PALEOCLIMATOLOGY

Second Clock Supports Orbital Pacing of the Ice Ages

For a while, it looked as if a water-filled crack in the Nevada desert might doom the accepted explanation of the ice ages. Twenty years ago, the so-called astronomical theory had carried the day. Oceanographers had found evidence implying that the march of ice ages over the last million years was paced by the cyclical stretching and squeezing of Earth's orbit around the sun, which would have altered the way sunlight fell on the planet's surface. But in 1988, researchers scuba diving in Nevada's Devils Hole came up with a climate record—captured in carbonate deposits in the crack—that seemed to contradict this chronology (*Science*, 6 April 1990, p. 31).

The Devils Hole record traced climate swings of about the same length as the marine record, but they were out of step with the variations of Earth's orbit. Most glaringly, these carbonates indicated a profound warming trend, which appeared to signal the end of the penultimate ice age, thousands of years before orbital variations could have begun to melt the ice. If the Devils Hole chronology was a true record of the world's ice ages, researchers would have to dump the astronomical mechanism and look for something new.

But now, after almost a decade of wrangling over whether inaccuracies in the dating of one record or the other might account for the conflict, an arbiter has come forward. On page 782 of this issue of *Science*, geochronologists Lawrence Edwards and Hai Cheng, of the University of Minnesota, and Michael Murrell and Steven Goldstein, of Los Alamos National Laboratory in New Mexico, present the preliminary verdict. They used a new clock, based on the radioactive decay of uranium-235 to protactinium-231, to check the dates of both the Devils Hole record and records of sea-level change in Barbados coral. The result: The marine record is right, and the astronomical theory is on solid ground.

But the new findings haven't settled the issue cleanly: Puzzlingly, the Devils Hole record seems to be correct as well. To most oceanographers, this bolsters their contention that the Devils Hole and marine records "are two fundamentally different beasts," says Steven Clemens of Brown University. He and others suggest that while the marine records trace the ebb and flow of the ice ages, Devils Hole may chronicle only the climate of a region as small as southwestern North America.

"They have convinced us that both kinds of dates are pretty firm," adds geochronologist Teh-Lung Ku of the University of California. "That gives us another layer of confidence that dating isn't the problem."

The original confirmation of the astronomical theory came in the late 1970s from sea-floor sediment, where the ratio of two oxygen isotopes traces how much water was locked up in the ice sheets when the sediment was deposited. This ice-volume signal showed that water flooded into the ocean from melting ice

ARTHUR BLOOM/CORNELL UNIVERSITY

Benchmarks. Terraces on the New Guinea coast record the high sea levels of past interglacial periods.

sheets about 128,000 years ago, marking the start of the last warm interglacial period. That was just when orbital variations would have maximized the amount of sunlight falling on Northern Hemisphere ice sheets. The coincidence had helped convince oceanographers that orbital variations paced the ice ages.

But because marine sediments are so difficult to date, the team of oceanographers studying this isotope record, the so-called spectral mapping group (SPECMAP), had only two or three direct dates for the sediment of the past million years. To fill in the chronology, they simply counted the "ticks" left in the isotope record by two known periods of the orbital clock, 21,000 and 41,000 years long. But a better, more directly dated record tended to confirm the sea-floor chronology. Corals that formed at the ocean's surface when melting ice pushed up the sea level, then died when the ice returned and sea level fell, have left terraces that can be dated by measuring the accumulation of thorium-230 from the decay of uranium.

Some of the coral dates were at odds with the astronomical predictions, however, and the Devils Hole record posed an even starker contradiction (*Science*, 9 October 1992, p. 220). Oxygen isotopes in the finely layered carbonate deposited there by ground water record the temperature of the atmosphere when the rain or snow fell. When Isaac Winograd of the U.S. Geological Survey in Reston, Virginia, Kenneth Ludwig of the Berkeley Geochronology Center in California, and their colleagues applied uranium-thorium dating to the carbonate layers, they found that the warmth of the last interglacial began 140,000 years ago in Nevada. That was long before orbital changes would have begun warming the Northern Hemisphere.

