20,000 Microbes Under the Sea

Scientists have discovered that nearly a third of all the life on this planet consists of microbes living under the seafloor in a dark world without oxygen. Many of these tiny creatures make so much methane gas that if even a small proportion of it is released, we might be overwhelmed by huge tsunamis, runaway global warming, and extinctions

By Robert Kunzig

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The thing about the mud hoisted from the bottom of the Black Sea in the summer of 2001—the thing that surprised and delighted the researchers aboard the *Professor Logachev*—was that there was hardly any mud at all. They were 75 miles west of the Crimean city of Sevastopol, 750 feet above an undersea slope along which sediment from the Dnieper River cascades down into the depths. With a set of giant steel claws guided by a video camera, they had taken a one-ton bite out of that slope and dumped the goopy mess on deck. It stank. That didn't surprise anyone—seafloor mud often contains hydrogen sulfide, which smells like rotten eggs. But they were struck by what else was in the sample: "Nearly one ton of biological material," says Walter Michaelis, a biogeochemist at the University of Hamburg in Germany, who led the expedition. "No sediment. No carbonates. It was a cubic meter of bacteria!"


Photograph by Jonathan Kantor

A few days later, Hamburg geologist Richard Seifert got a look at the seafloor where the bacteria came from. Diving in a little German submarine called *Jago*, peering through an acrylic porthole several inches thick, he saw a fog of floating particles. Then, looming out of the dark and into the sub's tight halo of floodlight, through curtains of rising bubbles that made it seem as if the sub were driving through champagne, Seifert saw chimneys—black, knobby spires, the tallest rising more than 13 feet off the seafloor. Chimneys made by erupting volcanic minerals are common at hot springs in mid-ocean ridges. But this was not a hot spring, and these chimneys were not built of volcanic rock. The pilot prodded one with *Jago*'s hydraulic arm. It was soft, like flesh. He knocked one over, felling it as if it were a tree to reveal its cross section. Under a black outer layer there was a thick layer of pink and a core that was harder and greenish gray.

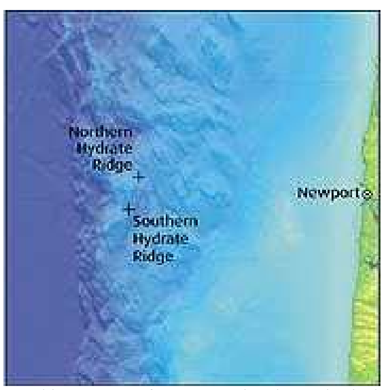
The chimney had been made entirely by single-celled microbes. The microbes formed the outer layers; the hard core was a carbonate mineral they had secreted. What Seifert and his colleagues had discovered was an outcrop—of life. The evidence is now clear that far below the sea, and far below the floor of the sea, in sediments all over the world, microbes live to astonishing depths—the record so far is half a mile—and in astonishing numbers. The deepest of the microbes make methane, which the ones in shallower sediments consume. To all of them, oxygen is poison. They are relics of an early period in Earth's history when methane was abundant and green plants had not yet given the planet oxygen. "Maybe the early Earth was all covered with blackish, pinkish slime," says Antje Boetius, a biogeochemist and geomicrobiologist at the International University in Bremen, Germany.

Today these ancient organisms have been pushed into obscure niches where oxygen does not penetrate. Mostly that means below the seafloor—except in a few special places like the Black Sea. With only the narrow Bosporus as an outlet, the Black Sea is seldom flushed, and the oxygen in its deep water, below 600 feet or so, has long since been depleted. No fish live at that depth. But microbes do, thriving on methane that bubbles up from below. The methane is made by the microbes' deeper cousins, and they are numerous.

The total mass of microbes living beneath the seafloor has been estimated at as much as a third of all the living stuff on the planet. The total amount of methane made by these microbes is probably greater than the mass of all known reserves of coal, gas, and oil. Methane is a potent greenhouse gas, and huge belches of microbial methane from deep reservoirs, where it resides mostly as frozen methane hydrate, have been linked to rapid changes in Earth's climate. They may have helped pull the planet out of recent ice ages, and they almost certainly helped end the Paleocene Epoch 55 million years ago with an intense burst of global warming. Nor are the potential impacts of deep-sea methane limited to climate. Blasts of it have been linked, in respectable journals, to mass extinctions, to undersea landslides that caused ocean-crossing tsunamis, and even to the mysterious disappearance of ships at sea.

