EARTH SCIENCE

When Climate Twitches, Evolution Takes Great Leaps

Earth's climate system has ridden a slow roller coaster for the past 60 million years. It warmed gradually until about 53 million years ago, reaching a peak that brought crocodiles to northern Canada; then it entered a long, undulating downgrade toward the ice-age world of the past few million years. Because the same span of time brought major evolutionary changes, including the rise of modern mammals, paleontologists have long assumed that these slow temperature changes helped spur the processes of evolution. But recent findings have suggested that another, more potent mechanism was also at work: Abrupt climate excursions, superimposed on these long-term trends, have now been linked to rapid periods of mammal evolution.

The evidence for short, sharp evolutionary shocks comes from studies of a pair of mirror-image climate shifts at opposite ends of the Eocene epoch, 55 million and 33.5 million years ago. In both cases, researchers studying the record of climate preserved in sea-floor sediments have found that a gradual climate change—warming in the first case, cooling in the second—suddenly steepened into a short-lived pulse of extreme warming or cooling. The short time scale of these events and their clear coincidence with turning points in the evolution of mammals are providing the tightest links yet between global climate change and evolution on land. And these climatic tremors also raise questions about the workings of the global climate system itself, leaving researchers to wonder whether such excursions might be the rule, rather than the exception, whenever climate is undergoing a long term change.

SMITHSONIAN INSTITUTION/MURAL BY JAY H. MATTERNES

Lost world. The flora and fauna of the Eocene were shaped by a burst of warmth at the beginning of the epoch and whisked away by a cold snap near its end.

The earlier of the two climate excursions explains a paleontological puzzle: the sudden appearance in North America of mammals cast in the mold of modern beasts. As paleontologist Philip Gingerich of the University of Michigan explains it, before the beginning of the Eocene epoch 55 million years ago, the archaic mammals that then lived in North America, in particular those whose fossils occur in the Bighorn Basin of Wyoming and Montana, were "chugging along" and evolving but not producing anything radically new.

When Gingerich started work in the Bighorn Basin 18 years ago, he recalls, he was hoping to trace how the older mammal forms, such as lemur-like primates and egg-laying mammals related to the platypus, evolved around the beginning of the Eocene into the modern mammal families such as rodents, primates, and split-hoofed animals such as the progenitors of deer, cows, and pigs. But the transformation happened too quickly, Gingerich says. "When things come in, they come in—bang!—right at [the beginning of the Eocene]." Whatever was behind the appearance of familiar mammals, it made things happen in a hurry.

Last year, paleoceanographers came up with a possible trigger for this evolutionary jump (*Science*, 20 September 1991, p. 1359). James Kennett of the University of California, Santa Barbara, and Lowell Stott of the University of Southern California found a sharp blip in the ratio of oxygen isotopes preserved in sea-floor sediment off Antarctica. Their interpretation of the isotope record, which can provide a gauge of water temperature, was that about 55 million years ago, during the gradual warming that culminated 2 million years later, the temperature of the deep sea soared from about 10°C to 18°C in just 2000 years. And those same 2000 years witnessed the extinction of more than 40% of the bottom-dwelling, unicellular animals called foraminifers. Kennett and Stott surmised that the ocean's circulation, which today has cold water sinking at high latitudes and returning to the surface at low latitudes, had temporarily reversed, flooding the deep sea with warm water for about 100,000 years.

This was strong circumstantial evidence that a global climate shift, signaled by the sudden ocean warming, had spurred the evolutionary changes on land. But there was still the question of timing. The coincidence of the mammal transition and the ocean warming was close, but researchers lacked the tools to determine whether they were in fact simultaneous. They might still have separated by as much as a million years.

