An About-Face Found in the Ancient Ocean

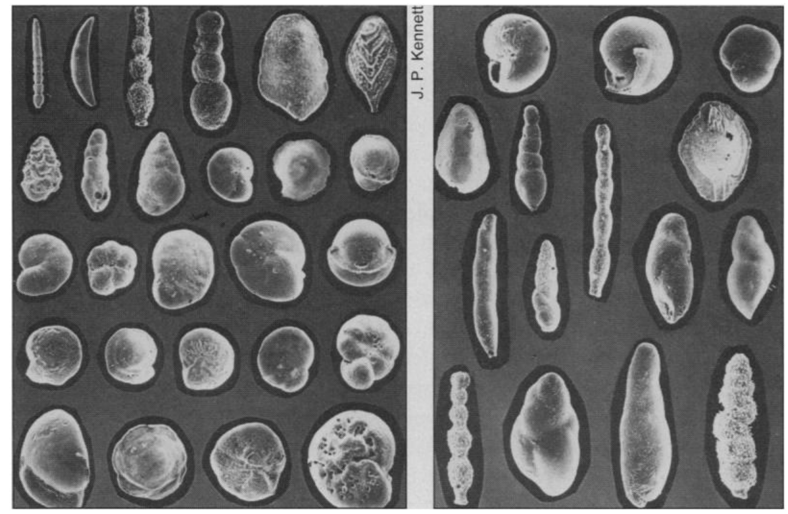
An abrupt influx of warm water due to a reversal of deep-sea circulation seems to have triggered a major extinction

EVEN NEAR THE EQUATOR, THE DEEP OCEAN holds memories of the poles. Near-freezing water sinks into the abyss in polar seas and spreads out into the deepest parts of the world ocean in a circulation pattern that seems to have prevailed for tens of millions of years of recent geological history. But 57 million years ago, according to a record just deciphered in a sediment core from the ocean floor off Antarctica, the familiar pattern reversed abruptly. In the space of just a few thousand years, warm and exceptionally salty water from shallow tropical seas flooded the deep ocean and spread to high latitudes. That may sound like a benign change, but for the unicellular animals living in the sea bed it was the greatest calamity of the past 90 million years. The same sediment interval that testifies to the circulation change also records the disappearance of 40% to 50% of their species.

The discovery, reported by paleoceanographers James Kennett of the University of California, Santa Barbara, and Lowell Stott of the University of Southern California in this week's *Nature*, sheds light on the capricious workings of the ocean in past epochs and points to a cause for an extinction event that had long puzzled researchers. More than that, it marks one of the few cases in which researchers have been able convincingly to link an extinction to a specific environmental change. Except in the case of the celebrated die-off 65 million years ago that included the dinosaurs—when many of the extinctions coincided precisely with an extraterrestrial impact—it is rare that killer and victim are caught in such a close embrace that a clear verdict might be rendered.

The incriminating evidence came from both technological innovation and good luck. The innovation is the Advanced Piston Corer (APC) operated from the Ocean Drilling Project's drill ship *Resolution*, which retrieved the crucial sediments in 1987 from beneath 2900 meters of icy water off the coast of Antarctica. Past deep-sea sampling efforts relied on a rotating bit and drill pipe of the sort used in oil drilling. But that equipment's twisting action had a nasty habit of churning samples of soft mud, laid down grain by grain and layer by layer, into unintelligible swirls. The APC, in contrast, punches out each section of core like a cookie cutter, leaving the delicate layering undisturbed.

No matter how gingerly the mud is sampled, though, its layering may already have been disrupted by bioturbation, the burrowing and churning of worms and other animals living in the topmost sediment layers. That's where the luck came in—in the form of the extinction itself. The event that killed off bottom-dwelling, unicellular animals—called foraminifers, or forams—also eliminated for a time the larger animals responsible for bioturbation.



