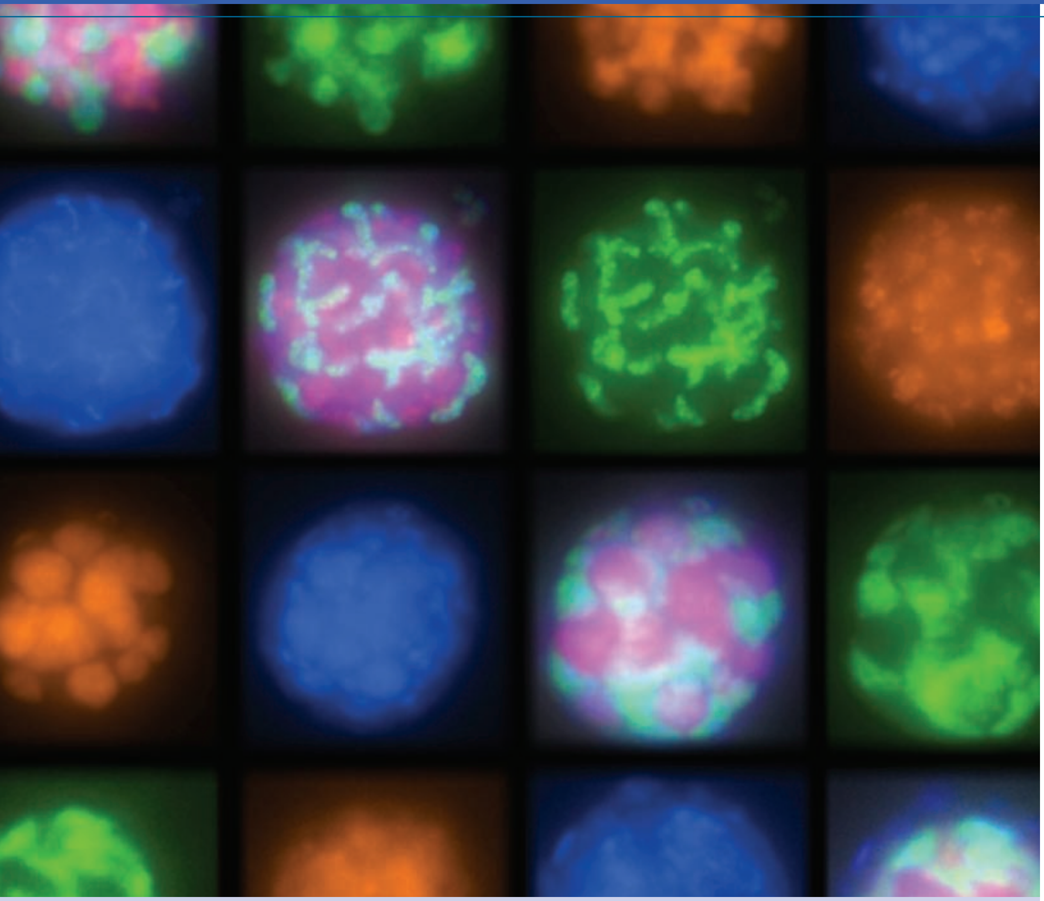
Diving for Microbes



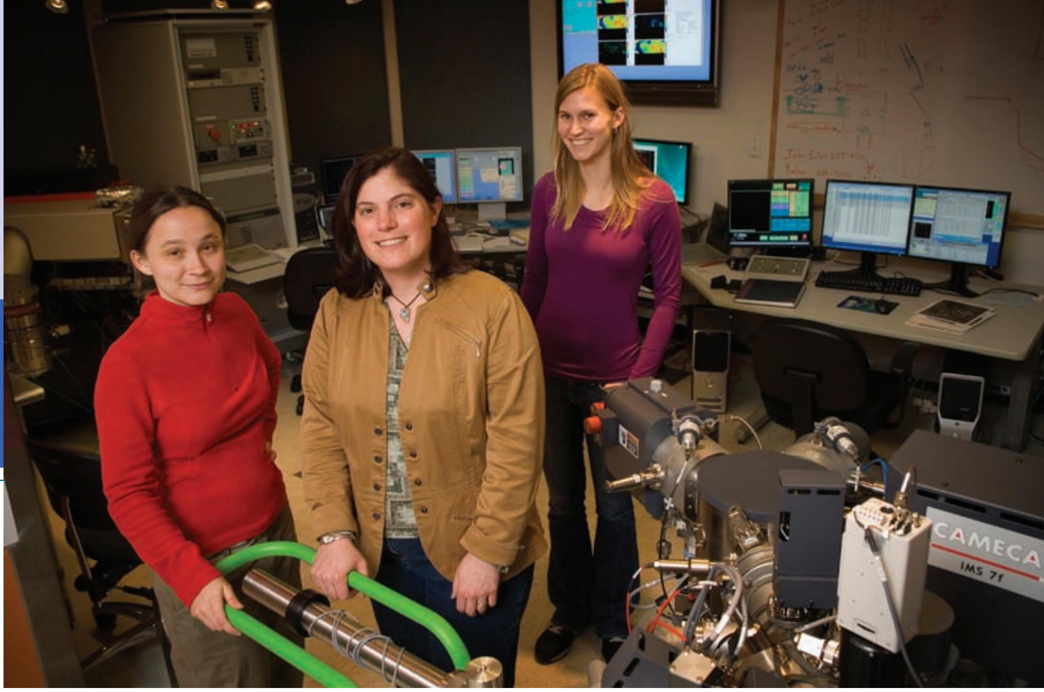
Sixteen panels of four different clumps of marine microorganisms collected from a methane seep off the coast of northern California. Each clump, called an aggregate, is about 10 microns (millionths of a meter) across. The microbes have been tagged with fluorescent markers. DNA glows blue.

