flicting vapor pressure requirements of the two kinds of traps. They compromised at an intermediate pressure. Today, they use two MOTs, one at a higher pressure than the other.

The final problem was that the quadrupole magnetic trap has a "hole" in it: a region in the center where the magnetic field is zero. Atoms there can be spin-flipped and lost from the trap. Cornell solved the problem by applying a rotating field, which moved this null-field point around the trap in such a way that the field was never zero where the trapped atoms resided. With that hurdle overcome, the team soon achieved a BEC.

Progress at MIT

When Ketterle arrived at MIT in 1990, he wasn't focused on achieving a BEC: The phase-space densities for trapped alkali atoms were then more than six orders of magnitude away from those required for a BEC, whereas the hydrogen gases cooled by Kleppner, Greytak, and company were within a factor of ten. Still, he says, he was intrigued by the possibility of combining laser cooling and evaporative cooling, being influenced by his mentor, Pritchard, and his office neighbor, Kleppner, both of whom had done pioneering work on these techniques.

Under Pritchard's direction, Ketterle attacked the challenge of creating a much denser cloud of atoms than had yet been achieved. The two devised a simple technique to circumvent several problems caused when excited atoms interact with the trapping light in the MOT. Pritchard and Ketterle blocked the repumping light in the center of the MOT, allowing already trapped atoms to spend most of their time in a hyperfine quantum state that did not absorb the trapping light. With such a "dark-spot MOT," they cooled an unprecedented number of atoms to high densities. The JILA experimenters also used the dark-spot idea, although its effect in their vapor cell MOT was to increase the number, and not the density, of the atoms.

Before his work on the dark-spot MOT, Ketterle told us, he thought that laser cooling could not get atoms dense enough for evaporative cooling to be effective. But in 1992, he and Pritchard concluded that the dark-spot MOT could provide a bridge between laser and evaporative cooling. At that moment, said Ketterle, "we set full sail for BEC and dropped everything else."

In 1993, Pritchard stepped aside in a remarkably magnanimous gesture. Ketterle was then a candidate for an MIT professorship, and wanted to continue working toward a BEC. To save Ketterle from having to compete in the shadow of his mentor, Pritchard bowed out of the BEC project and turned his laboratory over to Ketterle so that the former postdoc could continue the quest. Pritchard told Ketterle at the time, "I'm giving you the keys to the family car because I know you can drive faster than I can."

By 1994, Ketterle's group saw the onset of evaporation, and within the next year, they reduced the phase space by six orders of magnitude. They plugged the hole in the magnetic quadrupole trap by shining a laser beam through the center, and arrived at their destination with about 500 000 atoms in their condensate.

In retrospect, Ketterle realizes that the dark spot MOT was unnecessary; his group could simply have built a very quiet magnetic trap and waited for evaporative cooling to work. "We created overkill because we never thought it would work so easily," he says, "but that overkill was responsible for the dramatic progress of the field."

Biographies

Cornell earned a BS in physics from Stanford University in 1985 before going to MIT for his PhD. Although Pritchard was his adviser, Cornell did his thesis on single ion mass spectrometry rather than on laser cooling.

Wieman earned a BS in physics from MIT in 1973, doing undergraduate research there with Kleppner. For his PhD, earned in 1977, he worked under Theodor Hänsch at Stanford doing two-photon spectroscopy of hydrogen. He spent two years at Michigan before going to Colorado.

Ketterle earned his master's diploma in 1982 from the Technical University of Munich, writing his thesis in theoretical physics. He turned to experimental work—spectroscopy—to earn his PhD in 1986 under Herbert Walther at the Ludwig Maximilians University of Munich and the Max Planck Institute for Quantum Optics in Garching. After a first postdoc at Garching and a second one in chemical physics at the University of Heidelberg, Ketterle took his third at MIT.

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Isotopic Analysis of Pristine Microshells Resolves a Troubling Paradox of Paleoclimatology

In 1947, Harold Urey pointed out that the oxygen-isotope composition of fossil seashells could serve as a paleothermometer. The more ^{18}O a shell incorporated, he showed, the colder was the water in which it was formed. For decades now, the concentration of the heavy isotope ^{18}O in the microshells of foraminifera—single-celled marine animals—has been widely used to reconstruct the temperature profiles of ancient seas.

