NATIONAL GEOGRAPHIC MAGAZINE

Published: October 2011

World Without Ice

56 million years ago a mysterious surge of carbon into the atmosphere sent global temperatures soaring. In a geologic eyeblink life was forever changed.

By Robert Kunzig

Earth has been through this before.

Not the same planetary fever exactly; it was a different world the last time, around 56 million years ago. The Atlantic Ocean had not fully opened, and animals, including perhaps our primate ancestors, could walk from Asia through Europe and across Greenland to North America. They wouldn't have encountered a speck of ice; even before the events we're talking about, Earth was already much warmer than it is today. But as the Paleocene epoch gave way to the Eocene, it was about to get much warmer still—rapidly, radically warmer.

The cause was a massive and geologically sudden release of carbon. Just how much carbon was injected into the atmosphere during the Paleocene-Eocene Thermal Maximum, or PETM, as scientists now call the fever period, is uncertain. But they estimate it was roughly the amount that would be injected today if human beings burned through all the Earth's reserves of coal, oil, and natural gas. The PETM lasted more than 150,000 years, until the excess carbon was reabsorbed. It brought on drought, floods, insect plagues, and a few extinctions. Life on Earth survived—indeed, it prospered—but it was drastically different. Today the evolutionary consequences of that distant carbon spike are all around us; in fact they include us. Now we ourselves are repeating the experiment.

The PETM "is a model for what we're staring at—a model for what we're doing by playing with the atmosphere," says Philip Gingerich, a vertebrate paleontologist at the University of Michigan. "It's the idea of triggering something that runs away from you and takes a hundred thousand years to reequilibrate."

Gingerich and other paleontologists discovered the profound evolutionary change at the end of the Paleocene long before its cause was traced to carbon. For 40 years now Gingerich has been hunting fossils from the period in the Bighorn Basin, a hundred-mile-long arid plateau just east of Yellowstone National Park in northern Wyoming. Mostly he digs into the flanks of a long, narrow mesa called Polecat Bench, which juts into the northern edge of the basin. Polecat has become his second home: He owns a small farmhouse within sight of it.

One summer afternoon Gingerich and I drove in his sky blue '78 Suburban up a dirt track to the top of the bench and on out to its southern tip, which affords a fine view of the irrigated fields and scattered oil wells that surround it. During the recent ice ages, he explained, Polecat Bench was the bed of the Shoshone River, which paved it with cobbles. At some point the river shifted east and began cutting its way down through the softer and more ancient sediments that fill the Bighorn Basin. Meanwhile the Clark's Fork of the Yellowstone River was doing the same to the west. Polecat Bench now stands between the two rivers, rising 500 feet above their valleys. Over the millennia its flanks have been sculpted by winter wind and summer gully washers into rugged badlands, exposing a layer cake of sediments. Sediments from the PETM are exposed right at the very southern tip of the bench.

It is here that Gingerich has documented a great mammalian explosion. Halfway down the slope a band of red sediment, about a hundred feet thick, wraps around the folds and gullies, vivid as the stripe on a candy cane. In that band Gingerich discovered fossils of the oldest odd-toed hoofed mammals, even-toed hoofed mammals, and true primates: in other words, the first members of the orders that now include, respectively, horses, cows, and humans. Similar fossils have since been found in Asia and Europe. They appear everywhere, and as if out of nowhere. Nine million years after an asteroid slammed into the Yucatán Peninsula, setting off a cataclysm that most scientists now believe wiped out the dinosaurs, the Earth seems to have undergone another shock to the system.