All that may seem a lot of action to attribute to mud. But that's precisely the essence of what researchers have been finding lately: Seafloor mud is alive, and it is powerful. It's the whale we managed not to notice until now.

The thing about the mud that marine geologist and geochemist Erwin Suess hoisted from the bottom of the Pacific in 1996, half a mile down and 60 miles off Newport, Oregon, was that it was seething—cold, but seething. On the TV monitor aboard the research vessel *Sonne*, he could see the mud as it was brought to the surface. A few minutes later, on deck, "the whole cubic meter of stuff was bubbling," he says. "It was just one smelly olive green mess of sediment. People were hesitating, standing back, because it was just an awful smell, the hydrogen sulfide. So I rolled up my sleeves and reached in that mess and stood up to my ankles in it, and then touched this hard stuff—it was cold, ice cold. I threw it on the deck to get rid of the sediment, because it was all covered, and it broke open. It was pure white."



Graphic courtesy of NOAA National Geophysical Data Center

FROZEN: Scientists excavating the ocean floor have found huge chunks of frozen methane along Hydrate Ridge, about 60 miles off the coast of Oregon. The ridge is accretionary and lies only about 6 miles east of the deformation front where the Pacific tectonic plate plunges under North America.

A lot of photos were snapped on the *Sonne* that day and on later cruises to the same spot. The photos show rubber-gloved hands holding slimy hunks with the color contrast of a coconut: brownish on the outside, white on the inside. In some of the pictures you can see little craters in the white stuff, the hemispheric outlines of vanished bubbles. In others you see people boring into it with power drills, slicing it with knives, plunging it for safekeeping into basins of liquid nitrogen. You see young scientists grinning ear to ear as they hold pieces of the white stuff in their hands—showing the camera how it can be ignited, how it burns brightly with an orange flame.

The white stuff is methane hydrate, and it is weird. Researchers call it icelike. It is frozen solid, but it is not exactly ice. It is a form of clathrate, a term derived from the Latin word for cage. Methane hydrates consist of molecules of methane trapped in cages of H_20. Typically, six water molecules surround a single methane molecule, and many of those cages linked together form a crystal. Only at high pressures can methane insinuate itself into water this way. But if the pressure is more than 30 times the normal atmospheric pressure—easily exceeded under a thousand feet or more of water—hydrates can form at temperatures above 32 degrees Fahrenheit. This usually happens just beyond the continental shelf, where it slopes down into the abyss.

There is a precise curve of temperatures and pressures that define the depth at which methane hydrates exist. The bottom of that zone, deep in the seafloor mud, is where the temperature gets too high, toward Earth's hot interior; the top of the zone is where the pressure gets too low, moving toward the surface. Leave the zone in either direction and the partnership of methane and water dissolves. When you bring a chunk of methane hydrate up to the surface, the water melts and drips through your fingers; the methane gas wafts into the air.

Hydrates have been a curiosity for nearly 200 years. Natural methane hydrates were first discovered by Russian scientists in the late 1960s in Siberian permafrost—where the ground is so cold that hydrates can form at shallower depths and at lower pressures than under the sea—and then, in the 1970s, at the bottom of the Black Sea. (So much methane comes out of the Black Sea that sailors have reported seeing lightning igniting it at the surface.) It was not until the 1980s that researchers drilling into the ocean floor first began to understand that this stuff is everywhere. Usually, though, the frozen hydrates they brought up in cores were small, like pencil erasers.

The chunk that Suess brought up off Oregon was a foot and a half across. There was plenty of it to study. Over the years, as researchers have returned to the place they named Hydrate Ridge, they have learned a lot about how methane hydrate is created there. Hydrate Ridge is one of several accretionary ridges off Oregon, long layers of mud that get scraped off the Pacific tectonic plate as it plunges under the North American continent. Methane gets squeezed out of the deepest layers of sediments like water from a sponge and migrates up toward the seafloor. The southern summit of Hydrate Ridge, about 2,500 feet below the sea surface, is a field of mounds and depressions 10 to 20 feet across. It was from one of those mounds that Suess's team grabbed chunks of thick, pure methane hydrate.

There is a lot of methane under Hydrate Ridge. Under most frozen hydrate deposits is a layer of free methane gas occupying the pore spaces in the sediment. Typically, that's how the deposits are discovered because the boundary reflects sound well enough for a survey ship to detect it. Under some parts of Hydrate Ridge there is so much methane gas, says German geologist Gerhard Bohrman, that it is constantly bubbling up into the hydrate zone. There is so much methane that, as it freezes instantaneously to form hydrate, it draws all the water out of the seafloor ooze and dries it out completely—and often there is methane left over, trapped as large bubbles in the porous hydrate. Bohrman proved that by bringing a sediment core up in an autoclave. He kept it under pressure while he had it CT-scanned in a clinic in Palo Alto. Before that he and his shipmates had seen how buoyant the hydrate was: As they worked off the coast, large blocks of it sometimes bobbed to the surface near the ship.

