Ancient Sea-Level Swings Confirmed

Geologic benchmarks long touted by Exxon scientists apparently do record changes in global sea levels, but the driving force behind the oldest sea-level shifts remains mysterious

Back in the 1970s, the oil giant Exxon offered the world's geologists what the company saw as a precious gift. By analyzing the jumble of sediments laid down on the edges of the continents as the seas advanced and retreated, Exxon researchers had charted the rise and fall of sea level over the past 250 million years. If authentic, such information would indeed be valuable, for the ups and downs of the ocean hold a key not only to finding the world's oil and gas deposits, but perhaps also to tracking the waxings and wanings of the ice sheets—and the climate changes that drove them. But outsiders were dubious about the curves, in part because the supporting data were proprietary. So skeptical academics have struggled for the past 20 years to determine whether Exxon's gift was geological treasure or merely fool's gold.

Then, last month, oceanographers returned from drilling nearly 3 kilometers of core from the Straits of Florida and reported preliminary data that match Exxon's curves. Together with other, recently published results, the cores provide strong support for the contention that at least for about the past 40 million years, the records of changing sea level bestowed by Exxon are indeed a prize worth having.

Even some early doubters are now won over. "I'm saying, a little sheepishly, 'By golly, those Exxon guys seem to have gotten it pretty close to being right,' " says oceanographer Gregory Mountain of Columbia University's Lamont-Doherty Earth Observatory, who has been critical of the Exxon curves. Mountain, Kenneth Miller of Rutgers University, and colleagues recently reported evidence in support of the curves from seven core holes drilled off New Jersey. Bilal Haq, a former Exxon researcher who is now director of the Marine Geology and Geophysics Program at the National Science Foundation, is delighted with the endorsement. "Ken Miller and his colleagues were some of the biggest critics of the curve when it first came out," says Haq. "Now they are the biggest supporters."

But doubters remain. And even Haq readily concedes that much of the promise of the Exxon sea-level curves—particularly that of the most ancient records—has yet to be fulfilled. The problem is that researchers can see no mechanism to drive the oldest of the global sea-level changes. All they can think of are ice sheets—which are hard to envision in the warm climate that prevailed before about 50 million years ago.

ODP

Core knowledge. Bahama drilling *(top)* showed sedimentation changes in cores *(right)*.

The ocean's dipstick

The Exxon curves were born back in 1975, when Peter Vail, now at Rice University, and colleagues at Exxon Production Research Company in Houston claimed they had found the geologic equivalent of an oceanic "dipstick" preserved on the continental margins. Each time the sea retreated, the shoreline moved toward the edge of the continental shelf. The researchers argued that erosion of the exposed shelf created a distinctive gap in the geologic record, and that such gaps could be recognized in the radarlike seismic images of the sediments beneath the sea floor today. The team used these erosional gaps or unconformities as a sort of low-water mark on the dipstick of the continental margin's sediment pile. Once dated at a single site, these marks could be recognized elsewhere.

Exxon scientists scanned continental margins around the world, found many unconformities having the same ages, and concluded that only global falls of sea level could be responsible. Furthermore, some of the ups and downs of sea level were very rapid—taking only a million years to rise or fall tens or even hundreds of meters—and they concluded that only fluctuations in the size of major ice sheets could add or withdraw water from the ocean so quickly.

Those inferences add up to an impressive package of knowledge—assuming that the curves really contain all the goodies that the Exxon workers claimed. But academic researchers noted that other, more local mechanisms could also move shorelines back and forth across the continental margins. In particular, tectonic forces could have pushed the margins themselves up and down—in effect moving the dipstick itself. "We have problems [even] today figuring out what sea level [change] is because we can't work out whether the land is moving or the sea is moving," notes Christopher Kendall of the University of South Carolina. "We have nowhere to stand." Such local tectonic forces could have moved shorelines at different times at different places, without a global change in ocean volume. If so, the Exxon curves might be counterfeit rather than real.

The problem was compounded by the fact that Exxon researchers couldn't release the proprietary seismic and well data behind their curves. So academic researchers went in search of their own records from continental margins, hoping to independently confirm—or rebut—the Exxon curve.

