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The Deep and the Past

If the Milankovitch theory had been argued in a court of law, a motion to declare a mistrial would certainly have been in order on the grounds that the prosecution's case was based solely on evidence collected from the surface of the land. Since the sedimentary record of past climate on land was fragmentary, the witnesses who testified at the Milankovitch "trial" were not only biased, they were also poorly informed.

James Croll had been among the first to recognize the incomplete nature of the geologic record of climate, and he had anticipated the day when geologists would be able to obtain a more complete record of the ice-age sequence by delving into the sea bottom. "In the deep recesses of the ocean, buried under hundreds of feet of sand, mud, and gravel, lie multitudes of the plants and animals which . . . were carried down by rivers into the sea. And along with these, must lie skeletons, shell, and other exuviae of the creatures which flourished in the seas of these periods." Croll's description, however, had been purely speculative. For during most of his life, scientists actually knew more about the surface of the moon than they did about the depths of the sea.

But the sea would not keep her secrets for long. In 1872 the British government equipped a 2,306-ton steam corvette, *H.M.S. Challenger*, to make a round-the-world voyage of discovery that would last three-and-a-half years. Under the direction of C. Wyville Thomson, the *Challenger*'s six scientists developed techniques for taking soundings, collecting samples of water, capturing plants and animals, and dredging the bottom at all depths. When the expedition returned to England in 1875, much of the sea's mystery had been dispelled.

Observations made by the crew of the *Challenger* confirmed many of Croll's predictions. With the exception of a few bare ledges of basaltic rock, the sea floor was covered with a blanket of sediment. Along the margins of the continents, deposits transported to the ocean by rivers had been redistributed by currents. There, the sea bottom was covered with layers of sand and mud that contained fragments of plants and other materials derived from the land. But away from the continental margins much of the deep ocean floor was covered with fine-textured oozes. When the *Challenger*'s geologists examined samples of these oozes under the microscope, they found that many were almost entirely composed of the fossilized remains of minute animals and plants. It was not long before the living source of these tiny fossils was located. The nets that the expedition's biologists dragged through the surface waters of the ocean collected countless numbers of floating organisms (collectively known as plankton) whose mineralized remains were identical to those found on the sea floor. Clearly, the organic oozes had been formed over a long period of time by the slow rain of skeletons onto the sea floor.

Scientists on board the *Challenger* found that one type of ooze—composed of the limy remains of planktonic animals called forams—covered vast areas of the sea floor. This type of sediment was especially prevalent in temperate and tropical seas where depths did not exceed 4000 meters. Another kind of organic ooze was widespread in the colder waters of the Arctic and Antarctic seas. This type was primarily composed of opal, a glassy mineral extracted from seawater by planktonic animals called radiolaria, and by planktonic plants called diatoms. When the expedition ended, and the data that had been gathered were compiled into maps, the scientists found that the two types of organic ooze covered one-half of the sea floor—an area equal to that of all the continents combined. However, in the deepest parts of the sea, where depths exceeded about 4000 meters, the bottom was covered not with organic oozes but with a layer of brown clay that contained no fossils at all. At these great depths, it was explained, the properties of seawater were such that the opaline or limy skeletons were dissolved as fast as they rained down. All that remained here were fine particles of clay that had been wafted by currents or carried by winds.

After the *Challenger* expedition returned, an international team of investigators was organized by British scientist John Murray to analyze the staggering body of observations that had been made. By 1895 the analysis was completed and a 50-volume report published. Of particular interest to students of ancient climate was evidence that some species of forams (and other planktonic organisms) lived only in cold waters, while others lived only in warm waters. Thus, Croll's dream of extracting a complete record of climatic history from the layers of sediment on the sea floor was at last within reach. For as climate changed, the geographic extent of temperature-sensitive species would shift accordingly. The sequence of sedimentary layers at any given location would contain a permanent record of the ice-age succession.

Only one problem remained. Before scientists could reconstruct the history of climate from the succession of fossils deposited on the sea floor, they had to find a way of obtaining a cross-section of the sediment pile. Many attempts to obtain such a cross-section were made. The principle behind them was the same: a hollow steel pipe, forced into the sea bed, would extract a sediment "core" when it was removed. The earliest of these devices were called gravity corers, because the pipe was propelled into the sea floor by the force of gravity alone. A coring rig was lowered until it hung above the sea floor and then was released. The momentum gathered during its descent forced the pipe into the pile of sediment. Unfortunately, such devices were only able to collect cores about 1 meter long—not long enough to show the complete ice-age succession. To increase the depth of penetration, lead weights were attached to the coring rig, but little was gained because the frictional forces resisting penetration were too great. Other devices were tried, including an unusual one designed by Charles S. Piggot, which used dynamite to drive the pipe into the sea bottom. The method proved unsatisfactory, however, for the fossil record was badly distorted.