In the harsh conditions of the ocean floor, a mysterious medley of microbes survives by eating methane. By consuming this greenhouse gas, they prevent further warming of the planet. But little is known about these microbes, whose existence is indirectly essential to the rest of life on Earth, so researchers are diving into the sea to find out what secrets they may hold.

Off the western coast of Costa Rica, where the crust of the North American continent ends, the underwater terrain is smooth and barren. A thousand meters deep, the seafloor is beyond the reach of the sun and low in oxygen. “It’s just amazing—the bottom of the deep ocean at that site is surprisingly desolate,” says Anne Dekas, a graduate student in Assistant Professor of Geobiology Victoria Orphan’s lab. “It’s just flat and gray sediment for as long as you can see.” Breaking the monotony are occasional methane seeps—places where methane trapped in ice (see box) is released and bubbles out through cracks in the seabed—and at these seeps, Dekas says, “it’s completely different. It’s an oasis of life.” Boasting clams, crabs, tube worms, shrimp, and microbial mats, these dark, deep-sea oases are made possible by microorganisms that eat the bountiful methane, producing nutrients and sources of energy for the rest of the food chain.

But these microorganisms do more than just form the foundation of exotic ecosystems—they’re crucial for the entire planet. Methane is a powerful greenhouse gas, about 20 times more adept at trapping heat than carbon dioxide. The oceans are estimated to produce anywhere from 5 to 50 million metric tons of methane per year, a significant fraction of the 535 million or so metric tons of total methane annually released into the atmosphere via natural and human sources. Scientists say these deep-dwelling bugs consume about 80 percent of the methane that otherwise would have

Graduate student Abigail Green (left), Orphan (middle), and Dekas, at the Caltech Center for Microanalysis.



By Marcus Y. Woo

been released into the atmosphere from the oceans, so without these tiny critters, the accumulation of extra methane would heat the globe even more, accelerating the climate change that's threatening life on the planet.

These organisms are found wherever there are methane seeps, and despite how important they are, we know very little about them. Only in the last decade have researchers such as Orphan and those in her lab begun to figure out how these creatures live. It turns out that the bacteria form a symbiotic relationship with archaea—another form of microscopic life—to consume methane in oxygenless environments. "From an ecological and evolutionary standpoint, it's a fascinating system, because you have these two very different life forms that have been living together and coevolving together for many millions of years—and maybe many billions of years," Orphan says. Without sunlight or oxygen, these organisms can't produce energy like most of the life we're used to. They must resort to more creative ways, processes that may be similar to those used by the very first life on Earth nearly four billion years ago. As living fossils, they have something to say about the history of our planet.