The latest such study to be fully analyzed drew on the Ocean Drilling Project's (ODP's) 1993 cores from offshore New Jersey as well as two drill holes on the New Jersey coast. As they reported in *Science* (23 February, p. 1092), Miller, Mountain, and colleagues combined several dating methods to determine the age of 10 unconformities occurring between 10 million and 36 million years ago. Their results generally match Exxon's for that time. "I think the [Exxon] curve has done a very good job in getting the timing of global sea-level changes," says Miller. "They have about the right number [of unconformities], and [they're] about the right age."

But this single site in New Jersey does not make an airtight case, especially because the Exxon curves themselves relied heavily on data from this area. So although the curves match, the shoreline change could have been driven by local tectonic motions. The latest results from ODP Leg 166, however, sample a different area—off the Bahama Bank in the Straits of Florida. In addition to being far from New Jersey, this site had the added attraction of continuous deposition, as the deep straits accumulate sediment even during sea-level low stands. That and more abundant microfossils allow researchers to date low stands to within 200,000 years rather than the 0.5 million to 1 million years typical of offshore New Jersey, says marine geologist Gregor Eberli of the University of Miami, a co–chief scientist on Leg 166.

Drilling of Leg 166 wrapped up only last month, so complete results won't be out for years, but preliminary analysis supports the Exxon curve. "In some places we were spot on," says Eberli. "In other places, especially when you go back beyond 10 million years ago, we have a bit different times than [Exxon] has." But he notes that the global nature of the sea-level changes in earlier times gets additional support from recent data from offshore Brazil. There, Vitor Abreu and Geoffrey Haddad of Rice University, using well data provided by the Brazilian oil company Petrobras, tracked sea-level changes that correlate very well with the Florida data, Eberli says. The mismatches between his own results and Exxon's are understandable, he adds, given that the most up-to-date Exxon curve is now almost 10 years old: "We will refine their curve."

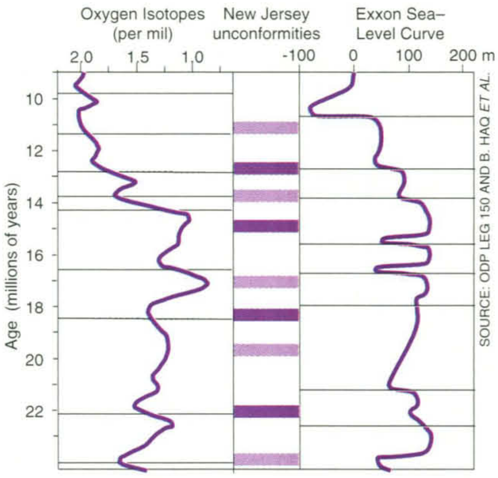
This double-barreled documentation of the curve hasn't yet swayed all doubters, though. Andrew Miall of the University of Toronto, for example, remains a staunch opponent. "I don't think this is good science at all. There are so many events in the Exxon curve and the margin of error in dating is so large that you could correlate anything with it," he says. Indeed, Miall has shown good correlations between the Exxon curve and randomly generated sets of events.

"Andrew's point is well taken," says Miller. Matching a sea-level change from one site to the Exxon curve is inevitably subjective, he notes, so there has been a tendency to make matches where none exist. But, he says, "we're nailing the timing. ... At some point, it's reasonable to say these changes are correlated and [therefore] they are causally related." Kendall agrees: "Whereas Miall is scientifically correct—it is difficult if not impossible to date all of these things perfectly—what we find is that it seems to be working."

A mysterious mechanism

Even if the Exxon curve is a faithful record of global undulations of sea level, it's likely to spark another controversy, over what's driving sea-level change. Researchers have presumed that the answer is the melting and growing of ice sheets. But the Exxon curve pushes the glacial explanation to the breaking point, for the curve rises and falls in a rapid rhythm throughout the past 250 million years—and Earth was thought to be too warm for ice sheets for much of that time.

