11

Pleistocene Temperatures

In 1949, when Ericson and Ewing were raising their first cores from the Mid-Atlantic Ridge, Cesare Emiliani was on his way to the University of Chicago to begin postgraduate studies in paleontology. He brought with him several rock samples from the northern Appenines in Italy, where he had been working as an oil geologist since his graduation from the University of Bologna in 1945. Emiliani planned to spend about a year at the University of Chicago, broadening his intellectual horizons and investigating some intriguing aspects of his Appenine samples.

At the University of Chicago, Emiliani met several young scientists who were working with Nobel laureate Harold C. Urey to find geochemical answers to many of the fundamental questions of earth history. One of these young scientists, Samuel Epstein, later remembered: "When I arrived in Chicago, the place was in a ferment. New ideas popped up every day. Not only did we have Harold Urey for inspiration, but there were other intellectual stars as well, including Willard Libby and Enrico Fermi." (Libby later received the Nobel prize in chemistry; Fermi was already a Nobel laureate in physics.)

Epstein was helping to develop an idea that Urey had originated in 1947. Urey theorized that it should be possible to use oxygen atoms to find out what the temperature of the ocean had been in the past. The technique was based on the fact that sea water contains two distinct types (isotopes) of oxygen atoms. One of these isotopes (oxygen-18) is heavier than the other (oxygen-16). Both types are present in the calcium carbonate skeletons of marine organisms. Urey had demonstrated theoretically that the amount of the heavier isotope that an animal extracts from the surrounding sea water depends on the temperature of the water. In cold water, the skeletons have higher concentrations of the heavier isotope. Therefore, he reasoned, it should be possible to calculate the water temperature during the lifetime of the organism by measuring the ratio of oxygen-18 to oxygen-16 in a fossil skeleton.

Epstein and Emiliani were among the researchers in Chicago who were convinced that Urey's method would provide valuable insights into the history of the earth. Before they could proceed further, however, they had to overcome two obstacles. The first was theoretical: the ratio of isotopes in the skeletons was influenced not only by the temperature of the water but also by the isotopic composition of that water. If that composition varied, it would be impossible for researchers to interpret temperatures accurately. But Urey and his colleagues were confident—overconfident, as events were to prove—that a solution to this problem would be found as their investigation progressed. The second obstacle was a technical one: instruments and laboratory procedures had to be developed that would provide researchers with extremely accurate isotopic data. This was the problem to which Epstein and his coworkers, Ralph Buchsbaum and Heinz Lowenstam, were addressing themselves when Emiliani arrived on the scene. After several years of work, Epstein's group succeeded in developing a laboratory procedure for measuring isotopic ratios with great accuracy. The way was open to investigate the potential of Urey's temperature method.

Urey soon realized that Emiliani's knowledge of fossils would prove useful in applying the new geochemical techniques. In 1950, he asked Emiliani if he would be interested in investigating the isotopic composition of foraminifera. Without hesitation, Emiliani accepted—here was a once-in-a-lifetime chance to open a new window on the geologic past. The other members of the Chicago team were already using the "isotopic thermometer" on fossils from remote geological periods, but Emiliani planned to apply the method to skeletons of foraminifera in Pleistocene deposits. His first measurements were made on bottom-dwelling forams collected from deposits in California in 1951. But when Hans Pettersson offered him eight piston cores raised by the *Albatross* expedition, Emiliani decided that a study of planktonic foraminifera had even greater potential. Soon, Ewing put several Lamont cores at his disposal; and Ericson, eager to verify his own climatic method, mailed to Chicago samples of four cores he had already analyzed.

By August 1955, Emiliani had analyzed eight deep-sea cores. His conclusions were published in an article called "Pleistocene Temperatures," which appeared in the *Journal of Geology* (1955). The article proved to be a landmark in the study of the ice ages. According to Emiliani, isotopic variations in cores taken from the Caribbean and from the equatorial Atlantic indicated that over the last 300,000 years there had been seven complete glacial-interglacial cycles. The data also seemed to indicate that during a typical ice age, surface waters in the Caribbean dropped approximately 6° C (Figure 33). Finally, Emiliani noted that the variations in isotopically estimated temperatures showed a reasonably good time correspondence with the Milankovitch radiation curves, and concluded that his observations tended to support the astronomical theory of the ice ages.

With the publication of his article, Emiliani found himself embroiled in three separate arguments. The first was with Ericson. Did the variations in the isotopic curve really reflect variations in temperature? Or did the variations in Ericson's *menardii* curve reflect the history of climate more accurately? Second, Broecker and Ericson questioned the accuracy of Emiliani's time scale. The third and last argument came from the many geologists who had rejected Milankovitch's theory. They held that the observed correlation between Emiliani's isotopic curve and Milankovitch's radiation curve was merely a coincidence.

In many respects, the first of these arguments was the most vital. If Ericson was right, and the isotopic variations were caused by something other than temperature changes, then the other two arguments lost much of their point. By 1964, the importance of finding a solution to the Ericson-Emiliani controversy was widely recognized. Wallace Broecker of Columbia University joined with Richard F. Flint and Karl Turekian of Yale in persuading the National Science Foundation to sponsor a conference on the problem. The goal of the conference would be to resolve the issue by having both Ericson and Emiliani present their ideas and the supporting data before a small group of specialists. In January 1965, a two-day conference was held at the Americana Hotel in New York City, and at Columbia's Lamont Geological Observatory.

Among those in attendance was John Imbrie, then Professor of Geology at Columbia University. For more than a decade, Imbrie had been studying bottom-dwelling fossils and using them to interpret the climates of remote geological periods. He had adapted a statistical method, called factor analysis, which had proved to be helpful in studying how marine animals respond when they are subjected to a variety of environmental stimuli simultaneously.