Before and during the crisis. *The sudden influx of warm, oxygen-poor water 57 million years ago transformed the diverse community of 60 foram species into a meager collection of 17 holdouts. Samplings of the community pre- and post-extinction are shown at left and right, respectively. Most of these forams are about 200 micrometers in size.*

The result was a sediment record detailed enough to reveal the decline of the forams with unprecedented resolution. Ellen Thomas of Cambridge University, who had the first look at the cores, saw at once that the foram extinction had taken far less than the 2 million years or so that had been assumed. When Kennett and Stott did detailed sampling along the core, they found that about 40% of the bottom-dwelling foram species vanished in less than 2000 years. And the abruptness is not an artifact, says Kennett. "I'm absolutely sure" that the sedimentary record is complete, he says.

The recognition of the abruptness of the deep-sea extinction 57 million years ago only deepened the mystery surrounding its cause. The bottom dwellers, after all, had sailed right through the mass extinction 8 million years earlier while forams in surface waters were dropping right and left and the dinosaurs were gasping their last. But the same few centimeters of sediment that recorded the extinction also bore a signature of the event that killed them.

Kennett and Stott found that signature by analyzing the ratios of different oxygen and carbon isotopes in the tiny shell-like remains of forams. The ratio of oxygen-18 to oxygen-16 can reflect the temperature of the water from which the forams made their carbonate skeletons. A change in another isotope pair, carbon-13 and -12, can indicate a change in the biological productivity of the ocean as a whole—perhaps due to a shift in circulation. Kennett and Stott found that both ratios dropped precipitously over the same 2000-year period that witnessed the demise of so many bottom-dwelling forams, then gradually rose again over the next 100,000 years. The precise coincidence of the two events in such a pristine record, Kennett and Stott argue, implies that whatever whipped the isotopes about must also have caused the extinctions.

That underlying event, Kennett and Stott argue, was a major reversal in ocean circulation, which flooded the deep ocean with warm water. According to the oxygen isotopes, the temperature of bottom waters at the Antarctic site soared from about 10°C to 18°C. The rapid warming itself might not have been fatal, but warm water carries less oxygen—a key factor, Kennett and Stott argue, in the deep-ocean extinction.

In an unusual show of unanimity, other paleoceanographers endorse Kennett and Stott's claim that ocean circulation must have reversed—a claim that was recently strengthened when Dorothy Pak and her colleagues at Lamont-Doherty Geological Observatory found matching isotope changes in cores from other sites. And researchers have been quick to offer explanations. Most agree that the warm, salty bottom water must have originated in the many shallow seas that then spread across tropical latitudes. As Garrett Brass and John Southam of the University of Miami and William Peterson of Pennsylvania State University argued a decade ago, such tropical seas would have been just the place to evaporate away lots of fresh water and make the remaining seawater salty enough and thus dense enough—in spite of its warmth—to sink to the bottom of the deep sea.

But there's no consensus about what could have caused the bottom water source to shift almost instantaneously, in geological terms, from the high latitudes to the tropical seas. Kennett and Stott suggest that this episode was just an extreme excursion in a circulation system in which warm, saline bottom water was already competing with cold bottom water from the high latitudes. Fifty-seven million years ago, they note, the world was in the midst of a gradual warming trend that, within a few million years, would culminate in the highest temperatures of the past 65 million years. They suggest that an already strong source of warm, saline deep water may have taken over temporarily when the warming atmosphere and increased precipitation near Antarctica reduced the density of surface waters there, shutting off the competing cold water source.

But Thomas argues that instead of being a blip on a long-term trend, the deep-sea warming of 57 million years may have been a singular event. Her proposed trigger is the massive outpouring of carbon dioxide-laden lavas that accompanied the early opening of the North Atlantic at about that time. A pulse of volcanic carbon dioxide might have caused a greenhouse warming large enough, she suggests, that warm, saline bottom water flooded a world ocean that had been previously dominated by cooler sources.

Whatever the cause of this deep-sea event, paleoceanographers will probably be spinning tales about other ones. "The more we look at the high-resolution record," says Kennett, "the more we're finding these brief, dramatic events having profound effects on Earth's biota." And the talk among paleontologists will not be limited to the deep sea; such oceanic events, because of their effect on global isotope chemistry, offer a way to correlate events in the ocean and on land.

