BIOTECHNOLOGY

Microbial Mining Boosts the Environment, Bottom Line

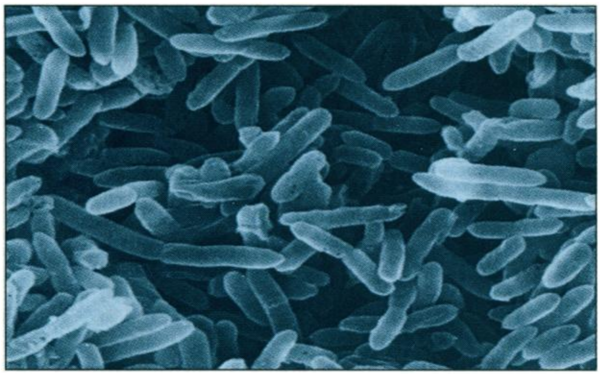
Although mining is one of civilization's oldest major technologies, it holds the dubious distinction of having escaped the waves of innovation that swept comparably ancient disciplines such as agriculture and medicine. Indeed, many minerals are mined today just as they were centuries ago: Crude ores are dug from the earth, crushed, and then the minerals are extracted, often by extreme heat or toxic chemicals. But some of these ancient, environmentally unfriendly methods may finally be on their way out.

Within the past few years, the mining industry has been turning with increasing frequency to a kinder, gentler way of extracting minerals from ores: microbes that leach them out with fewer of the harsh conditions of conventional methods. "Biomining," which has long been a staple in copper mining, is now beginning to find its way into two additional mining industries: gold and phosphate. Biomining "may bring us away from the more destructive physical mining methods," says Maribeth Watwood, an environmental microbiologist at Idaho State University in Pocatello.

But environmental benefits might not be enough to win the favor of mining executives if biomining weren't also bottom-line–friendly. And it is. Bioprocessing improves recovery rates, reducing capital and operating costs. What's more, it permits economical extraction of minerals from low-grade ores, which are being used more and more as high-grade reserves are depleted. "Biotechnology will be a major application for increasing the efficiency of mining," says Bill Kohr, a protein chemist who left Genentech 3 years ago to help found Geobiotics Inc., a Hayward, California, company that develops customized microbial brews for extracting ores.

Although biomining is just coming into widespread use, its roots extend deep into history. The first miners to make use of bacterial action were probably the Romans who worked the Rio Tinto copper mine in Spain 2000 years ago. They noticed that fluid running off the mine tailings was blue, an indication that it contained dissolved copper salts. The Roman miners were able to make use of that knowledge and recover the copper even though they did not know how the metal got into solution. Not until about 40 years ago did it become clear that the copper is in fact leached from the tailings by a bacterium: *Thiobacillus ferrooxidans*.

This bacterium, naturally present in certain sulfur-containing minerals, gets energy by oxidizing inorganic materials, such as copper sulfide minerals. This metabolism releases acid and an oxidizing solution of ferric ions, which can wash out metals from crude ore. It didn't take the mining industry long to make use of this discovery, and the first patent for a leaching process using the oxidizing bacteria was issued to the Kennecott Copper Corp. in 1958.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Tiny miners. This scanning electron micrograph shows bacteria, mainly *T. ferrooxidans*, used to extract gold ore.

The reason the copper industry was so quick to exploit biomining is that much copper, especially in low-grade ore, is bound up in a sulfide matrix; it can be recovered by traditional smelting only at great cost. In addition, the world is currently running out of smelting capacity because the depletion of high-grade ores means more ore has to be smelted to produce the same amount of copper. But oxidizing bacteria can reduce the need for expensive smelting facilities. A new smelter can cost $1 billion, while the technology required for biomining is "pretty unsophisticated," says Corale Brierley, a mining consultant based in Salt Lake City.

Poor-quality ore is simply dumped outside a copper mine and treated with sulfuric acid to encourage the growth of *T. ferrooxidans*. As the microbes chew up the ore, the copper is released and collected in a solution flowing into a catch basin. After the metal is extracted from the solution, the sulfuric acid can be recycled through the ore.

Currently, at least 25% of all copper produced worldwide, worth more than $1 billion annually, comes from such bioprocessing. This use alone, says microbiologist David Holmes of Clarkson University in Potsdam, New York, means that bioleaching of ores "ranks as one of the most important industrial applications of biotechnology in any area of the world today." (Biomining was also once used to extract uranium from crude ores, but no longer is.)