Now, some fancy dental work has provided the bridge. Geochemist Paul Koch of the Carnegie Institution of Washington's Geophysical Laboratory, paleoceanographer James Zachos of the University of Michigan, and Gingerich have found a distant echo of the ocean warming preserved in the mammal fossils themselves. Kennett and Stott's original analysis of ocean sediment showed that, along with the shift in oxygen isotopes, the ocean warming was accompanied by a sharp but brief shift in the isotope composition of the carbon in seawater carbonates—a change presumably related to the biological productivity of the ocean. As the ocean exchanged carbon with the air in the form of carbon dioxide, Koch and his colleagues reasoned, that signal would have passed through the atmosphere, to land plants as they took up the carbon dioxide, and finally to the teeth and bones of the animals that ate the plants. And when Koch and his colleagues measured the carbon isotopes in herbivorous mammal teeth found across 4 million years spanning the beginning of the Eocene, a geologically instantaneous spike like the one in the ocean showed up at exactly the right moment. It appeared just when archaic mammals disappeared and the new, modern mammals came in with a bang.

The abrupt warming seems to be guilty as charged, but exactly how it did its work is far from clear. One possibility, says Gingerich, is that the accelerated warming simply drove evolutionary adaptation fast enough to transform archaic mammals into recognizably modern forms. Or, the warming might have made cold, high latitudes hospitable enough for species from other continents to take advantage of the arctic land bridges that existed at that time and invade, wiping out indigenous species—an evolutionary turning point of a different kind. The problem with that scenario is that paleontologists have yet to identify progenitors of modern North American mammals on another continent.

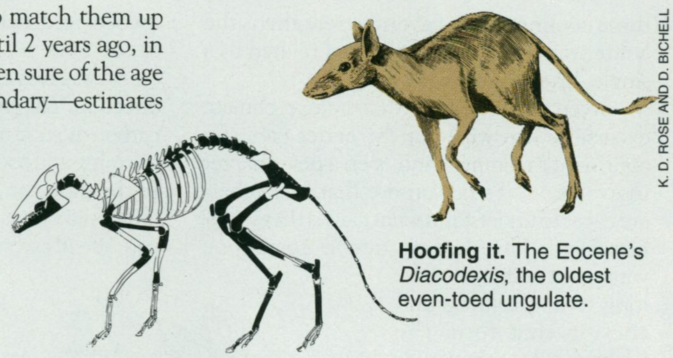
La Grande Coupure

Despite the missing pieces in this early Eocene climate-evolution connection, it's the clearest link earth scientists have between a change in climate and a watershed in evolution. It has a strong rival, however. At the other end of the Eocene, researchers have found another good example of a climate excursion that may have goaded evolutionary change. Again, the new result may solve a long-standing evolutionary puzzle: a turning point in the evolution of mammals in Europe perhaps half a million years after the boundary between the Eocene and the Oligocene epochs. This transition—so momentous that in 1909 it was dubbed "La Grande Coupure," the great break—saw as much as 60% of European mammals go extinct, to be replaced by rhinos, primitive deer and antelopes, and modern carnivores such as dogs, cats, and weasels.

In this case, paleontologists had already concluded that the direct culprit must have been a calamitous invasion of foreign species. The fossil record clearly traces an influx of new species from Asia, which poured into Western Europe from the east. But behind it all, they assumed, was a climate shift. The way was opened for the invasion, the paleontologists proposed, when the temperature of the gradually cooling Earth dropped low enough for ice sheets to start forming in Antarctica. The onset of glaciation might have drawn off enough seawater to lower sea level and expose a land bridge between Asia and Europe, which had been cut off from Asia by a seaway.

It was easy enough for paleontologists to invoke a new land bridge in the early Oligocene epoch, but paleoceanographers had big problems confirming that link. For one thing, the earliest oceanographic signals of glaciation—such as deposits of gravel and other debris dropped far out at sea by melting icebergs—were still fuzzy and open to interpretation.