During the first two decades that Gingerich labored to document the Paleocene-Eocene transition, most scientists saw it simply as a time when one set of fossils gave way to another. That perception started to change in 1991, when two oceanographers, James Kennett and Lowell Stott, analyzed carbon isotopes—different forms of the carbon atom—in a sediment core extracted from the Atlantic seafloor near Antarctica. Right at the Paleocene-Eocene boundary a dramatic shift in the ratio of isotopes in fossils of minuscule organisms called foraminifera (forams for short) indicated that an immense amount of "fresh" carbon had flooded into the ocean in as little as a few centuries. It would have spread into the atmosphere too, and there, as carbon dioxide, it would have trapped solar heat and warmed the planet. Oxygen isotopes in the forams indicated that the whole ocean had warmed, from the surface right down to the bottom mud, where most of the forams lived.

In the early 1990s the same signs of a planetary convulsion began turning up on Polecat Bench. Two young scientists, Paul Koch of the Carnegie Institution and James Zachos, then at the University of Michigan, collected half-inch clumps of carbonate-rich soil from each of the sediment layers. They also collected teeth of a primitive mammal called *Phenacodus*. When Koch and Zachos analyzed the carbon isotope ratios in the soil and the tooth enamel, they found the same carbon spike seen in the forams. It was becoming clear that the PETM had been a global warming episode that had affected not just obscure sea organisms but also big, charismatic land animals. And scientists saw that they could use the carbon spike—the telltale stamp of a global greenhouse gas release—to identify the PETM in rocks all over the world.

Where did all the carbon come from? We know the source of the excess carbon now pouring into the atmosphere: us. But there were no humans around 56 million years ago, much less cars and power plants. Many sources have been suggested for the PETM carbon spike, and given the amount of carbon, it likely came from more than one. At the end of the Paleocene, Europe and Greenland were pulling apart and opening the North Atlantic, resulting in massive volcanic eruptions that could have cooked carbon dioxide out of organic sediments on the seafloor, though probably not fast enough to explain the isotope spikes. Wildfires might have burned through Paleocene peat deposits, although so far soot from such fires has not turned up in sediment cores. A giant comet smashing into carbonate rocks also could have released a lot of carbon very quickly, but as yet there is no direct evidence of such an impact.

The oldest and still the most popular hypothesis is that much of the carbon came from large deposits of methane hydrate, a peculiar, icelike compound that consists of water molecules forming a cage around a single molecule of methane. Hydrates are stable only in a narrow band of cold temperatures and high pressures; large deposits of them are found today under the Arctic tundra and under the seafloor, on the slopes that link the continental shelves to the deep abyssal plains. At the PETM an initial warming from somewhere—perhaps the volcanoes, perhaps slight fluctuations in Earth's orbit that exposed parts of it to more sunlight—might have melted hydrates and allowed methane molecules to slip from their cages and bubble into the atmosphere.

The hypothesis is alarming. Methane in the atmosphere warms the Earth over 20 times more per molecule than carbon dioxide does, then after a decade or two, it oxidizes to CO_2 and keeps on warming for a long time. Many scientists think just that kind of scenario might occur today: The warming caused by the burning of fossil fuels could trigger a runaway release of methane from the deep sea and the frozen north.

Koch and Zachos concluded from their data that the PETM had lifted the annual average temperature in the Bighorn Basin by around nine degrees Fahrenheit. That's more than the warming there since the last ice age. It's also a bit more than what climate models predict there for the 21st century—but not more than what they forecast for the centuries to come if humans keep burning fossil fuels. Models also predict severe disruptions in the world's rainfall patterns, even in this century, especially in subtropical regions like the American Southwest. But how to test the models? "You can't wait 100 or 200 years to see what happened," says Swedish geologist Birger Schmitz, who has spent a decade studying PETM rocks in the Spanish Pyrenees. "That's what makes the PETM story so interesting. You have the end result. You can see what *did* happen."

What happened in the Bighorn was a wholesale rearrangement of life. Scott Wing, a paleobotanist at the Smithsonian National Museum of Natural History, has been collecting fossil leaves in the Bighorn for 36 summers—more leaves than he'll ever have time to examine as thoroughly as he'd like. Every year at summer's end, as he unpacks box after box of fossils, he tells himself that next year he'll be reasonable and stay in Washington, D.C., to catch up on his cataloging. But come July he's back digging again, hoping, as he puts it, "that lightning will strike."