And while researchers have been able to link the Exxon curve and ice volume during the recent past, the links peter out at earlier times. To measure past ice volume, researchers analyze the oxygen-isotope composition of carbonate sediments. As glacial ice grows



Sea changes. Some drops in sea level *(lines, left)* correlate with core unconformities *(colored bars, center)* and with rapid changes in isotopes *(lines, left).*

at the expense of seawater or melts into the ocean, it changes the isotopic composition of seawater and the carbonate skeletons of marine plankton.

Now the Leg 155 group has correlated these changes in oxygen isotopes with their New Jersey sea-level changes and with the Exxon curve, back to 36 million years ago. And in a paper in press in *Geology*, Miller and James Browning of Rutgers extend the link between isotopic changes and the Exxon curve to at least 43 million years ago. Abreu's analysis of isotope data also shows signs of ice-driven sea-level change, up to 49 million years ago. But before that, while the world was experiencing the warmest heat wave of the past 65 million years, both groups find that the correlation falls apart, leaving no mechanism to drive sea-level changes.

Yet the evidence for rapid, global change in sea level continues to accumulate. Heather Stoll and Daniel Schrag of Princeton University have used strontium preserved in carbonates to track the exposure of continental margin sediments during the period of relative warmth 90 million to 130 million years ago, when oxygen isotope records are unreliable. When falling sea level exposes sediment to leaching by fresh water, the amount of strontium in the world ocean increases. In work presented at last fall's meeting of the American Geophysical Union, the researchers found that seawater strontium doubled in a few hundred thousand years, suggesting rapid sea-level drops of 30 to 50 meters, and the drops coincide with major falls in the Exxon curve. Stoll and Schrag also turn to a glacial explanation, suggesting that ice sheets may have temporarily grown large enough to lower sea level—a provocative idea, given signs in the fossil record of balmy, high-latitude climes.

If glaciers didn't drive sea level up and down, what did? The jostling of tectonic plates has been suggested; Kendall has even speculated that meteorite impacts might have done the job in torrid times, by changing tectonic stresses. But there's little evidence for such theories. "People start having problems" with the Exxon curve in earlier times, concedes Haq, "because the mechanism is still unknown." Geologists may now be willing to accept Exxon's gift, but they haven't yet unwrapped all its meanings.

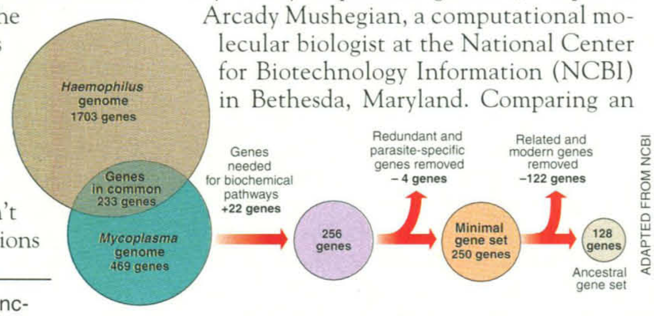
–Richard A. Kerr

GENOME MEETING

Seeking Life's Bare (Genetic) Necessities

COLD SPRING HARBOR, NEW YORK—How many genes does an organism need to survive? Last week at the genome meeting here,* two genome researchers with radically different approaches presented complementary views of the basic genes needed for life. One research team, using computer analyses to compare known genomes, concluded that today's organisms can be sustained with just 250 genes, and that the earliest life forms required a mere 128 genes. The other researcher mapped genes in a simple parasite and estimated that for this organism, 800 genes are plenty to do the job—but that anything short of 100 wouldn't be enough.

Although the numbers don't match precisely, those predictions "are not all that far apart," especially in comparison to the 75,000 genes in the human genome, notes Siv Andersson of Uppsala University in Sweden, who arrived at the 800 number. But coming up with a consensus answer may be more than just a genetic numbers game, particularly as more and more genomes are completely mapped and sequenced. "It may be a way of organizing any newly sequenced genome," explains Arcady Mushegian, a computational molecular biologist at the National Center for Biotechnology Information (NCBI) in Bethesda, Maryland. Comparing an



Stripping down. Computer analysis yields an estimate of the minimum modern and ancient genomes.

* Genome Mapping and Sequencing, Cold Spring Harbor, New York, May 8 to 12.