There is so much methane rising up under the southern summit of Hydrate Ridge that some of it bubbles all the way to the seafloor. "You build up too much free gas, and then you have an overpressured column," says Gerald Dickens, a marine geochemist at Rice University who went to Hydrate Ridge on a drill ship in 2002. "And the gas just cracks the sediment and migrates right up to the seafloor." Seafloor gas chimneys have been turning up in many places, Dickens says, now that researchers know how to recognize them on seismic readouts. And places where methane bubbles into the seawater, as it does at Hydrate Ridge, are commonplace around the world.

Ultimately, that methane is derived from bigger and more complex organic compounds in the buried sediment. That's why hydrates, like oil—and like fish—tend to be found along the world's coastlines, where the waters are rich in nutrients and plankton corpses fall like thick snow to the seafloor. It used to be thought that the methane in hydrates was made the way oil is—that Earth's internal heat makes methane, the smallest hydrocarbon, by cracking bigger hydrocarbons at depths of more than a mile below the seafloor. But then researchers started looking at the carbon isotopes in hydrates. They found that most hydrates, compared with the sediments around them, are enriched in the isotope carbon-12 and depleted of the heavier carbon-13. Heat would not be choosy that way about the molecules it cracks. Life, however, is choosy: All living things selectively take up carbon-12 and reject carbon-13.

The carbon-isotope ratio of seafloor hydrates indicates that the methane was made by microbes. “These microbes are forming enormous amounts of gas,” says Dickens. “But it’s not like the hydrates are just building up over time, because we’re also losing methane out of these systems.” The puzzling thing is that methane isn’t bubbling up *everywhere*. But that puzzle was solved at Hydrate Ridge.

Antje Boetius was a young biogeochemist aboard one of the research expeditions off Oregon in 1999. She had recently moved to the Max Planck Institute for Marine Microbiology in Bremen, which collaborates closely with Suess’s group, to learn a couple of fundamental techniques of molecular ecology she needed to complete her own research project in the Indian Ocean. That project was not related to hydrates or to the deep biosphere. It was “just regular deep-sea research—going to the big wide cold ocean,” Boetius says now, as one who has left all that behind. The discovery she made at Hydrate Ridge changed her career.

What captured Boetius’s imagination there were the clusters of organisms, known as cold-seep communities, which had taken up residence around the places where methane seeps from the seafloor. Suess was among the first researchers to discover a cold-seep community. While he was working at Oregon State two decades ago, some of his colleagues explored a seafloor hot spring near the Galápagos Islands and brought back specimens of giant white clams collected with the submersible *Alvin*. The first time Suess got to dive in *Alvin*, in 1984, it was nearly 5,000 miles northwest of the Galápagos, just a few miles west of Hydrate Ridge and nowhere near a hot spring. Yet “there were the same damned critters,” he says. Not just clams but also tube worms and thick mats of bacteria, white or bright orange. Years later Suess would see those same mats draping the mounds at Hydrate Ridge, with the clams huddled around their edges.

Graphic by Don Foley, based on map produced by U.S. Geological Survey

GAS HYDRATES EVERYWHERE

The red dots indicate where researchers have proved that gas hydrates exist and where they are suspected to exist. But no matter where researchers now drill under the sea, they find methane, often in the form of a hydrate. Major concentrations off the coast of the United States have been found along the edge of the continental shelf between New Jersey and Georgia. U.S. Geological Survey researchers estimate that the Blake Ridge alone, off the South Carolina–Georgia coast, contains 30 times as much methane as Americans consume in natural gas every year.

In the meantime, cold-seep communities had been discovered all over the world. They remained a mystery. As Boetius puts it, “Where does it all come from?” In most of the big wide cold ocean, life on the seafloor is much sparser than it is at hot springs and cold seeps because it is sustained only by scraps of organic matter falling from the sunlit surface waters—by trickle-down photosynthesis. At hot springs on mid-ocean ridges, life is sustained by chemosynthesis; the energy source is not the sun but hydrogen sulfide made by hot water flowing over volcanic rock. Sulfide-eating bacteria use that energy to make carbohydrates and build tissue, and the animals either eat the bacteria or incorporate them as symbionts in their tissues. The clams and tube worms at seeps do likewise, but there is no heat source, so the mystery remains: Where does all the sulfide come from?