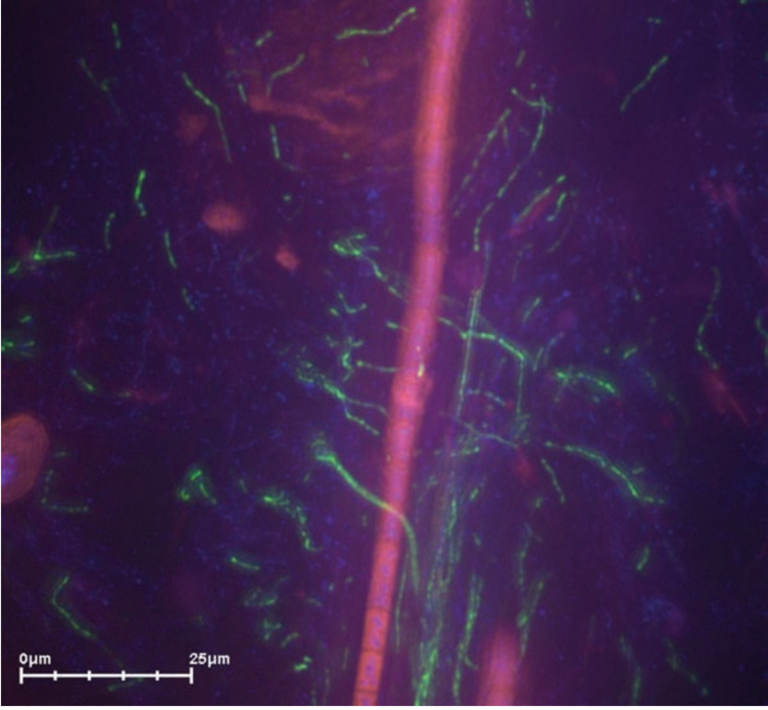
Even though bacteria and archaea—which are as biochemically different from each other as bacteria are from humans—are so small we may forget about them, they far outnumber all other living things on Earth. In your body alone, there are 10 times more bacterial cells than human ones. Scientists estimate that the planet has 5×10^{30} microorganisms—that's more than a hundred million times the number of stars in the observable universe. Scoop up all these little critters together, and they'll weigh several hundred billion metric tons, a mass about a thousand times greater than that of all the people on Earth. The majority of the planet's microbes are believed to live inside Earth's crust or just below the seafloor, regions that are scarcely understood and explored, so many more bug-based ecosystems are likely still undiscovered.

Often unjustly maligned, microbes are essential for life. "They are an integral part of almost every facet of our planet," Orphan says. No species of archaea are known to cause diseases, and only a small fraction of bacteria do; most are harmless or even helpful. Bacteria help digestion, and, as biologists are finding, they play essential roles in our immune systems and overall health (see *E&S* 2009, No. 1).

For the rest of the world, microorganisms ensure that carbon, oxygen, sulfur, and other elements critical for life flow through the global ecosystem, providing the nutrients by which every plant and animal exists. "Bacteria and archaea run the planet—chemically speaking—and they have for billions of years," Dekas says. "For instance, the evolution of oxygenic photosynthesis in bacteria is

FIRE ON ICE

Given the right combination of temperature and pressure, methane molecules can get trapped in the crystal structure of water ice to form a so-called methane clathrate (inset), also known as a methane hydrate or simply methane ice. The result is a chunk of normal-looking ice but for one exception: it burns. This cold combustible forms in deep-ocean sediments, but also underneath the permafrost in the Arctic regions. The U.S. Geological Survey estimates that deposits in Alaska contain 2.4 trillion cubic meters of the frigid flammables, prompting some to consider it as a potential fuel source. But even if we never harvest it and burn it, it's still likely to contribute to climate change: as the planet warms, melting permafrost will expose the hydrates, which will in turn melt and release the methane, triggering more warming.



Using a technique called fluorescence *in situ* hybridization (FISH), the researchers took this image of sulfate-reducing bacteria (green) and cyanobacteria (red) from a bacterial mat. The scale bar is in microns.

the reason there's oxygen in the air." Orphan adds, "As some of my colleagues say, every fifth breath you take, thank a microbe." And in the last year, Orphan's lab discovered that the methane-consuming microorganisms play a surprising role in the global nitrogen cycle. They are among a whole group of bugs that help convert gaseous nitrogen into forms usable by other creatures. Without these microbes, the planet would run out of biologically available nitrogen in less than a month.

METHANE MUNCHERS

Most of the life we're accustomed to—be it bird, fish, or human—needs oxygen to harness the energy locked in the chemical bonds of sugars. But instead of glucose, the bacteria and archaea at the seeps take in methane as their food—and they do it anaerobically, that is, without oxygen. Methane, of course, is the main ingredient of natural gas, the fuel that you might use to boil your spaghetti. Clearly, it's easy to extract energy from methane: just add oxygen and a little spark, and you ignite a fiery reaction, in which electrons are transferred from methane to oxygen, producing carbon dioxide, water, and lots of energy. In chemical parlance, the methane is "oxidized" and the oxygen is "reduced."