Despite the limitations of gravity coring, a German paleontologist named Wolfgang Schott agreed to examine a group of cores that had been raised from the floor of the equatorial Atlantic Ocean by the German *Meteor* expedition of 1925–27. Schott's results, published in 1935, set the pattern for future work on Pleistocene plankton. He began by mapping the distribution patterns of 21 different species of planktonic forams (minute surface-dwelling animals) on the present sea bed. Then, taking samples at regular intervals along his one-meter cores, he took a census of each sample. Schott found that he could distinguish three layers. In most cores, the top 30 or 40 centimeters contained an assemblage of foraminifera very different from that which was contained in the underlying layer. The assemblage in the top layer (Layer 1) was identical to that now accumulating on the sea floor. The underlying layer (Layer 2) was composed of many of the same species, but they were present in different proportions. Thus, while Layer 1 contained mostly "warm" species of forams, Layer 2 contained a higher proportion of "cold" species. In fact, one species of foram occurred only in Layers 1 and 3, and was completely absent in Layer 2. The name of that species, *Globorotalia menardii*, would be on the lips of geologists for many years to come. For Schott came to the conclusion that the sediment layer containing no *menardii* had been deposited in the last ice age when surface waters in the equatorial Atlantic were too cold to support the species. According to this view, the *menardii*-rich Layer 1 had been deposited since the glaciers retreated. Layer 3, which also contained *menardii*, was apparently a record of the interglacial interval that had preceded the last ice age.

Schott's results whetted the appetites of paleontologists for cores longer than the gravity devices were capable of producing. After all, if Schott had found a record that extended back all the way to the last interglacial age in a core only one meter long, how much more could be learned from a core that was 10 meters long?

The coring problem was finally solved in 1947, when a Swedish oceanographer, Björe Kullenberg, arranged a piston in such a way that sediments were sucked up into a coring tube while the tube was being driven into the sea floor. Because this device routinely obtained cores 10 to 15 meters long, it made possible a new era in the investigation of climatic history.

The Swedish Deep-Sea Expedition of 1947–48 was the first to use the Kullenberg corer. Led by Hans Pettersson, a crew of scientists sailed the research vessel *Albatross* around the world and obtained long cores from every ocean basin. Cores from the Pacific were sent to Gustaf Arrhenius at the Scripps Institution of Oceanography in California. By chemically analyzing these samples, Arrhenius discovered that the concentration of calcium carbonate (lime) fluctuated cyclically: layers characterized by high concentrations of limy fossils alternated with layers having lower concentrations. To explain these variations, Arrhenius reasoned that the intensity of circulation in the Pacific might have been different during an ice age than during an interglacial interval—and that it was these changes in circulation intensity that were reflected in the varying concentrations of calcium-carbonate fossils.

Arrhenius's research demonstrated that chemical as well as paleontological evidence could be used to study Pleistocene climates—at least in the Pacific. Soon, investigators at Columbia University began measuring calcium carbonate concentrations in cores taken from the Atlantic Ocean, and found that sediments from this ocean were also characterized by calcium carbonate cycles. But these cycles were opposite from those in the Pacific cores: ice-age deposits exhibited low concentrations of lime, interglacial deposits exhibited high concentrations. Evidently, the two oceans responded differently to changing climates.

The work of Arrhenius showed that sediments in the Pacific accumulated at a very slow rate—about one millimeter per century. In one sense, this was a boon to paleontologists, for it meant that even relatively short cores contained a record of the entire Pleistocene sequence. But the slow rate of deposition was also a disadvantage, for it made it almost impossible to study the details of climatic history recorded in the Pacific cores.

In the Atlantic Ocean, however, sediments accumulated at much faster rates, generally about two or three millimeters per century, so that cores taken here could be expected to contain a more complete record of climate. Geologists therefore awaited with interest the results of an investigation of 39 long Kullenberg cores that had been raised from the bed of the Atlantic by Hans Pettersson. These cores were analyzed by three scientists at the Scripps Institution of Oceanography: Fred B. Phleger, Frances L. Parker, and Jean F. Peirson. Their monograph, published in 1953, demonstrated that the long Atlantic cores recorded at least nine Pleistocene ice ages. They also found that the process of interpreting climatic history by studying deep-sea sediments was not without its problems: for several of their cores contained shallow-water forams which had obviously been displaced in some way from environments near shore. Just how these displaced faunas—and the layers of sand that were associated with them—came to be mixed in with the particles accumulating as a slow planktonic rain, was a mystery.