Another related question presented itself to Boetius at Hydrate Ridge: Where does all that methane go? Most of the methane made in the deep sediment layers by microbes never gets to the surface. For decades geologists have reported that methane concentrations decrease as sediments become more shallow. Meanwhile, sulfate does just the opposite: It's abundant in seawater, but its concentration in sediments decreases steadily with depth. Invariably, there is a layer where both compounds dwindle rapidly—as if they were both being used up by the same process.

Geologists had suggested one process: Maybe there were methane-eating microbes in that sediment layer—microbes that were oxidizing methane with sulfate rather than oxygen because at that depth there is no oxygen. The trouble was, microbiologists had never been able to find such microbes. Friedrich Widdel, a microbiologist at the Max Planck Institute, looked in all sorts of anoxic sediments, from tidal flats to sewage sludge; he would take a sample, add methane to it in the lab, and see if anything ate the methane. "Nothing ever happened," says Boetius. "One postdoc—he's still at Max Planck—he tried for five years. It happened to all of us. I know a hundred microbiologists who tried." Not surprisingly, some concluded the mystery microbes didn't exist.

But Boetius had a strong reason to believe. It was the other mystery, the one that had brought her to Hydrate Ridge in the first place—all those sulfide-eating clams and bacterial mats squatting on a methane vent. In theory, the missing microbes might solve that mystery too: In using sulfate to oxidize methane, they should be reducing the sulfate to hydrogen sulfide. Nor did this complicated chemical transaction necessarily have to be going on in a single microbial cell. In 1994 Tori Hoehler of the NASA Ames Research Center had suggested that two separate species of microbe, a methane eater and a sulfate reducer, might be collaborating symbiotically in the deep-sea mud.

When Boetius got her Hydrate Ridge mud back to the lab in Bremen, she quickly saw that this idea was promising. She measured the rate at which sulfate was being reduced in the mud and found the highest rate ever measured in marine sediments. She stained the sediments with a dye that would cause microbial DNA to fluoresce under her microscope so she could count the number of microbes in the mud. She found up to 3 trillion cells in an ounce. Normal marine sediments have a mere 30 billion.

Then she tried to identify those microbes using a technique called FISH, for fluorescence in situ hybridization. She had learned it in the lab of molecular geneticist Rudi Amann. In FISH, the fluorescent dye is attached to a genetic probe that binds only to the equivalent gene in a certain kind of microbe. By using a series of probes, a researcher can get increasingly specific about which microbes are in sediment—as long as someone has made probes for them. Boetius was fortunate to have a probe made by Ed DeLong of the Monterey Bay Aquarium Research Institute, who along with German researcher Kai-Uwe Hinrichs had recently identified the genes of a possible methane eater in sediments off California.

Boetius's big moment happened in a dark room at the Max Planck Institute late on a Saturday night, when she would have rather been out dancing. She was sitting in front of the microscope, staring at images of sediment slices. She had used probes designed to detect 20 different species of sulfate-reducing bacteria before she finally found one that would produce glowing dots on the screen. The probe from DeLong and Hinrichs, on the other hand, had worked right away: The Hydrate Ridge sediments were loaded with their methane eater, which is not a bacterium at all but a species of Archaea, an ancient group of microbes that diverged from bacteria billions of years ago and are as distinct from them now, genetically speaking, as humans are.

Boetius was trying to count those dots on her computer screen, first the archaea and then the sulfate reducers, to find out how many were in her sediments. The cells were clumped together, which made them maddeningly hard to count. Then, in her growing irritation, she noticed something. “I see these stupid clusters of archaea, and now I see these stupid clusters of sulfate reducers,” she says. “And they had a very funny shape. The archaea looked like real clumps—lots and lots of cells sitting together. The sulfate reducers were like shells, a circle of sulfate reducers with nothing in the middle. And, really, I sat there for two hours before it finally popped into my head.”