For another, investigators faced the same timing problem that Koch and his colleagues had faced at the beginning of the Eocene. Even if they had found signatures of a dramatic cooling that seemed to come at the right time, they might not have been able to match them up with the events on land. Until 2 years ago, in fact, investigators weren't even sure of the age of the Eocene-Oligocene boundary—estimates had ranged from 48 million to 32 million years ago. But thanks to the new technique of argon-argon isotope dating (*Science*, 14 August, p. 878), geochronologists are homing in on an age for the boundary of about 34 million years, which would place the putative climate shift and land bridge at about 33.5 million years ago. In addition, the faint traces that Earth's flip-flopping magnetic field has left in sediments have allowed researchers to construct a common timeline for events on land and in the oceans.



K. D. ROSE AND D. BICHELL

Hoofing it. The Eocene's *Diacodexis*, the oldest even-toed ungulate.

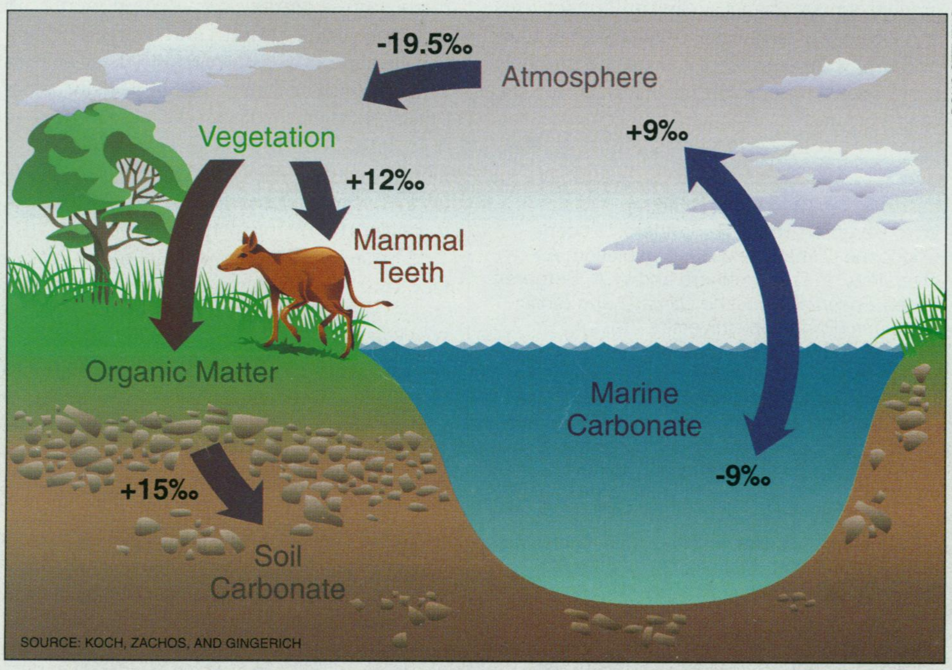
A shift in time

As dating techniques were being refined, paleoceanographers were pushing the first evidence of ice sheets in Antarctica back toward the time of the postulated land bridge more than 33 million years ago. Sand and pebbles scarred by moving glaciers were turning up in deep layers of sediments of that age far from the Antarctic coast. And variations in the oxygen isotope composition of marine microfossils that couldn't be accounted for by temperature changes suggested that water was being drawn out of the oceans and locked away in an ice cap as early as 33 million or 34 million years ago.

But the picture of early Oligocene glaciation was still too fuzzy to clinch the link between the cooling recorded in the ocean and the die-off in Europe. To get a clearer picture of the timing of the cooling event, paleoceanographers James Zachos of the University of Michigan and James Breza and Sherwood Wise of Florida State University took a close look at 120 meters of mud cored from the southern Indian Ocean by the Ocean Drilling Program's drill ship *JOIDES Resolution*. Researchers normally take only one small sample from the middle of every meter and a half or so of core; the analyses are usually just too tedious to do more, as kilometer after kilometer of core come in from the drill ship. But Zachos and his colleagues sampled every 12 centimeters or so, or roughly every 10,000 to 20,000 years of the record, across the core where the glaciation was recorded. The glaciation imprinted in the cores turned out to be a humdinger.