But while copper mining may be the area where biomining is in widest use today, an even more important application is now appearing on the horizon: gold mining. "It was a logical step to apply what was used with copper to gold," says microbiologist James Brierley of Newmont Mining in Salt Lake City. Part of that logic had to do with some powerful economic incentives.

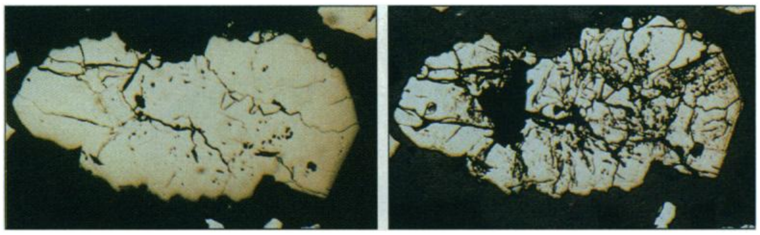
Until recently, the gold-mining industry had depended mainly on high-grade ores near the earth's surface. By the early 1980s, however, those high-quality ores were playing out, forcing miners to rely on lower grade ores deeper in the mines. And low-grade ores are much more difficult to process, says James Brierley: "High-grade gold ores, near a mine's surface, have been naturally oxidized by bacteria, sunlight, and water." But the gold in the low-grade ores is present as sulfides, and these ores require costly pretreatment by roasting or pressure oxidation to burn off the sulfides before the gold can be extracted with cyanide.

Biomining makes it possible to skip these costly steps by taking advantage of bacteria such as *T. ferrooxidans* for pretreating gold ores. Gencor (Pty) Ltd. opened the first pilot plant to test biomining's effectiveness in 1986 at its Fairview mine in South Africa, where most of the ore is the refractory sulfide type. The company found that not only can microbes pretreat the ores—they can do it better than conventional, energy-intensive techniques, increasing the rate of gold recovery from 70% to 95%. Supported by results like those, the pilot plant was upgraded to a commercial operation in the early 1990s. And Gencor is now aiding in construction of four more biomining plants, two in Australia and one each in Brazil and Ghana.

Gencor's operations illustrate another point about biomining research. The leading work is often done outside the United States. "It's like the Winter Olympics; we rank fourth or fifth," says molecular biologist Simon Silver of the University of Illinois in Chicago. "Other countries, such as South Africa and Australia, are way ahead of us."

Still, U.S. companies haven't dropped out of the race altogether. Just this February, for example, Newmont Mining announced a new patented process that brings bioleaching of gold to the Northern Hemisphere for the first time. The Newmont operation in Nevada uses a newer and simpler extraction process that makes it economically feasible to extract gold from very low-grade, sulfidic gold ores, once thought to be worthless. Instead of mixing ore with a bacterial brew in huge, stirred reactors as the Gencor process does, this new scheme simply deposits bacterial cultures and fertilizers, which nurture the microbes, on open ore heaps that rest on an impermeable base.

"Bio-oxidation offers a new, low-cost alternative for the refractory ores [and] appears to have considerable cost-savings over conventional alternatives," says Holmes. In one operation, for example, bio-oxidation costs $18.47 per ton, whereas at one mine in Nevada, conventional pressure oxidation costs $20.31 per ton—a significant savings because it's not unusual to treat hundreds of tons of ore per day at each mine.



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Before and after. Thirty days of bioleaching with *T. ferrooxidans* have corroded this pyrite crystal, exposing the occluded gold.

Gold and copper are intrinsically valuable commodities, and that's part of what's driving the interest in biomining in those areas. Phosphates, on the other hand, are not as intrinsically valuable as the metals are—but their extraction certainly qualifies as "big-time mining," says Gerald Mead, a vice president for research at J.R. Simplot Inc. in Pocatello, Idaho. Phosphate for fertilizer is the world's second largest agricultural chemical (after nitrogen); about 5.5 million tons are produced every year in the United States alone. Another 1.1 million tons of higher quality phosphate are used as an additive in soft drinks and in manufacturing detergents, rubber, and industrial chemicals.

Phosphates have traditionally been extracted from ores either by burning at high temperatures, which yields solid phosphorus, or by treatment with sulfuric acid, which yields phosphoric acid and huge amounts of useless, low-grade gypsum. But last year Alan Goldstein of California State University in Los Angeles, Robert Rogers of the Idaho National Engineering Laboratory in Idaho Falls, and Simplot's Mead developed a bioprocessing technique that take can take place in much milder conditions.