Before becoming a Professor of Oceanography at Scripps, Phleger had spent several years at the Woods Hole Oceanographic Institution on Cape Cod. While there, he had hired David B. Ericson to assist him in the laboratory and on shipboard. Ericson had become convinced of the need for research on marine sediments while he was Assistant Geologist at the Florida Geological Survey. Also working at Woods Hole was a geophysicist, Maurice Ewing, who was taking the first steps along a path that would eventually lead him to important discoveries about the nature of the earth's crust underneath the oceans. In 1949, Ewing was planning an expedition to the Mid-Atlantic Ridge, and he wanted an assistant experienced in the study of marine fossils. Ericson was his man.

In 1950, Ewing took a position at Columbia University and moved to New York City, taking his cores with him. Ericson later remarked that he "went along with the cores." Soon, a group of senior scientists, technicians, and students gathered at Columbia, attracted by Ewing's research on the origin of the ocean basins. The group quickly outgrew their quarters in Columbia's Schermerhorn Hall. By good fortune, Columbia had recently acquired a country estate in Palisades, New York. The estate had been given to the university by Thomas Lamont. Ewing's group moved out to the Lamont estate, and within a few years developed the Lamont Geological Observatory into a world-renowned center for oceanographic and geophysical research.

Realizing the potential importance of the core studies, Ewing insisted that Lamont vessels take piston cores every day, no matter what other research activities they were engaged in. Hundreds of cores were raised each year and stored for future study. The Lamont core collection soon became the largest in the world, and Ericson found himself in an ideal position to study the history of climate. Already familiar with the work done by Schott and by the Scripps group, he was eager to expand their findings and to work out the history in greater detail. But in some areas of the ocean, layers of displaced sediment similar to those which had stumped Phleger posed a serious problem. These layers of sand and shells—transported in some way from shallow coastal waters—distorted the climatic record produced on the deep-sea floor by the slow rain of planktonic particles.

In 1952, while Phleger's monograph was still in press, the riddle of the displaced layers was solved by two of Ericson's colleagues at Lamont. By investigating records of an earthquake that had occurred on the Grand Banks of Newfoundland in 1929, Bruce C. Heezen and Maurice Ewing were able to identify the process by which displaced layers form. The 1929 earthquake had triggered a sediment slide on the ocean floor. Particles of sediment, suspended in a turbid layer of water near the bottom, had flowed downslope. Moving with the speed of an express train, this turbidity current had broken submarine telephone cables and spread a layer of sand and mud over a wide area, disrupting the normal sedimentation process in deep water.

Now that Ericson understood what had caused the displaced layers, he was able to devise methods for identifying them, and thus remove the sedimentary static from the climatic signal. He and his assistant, Goesta Wollin, began examining every core in the Lamont library—no mean task, since they were now being collected at the rate of 200 cores per year. To speed up the process, Ericson followed a simplified version of the laboratory procedure originally developed by Schott. Instead of counting the number of individuals representing every foram species in a sample, Ericson and Wollin concentrated their attention upon the few species they considered to be particularly sensitive to changes in climate (Figure 32). Originally, they simply estimated the abundance of these indicator species. Later, as more precise results were demanded, actual counts were made. In lower latitudes, the prime candidate for this monitoring role was *Globorotalia menardii*, the species that Schott had found exclusively in his two warm layers. Ericson's work in cores taken from low latitude sites in the Atlantic confirmed Schott's idea, for here fluctuations in *menardii* abundance provided a clear record of changing climate. But in cores taken from higher, colder latitudes, *menardii* never occurred at all. In these latitudes, other species had to be used to monitor changes in past climate.