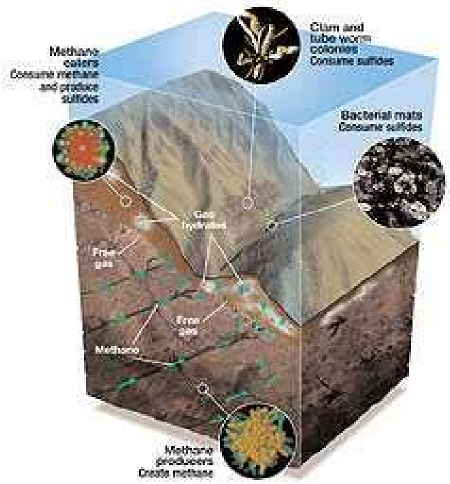
The sulfate reducers were stuck to the archaea, forming a shell around them. Tori Hoehler’s idea of a microbial consortium suddenly looked compelling. Boetius and Widdel and graduate student Katja Nauhaus at Max Planck later performed the same experiment they and other microbiologists had done so many times before in vain—injecting methane into the sediment. But this time it vanished, and sulfide appeared in its place. Each clump was less than one-thousandth of an inch across and contained hundreds of cells. There were about 900 million clumps in every ounce of sediment at Hydrate Ridge.

The archaea in Boetius’s clumps were close relatives of other archaea that live a quarter or a half mile down—the ones that make the methane in the first place. The methane makers assemble the gas from hydrogen and carbon dioxide; the methane eaters do something like the reverse—but not quite, because they don’t seem to give off hydrogen. In some way that remains unclear, they pass energy onto the sulfate reducers that surround them. What the archaea get in return is also not clear. “There’s some kind of delicate interaction that we do not understand,” says Widdel. He has a postdoctoral student and a graduate student trying to grow the consortium in a laboratory, knowing that the reason he and other microbiologists failed to do so in the past is that the microbes grow extremely slowly. “We know it will take time,” Widdel says. “We might need two or three Ph.D. theses.”

Why is it worth the trouble? Boetius and her colleagues have found the consortium in 20 or so other places around the world—everywhere they have looked, including a mud volcano in the Arctic Ocean, and at cold seeps and hydrate mounds in the Gulf of Mexico. Two years ago, in a kind of crater off the Democratic Republic of the Congo, 10,000 feet down, a team led by Myriam Sibuet of the French Research Institute for Ocean Exploitation, discovered a spectacular cold seep with a vast field of clams and mussels, blue shrimp, purple sea cucumbers, and six-foot-long tube worms growing in bushes next to mounds of gas hydrate. Boetius’s microbes were in the mud there too. Boetius thinks her consortium, or something like it, provides sulfide at cold seeps everywhere. It is at the base of the food chain for these seafloor oases.

In the Black Sea, on the other hand, the consortium is the food chain. The mats on the seafloor there, and the walls of the chimneys, are a thick patchwork of methane-eating archaea and sulfate-reducing bacteria. The carbonate cores that allow the chimneys to stand tall are a by-product of the microbes’ metabolism. (At Hydrate Ridge there are giant slabs of carbonate.) A network of microscopic channels allows water to circulate through the chimneys, supplying the microbes with the chemicals they need. “It’s astonishing that as microorganisms they build up structures like that,” says Seifert.

It’s astonishing, too, to think what Earth would be like if these microorganisms didn’t exist. All the methane that is now being converted to carbonate and biomass would instead be bubbling freely from the seafloor—everywhere. Hinrichs and Boetius have estimated that an additional 300 million tons a year of methane would escape from the mud. It’s not clear how much of a greenhouse effect that would produce, but it's a good bet that Earth would be a lot warmer—much as it would be, say, if there were no plants drawing carbon dioxide out of the atmosphere. "Everybody knows that our planet would be a different planet if there weren't any plants," says Boetius. "But nobody has thought about who keeps us from having a methane atmosphere." All of which is a lot more than a thought experiment—because in the past the microbes have not always succeeded as well as they do today.



Graphic by Don Foley (click to enlarge 62k)

AN UNSTABLE ECOSYSTEM

The seafloor methane cycle is a loop in the planetwide carbon cycle that governs climate—a loop that has mostly been ignored. The methane cycle is run by microbes. Hundreds of yards below the seafloor, microbes called archaea produce methane from hydrogen and carbon extracted from organic sediments. The methane bubbles up along faults and fissures (green arrows). As it approaches the seafloor, it chills, and in many places it freezes, together with water in the mud, into solid methane hydrate (white). The hydrate is extremely unstable; as it gets buried deeper by fresh sediment falling on the seafloor above, it warms enough to release its methane again. A small fraction of all the methane bubbles up from the seafloor at cold seeps, which are turning out to be extremely common along the edges of continents. But ordinarily most of the methane never makes it into the water. Instead, it gets eaten by other species of archaea, which in turn supply energy to microbial partners, bacteria that can reduce sulfate in the mud to hydrogen sulfide. It is this foul-smelling compound that provides food for the clams, tube worms, and other animals that cluster around cold seeps on the seafloor itself. The trouble with this fascinating cycle, as far as humans are concerned, is that it is extremely unstable. "You can build up enormous amounts of methane over time," says Gerald Dickens, both in the frozen hydrates and as free gas below them. When that happens, it doesn't take much—a submarine landslide or a slight warming of the bottom water—to release potentially catastrophic burps. —R. K.