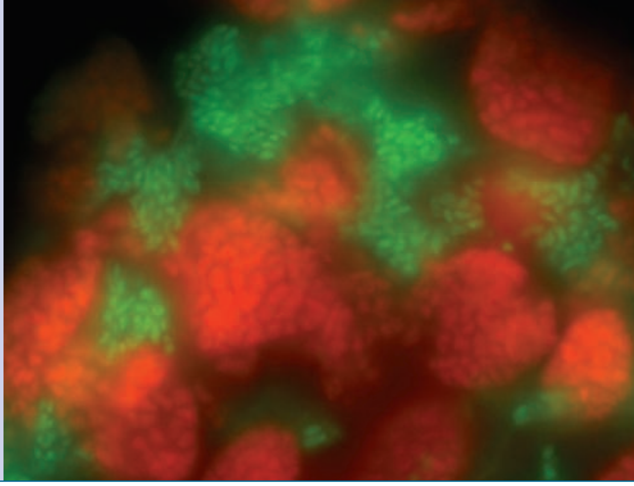
Without oxygen in the seafloor mud, these microorganisms have to oxidize methane with some other agent. One popular compound is sulfate, a salt abundant in seawater. Geochemists first proposed this process in 1976, when they looked at how the chemistry of the sediment changed with depth and discovered that methane consumption coincided with a decrease in sulfate. Because they knew of no physical process that could cause this curious correlation, they concluded that the origin must be biological—some organism was oxidizing methane and reducing sulfate.

The problem, though, was that combining methane and sulfate produces so little energy that nobody thought it could support any sort of life. Some microbiologists tried to grow a sulfate-reducing organism with methane as its sole carbon and energy source in the lab, Orphan says, but they were unsuccessful. Now, researchers know that the conditions at methane seeps (and many other natural environments) are too complex to be easily reproduced in a petri dish—in fact, scientists still haven't been able to grow pure cultures of 99 percent of all known microorganisms. Over the years, follow-up studies about whether anaerobic methane-eaters really did exist would occasionally appear in the literature, but nobody took them that seriously, according to Orphan. "The field remained dormant for several years," she says.

"Several years" ended up becoming two decades before advances in molecular biology provided the tools needed to revisit the mystery of the methane seeps. In 1999, Orphan started working on this problem as a graduate student with Ed DeLong at the Monterey Bay Aquarium Research Institute. There, a collaboration with Kai-Uwe Hinrichs, who at the time was a postdoc at the Woods Hole Oceanographic Institution in Massachusetts, proved to be pivotal in defining her scientific career. "I happened to be in the right place at the right time," she says.

Researchers were finally finding microorganisms living in the methane seeps, and some indeed appeared to be eating methane. Hinrichs was studying lipids, a class of molecules that includes fat, in samples of archaea from methane-seep mud. He discovered that some of these lipids didn't have as much carbon-13 as they ought to have. (The usual form of carbon, carbon-12, has six protons and six neutrons, while carbon-13, which accounts for about 1 percent of the total carbon on Earth, has an extra neutron.) The only way that the archaea could have such a dearth of carbon-13 is if the microbes were getting their carbon from methane, whose carbon atom is almost always of the carbon-12 variety.

There were other clues as well, Orphan says. Tori Hoehler, now at the NASA Ames



Right: These festive blobs are clusters of microorganisms. The methane-eating archaea are tagged with a fluorescent protein to glow red, and the sulfate-reducing bacteria are tagged to glow green.

Below: The researchers explore the site of a whale carcass via remote-controlled robot.

Research Center, proposed that, given the right conditions, maybe organisms could eat methane with the help of sulfate. Some archaea were known to produce methane, and there were hints that perhaps the reverse process—i.e., methane consumption—was also practical.

In addition to the low-carbon-13 lipids, Hinrich and Orphan found DNA that was closely related to those of the methane-producing archaea. The clincher came in 2001, when Orphan, along with Christopher House at Penn State, Hinrichs, Kevin McKeegan at UCLA, and DeLong, found carbon-13 depletion directly in the archaeal cells. To make this discovery, the researchers combined two techniques—fluorescence *in situ* hybridization (FISH) and secondary ion mass spectrometry (SIMS), which allowed them to directly identify the microbial cells and their isotopic compositions. "This was the first real, concrete evidence that these organisms with sulfate-reducing bacteria were indeed catalyzing this process," says Orphan.

Since then, the field has flourished, with dozens of groups around the world studying these methane-eating microbes. "The story of anaerobic methane oxidation started with geology and geochemistry," Orphan notes, and the lines between traditional disciplines have blurred. "The whole field of geobiology has blossomed because of these close interactions between geologists, geochemists, and microbiologists." Orphan herself is a prime example. Since she came to Caltech in 2004, her lab has been adapting techniques from geochemistry, molecular biology, and microbiology to try to understand these organisms at the genetic and cellular level.

PRYING OPEN THE BLACK BOX

These microbes survive because of a symbiotic partnership in which the archaea oxidize methane and the bacteria reduce sulfate. Because this requires specialized geochemical conditions that are regulated by this partnership, the archaea and bacteria have to be close together. They form clumps of about 100 to 500 cells that resemble bunches of grapes but are only a few microns, or millionths of a meter, in diameter. These clumps, called aggregates, take on a variety of arrangements: sometimes a layer of bacteria encompasses the archaea, and sometimes the two mingle. One of the questions Orphan's lab is trying to answer is how these arrangements influence the rate of methane oxidation and cellular growth.