One possible explanation for the conflict was that one or both sets of dates had been skewed by chemical alteration of the rock, which could add or deplete the uranium or thorium. Any exchange—say, with ground water seeping through an old coral bed—would change the setting of the thorium clock and produce an erroneous age. "There was always some degree of uncertainty about the thorium-230 ages," says Edwards, "because you never had a good way of determining whether the age was accurate or not."

Now Edwards and his colleagues have come up with the first reliable check on age-altering chemical changes. This check involves the element protactinium, which is also a decay product of uranium but comes from a different isotope than thorium. Chemical alteration should have similar effects on both clocks. But because the uranium "parents" of protactinium and thorium decay at different rates, an altered sample will yield different thorium and protactinium ages, while reliable ages will agree. To get the most precise reading from this second clock, Edwards and his colleagues directly counted individual protactinium atoms with a new mass-spectrometric technique, instead of trying to estimate the element's abundance by measuring its own slow decay. "It's a technological tour de force," says Ludwig.

Edwards applied this procedure to samples from both the Barbados coral and Devils Hole. He found that "most, but not all, of the samples [of Barbados coral] that we thought were accurate are." But the protactinium-thorium approach also supported the dating of Devils Hole samples. This should put to rest any question about the reliability of the Devils Hole ages, says Ludwig.

Oceanographers are quite content with this split decision. It puts the last interglacial, as recorded in the coral, somewhere around 129,000 to 120,000 years ago—about where oceanographers always had it. Although the earlier warming at Devils Hole appears to be real, it must have been a local event, say climate researchers. Thomas Crowley of Texas A&M University notes, for example, that some marine records from midlatitudes in the Atlantic and Pacific show signs of an early warming without a massive melting of glacial ice. The ocean's most frigid waters might have retreated far enough northward to allow continental midlatitudes (including Devils Hole) to warm, but not so far as to allow wholesale glacial melting, he says.

Winograd, though, continues to think that Devils Hole might be recording global climate changes. He says that if Edwards had checked more coral ages, the marine record might have fallen into line with Devils Hole. He notes that some corals from places such as Hawaii, Australia, and the Bahamas put the interglacial sea level rise as early as 134,000 years ago, and some maintain a high sea level as late as 110,000 years ago. "These dates, if correct, are clearly incompatible with [orbital] forcing," says Winograd. "If Edwards had redated these, that would have been new."

Edwards will be extending his testing of coral ages beyond Barbados, but he suspects that the anomalous ages found elsewhere will not hold up. Geochronologist James Chen of the California Institute of Technology, who produced some of the older dates, agrees with Edwards, saying those dates can be "peculiar" and "should not be taken too seriously."

Other records are also yielding new support for the orbital theory. Oceanographer Maureen Raymo of the Massachusetts Institute of Technology has dated marine cores without using the shorter orbital cycles to measure time. She simply assumed that sediment accumulated steadily between the oceanographers' three traditional dates and then combined the oxygen isotope records of 11 cores longer than 800,000 years. The average ages of the seven ice-age deglaciations in that interval came "very, very close to SPECMAP ages," she says.

Even a terrestrial source—Jewel Cave, 1500 kilometers north-northeast of Devils Hole in the Black Hills of South Dakota—seems to be lining up on the side of orbital pacing. Cave carbonates analyzed by Derek Ford and his colleagues at McMaster University in Hamilton, Canada, and Joyce Lundberg of Carleton University in Ottawa, put the end of the penultimate ice age between 131,000 and 129,000 years ago, with the interglacial warmth lasting until about 119,000 years ago. "We've got it pretty much nailed exactly where the ocean-core people put it," says Ford. If such claims hold up, the orbital theory of the ice ages will win a second round.