The long-awaited Ericson-Emiliani debate of 1965 was inconclusive. On the one hand, Ericson demonstrated that his zonation scheme applied to hundreds of Atlantic cores and presented evidence that his main indicator species (*menardii*) was indeed sensitive to changes in ocean temperature. He also criticized Emiliani's assumption that changes in the isotopic composition of the ocean during the Pleistocene had been so small as to have little effect on his paleotemperature estimates. In fact, Ericson argued, many isotope chemists had drawn just the opposite conclusion—that ice sheets contained such high concentrations of the light oxygen isotope that significant changes in the isotopic composition of the ocean must occur during the ice-age cycle. It was, therefore, quite possible that the isotope variations measured by Emiliani were not connected at all with ocean temperatures, and only reflected changes in the volume of the ice caps.

For his part, Emiliani criticized Ericson for relying mainly on only one species, and he presented data (gathered by Louis Lidz) that supported the oxygen-isotope results. Lidz had studied many different foram species in two of Emiliani's cores and had found that fluctuations in their abundance correlated well with fluctuations in the isotope curves. Emiliani also argued that the Pleistocene ice caps were probably not as rich in oxygen-16 as geochemists thought, and reiterated his belief in the accuracy of his temperature estimates.

Although he was more an onlooker than an active participant in the debate, Imbrie pointed out that Ericson and Emiliani were both ignoring the possibility that factors other than temperature might have operated to cause variations in foram concentration. For example, changes in the salt content of the water, or in the amount of available food, would certainly have an influence on foram populations. He then went on to suggest that the application of statistical techniques to the entire assemblage of foram species should make it possible to separate the temperature effect from other environmental influences. Before the conference ended, Imbrie had decided to make this attempt himself.

Ericson was ready with help and advice, and he suggested that Imbrie should investigate one particular core in detail. This core (already analyzed for *menardii* by Ericson and Wollin) was known as V12–122 because it had been taken by the Lamont research vessel *Vema* on the 12th cruise and 122nd station. Imbrie found an able associate in Nilva Kipp, an undergraduate at Columbia's School of General Studies, who had written an impressive term paper on the Ericson-Emiliani controversy. Working together over the next three years, first at Columbia and then at Brown University, Imbrie and Kipp developed a multiple-factor method for climatic analysis that took into account abundance variations in all 25 species of planktonic forams. In many respects, their approach was a computerized extension of the technique used by Wolfgang Schott in 1935. Schott's first step had been to show the present distribution of each foram species on a series of maps. Imbrie and Kipp followed this procedure, and then went on to write equations to express the relationship between the species abundances on the sea floor and various properties of the surface waters. These properties included summer and winter temperatures and salinity (salt content). Working down through the core, the equations—which had been developed for the present sea floor—were used to estimate summer and winter temperatures and salinity for past epochs.

By the summer of 1969, Imbrie and Kipp were sure that their multiple-factor technique produced dependable results. In the meantime, Broecker and Jan van Donk had conducted an isotopic analysis of the same core (V12–122), making it possible to compare the results of the methods developed by Ericson, by Emiliani, and by Imbrie and Kipp. The comparison convinced Imbrie and Kipp that Ericson had been wrong—and Emiliani, half right. For where Ericson's zones showed cold temperatures, both the isotope and multiple-factor methods showed warm intervals. Apparently, some environmental factor other than surface water temperature (but often correlated with it) caused *Globorotalia menardii* to appear and disappear cyclically in deep waters of the Atlantic Ocean.

On one fundamental point, however, the results of the multiple-factor technique did not mesh with Emiliani's. Imbrie and Kipp's research showed that the temperature of Caribbean surface waters had dropped only 2° C as the world entered each ice age—not the 6° C postulated by Emiliani. The multiple-factor method showed that changes in the salinity of surface waters in the Caribbean had affected the foram population in that area along with changes in temperature. By attributing all of Lidz's faunal variations to temperature, and ignoring other influences, Emiliani had overestimated the magnitude of the temperature change. If Imbrie and Kipp were right in their estimate of a 2° C lowering of Caribbean temperatures during ice ages, an important conclusion could be drawn: much of the isotopic variation must be due to changes in the volume of the ice sheets—not to changes in temperature.

Eager to announce their results, Imbrie was elated when Emiliani invited him to speak at an international scientific meeting to be held in Paris in September 1969. But he arrived late, and his lecture had to be rescheduled—for four o'clock on Friday. In Paris, on a warm September afternoon, there are distractions attractive enough to lure even the most dedicated of scientists away from a lecture hall. When Imbrie finally spoke, it was to an audience of two. Half of the audience understood no English. The other half was Nicholas Shackleton—a young British geophysicist who, unknown to Imbrie, had already published data suggesting that much of the observed isotopic variation reflected changes in the volume of global ice.

Meeting after the lecture, Imbrie and Shackleton were delighted to find that their independent approaches to the study of climate history had led to the same tentative conclusion. Although they realized that many more cores would have to be analyzed before they could be certain, the available data seemed to indicate that fluctuations in Emiliani's isotope curve were recording primarily variations in the total volume of the ice sheets.

To some scientists, perhaps even to Emiliani himself, such a result might be a disappointment. Hopes had been high that Urey's geochemical method would provide a method for estimating the temperature of Pleistocene oceans. But to the two men in Paris, it seemed that the importance of the isotope curve would be greatly enhanced if its role as a device for measuring global ice volume could be firmly established. After all, what could be more useful in the analysis of Pleistocene history than to know how the size of the ice sheets varied with time? Given the isotope technique to record the volume of ice, and the multiple-factor technique to record the temperature of the ocean, a way might yet be found to test some of the competing theories of the Pleistocene ice ages.