Three distinct lineages of archaea can eat methane, Orphan explains, and they live with at least two species of sulfate-reducing bacteria, *Desulfosarcina* and *Desulfobulbus*. Together, the symbiosis produces a little energy along with bicarbonate and hydrogen sulfide, which bigger organisms like clams, crabs, shrimp, and tube worms in turn metabolize. The oxidation process isn't a one-step reaction, however, and it remains

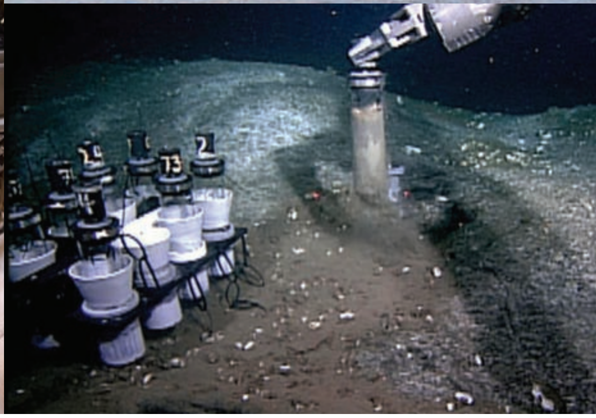
DEAD WHALE FALLS

Food is scarce at the bottom of the ocean. Organisms forced to live with such bare cupboards rely on manna from above in the form of sinking dead sea creatures. And when a whale falls, it's a buffet, spawning an entire ecosystem of animals like worms and fish, as well as microbes. "You can imagine if a big whale lands in your backyard, you're set for years," says Orphan. In collaboration with Bob Vrijenhoek at the Monterey Bay Aquarium Research Institute, her group has been conducting an extensive study of whale-fall ecosystems since 2003. Because they are self-contained, they provide a perfect natural laboratory to study deep-sea microbial carbon cycling. The team wants to know how carbon flows through the system, and is observing how the microbial communities change as the whale is slowly devoured. One of the surprises they've found is that the whale carcass (if it can be called that; after the larger animals are through with it, all that's left are some bones and baleen—or just a dark spot on the sea floor) provides such a nutrient boost that all sorts of metabolic processes happen, including methane consumption.

The first dead whale in the Monterey Bay Canyon was found by accident, Orphan says, but when scientists made it known they were interested in sunken cetaceans, fishermen and the Coast Guard started calling in whenever they saw a whale go belly-up. Now, the team is following five fallen whales at depths ranging from 600 to 2,900 meters.

Right: Dekas holds one of the tubes used to take sediment samples. Behind her is a robotic sub called the *Doc Ricketts,* which is operated out of the Monterey Bay Aquarium Research Institute. Orphan's lab uses this vehicle to study whale falls.

Far right, top: The *Atlantis* research vessel.



Far right, bottom: *Alvin*'s robot arm takes a sample of the seafloor. After picking up the mud, the arm drops the tube into the empty white canister on the left.

largely a black box.

Scientists do know that the archaea enable methane and water to react and produce an unknown intermediate compound that goes to the bacteria, which complete the job by transferring electrons to the sulfate. But no one knows what this intermediary is—or for that matter, many other details about the process. We aren't even sure how much these organisms depend on each other to live, Orphan says. "We think they require each other for anaerobic methane oxidation, but there are occasions where you find these archaea without bacteria. We're still in the process of seeing if those archaea are active, or if they were at one point attached to a bacterial buddy."

To pry open the black box of the methane-eating microbes, Orphan and her colleagues must go to sea. Methane seeps tend to form at the continental margins, the line on the seafloor where the continental crust stops and the oceanic crust starts. The researchers spend days to weeks aboard ship, using remote-controlled robot submersibles to stick half-meter-long tubes into the seafloor, capturing cylindrical cores of mud teeming with microorganisms. Thin samples are sliced from the cores as soon as they are hauled in, preserving any variations with depth for later analysis.

Orphan often sails on the *Atlantis*, an 84-meter research vessel owned by the Navy and operated by the Woods Hole Oceanographic Institution that can support a crew of 36 for up to two months. And with *Atlantis* comes *Alvin*, a deep-diving, three-person minisub. Built in 1964, *Alvin* has taken thousands of scientists to the ocean depths and in 1966 was used to find a missing hydrogen bomb off the coast of Spain, but its biggest claim to fame may be exploring the wreck of the *Titanic* in 1986.