Since the mid-1980s, however, models of CO_2 greenhouse warming have confronted ^{18}O data from fossil planktonic (floating) foraminifera with the so-called "cool-tropics paradox." In stark defiance of the global climate models,[1] the planktonic ^{18}O data seemed to suggest that 50 million years ago, a time when the CO_2 level was almost certainly much higher than it is today and the Arctic was balmy enough for crocodiles and giant monitor lizards, tropical ocean surfaces were about 10°C *cooler* than they are now.

> If fossil isotopic data tell us that the tropical ocean was much cooler 50 million years ago than it is now, then either the data are flawed or we understand very little about global warming.

A new analysis of planktonic foraminifera from the late Cretaceous to the late Eocene (67–35 million years ago), by Paul Pearson (University of Bristol) and coworkers, does much to lay the troubling cool-tropics

paradox to rest.[2] Because planktonic foraminifera, while they live, float at or near the surface, researchers had assumed that their ^{18}O concentration reflects the temperature of the sea surface. But Pearson and company, doing isotopic analyses of unusually well-preserved samples of pristine shells selected with the help of electron microscopy, conclude that the surprisingly high ^{18}O level of traditional samples is a misleading consequence of extensive recrystallization of the fossil shells in the much colder waters at the bottom of the sea. (See figure 1 and the cover of this issue.)

Daniel Schrag (Harvard University) reached much the same conclusion a few years ago by means of a mathematical model of the recrystallization of these very porous microshells buried on the seafloor.[3] At higher latitudes, where there's less temperature contrast between the surface and the bottom of the sea, recrystallization is less of a problem for ^{18}O paleothermometry.

What's past is prologue

The surface temperature of the tropical oceans 50 million years ago is an issue of more than just academic concern. Before the end of this century, atmospheric CO_2 levels are expected to reach, at the very least, twice the preindustrial level of 280 parts per million. To learn what this portends for our climate, one wants to look back to a time when CO_2 levels generally exceeded 1000 ppm.

The fossil record makes it quite clear that, 50 million years ago, middle and high latitudes were much warmer than they are now. At the latitude of London, there were mangrove swamps, and mean annual temperatures were as much as 15°C warmer. Independent of the climatic evidence, we know from carbon-cycle models and from a variety of proxy indicators that atmospheric CO_2 levels were very high during that phase of Earth's history. One has to make do with proxy indicators like leaf stomata or boron isotopic ratios[4] because direct measurement of CO_2 levels in ice-core bubbles takes us back only a few hundred thousand years.

The essential problem is that CO_2 greenhouse climate models have been unable to reconcile the indisputably moderate polar and midlatitude conditions of those distant epochs with the planktonic ^{18}O evidence that the tropical oceans were then barely warmer than the oceans at mid-latitudes. So small a latitude gradient would require an extraordinarily efficient heat-transport system that the global modelers cannot simulate.[5] At stake is the whole question of CO_2 global warming prediction and its attendant policy issues.

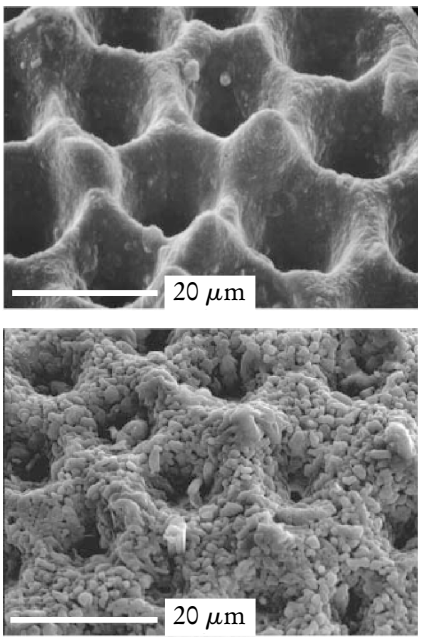

FIGURE 1. ELECTRON MICROGRAPHS contrast Eocene fossil shells of planktonic foraminifera in different states of preservation.[2] The many pores of the complex structure (see the cover of this issue) belie the fact that each shell is the work of one single-celled creature. The top specimen is from a nearly pristine sample preserved in impermeable clay. The more typical bottom specimen is a related species whose pores exhibit extensive calcite recrystallization through long-term contact with seawater.