Zachos and company found that the shift in oxygen isotope composition and the appearance of ice-rafted debris 1300 kilometers from the Antarctic coast precisely coincided, reinforcing the conclusion that a sizable ice cap had formed. Based on the size of the isotope shift, Zachos and his colleagues estimate that the ice cap contained at least 70% of the volume of its present-day counterpart. And that surge of glaciation was not only big, it was also brief. Superimposed on a cooling that had gone on for 20 million years, the Antarctic ice age had lasted no more than a few hundred thousand years.

That would have been enough time for the catastrophic influx of foreign species across a newly exposed land bridge and into Europe—if the glaciation and the Grande Coupure really do coincide. Without a time marker as distinctive as the carbon isotope signal that linked ocean and land events at the beginning of the Eocene, investigators can't narrow the uncertainty to less than a million years or so. But a third climate-related event in the earliest part of the Oligocene is adding to researchers' confidence about the timing. From studies of the size and shape of fossil leaves, paleobotanist Jack A. Wolfe of the United States Geological Survey in Denver has concluded that just after the end of the Eocene, cold-weather vegetation took over North America in response to a temperature drop of at least 13°C. As Prothero notes, the rough coincidence of all



DOUG STEVENS

A sea-land connection. Shifts in seawater carbon isotopes leave their echo on land, making it possible to trace a climate evolution link 55 million years ago. A characteristic shift in isotopic composition takes place at each step.

three cooling-related events strengthens the contention that they are indeed related to a single, brief, global cold spell.

Given the evidence that abrupt climate excursions can wipe out the better part of a continent's mammals and open a new chapter in evolution, it's no surprise that researchers are eager to understand what causes them. Climatologists have had no trouble coming up with possible causes for the long-term warming and cooling that form the background for these sudden events. The gradual warming that peaked 53 million years ago, for example, may have resulted when volcanoes or hot springs on the ocean floor drove excess carbon dioxide into the atmosphere; the long-term cooling of the Eocene and early Oligocene may have ensued when drifting continents changed the pattern of ocean currents, which affect climate by ferrying heat around the world. Alternatively, the uplift of the Himalayas and the Tibetan Plateau could have spurred the cooling by redirecting atmospheric circulation.

K. D. ROSE AND L. KIBIUK

Progenitor primate. *Tetonius*, one of the oldest known primates.

But neither the warming spike that ushered in the Eocene nor the pulse of cooling that followed it has any obvious trigger such as an asteroid impact. Zachos and company, however, see clues in the similarities between the events. Both were short-lived, lasting only about 100,000 years. Both were embedded in long-term temperature trends having the same direction as the short-term events. And both seem to have been accompanied by changes in ocean circulation and carbon cycling.

All those parallels lead Zachos and his colleagues to suggest two separate mechanisms that may work together to produce short-lived climate excursions during a time of gradual change. One is a tendency, proposed earlier by other researchers, for a gradually changing climate to jump from one relatively stable state to another. In one example, gradual cooling might lead to the sudden onset of an ice age when the temperature reached a critical threshold below which snow no longer melts away each summer and begins to accumulate rapidly from year to year. During gradual warming, ocean circulation might create another threshold; at a certain point in the warming trend, ocean currents might suddenly reorganize, causing the warming to surge.

Threshold crossings might explain the abrupt onset of the two excursions, but not their brief duration before climate returned to a new but less extreme state. To account for the temporary overshoot, the Michigan group invokes feedbacks—the tendency of some processes, once pushed in one direction, to feed on themselves and drive even further in that direction. The greenhouse effect of atmospheric carbon dioxide might lead to feedbacks in both warming and cooling, says the Michigan group. In the short run, note the researchers, the microscopic plants of the ocean's surface waters can affect carbon dioxide concentrations by pumping carbon from the atmosphere into the deep sea in the form of a rain of organic debris. If an abrupt change in circulation during a cooling drove that pump faster by supplying more nutrients to the plants, for example, the greenhouse effect would weaken and climate would cool even further. Only when the slow overturn that links surface waters with ocean depths—a much stronger influence over atmospheric carbon dioxide than the surface waters—took control thousands of years later would the global greenhouse stabilize.