Inside the compact vehicle—whose interior, Dekas says, isn't much bigger than the front seat of a car—the two passengers are each glued to their own window, directing the pilot where to go. Even though they know the coordinates of some of the methane seeps, pinpointing their exact location can still be a challenge. "When we first got to the bottom, all we could see was this gray, silty, ocean-bottom nothingness," Dekas says of her thousand-meter dive off the coast of Costa Rica last February. "Our first job was to look out the window for organisms that live on the waste products of anaerobic methane oxidation—creatures like clams, tube worms, or a kind of white fuzz on the ground, which would be a sulfide-oxidizing bacterial mat. Once we started to see them, we'd call them out to each other: 'Oh! A bush of tube worms over here!'" A typical dive at the bottom of the ocean lasts about seven hours, which raises the question of restrooms. "They give you a bottle—with an attachment if you're a woman," Dekas answers. "There's no privacy; you become really good friends really quickly."

In 2006, *Alvin* took Orphan down 500 meters to the floor of the Eel River Basin, about 30 kilometers off the coast of Eureka in northern California. It was these samples that led to the discovery that deep-sea methane oxidizers not only curb oceanic methane emissions, but also may play a role in the cycling of nitrogen. "Nitrogen is in DNA and all of your proteins," says Dekas. "It's pretty much an essential element for life." But in its gaseous state, nitrogen takes the form of two atoms sharing electrons in a tight triple bond. You need a lot of energy to break that bond and reduce N_2 to a biologically usable form such as ammonia (NH_3), a process called nitrogen fixation. In fact, wresting those two nitrogen atoms apart takes about 800 kilojoules per mole, with a mole being about 6.022×10^{23} molecules. Since the methane-eating microbes had to

"When we first got to the bottom, all we could see was this gray, silty, ocean-bottom nothingness," Dekas says.

Far left: Posing with *Alvin* are postdoc Burt Thomas (USGS), Orphan, postdoc Jake Bailey, Dekas, Shana Goffredi, and postdoc David Fike.

Leftt: Orphan at the controls of a robotic sub.

subsist on a meager energy budget—the methane oxidation reactions only yield about 40 kilojoules per mole of methane at the seeps—no one thought they could afford to fix nitrogen.

But in 2008, the researchers found genes in the archaea that suggested otherwise. This collaboration consisted of postdoc Annelie Pernthaler, now at the Helmholtz Centre for Environmental Research in Leipzig, Germany; Dekas; C. Titus Brown (PhD ’07), then a biology postdoc who is now an assistant professor at Michigan State University; Shana Goffredi, then a senior research fellow and now an assistant professor at Occidental College; Tsegereda Embaye, a technician with the lab; and Orphan.

In order to get to the genomes, the researchers first had to single out the microbial cells from a patch of mud—a task more daunting than retrieving the proverbial needle from the haystack.

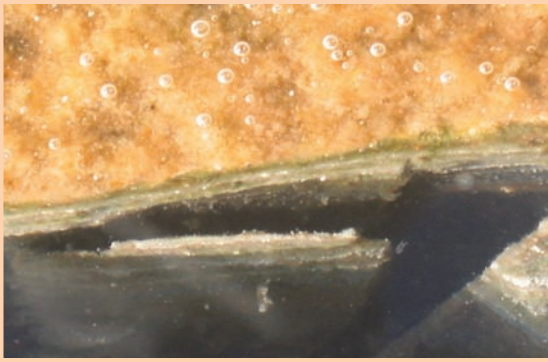
Magnets work well for finding needles, and coincidentally, Orphan’s lab developed a Caltech-patented technique called magneto-FISH to find the microbes. (Remember, FISH stands for fluorescence *in situ* hybridization.) The ribosome, the protein-making machine of every species, includes unique molecules of RNA, a one-stranded molecule that is similar to DNA. Both RNA and DNA are made up of a sequence of “bases”—the letters of the genetic alphabet. RNA and DNA can bind to each other by matching letters on the DNA strand with complementary ones on the RNA strand. Thus, you can pick out an RNA strand with a DNA probe—if you know the sequence of the RNA you’re looking for, you can design a single-stranded fragment of DNA with the complementary sequence of bases. The probe will then bind to that specific RNA molecule. Attaching a fluorescent molecule to the probe turns it into a marker, illuminating the bound RNA—and, therefore, the cells you want to find. These probes come in several colors, allowing the researchers to distinguish the bacteria from the archaea by their hues.

But you still have to get the bugs out of the mud, and this is where “magneto” comes in. The researchers attach tiny magnetizable beads, about five microns in diameter, to an antibody that targets the fluorescent molecules. The antibodies then bind to the outside of the glowing archaeal cells. Using a magnet, the researchers can then lift the cells out of the muck.