A few years ago it did. "I looked for about ten years for a fossil deposit like this," Wing said. We were sitting on a hillside 15 miles south of Highway 16 between Ten Sleep and Worland, west of the Bighorn Mountains, hammering at rocks from a trench dug by Wing's assistants. On distant slopes you could see the neat horizontal stripes of red, interspersed with gray and yellow, that identify that earth as dating from the PETM. Down in the hollow a pump jack seesawed out of earshot; from the top of the hill you could see half a dozen more. In the intermittent silences of our conversation, the only sound was the music of the hammers—muffled thuds, distant resonating pings as from a tuning fork, and crunching as the rocks gave way. When you tapped one persistently enough, it yielded along the plane separating two layers of mud, and sometimes that exposed, like the cream in an Oreo, a leaf preserved so perfectly that with Wing's loupe you could see trails eaten into it by insects 56 million years ago.

Wing knew immediately when he'd found his first deposit of leaves from the PETM. "Many of the plants I had never seen," he said. The fossils he'd already collected showed that before and after the warming the basin was covered with a dense forest of birch, sycamore, dawn redwoods, palm trees, and evergreens that resembled magnolias. The ground would have been squishy underfoot, in places as swampy as the Atchafalaya or the Okefenokee are today. The Bighorn in both the Paleocene and the Eocene was like northern Florida is now.

But at the height of the PETM, Wing has found, the landscape morphed into something completely different. It became more seasonally dry and open, like the dry tropical forests of Central America. As the planet warmed, new plant species migrated rapidly into the basin from as far south as the Gulf Coast, a latitudinal distance of nearly a thousand miles. Many were beans—not garden-variety ones, but trees of the same family, similar to modern mimosas. And most had been riddled by bugs.

Of the hundreds of fossil leaves examined by Wing and his colleague Ellen Currano, of Miami University in Ohio, nearly six in ten have holes or curving channels chewed into them by insects. Maybe the heat had revved up the bugs' metabolism, causing them to eat more and reproduce more. Or maybe the extra carbon dioxide had directly affected the plants; when CO_2 is injected into modern greenhouses, the plants grow more, but their protein content is lower, making their leaves less nutritious. The same may have happened in the hothouse world of the PETM—maybe the insects had to eat so much foliage just to fill up.

Yet the bug-chewed PETM leaves were also much smaller than those of their Paleocene ancestors, because, Wing said, rainfall had dropped by around 40 percent. (When water gets scarcer, plants cut down on water loss by shrinking their leaves.) The drop in rainfall also gave the soil a chance to dry out every year and the iron in it to oxidize and turn rust red. These seasonally dry soils became the broad bands that now stripe the hillsides. Then, at the height of the PETM, the red beds disappeared—not because the climate got wetter overall, Wing said, but because the rains became more concentrated, like monsoons. The rivers in the basin constantly jumped their banks and flooded the countryside, washing away soil before it could deepen.

In the eastern Pyrenees, Birger Schmitz has found more dramatic evidence of catastrophic flooding during the PETM. He and colleague Victoriano Pujalte, from the University of the Basque Country in Bilbao, Spain, identified the trademark carbon spike at the base of a rock formation that, though now high in the mountains, probably lay on a coastal plain back then. A field of boulders had been washed out of the budding mountains and tossed onto a vast floodplain that the scientists believe extended over thousands of square miles. Some boulders were two feet across and could have been put there only by exceptionally violent water. Deposited over centuries by channel-jumping rivers, they're like fossil imprints of the energy in the hothouse atmosphere.