The new technique uses two bacterial strains, *Pseudomonas cepacia E-37* and *Erwinia herbicola*, that were screened from hundreds of bacterial types. These bacteria were chosen because they have an unusual ability: a direct oxidative pathway that converts glucose into gluconic and 2-ketogluconic acids, which can substitute for sulfuric acid in dissolving the phosphates from ore—and can do it at room temperature. "It's an all-around environmentally better process," says Rogers. Mead expects his company to have a pilot plant running in 2 years and a full-scale plant before 2000.

With enthusiasm for biomining at an all-time high, the big challenge now is to increase efficiency. "At the present time, only indigenous microorganisms, that occur naturally in dumps or mine run-off, are used in bioleaching operations," says Holmes. And that, he argues, means the process is in its very early stages: "equivalent, in a sense, to using wild wheat for farming or an unselected strain of *Penicillium* for producing penicillin."

Much of the current research in this field is focused on finding microbial strains that are better suited to large-scale industrial processing. One problem, for example, is that bio-oxidation releases large amounts of heat, and it can raise temperatures to the point where the bacteria currently in use are slowed down or killed. To circumvent this problem, Paul Norris of the University of Warwick in Coventry, England, is working with the Australian mining firm, CRA Advanced Technical Development, to isolate and evaluate organisms known as *Archaebacteria* for use in biomining. These primitive thermophiles, or heat-loving bacteria, are poorly studied microorganisms typically found in deep-sea vents and in hot springs in places such as Yellowstone National Park, Iceland, and New Zealand. They thrive in temperatures up to 100°C or higher, which would devastate ordinary bacterial colonies.

Soon, these heat-lovers will be put to the test in industry: Later this year, Gold Mines of Australia Ltd. will begin using thermophiles developed by Bac-Tech (Australia) Pty. Ltd. to extract gold at their Youanmi mine in western Australia.

Another goal is to find—or engineer—new bacterial strains that can stand up to the presence of heavy metals, such as mercury, cadmium, and arsenic, that poison the microbes and slow down bioprocessing. Silver of the University of Illinois has taken a step toward finding strains resistant to these poisons by showing that some microbes have enzymes that either protect their basic activities from heavy metals or help pump metals out of the bacteria. He is also working to identify genes that help microbes deal with heavy metals, since such genes might be used for genetic engineering of resistant strains.

Genetically engineering a bacterium to resist heavy-metal poisoning, however, may not be an easy job. Microbiologists know much less about *Thiobacillus* and the other bacteria used in biomining than they do about such organisms as *Escherichia coli*, the lab favorite that has been used for most bacterial gene transfer systems. Indeed, Geobiotics' Kohr estimates that genetic engineering of microbes for bioprocessing will take 5 years or more.

Although 5 years might seem a long time at the pace of much of today's science, that time frame actually says a lot about the speed of recent developments in biomining. It took almost two millennia for the curious phenomenon noticed by the Roman miners at Rio Tinto to become a major improvement in copper mining. But the next round of improvements is likely to come much faster. Says Bruce Kelley of CRA Advanced Technical Development: "Bioprocessing has struggled up the commercial hill and now it's at the top."

–Anne Simon Moffat

Some Microbes Used or Under Investigation for Biomining

Organism	Application	Carbon Source	Energy Source	pH Range	Temperature
Thiobacillus ferrooxidans	Copper, gold mining	CO_2	Pyrite (FeS_2); other mineral sulfides	1–3.5	20–40°C
Moderate thermophiles (Diverse species)	Gold mining pilot studies	CO_2	Iron, sulfur, mineral sulfides	1–3.5	50–55°C
Extreme thermophiles *Archaebacteria*	Under investigation	CO_2	Iron, sulfur, mineral sulfides	1–3.5	55–110°C
Pseudomonas cepacia E-37	Phosphate mining	Diverse sources	Glucose, other sugars	2.5–5	4–40°C

Additional Readings

J. Brierley and L. Luinctra, "Heap Concept for Pretreatment of Refractory Gold Ore," in *Biohydrometallurgical Techniques*, vol. 1, A.E. Torma, J. C. Wey, V. I. Lakshmanan, Eds. (The Minerals, Metals, and Materials Society, Warrendale, PA, 1993).

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