By 1956 Ericson was convinced that his simplified climatic method was valid, and he could point to supporting evidence from two different lines of research. One line was that followed by his colleagues at Lamont, Wallace S. Broecker and J. Laurence Kulp. When these geochemists dated the boundary between Ericson's two uppermost sediment layers—the upper one containing *menardii* specimens and the lower one containing no such specimens—they found that the transition occurred abruptly about 11,000 years ago. This date was very close to the radiocarbon age found for a sudden change in temperatures on land. In an article published in 1956, Ericson, Broecker, Kulp and Wollin concluded: "The core data point definitely to the period immediately before and after 11,000 years as a very critical period in glacial history. Further correlation of events both in the ocean and on land during this interval may lead to an understanding of some of the factors causing glaciation." The collaboration that

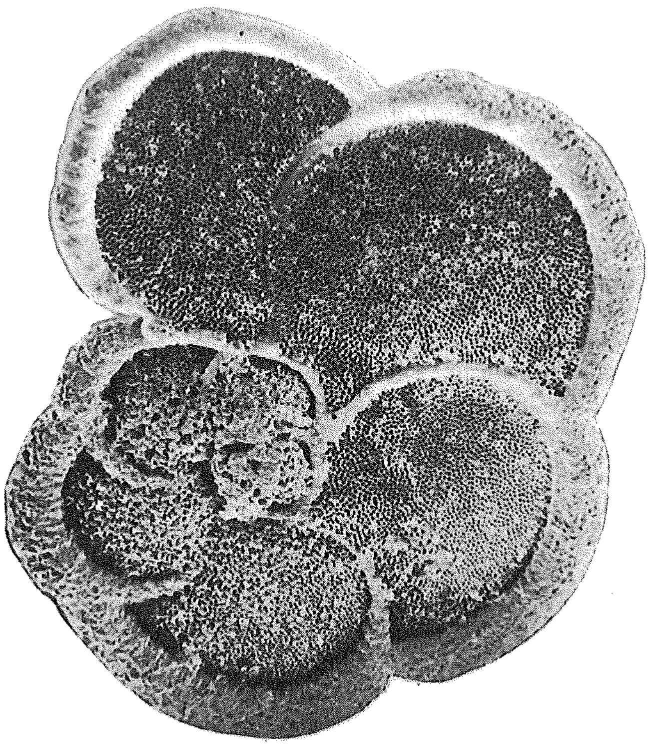

Figure 32. A fossil from the deep-sea floor. Upon death, the mineral remains of many surface-dwelling animals and plants fall to the sea floor and build up thick deposits of sediment. The shell shown here is that of *Globorotalia menardii*, a species of planktonic foram used extensively by D.B. Ericson as an indicator of Pleistocene climate. The specimen is about one millimeter wide. (Courtesy of A. Bé.)

produced this article reflected an emerging pattern of interdisciplinary study that would eventually become the hallmark of Lamont research.

The other investigation, which seemed at first to provide an independent confirmation of Ericson's climatic results, was the development of a different method for estimating the temperature of Pleistocene oceans. Developed in 1955 by Cesare Emiliani at the University of Chicago, the method was based on the isotopic composition of oxygen atoms in fossil forams. When the two methods were applied to the same cores, the results agreed quite well over the more recent part of the record. Over the older parts of the record, however, the results did not agree—a fact which would be the subject of a great deal of debate in the years to come.

By 1961, Ericson had studied more than a hundred cores, and was ready to generalize his scheme of climatic history. To facilitate discussion, he coined a set of terms that would eliminate the need for such convoluted phrases as "The third zone from the top lacking *Globorotalia menardii*." The simplified system (suggested by a harried editor working on the manuscript of the 1961 article by Ericson, Ewing, Wollin, and Heezen) used the letters of the alphabet to denote layers in the core. Thus the warm zone at the top of the cores became known as Ericson's Z Zone, representing postglacial time. The Y Zone represented the last major glacial advance; and the X Zone was the preceding interglacial, with temperatures similar to those of today (Figure 33). The new scheme was quickly adopted, making it easier to refer to an important characteristic of Ericson's climatic curve: the V Zone, which contained high concentrations of *menardii*, was unusually long. The underlying U Zone, without *menardii*, was unusually short. Ericson pointed out that his long V Zone compared well with the Great Interglacial recognized by Penck and Brückner in their study of European climate. Although Ericson himself did not support the Milankovitch theory, scientists who did were able to draw comfort from the *menardii* curve.