–Richard A. Kerr

MEDICAL IMAGING

New Technique Maps the Body Electric

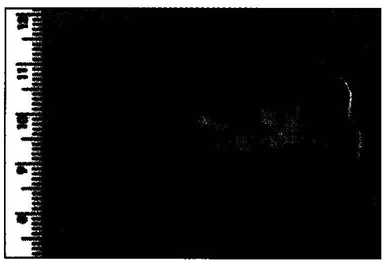
Medical imaging is built on gifts from physics, among them x-rays, nuclear magnetic resonance, and radioactive decay. Now, yet another imaging technology may be emerging from the physics world. At last month's Vancouver meeting of the International Society for Magnetic Resonance in Medicine, two National Institutes of Health scientists introduced Hall-effect imaging (HEI), a strategy for combining ultrasound with magnets and electrodes to map variations in the electrical conductivity of tissues.

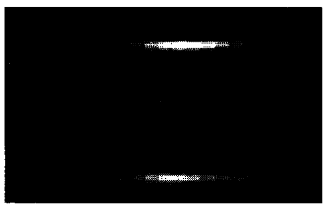
Those variations may allow clinicians to distinguish tumors, fatty plaques, or areas of ischemia from normal tissue, something that's difficult with ordinary ultrasound. The technique also should provide better contrast than ultrasound, while retaining a cost advantage over magnetic resonance imaging, say the developers, Han Wen and Robert Balaban, of the National Heart, Lung, and Blood Institute. So far, the most complex specimen that Wen and Balaban have imaged is a pig kidney, but other medical-imaging specialists believe their technique could eventually have broad applications.

"This has the potential to be a very valuable approach to imaging," says Nathaniel Reichek, head of cardiology at the Allegheny General Hospital in Pittsburgh and a leader in the field of cardiac imaging. He notes, however, that "the approach stands just on the doorstep of development. It's a very long path from there to widespread use."

The method makes use of the Hall effect. Electric charges (for example, ions in biological tissue) follow curved paths when they move in a magnetic field. Because positive and negative charges curve in opposite directions, they diverge, giving rise to a so-called Hall voltage. In biological tissue, an ultrasound beam can create the motion while an external magnet imposes the field. The size of the resulting Hall voltage is determined largely by the tissue's conductivity.

To maximize the signal-to-noise ratio, Wen actually runs the system in reverse—applying voltage pulses through electrodes and picking up the resulting vibrations with an ultrasound detector. After some mathematical manipulation, the ultrasound signal gives a profile of the conductivity along the direction the detector is pointed. As with conventional ultrasound, the detector must be moved to collect a full three-dimensional image.





H. WEN

Lighting up. In a pig kidney *(above)*, Hall-effect imaging maps conductivity variations *(lower right)*, while conventional ultrasound *(upper right)* is sensitive to density.

Like ultrasound, HEI requires a continuous acoustic path from skin to imaged tissue, so it cannot see through bones or the air in lungs, for example. The technique also requires a magnet and a voltage pulser, which aren't needed for conventional ultrasound. But because HEI stimulates acoustic waves in the tissue, the ultrasound needs to travel only one way rather than round trip, as in conventional ultrasound imaging. That should give HEI deeper penetration and better resolution. Wen believes, however, that the method's real strength is its sensitivity to conductivity variations.

He explains that when conventional ultrasound imaging of the interior of a blood vessel reveals a bulge, for example, "it's very hard to tell whether that bulge is just a harmless fibrous lesion, or whether it's actually a more dangerous fatty plaque. Now, potentially you could use this technique, because there's a big difference in conductivity between these two types of tissue." Wen and Balaban also propose using HEI to observe the stages of tumor development, to diagnose ischemic (oxygen-deprived) heart tissue, and perhaps to distinguish breast tumors from cysts.

Last summer, Wen tested the system on a slice of bacon and found that it revealed the fat and muscle layers with greater contrast than ultrasound could; he has since moved on to pig kidneys. Before applying the system to entire animals, he wants to add an improved voltage pulser and real-time image processing. (Currently, the analysis must be done after the data are collected.) He plans to begin imaging animals within the next year.

Reichek thinks it's a worthwhile effort and hopes eventually to use HEI to diagnose scar tissue and other abnormalities of the heart: "Genuinely novel approaches to biological imaging don't come along all that often, and this is one of them."

–David Ehrenstein

David Ehrenstein is a science writer in Bethesda, Maryland.