Just off the coast of Norway there is a 1,000-foot-high rock cliff that fishermen long ago named Storegga. The name means "big edge." Storegga is at the edge of the continental shelf, where the bottom drops out on fishing boat depth-sounders. On the seafloor here, the bottom dropped out about 8,200 years ago in a massive landslide.

The landslide was one of the greatest in Earth's history. It probably started on the middle of the slope, in a layer of weak, porous sediment, says Jürgen Mienert, a marine geophysicist at the University of Tromsø in Norway. It then propagated rapidly back toward the shelf, as if the slope were a hamburger and a giant from the abyss had taken bites out of it. They were big bites: Blocks of mud perhaps 20 miles long, a couple of miles wide, and 150 feet high rushed down the slope. More than 1,000 cubic miles of sediment and rock shifted. The slide ran out 500 miles to the northwest, north of Iceland, where it met the Mid-Atlantic Ridge and was diverted south. Over an area of 35,000 square miles, the whole ocean was as muddy as the Mississippi after a storm, and the seafloor was wiped clean of whatever lived there. “The whole slide happened in a very short time,” Mienert says. “Perhaps in a few weeks, perhaps a few days, perhaps a couple of hours.”

At the edge of the shelf, where the giant hit rock too hard to bite, there is a now a cliff—Storegga. The landslide made a hole in the ocean into which water rushed down, then bounced back. The disturbance propagated a tsunami that flooded coastal areas as far away as Scotland. Along the coasts of Scotland and Norway, the wave ranged between 20 and 50 feet high. It may have crested at 65 feet as it roared up narrow Norwegian fjords.

Photograph courtesy of GEOMAR, Kiel, Germany

FLAMMABLE: Graduate students Barbara Teichert and Marcus Elvert, aboard the RV Sonne at Hydrate Ridge, marvel at how easily methane hydrate burns. Water molecules surround methane molecules to form the hydrate. The water quickly melts at surface pressures, releasing the methane.

To say that the cataclysm was caused by deep-living microbes would be excessive—but their methane may have had a lot to do with it. There are gas hydrates under the seafloor at Storegga today, and before the slide, says Mienert, there were probably a lot more. Around 11,000 years ago, as the last ice sheets retreated from Norway and the Norwegian Sea, Atlantic water flowed in and warmed the bottom by about 9 degrees Fahrenheit. Mienert’s team has calculated that it would have taken about 3,000 years for that warming to propagate down through the sediment to the base of the hydrate stability zone, where methane is always on the edge of becoming gas. Right at the time of the Storegga slide, the hydrate was being melted by global warming.

On the continental shelf just north of the headwall of Storegga, there are cracks in the seafloor, maybe 3 miles wide and 50 feet deep and dotted with round pockmarks. That’s where the methane came out. Frozen hydrate cements sediments together. Melted hydrate, with gas bursting to get out, weakens them. There was already a layer of weak sediments on the Norwegian continental slope, and it is probable that an earthquake was what triggered the slide. But it’s equally probable that the gradual melting of the hydrates made it possible—and made it worse.

And it’s likely to happen again, somewhere. In the spring of 2000 a team of American researchers caused a tremendous stir when they announced that they had found cracks and pockmarks, much like the ones off Norway, at the edge of the continental shelf near Cape Hatteras. So far they have no way of computing the risk of an undersea landslide there, and thus the possibility of a large tsunami submerging the mid-Atlantic seaboard—although it’s surely less imminent than the next major hurricane. They are, however, confident that those cracks and pockmarks are places where methane has exploded from the seafloor. Pockmarks are turning out to be extremely common, especially in the Arctic; Mienert has seen fields of them in the Barents Sea. Finds like that, along with sediment cores and ice cores that show how the amount of methane in the atmosphere and ocean has fluctuated dramatically in the past, have led to a slew of “methane burp” theories. Huge quantities of methane, the theories say, have escaped from seafloor hydrates at various times in the past, wreaking havoc.