But it will take more than the two climate twitches at either end of the Eocene to firm up these speculations. To get a better reading on what causes these climate excursions, and how important they have been in the history of life, paleoclimatologists and paleontologists will be teaming up to test other seemingly gradual climate transition/extinction pairs for possible abruptness. Closer to home, climate researchers are wondering: If gradual climate change lasting millions of years was enough to derail the climate system temporarily, what is in store during the uniquely rapid greenhouse warming predicted for the next century?

–**Richard A. Kerr**

Additional Reading

W.A. Berggren and D.R. Prothero, "Eocene-Oligocene Climatic and Biotic evolution: An Overview," in D.R. Prothero and W.A. Berggren (Eds.) *Eocene-Oligocene Climatic and Biotic Evolution* (Princeton University Press, Princeton, N.J., 1992).

P.L. Koch, J.C. Zachos, P.D. Gingerich, "Correlation Between Isotope Records in Marine and Continental Carbon Reservoirs Near the Palaeocene/Eocene Boundary," *Nature* **358**, 319 (1992).

J.C. Zachos, J.R. Breza, S.W. Wise, "Early Oligocene Ice-Sheet Expansion on Antarctica," *Geol.* **20**, 569 (1992).

J.C. Zachos, K.C. Lohmann, J.C.G. Walker, "Abrupt Climate Change and Transient Climates During the Paleogene: A Marine Perspective," submitted for publication in the Centennial Volume of *J. Geol.*

PROTEIN STRUCTURE

An Intimate Look at Nitrogen's Bio-Partner

Nitrogen is a star of biological chemistry—a vital player in nucleic acids such as DNA and in the proteins responsible for every organism's structure and function. It can be a reluctant performer, though: Atmospheric nitrogen, its two atoms joined by a strong triple bond, ordinarily won't link up with other elements except under extreme duress, such as the high temperatures and pressures created in a lightning bolt or in industrial syntheses. Indeed, nitrogen might never have won much of a part on the biological stage without help from a powerful costar, an enzyme called nitrogenase, which can break the strong bonds of atmospheric nitrogen and "fix" nitrogen into ammonia (a precursor of other nitrogen-containing compounds), even at room temperature and pressure. But for decades the enzyme that performs this feat has remained in the shadows, the details of its structure and workings a mystery—until now.

In this issue of *Science*, protein crystallographer Doug Rees of the California Institute of Technology and his colleagues chase away some of those shadows. On pages 1653 and 1677, they offer a close look, based on years of painstaking x-ray crystallography, at the nitrogenase complex's two components: an iron-containing protein and a larger, molybdenum- and iron-rich partner (the so-called MoFe protein). The resulting portrait is detailed enough to allow the researchers to speculate about how the enzyme plays part of its role—how it uses adenosine triphosphate (ATP), the chief energy currency of the cell, to power the nitrogen-fixing process.

The entire picture isn't in focus yet—a fact that was underscored at last month's American Chemical Society meeting in Washington, D.C. There, Purdue University crystallographer Jeffrey T. Bolin, who has been racing Rees' group to unravel the structure of nitrogenase, presented unpublished data about the structure of the metal-containing centers of the MoFe protein—data that bear out much of Rees' model but contradict some parts of it. But chemists and geneticists are already eyeing the new structure as a guide to designing synthetic catalysts that could mimic the activity of the natural enzyme, which is found only in certain bacteria that live in the soil and on the roots of a few tropical plants and legumes such as peas and alfalfa. To Harvard Univer-