In the meantime, however, Ericson had become acutely aware of a conflict between the isotopic temperature method used by Emiliani and his own fossil scheme. In an attempt to resolve the conflict, Ericson and Emiliani analyzed samples from the same three Caribbean cores—each using his own method (Figure 33). Emiliani's method provided estimates in degrees Celsius, while Ericson's scanning method revealed only general temperature trends. Following the system developed by Arrhenius, Emiliani numbered his inferred temperature variations from the top down. As discussed in Chapter 11, the two methods produced broadly similar patterns for the intervals W-Z in Ericson's scheme (Stages 6-1 in Emiliani's). Only when the pattern was examined in greater detail did disturbing differences begin to be revealed. Ericson's X Zone was shorter than Emiliani's Stage 5, and many of Emiliani's cores showed a short but distinct warm interval in Stage 3 that had no counterpart in Ericson's Y Zone. Moreover, Ericson's unusually long V Zone showed up in Emiliani's scheme as several separate fluctuations. And Ericson's U Zone (cold) de-

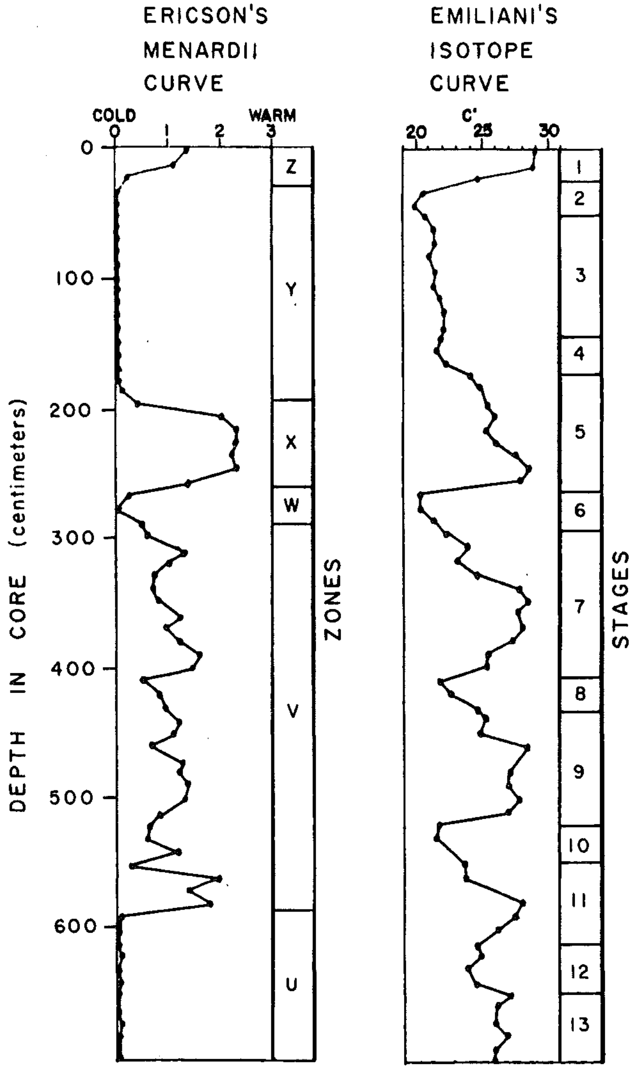

Figure 33. Succession of Caribbean ice ages according to Ericson and Emiliani. Fluctuations in the abundance of *Globorotalia menardii* down a deep-sea core from the Caribbean (A179–4) were interpreted by D.B. Ericson as a climatic record. Cold intervals were referred to as Zones U, W, and Y; warm intervals as Zones V, X, and Z. Measurements of the oxygen-isotope ratio made by C. Emiliani from samples of the same core were also interpreted as a climatic record. Warm intervals were referred to as Stages 13, 11, 9, 7, 5, 3, and 1; cold intervals as Stages 12, 10, 8, 6, 4, and 2. (Data from C. Emiliani, 1955 and D.B. Ericson et al., 1961.)

parted dramatically from Emiliani's warm Stages 11 and 13. No satisfactory explanation for the divergence between the two schemes was to be found for almost a decade.

By 1963, Ericson, Ewing, and Wollin had made great strides toward their goal of charting the climatic history of the Pleistocene Epoch. After analyzing "more than 3000 cores raised from all the oceans and adjacent seas during 43 oceanographic expeditions since 1947 . . . we have found eight containing a boundary clearly defined by changes in the remains of planktonic organisms." This boundary, they concluded, marked the onset of the first ice age of the Pleistocene. The boundary to which they referred marked the extinction of a group of star-shaped fossil plants called discoasters, an event which they estimated had occurred 1.5 million years ago.

But geologists in general remained unconvinced of the correctness of the conclusions reached by Ericson and his colleagues. They questioned the chronology, because that was based on assumptions that were difficult to prove. And they questioned the climatic interpretation Ericson had given to the sequence of *menardii* zones. In 1964, Ericson and Wollin explained their methods in a book, *The Deep and the Past*. Yet skepticism remained. After all, Emiliani had obtained quite different results—and derived them from sediments of the same ocean, and from some of the very same cores.