Pernthaler and her colleagues used magneto-FISH on the archaea and found *nif* genes, which were known to encode enzymes needed to fix nitrogen gas. But just because the microbes have the necessary genes to fix nitrogen doesn’t mean they actually do so. To find out, Dekas, Orphan, and Rachel Poretsky, a postdoc, incubated the cells for six months in an atmosphere of methane spiced with nitrogen gas made

MATS OF MICROBES

Bacterial mats are layered carpets of bacteria that thrive in extreme environments—salt flats, hot geothermal vents, or ocean bottoms. At several centimeters thick, and sometimes stretching for hundreds of square kilometers, these masses of microbes can be vast. With different species of bacteria in every thin layer, they are also one of the most diverse ecosystems on the planet, Orphan says, and likely covered Earth before the rise of multicellular organisms. Orphan’s lab studies the biochemistry and changing abundances of sulfur isotopes in layered mats like this one, taken from the Guerrero Negro saltworks in Baja California Sur. At the top layers of the mats, where sunlight is plentiful, photosynthesis with oxygen occurs. But further down, the microorganisms survive through processes without oxygen. These mats, which look sort of like moldy lasagna, were prevalent early in Earth’s history and likely influenced sulfur cycling on a global scale. Like the microbes at methane seeps, these mats show how life endures in unexpected places. e&s



Right: Layers of a bacterial mat. The orange layer is made of microorganisms—mainly diatoms and cyanobacteria—that use photosynthesis to make energy. The microorganisms that make up the black layer are anaerobic, producing energy by sulfate reduction, fermentation, or other oxygenless processes.

Left: The researchers encounter an octopus as they take samples in the Eel River Basin.

Right: While on a dive, Orphan finds an impressive surprise.

from nitrogen-15. (Like carbon-13, nitrogen-15 is a stable, naturally occurring isotope, making up about 0.36 percent of the world's nitrogen.) The presence of nitrogen-15 in the archaeal cells would therefore show that they were fixing nitrogen.

The team looked for the nitrogen-15 with a technique called nanoscale secondary ion mass spectrometry (nanoSIMS), in which the cells were scanned by a beam of cesium ions. These heavy, high-energy particles blasted the cells into oblivion, and whatever lighter ions bounced back out from the wreckage were collected and identified. The result was a map of the nitrogen-15 distribution in the archaea and their bacterial partners.

When the researchers combined these maps with FISH-generated images of the bacteria-archaea clusters, they saw nitrogen-15 concentrated in the archaeal cells. "That's when we knew that the archaea were able to fix nitrogen, because we could see nitrogen-15 in their biomass," Dekas says. To a lesser degree, nitrogen-15 was also present in the bacterial partner, meaning that the archaea were sharing the valuable nutrient.

> "That's where I see my big contribution," Orphan says. "To be able to do these experiments with living communities and environments that likely have relevance for early Earth ecosystems."

To compensate for the energy-intensive process of fixing nitrogen, the microbes slowed their growth. When the organisms were incubated with ammonia, which takes far less energy to break down, they grew about 20 times faster than those forced to fix nitrogen gas.

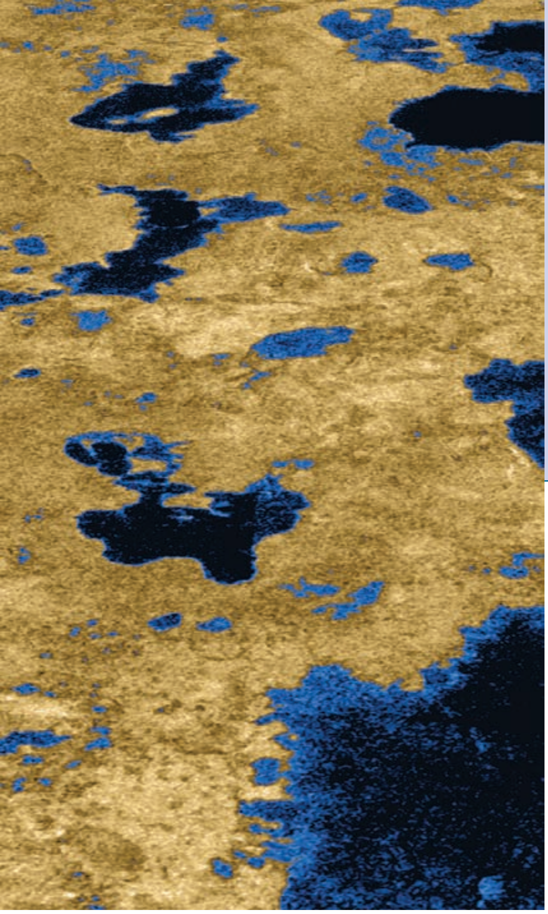
This discovery, which was published in the October 16, 2009, issue of *Science*, has also shed light on the global nitrogen cycle. Previous attempts to balance the global nitrogen budget had come up short—more nitrogen was being consumed than was being fixed. The archaea at the methane seeps don't fix enough nitrogen to make up the difference, but the fact that they are doing it suggests that other organisms in unexpected places may also be fixing nitrogen, and together, these overlooked sources may be significant. The find also poses the question: what else are these microorganisms capable of?