One of the worst catastrophes in Earth’s history, for instance, happened 250 million years ago at the end of the Permian Period, when something wiped out most of the animals. Many researchers blame an asteroid impact, but geologist Gregory Retallack of the University of Oregon has suggested that methane burps from below the seafloor produced a “postapocalyptic greenhouse” that drained oxygen from the atmosphere, leaving animals gasping. If that had happened, it would have reduced the oxygen concentration at sea level to what it is at 16,000 feet today. Gregory Ryskin, a chemical engineer at Northwestern University, favors an even more dramatic scenario. So much methane accumulated in stagnant seas at the end of the Permian, he argues, that when it finally erupted, it ignited, setting most of the planet on fire. Even marine organisms weren't safe; the rising methane brought up anoxic water from the deep, suffocating them. Ryskin thinks we should be keeping a close watch on places like the Black Sea.

Although not many researchers are as concerned as he is, there is evidence that methane escaping from hydrates might have affected climate a lot more recently than the Permian. If so many pockmarks are visible on the seafloor today, it is because they are relatively fresh and haven't yet been filled by sediment washing down to the sea from rivers. The pockmarks date from the last ice age. Submarine landslides, like the one at Storegga, seem to have occurred frequently as the last ice sheets receded, as well as at the end of previous glaciations. Marine geologist James Kennett of the University of California at Santa Barbara has proposed that bursts of methane from seafloor hydrates were synchronous with, and largely responsible for, virtually all the warmings the planet has experienced over the last 800,000 years. Changes in ocean currents, Kennett says, triggered the methane bursts by channeling warmer water over continental slopes, as at Storegga.

Of the many questions that cling to scenarios of methane-driven climate change, the biggest is this: Can methane from melting hydrates actually make it from the seafloor to the atmosphere?

"I would argue that there's zero evidence for that," says Gerald Dickens, a leading expert on seafloor hydrates and their role in climate change. Zero is a bit strong—Suess and Bohrman have seen blocks of hydrate floating on the sea surface off Oregon. And in the Gulf of Mexico, a team led by Ian MacDonald of Texas A&M at Corpus Christi has observed gas bubbles coated with oil rising to the surface, leaving slicks that are visible on satellite images. But so far, as Dickens says, no one has shown that quantities of methane large enough to change the climate would reach the atmosphere. For one thing, methane bubbles, when they are not coated with oil, tend to dissolve in seawater. For another, aerobic bacteria in the water consume methane. In Dickens's view, what would make it into the air is the carbon dioxide that the methane eaters give off.

CO2, of course, warms the planet, just not as sharply as methane. Dickens himself proposed the most widely believed case for a climate change involving hydrates. He says it probably happened at the end of the Paleocene Epoch 55 million years ago. Not much that we care about died then; the most prominent victims were deep-ocean microscopic foraminifera that live on the seafloor. But in their tiny shells of carbonate those forams preserve evidence of what happened. Their carbon-isotope ratio shows that all of a sudden there was a lot more light carbon-12—the kind that living organisms favor, the kind in seafloor hydrates—in the water around the forams.

If roughly 2,000 gigatons of methane came out of hydrates then, Dickens calculates, it would explain the isotope excursion. The excursion has been detected in sediments all over the world, and that's how Dickens pictures the increase in methane emissions—50 cold seeps wherever there now is one, all over the world. Even before the hydrates melted, he says, the planet had been warming for a long time, by about 7 degrees Fahrenheit, which melted the hydrates. The methane releases added another two or three degrees. In other words, their impact was not catastrophic, but it was not trivial either.

Today people are warming the planet by putting carbon dioxide in the atmosphere—and methane too. There are methane-generating archaea in our rice paddies, for instance, and also in the intestines of cows. Might we be about to trigger some serious burps? Euan Nisbet, a geologist at the University of London, points out that the Arctic, where the warming is expected to be strongest, is vulnerable—both on land and in shallow seas there are hydrates that are stabilized mostly by low temperatures rather than by high pressures. The methane there "would probably take some decades or centuries to come out," he says. "But once it started, it would be essentially unstoppable."

Nisbet and virtually every other researcher say there is no need to panic—but everyone agrees it would be reassuring if we understood a little better how carbon cycles through our planet. The problem, Dickens says, is that we have been ignoring a large part of the cycle. We've been assuming it stops at the seafloor, that organic matter buried there by the steady snow of sediments is removed from the cycle forever. But it isn't. Archaea deep in the mud convert it into methane, and the methane ends up in giant frozen reservoirs, and some of it leaks back into our ocean and maybe into our atmosphere. The reservoirs are always changing, always waxing and waning, always charging and discharging; Dickens compares them to electric capacitors. He compares them also to more familiar carbon reservoirs.