While bean trees were blooming in the Bighorn Basin, *Apectodinium* was blooming all over the ocean. The species is an extinct form of dinoflagellate—a group of single-celled plankton, some of which today give rise to toxic blooms known as red tides. All dinoflagellates have two flagella that they whip around to propel themselves through the water, a distinctive maneuver that Henk Brinkhuis, of Utrecht University in the Netherlands, demonstrated for me one day by folding one arm through his legs, the other around his slightly protruding belly, and flapping both. In the winter *Apectodinium* cells would retreat into hard cysts that sank to the seafloor. The following spring a flap on each cyst would fly open like a trapdoor—Brinkhuis stuck a finger in his cheek and made a cork-popping sound. The cell would then crawl out and ascend to the sea surface, leaving the empty cyst behind for Brinkhuis and his colleague Appy Sluijs to recognize in sediment samples 56 million years later—its open flap the only clue to a space-alien-like life history. In Brinkhuis's office there is a poster that reads, "Everything I know I learned from *Star Trek*."

Before the PETM, Brinkhuis and Sluijs find *Apectodinium* only in the subtropics. But in PETM sediments they find it all over the world—confirmation that the ocean was heating up everywhere. In the Paleocene the summer water temperature in the Arctic Ocean was already around 64 degrees Fahrenheit; during the PETM it shot up to around 74. Swimming there would have been like swimming today on the mid-Atlantic seaboard, which, judging from a New Jersey sediment core that Brinkhuis and Sluijs have also analyzed, would have been like the Caribbean. Today the water at the deep seafloor is just above freezing; in the PETM it was in the 60s.

As the ocean absorbed the carbon dioxide that was warming the planet, the water also became acidified, just as it will over the next century as CO_2 levels rise again. This is borne out in some deep-sea sediments, where the PETM is as obvious as the stripes in the Bighorn Basin. In 2003 Sluijs went along on an expedition led by James Zachos to the Walvis Ridge, a submarine mountain range in the South Atlantic. They extracted sediment cores from a range of depths on the flanks of the ridge, and in each case as soon as they opened the core on deck, they could see the PETM layer immediately. "It just stands out amazingly," Sluijs says. "It's just red clay."

The clay stood out because of what it lacked: the white ooze of calcium carbonate that brightens the sediments above and below the PETM. During the PETM the acidified ocean had dissolved the calcium carbonate away. At this point one might expect a simple morality tale: Acidified ocean wipes out myriad life-forms, dissolving the shells of corals, clams, and forams—the scenario many scientists now envision for the 21st century. But the PETM is more puzzling than that. Although coral reefs in the Tethys Ocean, a Mediterranean Sea forerunner that cut through the Middle East, seem to have suffered badly, the single documented mass extinction at the PETM is an unexpected one: It struck as many as half the species of forams that lived in the bottom mud. They were cosmopolitan species, adapted to a wide range of conditions, and they should have been able to handle whatever the PETM threw at them.

Given the degree of acidification of the ocean, Zachos and his colleagues have estimated that an initial burst of around three trillion metric tons of carbon flooded the atmosphere, then another trillion and a half leaked out more gradually. The total of 4.5 trillion tons is close to the total carbon now estimated to be locked up in fossil fuel deposits; the initial burst corresponds to about three centuries' worth of human-caused emissions at the current rate. Though the data aren't conclusive, most scientists assume the PETM release was slower, taking thousands of years.

However fast the carbon was released, it would have taken far longer for geologic processes to remove it. As the carbonates on the seafloor dissolved, counteracting the acidification, the ocean was able to absorb more CO_2, and within a few centuries or millennia of the sudden release, the atmospheric CO_2 peak had passed. Meanwhile CO_2 was also dissolving into rain droplets, which leached calcium from rocks on land and washed it to the sea, where it combined with carbonate ions to make more calcium carbonate. The process, called weathering, happens all the time, but it happened faster during the PETM, because the climate was hotter and the rain more acidic. Gradually the rain scrubbed the added CO_2 from the atmosphere, and eventually it wound up in limestone at the bottom of the sea. The climate slowly returned to its previous state. "It's just like with fossil fuels today," Zachos says. "We're taking what took millions of years to accumulate and releasing it in a geologic instant. Eventually the system will stick it back into rock, but that will take hundreds of thousands of years."

