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## Temperatures from Fossil Shells

*Climate science required the invention and mastery of many difficult techniques. These had pitfalls, which could lead to controversy. An example of the ingenious technical work and hard-fought debates underlying the main story is the use of fossil shells to find the temperature of oceans in the distant past. For other examples, see the essays on Uses of Radiocarbon Dating and Arakawa's Computation Device.*

The oceans swarm with tiny plankton, including countless foraminifera (nicknamed "forams"), single-celled animals that scavenge with pseudopods wiggling through holes in their shells. When forams die, their tiny shells drift down into the ooze of the seabed and there endure for ages, so numerous in some places that they form thick deposits of chalk or limestone. Different species can be identified under the microscope by the striking architecture of their shells, as elaborate as candelabra. Wolfgang Schott, inspecting findings of the German *Meteor* oceanographic expedition of 1925-27, realized that the species whose shells were found in the muck of the seabed depended sensitively on the temperature of the water where the creatures had lived. The mix of foram species could serve as a thermometer of past climates.<sup>1</sup>

In the 1950s, the nuclear chemist Harold Urey devised another way to use the shells to measure ancient temperatures. He found he could take the temperature of an ancient ocean by measuring the oxygen that forams built into their shells. The rare isotope oxygen-18 is a bit heavier than normal oxygen-16, and biologists had shown that the amount of each isotope that a foram takes up varies with the temperature of the water. The isotopes were fossilized with the shells, and the ratio of isotopes ( $O^{18}$  to  $O^{16}$ ) could be determined with the new and exacting techniques of mass spectrometry.<sup>2</sup> Urey and his team at the University of Chicago refined these tools, developed for nuclear studies, and applied them to calcite in fossils. They found plausible temperatures clear back to the Cretaceous era, more than 100 million years ago.<sup>3</sup>

Many problems had to be solved along the way. First of all, cores had to be extracted from the sticky sediments of the ocean floor without disturbing the layers. Börge Kullenberg solved the problem for a Swedish Deep Sea Expedition in 1947. He put a piston inside a tube and pulled the piston up to suck in sediment while the tube was being shoved into the seabed. Kullenberg could recover cores more than 20 meters long. Back in the lab, somebody would put a sample of the muck under a microscope and tease out a few hundred of the shells, each no bigger than the period at the end of this sentence. Next, pure carbon dioxide gas had to be extracted from the organic compounds without altering the ratio of isotopes, typically by grinding down the shells and roasting the powder in a stream of helium gas. Then the oxygen isotopes in the gas could be

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<sup>1</sup> Schott (1935).

<sup>2</sup> Urey (1947).

<sup>3</sup> Urey et al. (1950).

analyzed in a mass spectrometer. Workers needed to be very careful to avoid contamination by any other source of gas, such as their own breath. All these processes had to be reduced to a routine that a lab technician could execute reliably hundreds of times over. Urey, already a Nobel Prize winner, called it “the toughest chemical problem I ever faced.”<sup>1</sup>

In 1955 Urey’s student Cesare Emiliani conquered the problem. His data lay within slimy cylinders of mud and clay, totaling hundreds of meters in length, extracted from the seabed in recent years and carefully stored away in oceanographic institutions. Emiliani relied on the loan of cores pulled up by various expeditions (in this case from the Oceanographic Institute at Göteborg, Sweden, the Lamont Geological Observatory in New York and the Scripps Institution of Oceanography in California). He was also helped by advice about locations on the sea-floor where the sediments had been laid down most regularly and continuously. And he required technical assistance on chemistry and so forth from fellow members of Urey’s research group. From each of many hundreds of layers of sediment in the cores, he took a sample and found its oxygen-isotope temperature. The product was a remarkable record of temperature changes stretching back nearly 300,000 years.<sup>2</sup>

This sort of work needed money. Emiliani, for example, received funds from the U.S. Office of Naval Research, the Atomic Energy Commission, and the National Science Foundation. The work also needed a stock of cores, carefully preserved in their thousands (eventually a great many thousands) as long rods of damp clay. One pioneer of climate history studies, Nicholas Shackleton in England, used cores drilled by the pathbreaking *Challenger* expedition, a century back, before turning to Lamont cores. The autocratic founder and director of Lamont, Maurice Ewing, had insisted that the institution’s two ships pull up cores regularly wherever they happened to wander on the seven seas. He was criticized for taking more cores than anyone could analyze, but he stored them up on the principle that somebody, someday, would learn something from them.<sup>3</sup>

While Emiliani and others pursued the oxygen isotopes, others continued to estimate temperatures from the assemblage of foram species found in a given layer in a core. Carbon-14 dating could lay out an accurate chronology for the changes—provided one could assemble a collaboration including oceanographers willing to share their deep-sea cores, a radiochemistry laboratory capable of determining the dates, and an expert in the arcane skill of foram shell identification. A leading such expert, David Ericson, collaborated with others at Lamont to dispute Emiliani’s temperature curves. They cast doubt, first, on his timing of the changes, and second, more serious still, on his claim that past ice ages had brought a huge drop in the Caribbean Sea’s temperature. Emiliani in return cast doubt on Lamont’s reports, pointing out

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<sup>1</sup> “toughest:” Emiliani (1958b), p. 54; Emiliani (1955), p. 539, lists crucial breakthroughs: in mass spectrometry (Nier), in extracting carbon dioxide from the carbonate (McCrea), and in calcium compound extraction (Epstein). See p. 548.

<sup>2</sup> Emiliani (1955).