PUSHING THE BOUNDARIES OF LIFE

When the microbes eat methane, electrons are transferred from the hydrocarbon to the sulfate. Now Orphan, with Christopher House and graduate student Emily Beal at Penn State, have discovered that the microbes can reduce other compounds as well. Even though sulfate reduction is the best-known way to oxidize methane anaerobically, it's not necessarily the most energetically favorable. Orphan, House, and Beal discovered that manganese and iron also did the trick, describing their findings in the July 10, 2009, issue of *Science*. Carried out to sea by rivers, both metals are abundant: if all of the world's biologically available manganese and iron were used, they could account for perhaps one-quarter of all anaerobic methane oxidation.

Beal incubated sulfate-free methane-seep mud for 10 months with either manganese or iron. The microbes reduced the metals very slowly—likely because as solids, the metals require more time to react. But at 556 kilojoules and 270 kilojoules per mole for manganese and iron, respectively, there's a lot more bang for the buck. It's still unclear which bugs are reducing these metals, but it appears that they're the same archaeal and bacterial symbionts that reduce sulfate, Orphan says, showing that these partnerships are quite versatile.

The fact that these microbes can consume methane several ways means there's a good chance similar organisms existed on the early Earth. Oxygen didn't appear on the planet until less than 2.5 billion years



Left: During a flyby of Titan in 2006, Cassini took this false-color radar image of the moon's surface. In general, brightness corresponds to roughness. The dark areas are very smooth, suggesting they could be lakes or seas.

Below: What was once a whale is now just a smattering of bones and baleen. On the right, crabs crawl on carbonate outcrops.

ago—also through bacteriological activity, as described in *E&S* 2005, No. 4—but the first forms of life appeared some 1.5 billion years earlier. Methane wasn't the only substance around at the time, but it certainly would've been a convenient source of food . . . if it could be eaten.

Studying these bugs, then, is also a way to understand primordial Earth and to unravel the evolution of early life. The present-day organisms that populate methane seeps probably share much of their DNA with those first earthlings. Genetic analyses could trace their evolutionary relationships back to the earliest life forms, Orphan says. And, in some sense, today's seep-dwellers are living fossils whose biochemistry could help researchers better understand ancient environmental conditions and interpret the hazy history embedded in the few old rocks that still exist. "That's where I see my big contribution," she says. "To be able to do these experiments with living communities and environments that likely have relevance for early Earth ecosystems."

The implications might go beyond our planet. The discovery of methane-seep communities and deep-sea hydrothermal vent communities in the 1970s raised some hopes of eventually finding extraterrestrial life. If creatures can thrive in such dark and cold conditions without oxygen, then maybe life could also take hold in even harsher, more alien environments. "For much of the time of life on Earth, life was dominated by anaerobic metabolism," says Dekas. "And if there's life on other planets, then that's probably what's going on there, too."

Could methane be a sign of E.T.? That's one reason why astronomers are fascinated with Saturn's largest moon, Titan, which has a thick nitrogen atmosphere with trace amounts of methane. In 1980 and 1981, the Voyager 1 and 2 spacecraft found evidence of methane lakes on Titan's surface. The ESA's Huygens probe landed on Titan in 2005, and although it didn't splash onto a methane ocean like scientists thought it might, it returned a trove of images showing apparent river flows and channels, as well as finding a constant drizzle of methane rain. But Huygens found no signs of life, nor has the spacecraft that brought it there, JPL's Cassini orbiter. Cassini has, however, mapped countless smooth features that look like lakes and seas—the largest surpassing Lake Superior in area.

Needless to say, scientists have a lot to learn about the archaea and bacteria that together do so much for Earth—laying the foundations for a deep-sea ecosystem, helping to shepherd the global cycling of vital elements, and preventing methane from further warming the planet. "If all bacteria and archaea just stopped functioning, life on Earth would come to an abrupt halt," Dekas says. "I can't think of anything as important as that."

Victoria Orphan received her BA in aquatic biology in 1994 and her PhD in ecology, evolution, and marine biology in 2001 from UC Santa Barbara. After a stop at NASA Ames Research Center, she became an assistant professor at Caltech in 2004.

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PICTURE CREDITS
12 — Anne Dekas; 13 — Bill Youngblood; 14 — Jessica Zha and Victoria Orphan; 15-19 — Victoria Orphan; 17 — Chris House; 19 — NASA/JPL/USGS