Matt Huber, a climate modeler at Purdue University who has spent most of his career trying to understand the PETM, has also tried to forecast what might happen if humans choose to burn off all the fossil fuel deposits. Huber uses a climate model, developed by the National Center for Atmospheric Research in Colorado, that is one of the least sensitive to carbon dioxide. The results he gets are still infernal. In what he calls his "reasonable best guess at a bad scenario" (his worst case is the "global-burn scenario"), regions where half the human population now lives become almost unbearable. In much of China, India, southern Europe, and the United States, summer temperatures would average well over 100 degrees Fahrenheit, night and day, year after year.

Climate scientists don't often talk about such grim long-term forecasts, Huber says, in part because skeptics, exaggerating scientific uncertainties, are always accusing them of alarmism. "We've basically been trying to edit ourselves," Huber says. "Whenever we see something really bad, we tend to hold off. The middle ground is actually much worse than people think.

"If we continue down this road, there really is no uncertainty. We're headed for the Eocene. And we know what that's like."

In the PETM the heat drove tropical species toward the Poles, and animal and plant species from all continents could cross land bridges and blend together. Hoofed running animals, the ancestors of horses and deer, showed up in the Bighorn. A little bit later, perhaps as the climate got wetter again and the forest canopy began to close over the more open land that had favored the runners, the first true primates showed up.

Humans, along with every other primate living today, are descended from a PETM primate—just as perissodactyls such as horses, tapirs, and rhinos are descended from another PETM ancestor, and artiodactyl ruminants such as deer, cows, and sheep from still another. The species that appeared suddenly in the Bighorn may have migrated from Asia, where fossil specimens that are slightly older than the Bighorn's have been found. Those species in turn must have had ancestors deeper in the Paleocene. But so far there are no Paleocene fossils a paleontologist would look at and call a primate or a horse—and it is not, Gingerich told me, for lack of looking.

During the PETM itself a strange thing happened to some mammals: They got dwarfish. Horses in the Bighorn shrank to the size of Siamese cats; as the carbon ebbed from the atmosphere, they grew larger again. It's not clear whether it was the heat or the CO_2 itself that shrank them. But the lesson, says Gingerich, is that animals can evolve fast in a changing environment. When he first drove into the Bighorn four decades ago, it was precisely to learn where horses and primates came from. He now thinks that they and artiodactyls came from the PETM—that those three orders of modern mammals acquired their distinctive characteristics right then, in a burst of evolution driven by the burst of carbon into the atmosphere.

After 56 million years primates, then the size of mice or rabbits, are directing the show. They have tamed other descendants of the PETM—horses, cows, pigs, sheep—and spread with them around the planet. They have moved beyond agriculture to a mode of living that, while infinitely varied, is almost invariably powered by fossil fuels. As Gingerich and I bounced in his Suburban along the top of Polecat Bench, through the tall grass of deserted pastures, we saw pump jacks nodding slowly back and forth, bringing oil from the Cretaceous period to the surface, as they do throughout the Bighorn. To the east, in the Powder River Basin, giant shovels scratch at Paleocene coal seams that keep the lights on in one of every five houses in the U.S.

Fossil fuel burning has released more than 300 billion tons of carbon since the 18th century—probably less than a tenth of what's still in the ground or of what was released at the PETM. That episode doesn't tell us what will happen to life on Earth if we choose to burn the rest. (Global emissions set another record last year.) Maybe there will be a burst of evolutionary innovation like the one that gave rise to our primate ancestors; maybe this time, with all the other pressures on species, there will be mass extinctions. The PETM merely puts the choice in long perspective. Tens of millions of years from now, whatever becomes of humanity, the whole pattern of life on Earth may be radically different from what it would otherwise have been—simply because of the way we powered our lives for a few centuries.