the laboratory. Deep samples often yield 100 or 1000 times more cells that appear to be intact but don't grow in culture. If they were truly alive, and preferred some environment not offered in the lab, the estimate of deep biomass could soar toward that at the surface.

Certainly, the amount of life drops off with depth. Agricultural fields might host a billion or more culturable cells per gram of soil, notes Onstott, but abundance falls exponentially below the land surface, according to the best available data. In the deep Taylorsville Basin, the figure drops a millionfold, to one to perhaps 10,000 culturable cells per gram.

And researchers are being reminded time and again how brutal life can be at its extremes. The biggest problem isn't temperature, which increases with depth. The great stress in the first few kilometers of continental rock seems to be hunger: The deep subsurface suffers from the greatest scarcity of nutritional resources on the planet. Microbes rapidly remove oxygen, nutrients, and consumable organic matter from ground water as it descends, leaving meager pickings for their deeper brethren. Onstott suspects that in the deep Taylorsville Basin, microbes have been eking out an existence without resupply from descending ground water for more than 180 million years.



S. A. NIERZWICKI-BAUER/RPI

Life in the slow lane. All cells in this 180-meter-deep sample stain blue *(left)*, but only active ones stain red (*right*), showing that many deep microbes are inactive.

In analytical and modeling work done with Hsin-Yi Tseng of Princeton and presented last December at the meeting of the American Geophysical Union (AGU), Onstott argued that geologic events conspired first to sterilize the 230-million-year-old rock with extreme heat. Then, uplift of the strata gave surface water the high ground; from there it could sink into deep rock, ferrying microbes down with it. Finally, erosion removed the highlands from which the ground water was sinking and so cut the deep rock off from the surface. Today, the researchers calculate, topographic relief is so low, and the rock so nearly impermeable, that water would take at least 50 million years to seep to the sampled depth—perhaps as long as 180 million years. "It becomes geologically and hydrologically unreasonable to get [the microbes] there recently," Onstott concludes. Most other researchers are not yet prepared to agree that such depths are completely cut off, however, if only because such interminable isolation is "just so difficult to prove," notes Lovley.

Novel life forms. If Onstott is correct, the Taylorsville microbes, although not quite a slice of life preserved from the age of the dinosaurs, would be direct descendants of surface life from that time. Most are turning out to be new species, says David Balkwill of Florida State University, who is using ribonucleic acids to identify the Taylorsville microbes. He and David Boone of the Oregon Graduate Institute have already found the first member of the bacterial genus *Bacillus*, *B. infernus*, that cannot tolerate oxygen.

Thanks to the isolation and the scarcity of nutrients, life at great depths must be extremely slow paced as well as sparse. Using the amount of carbon dioxide produced by the oxidation of organic matter as a guide, Onstott estimates that microbial activity in the deep Taylorsville Basin occurs at a rate 10^{-15} that in soil. A deep bacterium "doesn't do much," says microbiologist David White of the University of Tennessee, Oak Ridge. "It's very good at doing nothing," or as close to doing nothing as life gets. Onstott guesses that cells may be dividing once a year or once a century, rather than every few minutes, as in an infection, or every few hours, as in soil.

Other researchers can't imagine even that level of activity, noting that the microbes may not be "alive" all the time. "Bacteria don't have to grow," notes marine microbiologist Holger Jannasch of Woods Hole Oceanographic Institution in Massachusetts. "They will sit there until someday they have a chance to grow, [but] we really haven't understood yet how microorganisms, especially their spores, survive that long." A few of the Taylorsville Basin microbes do produce inactive spores of the sort capable of prolonged "suspended animation"; the others might be "salted out" most of the time, says microbiologist Tommy J. Phelps of Oak Ridge National Laboratory in Tennessee. He imagines a microbe caught in a microscopic pocket of highly concentrated brine, with the salt crystallizing around the cell and dehydrating it. When conditions improve, it might rehydrate, revive, and grow.

Alternatively, deep microbes may be making a steady, although not spectacular, living by feeding on the rock itself. In 1995, Stevens and McKinley of PNNL reported that water pumped from as deep as 1500 meters in the volcanic rock of southeastern Washington state contained a surprising abundance of microbes, hydrogen, and methane (*Science*, 20 October 1995, p. 377). To them, that mix looked like a self-contained community. Weathering of the rock by the 30,000-year-old water would produce hydrogen, which the microbes could use as an energy source to convert dissolved carbon dioxide to biomass, producing methane as a byproduct.

Now, Stevens, McKinley, and James Fredrickson, also of PNNL, have created just such an ecosystem in the laboratory. They have coaxed a variety of microbes to grow on a diet of crushed basaltic rock that reacts with oxygen-free water to produce hydrogen—the only energy source in their ecosystem. At the AGU meeting, the PNNL group reported that the weathering of a number of common silicate- and iron-containing minerals produces hydrogen. They concluded that microbial ecosystems "based on rock weathering may be widespread in nature."

And not just on Earth. Researchers see the deep biosphere as just the place to consider what life on Mars, or even on Jupiter's moon Europa, might be like today. If a body like Mars ever hosted life, it must have permeated the subsurface, the reasoning goes, and the conditions there today are thought to be every bit as hospitable to life as is Earth's subsurface: mild temperatures, liquid water, dissolved minerals, and plenty of rock surface.

Even if Earth's subsurface life equals just 0.1% of the total terrestrial biosphere, "that's a lot if you look at how prolific life is on the surface," says Onstott. "You look at other planets where there's no sign of life on the surface at all, but conceivably at great depth a biomass comparable to that on Earth, and you begin to realize how important the subsurface biosphere is." Studying Earth's deep biosphere might thus inform the study of putative fossil microbes in meteorites from Mars or observations and samples taken from the Red Planet. So the reality of life underground may turn out to be even more fantastic than the dragons, fairy folk, and dwarves of our imagination.

–Richard A. Kerr