Telltale isotopes

The stable heavy isotope ^{18}O accounts for about 0.2% of the oxygen in seawater. This slightly heavier nucleus affects evaporation, precipitation, and crystal formation. Rainwater and polar ice caps, for example, have less of the heavy isotope than does sea water. Urey argued, on thermodynamic grounds, that the formation of crystalline $CaCO_3$ (calcite) in sea water with dissolved calcium should involve some isotopic fractionation: The fraction of ^{18}O incorporated into the calcite should decrease with increasing water temperature, essentially because the heavier nucleus slows down the vibrational modes of the H_2O molecule.

To exploit this isotopic effect for paleothermometry, one has to correct for the extent of the polar ice caps and glaciers at the time in question. From the late Cretaceous to the late Eocene, ice caps were negligible. Therefore seawater was correspondingly lighter in oxygen than it is now, when so much of the lighter water is locked up in polar ice.

There's also the complication that different planktonic species, though they all float in the top few hundred meters, live at different depths below the surface, often changing habitat with the seasons. Some species, for example, keep to the topmost precincts because they live symbiotically with photosynthesizing algae. Not knowing the detailed life cycles of all the long-extinct creatures in these paleoclimate studies, researchers customarily deduce surface temperature for a given multi-species sample from the species that yields the lowest ^{18}O fraction, presumably corresponding to the habitat closest to the surface.

Another heavy isotope, carbon-13, helps to differentiate habitats. "It's also what makes our study convincing," Pearson told us. Dissolved carbonate in the ocean becomes steadily poorer in ^{13}C with increasing depth. That's because organic processes, which send a steady rain of biological debris to the bottom, preferentially sequester the lighter ^{12}C. Thus the shells of different planktonic species exhibit quite a range of ^{13}C concentrations, correlated with the depths at which they were formed. In fact, the considerable range of ^{13}C fractions found in traditional planktonic foraminifera samples has often been invoked as an argument against the notion that recrystallization might invalidate the ^{18}O data. If recrystallization at the seafloor seriously corrupts the ^{18}O results—so the argument goes—it would also largely wipe out the ^{13}C differences between species.

Pristine preservation

To acquire samples of pristine fossil microshells, uncorrupted by posthumous recrystallization, Pearson and company availed themselves primarily of impermeable clay deposits, laid down in shallow seas off East Africa during the epochs in question and now embedded in surface rock formations on the coast of Tanzania. Electron microscopy verifies the expectation that the impermeability of the clay has left the shells essentially free of recrystallized calcite.

In figure 2, the isotopic composition of one of these pristine Tanzanian samples, 45 million years old, is compared with that of a traditionally selected deep-sea sample of about the same age from the Angola basin in the South Atlantic. By convention, the

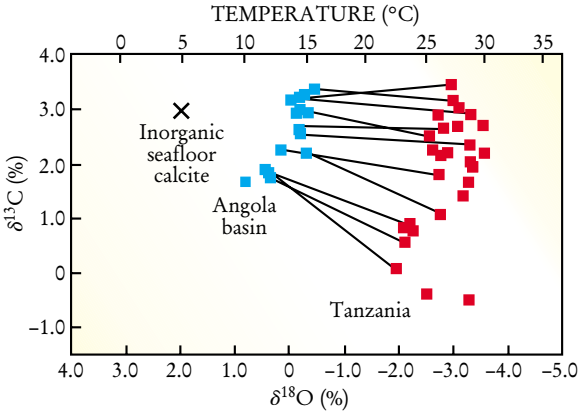

FIGURE 2. ISOTOPIC COMPOSITIONS of two different samples of fossil planktonic foraminifera shells suggest conflicting tropical sea surface temperatures 45 million years ago. The oxygen-18 excess, δ^{18}O, relative to a laboratory calcite standard, is plotted for various species against the carbon-13 excess, δ^{13}C. Common species are connected by lines. δ^{18}O serves as a paleothermometer. The well-preserved Tanzanian sample (red) suggests a sea about 15°C warmer than does the Angola basin sample (blue), which is compromised by posthumous recrystallization on the ocean floor. Variations within each sample reflect the different depths at which species floated. The recrystallization metamorphosis appears to converge on a point corresponding to inorganic calcite made entirely on the ocean floor. (Adapted from ref. 2.)