A case in point: James Zachos of the University of Michigan and Paul Koch of the Carnegie Institution of Washington's Geophysical Laboratory have traced the carbon isotope signal 57 million years ago to land plants and the tooth enamel of herbivorous mammals of the Big Horn Basin in Wyoming. Now they are using the easily identified excursion as a time marker in the terrestrial fossil record. That's a pretty long reach for the few liters of ocean-floor mud that started it all. ■ RICHARD A. KERR

Fetal Brain Signals Time For Birth

In sheep, reproduction runs like clockwork. Twenty one weeks—give or take a day or two—after a ram impregnates a ewe, a little lamb is born. For years, scientists have tried to figure out the crucial change in the developing fetus that signals the time has arrived for pregnancy to end. Now, two teams, one in the United States and the other in New Zealand, have come up with compelling evidence that a tiny nucleus in the fetal sheep brain plays a crucial role in bringing gestation to a close.

Understanding how the timing of pregnancy is controlled has enormous implications for human health. The American College of Obstetricians and Gynecologists reckons that between 6% and 8% of all pregnancies terminate prematurely, and premature infants are at a far higher risk of birth-related defects and infant mortality than full-term infants.

Neural timekeeper. *McDonald* (left) *and Nathanielsz point out key nuclei.*

Researchers have long known from work in sheep that hormones released by the fetal pituitary and adrenal glands are involved in terminating pregnancy. Just prior to birth there is a rise in the production of adrenocorticotropic hormone (ACTH) from the pituitary, followed by an increase in cortisol from the adrenal gland. Adding ACTH or cortisol to the fetal blood supply will shorten gestation. The increased cortisol alters the enzymatic balance in the mother's uterus, and this leads to the start of labor.

Peter W. Nathanielsz and Thomas J. McDonald of the Laboratory for Pregnancy and Newborn Research at the Cornell University Veterinary College in Ithaca, New York, wanted to find out what was responsible for initiating this rise in ACTH. They focused their attention on the paraventricular nucleus of the hypothalamus, a part of the brain that clearly plays a role in controlling pituitary hormones in the adult animal. Details of their work, which was supported by the National Institute of Child Health and Human Development appear in the 15 September issue of *The American Journal of Obstetrics and Gynecology*.

At 120 days of gestation, they performed surgery on nine fetal lambs. In five, they destroyed the paraventricular nuclei on both sides of the brain; in the other four they merely inserted the same instruments into the fetal brain, but left the nuclei intact. All four of the control animals delivered right on schedule, but the five animals missing their paraventricular nuclei showed no sign that birth was imminent, and the researchers artificially terminated the pregnancies after 23 weeks in order to study the fetal brains.

In the New Zealand study, Peter D. Gluckman and colleagues at the University of Auckland looked at 29 fetal sheep, removing a variety of brain structures including, in some cases, the paraventricular nuclei. Only the animals missing the paraventricular nuclei showed a significant lengthening of the time of pregnancy. Their work will be published in an upcoming issue of *The American Journal of Obstetrics and Gynecology*.

Nathanielsz says he believes that the paraventricular nucleus acts as a tiny computer, assessing signals from various developing organs. When the organs have reached the proper degree of development, the paraventricular nucleus sends a hormonal signal to the pituitary to start producing ACTH, thereby initiating labor.

But how good a model is the sheep for understanding how pregnancy works in humans? There are clearly differences. For one thing, the birth of anencephalic babies—infants with no brain at all—generally does not have to be induced, which suggests that the paraventricular nucleus is not crucial for terminating pregnancy. But Charles Wood, a physiologist at the University of Florida at Gainesville, points out that gestation times for anencephalic babies vary enormously, indicating that something in the control mechanism has probably gone awry. He believes the work by Gluckman and Nathanielsz is a crucial piece of the puzzle of how pregnancy is controlled. The trick now, he says, will be to figure out what factors control the activity of paraventricular nuclei. That's something Nathanielsz says he is already looking into. ■ JOSEPH PALCA