<sup>3</sup> McNutt (2000), pp. 54, 60; Wertenbaker (1974), pp. 103-05.

among other things how the smearing of sediment layers by burrowing worms (“bioturbation”) could have biased their results. Debate broke out at scientific meetings and in journals, where Emiliani strenuously defended his position, loth to admit error. Corrections that an outside observer may find unproblematic can strike some scientists as an unjust attack on their proudest accomplishments.

Such debates were nothing new. The ice ages, as one expert ruefully remarked, had been “a battleground for scientists” for over a century. A main reason for the fierce controversies, he suggested, was the “close connection with the evolution of man.”<sup>1</sup> Many people, including in particular Emiliani, thought that the timing of ice ages must say something fascinating and important about how our species had emerged.<sup>2</sup>

A decade passed before scientists resolved the discrepancy between oxygen-isotope and foram temperatures. There were many possible sources of confusion. In particular, as Emiliani himself had noted, the temperature you got from a given species of foram reflected where it lived in the sea, whether near the surface or in the colder depths. You had to take it on faith that in the distant past a given species had lived at the same depth as its present-day descendants, despite any changes in currents, salinity, etc. But the problem turned out to be even subtler. The long-term fluctuations of the oxygen isotopes in foram shells were not caused mainly by changes of the water’s temperature at all. Alongside the biophysics of the forams, another kind of physics had been at work.

Back in 1954, Willi Dansgaard had pointed out that the ratio of  $O^{18}$  to  $O^{16}$  in snow would depend on a variety of factors. He had realized that processes in clouds might act like the distilleries that people used to concentrate particular isotopes. The processes would be influenced by the temperature of the seas where the water evaporated, for the heavy isotope would have a harder time evaporating than the lighter one. You also had to consider what happened as the water traveled on the winds, and the temperature of the clouds where the moisture crystallized into snow.<sup>3</sup> When snowfall built up continental ice sheets, the process had withdrawn from the oceans more of the lighter isotope than the heavier one. Thus no matter what the temperature of the water where the forams lived, during a glacial period their shells wound up with less of the lighter isotope. The changes that Emiliani had detected reflected mainly the changing volume of the planet’s ice sheets.

Emiliani discussed the problem at some length in his 1955 paper, but he had not thought a large correction was needed.<sup>4</sup> For decades he vigorously defended his original conclusions. Other scientists gradually decided he was mistaken. The tipoff was the fact that the isotope variation was found not just in regions where cooling would be expected, but everywhere in the world’s

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<sup>1</sup> Ericson and Wollin (1968), p. 1227.

<sup>2</sup> Emiliani (1956); Emiliani (1958b).

<sup>3</sup> Dansgaard (1954); Dansgaard (1964).

<sup>4</sup> Emiliani (1955), pp. 543-44.

oceans. In fact, the water temperature in the Caribbean had probably dropped only a reasonable 2°C or so. Nevertheless, as one of Emiliani's critics acknowledged, his work remained "of inestimable value." Indeed "its value is in a sense enhanced by the certainty that it is a time-sequence for terrestrial glacial events, rather than oceanographic events."<sup>1</sup>

There was nothing extraordinary in such a combination of discovery and error. Every great scientific paper is written at the outside edge of what can be known, and deserves to be remembered if there is a nugget of value amid the inevitable confusion.

Meanwhile the techniques advanced. For example, Shackleton worked out a way to measure oxygen isotopes in minuscule samples, combining ingenuity with laborious detective work. (Among other things, he discovered that his instrument "remembered" previous measurements, for its copper tubing absorbed a trace of oxygen. He had to replace the copper with stainless steel.) This opened the way to detailed measurements on the less abundant forams that lived in the deep sea.<sup>2</sup> As an alternative and a check, Ericson and others continued to develop the "thermometer" given by an assemblage of foram species. This method had great potential, but also countless details and pitfalls. The workers learned to notice and exploit subtle effects, such as a change in the shell's manner of coiling (left-handed to right-handed) for a particular species at a particular temperature.<sup>3</sup> Analyzing foram assemblages in the best cores, researchers confirmed the oxygen-isotope results for the precise timing of glacial cycles.<sup>4</sup>

The advances in technique inspired a bold plan to create maps of the world's ocean surface temperatures at given epochs in the past. The complexities were so great that it took another two decades of vehement argument to get even partial agreement about just what the forams had to tell about ancient temperatures. As usual in geophysics, no technique stood on its own. It was the agreement among different types of evidence, once this was finally thrashed out, that convinced scientists they were getting down to the true facts.<sup>5</sup>

**Related:**

Past Cycles: Ice Age Speculations

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<sup>1</sup> The dominance of ice volume was pinned down by Shackleton (1967), quote p. 17; see also Dansgaard and Tauber (1969); Imbrie and Kipp (1971); Emiliani (1992), complaining that Shackleton's conclusion was "almost universally (and uncritically) accepted" and arguing that at least part of the effect is indeed temperature; for discussion Bradley (1985), pp. 179-80.

<sup>2</sup> Shackleton (1965); that this opened the way is attested by Broecker (1995), p. 285.

<sup>3</sup> Changes of direction were reported, but only tentatively connected with climate shifts, in Ericson et al. (1955).

<sup>4</sup> E.g., Ericson and Wollin (1968); the key work was Imbrie and Kipp (1971); for a general review of "transfer functions" to deduce temperatures from assemblages of species, see Sachs et al. (1977).

<sup>5</sup> Emiliani and Ericson were involved again. A summary with references is Bradley (1999), pp. 223-26.