isotopic fractions of ^{18}O and ^{13}C are given as percentages in excess of the isotopic fractions in a convenient laboratory calcite standard—the so-called Vienna Pee Dee Belemnite standard. (The Pee Dee is a river in South Carolina.)

The ^{18}O excess, corrected for the absence of polar ice caps at the time, translates into the temperature at which the shells were formed. The more ^{18}O, the colder the water. Assuming that the range of temperatures in the pristine Tanzanian sample reflects the different depths at which the various floating species resided, the authors take the highest temperature—about 30°C—to have been the temperature at the surface. The traditional Angola basin sample in figure 2, presumably corrupted by evident recrystallization, suggests a much chillier surface temperature of about 16°C.

The ^{13}C range of the Tanzanian sample is another manifestation of the vertical range of the habitats of different species. The lines connecting the same species in the two samples shows the ^{13}C range shrunk to half its pristine width. The argument that both the oxygen and carbon isotopic changes are due to recrystallization is strikingly bolstered by the observation that the changes appear to be converging on the point in the figure that represents the expected isotopic composition of purely inorganic calcite precipitated at the seafloor.

Because the traditional Angola basin sample is about halfway between the pristine sample and the convergence point on this plot of carbon and oxygen isotopic fractions, the Pearson group concludes that roughly half the calcite in the fossil microshells of the traditional sample has been replaced, over the eons, by recrystallized material.

The paper concedes that the two samples may have been somewhat different from the start. Unlike the planktonic foraminifera of the Angola basin, those in the Tanzanian sample lived in shallower coastal waters. Nonetheless, the authors argue, the new results should help to free the discussion of global warming from the cool-tropics paradox that has bedeviled paleoclimatology. "For those parts of the late Cretaceous and Eocene epochs that we have sampled, tropical temperatures were at least as warm as they are today, and probably several degrees warmer."[2] If it were otherwise, we would have trouble believing any of the CO_2 greenhouse models.

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Can Polymeric Carbon-60 Be Magnetic?

A research team has polymerized carbon-60 at high pressures and temperatures and reported[1] that the product exhibits ferromagnetic properties at surprisingly high temperatures: near 500 K. Naturally, such an announcement elicits skepticism, because the constituent molecules have no magnetic moments and also because there have been premature claims of ferromagnetic behavior in other organic polymers.[2]

The experimenters—who hail from Russia, Sweden, Germany, and Brazil—were themselves duly cautious about this serendipitous result, discovered while they were looking for superconductivity. After spending two years ruling out spurious effects from possible impurities, the collaborators decided to publish. "They've made a reasonable argument for ferromagnetism," comments Joe D. Thompson of Los Alamos National Laboratory, "and produced compelling evidence that the material should be studied further."

If a recent experiment is confirmed, theorists will be challenged to explain the evidence for weak ferromagnetism in a compound made solely of carbon.

Further studies will be motivated by two factors. One is the intrinsic curiosity about what might cause magnetic behavior in a structure made solely of carbon, an atom that has no unpaired electrons.

The second factor is interest in possible applications. Considerable research is already focused on producing molecule-based magnets, fueled by the ease with which such magnets might be made and the ability to modulate their properties by synthetic chemistry techniques. Some researchers have looked for magnets that have no metallic atoms and that hence might be less dense. However, as team member Tatiana Makarova of the Ioffe Physico-Technical Institute in St. Petersburg, Russia, cautions, "the application of this material is only a dream. The samples are very expensive because we start with a costly commercial fullerene and use nearly the same technology as that for making artificial diamonds."

Magnetism was seen in a metal-free organic compound about ten years ago,[3] but it had a very low Curie temperature