"It's almost like you've got to think of them like forests," he says, "where you have photosynthesis and respiration and trees growing and expanding and dying—there's always this carbon turnover through the biomass. Well, it's the exact same sort of thing. It's this big carbon storehouse, but it's all in methane, and it's all controlled by the microbes." And there's the rub: If methane hydrates are like forests, then we don't understand the trees.

In 1987, in a laboratory of the Scottish Marine Biological Association in Oban, Scotland, geologist John Parkes opened a series of 20-ounce cans that had been shipped to him from Peru. Inside each was a two-inch-thick disk of mud. Parkes was dressed warmly, because he was working in a chilly room at 60°F. Geochemists on the drill ship, on the expedition led by Suess, had cut slices from several drill cores with sterile knives, capped them, flushed them with nitrogen to banish all oxygen, sealed them in cans, and sent them to Oban.

Parkes opened the cans and extracted tiny cores from each. In those tiny cores he found that he could detect bacterial activity—the reduction of sulfate to smelly sulfide, for instance. Staining minute samples of sediment with a fluorescent dye that binds to DNA, he found he could count cells under his microscope, just as Boetius would do with her Hydrate Ridge samples many years later. At the time no one had done this with drill cores. And when all of it was done, says Parkes, "we'd discovered 10 percent extra biomass on Earth." More recent estimates place it at more like 30 percent.

Parkes's peers did not rush to anoint him. For decades geochemists had been reporting that sulfate and methane were mysteriously vanishing in sediments. For decades, too, petroleum geologists had been reporting that some kind of microbe seemed to be chewing up oil in deep reservoirs. "These facts were staring us in the face, but nobody put it all together," says Parkes. When he did, it was suddenly controversial. People suspected that his samples were contaminated by surface bacteria. They refused to see the whale.

They see it now. Two years ago the drill ship *Joides Resolution* went back to the same waters off Peru where Parkes's first samples had been taken. This time Parkes was on board, along with a dozen other microbiologists and a few geochemists, including Dickens. It was the first expedition specifically designed to study the deep biosphere. And the first result was simply to confirm what Parkes had been saying all along. "There are masses of bacteria down there," says Bo Barker Jørgensen of the Max Planck Institute, who was cochief scientist of the expedition.

The researchers found microbes in all the sediments they examined. There were more under the coastal waters of Peru than in the open Pacific; more near the seafloor than 1,400 feet below it. But there were intact microbes everywhere. In the upper layers, typically, they were reducing sulfate; in the lower ones they were making methane; and in between they were oxidizing methane.

The existence of the deep biosphere is established—but it remains an astonishing paradox. "From all we understand about the energy requirements just to stay alive, it's much higher than the energy they have," says Barker

Jørgensen. If the deep microbes spend as much on maintenance as surface microbes do, he says-repairing radiation damage to their DNA, keeping their membranes intact—they should have nothing left for the microbial prime directive: divide and multiply. Barker Jørgensen's expedition looked for some new energy source in the sediment, some exotic new combination of fuel and oxidant, and found none.

Parkes thinks the microbes' secret is their slowness: "These things are dividing every thousand, ten thousand, hundred thousand years. There's nothing to eat them; bacteria near the surface have to grow fast because they get eaten by protozoa and ciliates, but we've not detected those kinds of organisms in the subsurface. So bacteria there can concentrate on maintenance, rather than wasting energy on division." And yet they must have lived long enough and divided often enough and mutated often enough to evolve through natural selection, because they are well-adapted to their environment. Parkes has found microbes in deep sediments that grow best at precisely the pressure at which he found them. "They are responding on geological timescales," he says. "That's the fascinating thing."

Microbes living under the seafloor today, Parkes speculates, may have survived the growth and splintering of continents, the opening and closing of oceans; they may have been buried, subducted, frozen in hydrate, and spat out of a mud volcano, only to be buried, subducted, and spat out again. While we were waiting for our evolutionary fast lane to be paved, racing through all of human prehistory and history in the time it takes one of them to divide once, they have been living in time with the planet's deepest, slowest rhythms. They have been living almost like rock, which is precisely what made them so easy to miss. They have always been there, from the deepest past, but only now have they finally penetrated into our awareness. Given their collective influence, it's about time.

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