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The Milankovitch Controversy

With the publication of the Milankovitch theory in 1924, the attention of the scientific world was once again focused on the ice-age problem. Not since Agassiz first presented his glacial theory in 1837 had such widespread interest been expressed in the history of the earth; and not since the argument between Agassiz and Buckland had there been such an extended controversy over a climatic theory.

Fueling the controversy were the geological facts that had been gathered in the 60 years since James Geikie succeeded in settling the drift question. Geikie's work had inspired two generations of geologists to scour the globe for more evidence of past climate. Facts about the ice ages were abundant. What geologists needed now was a theory to integrate these facts and provide a comprehensive explanation of the ice ages. Milankovitch offered them just such a theory.

The most valuable feature of the Milankovitch theory was that it made testable predictions about the geological record of climate. It predicted how many ice-age deposits geologists would find, and it pinpointed when these deposits had been formed during the past 650,000 years.

These predictions were contained in three nearly identical radiation curves that showed past changes in summertime radiation at latitudes 55°, 60°, and 65° North (Figure 24). In theory, each radiation minimum caused an ice age. In all, there were nine minima, each appearing on the graph as a narrow projection extending well below the average level of radiation. Köppen and Wegener stressed the fact that these minima were not evenly spaced, but formed a distinctive, irregular pattern. The last three minima were grouped together, forming a triplet; these should correspond to ice ages 25,000, 72,000, and 115,000 years ago.

The other six minima were arranged in pairs. Milankovitch himself had pointed to the unusually long interval of high radiation that occurred about in the middle of the graph. He predicted that this interval would be represented in the geologic record by a very long interglacial age.

As soon as the astronomical theory was published, geologists familiar with the record of drift attempted to test the theory by counting the number of tills and by determining when they had been deposited. However, both objectives proved very difficult to achieve. Because each glacial advance tended to destroy the drifts of earlier glaciations, the succession of tills in most places was incomplete. Moreover, geologists had no accurate method of determining the age of any till. The best they could do was to make rough estimates of the duration of each ice age, and of each interglacial age, by noting the thickness and extent of the layers of till and soil.

Persevering in spite of these problems, geologists in North America—led by Thomas C. Chamberlin of the University of Chicago and Frank Leverett of the U.S. Geological Survey—concluded that there had been four major ice ages. The drift sheets corresponding to these ice ages were named for the states in which they were most easily studied. From the bottom up, the sequence of drifts was: Nebraskan (the oldest), Kansan, Illinoian, and Wisconsin (the youngest). Other geographic names were used to represent each of the interglacial intervals (Figure 28).

Armed with this impressive array of facts and names, geologists ranged themselves for or against the Milankovitch theory. Those who were pro-Milankovitch pointed out that the four North American drifts matched the four radiation groups (one triplet and three doublets) postulated by the theory. Opponents of the astronomical theory replied that since the ages of the North American drifts were known only within very broad limits, there was no way of being sure that any radiation minimum actually coincided with an ice age. The attempt to test the astronomical theory in this way was therefore inconclusive.

An entirely different approach to the problem of deciphering the ice-age succession had been developed in the 1880s by Albrecht Penck, a German geographer studying river valleys along the north slope of the Alps. Penck had discovered that the lower portion of each of these valleys was a flat surface (called a strath) that the river was eroding into a layer of gravel. At higher elevations along both sides of the valleys Penck found three terraces—flat-topped embankments separated from each other by steep scarps. The terraces were composed of gravel layers similar to those which he had found on the valley floor. Penck had reasoned that each gravel layer had been formed during a cold climate when frost action and lack of vegetation had increased the rate of erosion. During intervals of warm climate, the rivers had evidently stopped depositing gravel, meandered from side to side, and cut a flat strath. Penck had concluded that the flat parts of the terraces were portions of former straths that had been formed during earlier interglacial intervals: the higher the terrace, the older the age of the corresponding interglacial. Each gravel deposit was therefore interpreted as a remnant of a more extensive layer that had been deposited during an ice age.

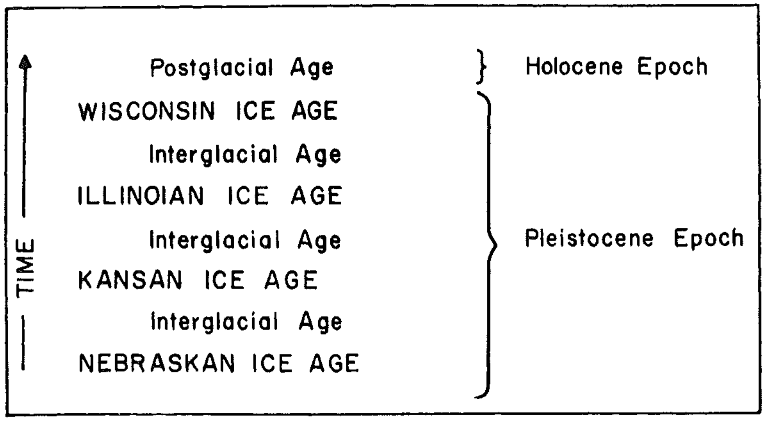

Figure 28. Theoretical succession of North American ice ages. By the end of the nineteenth century, glacial drifts corresponding to four Pleistocene ice ages had been recognized and named. Subsequent work has shown the existence of many more ice ages.

According to Penck's scheme, the sequence of Alpine gravel layers offered scientists what the drift sheets had not—a complete record of the glacial succession. Since there were four layers of gravel, there must have been four Pleistocene ice ages. And many geologists assumed, without proof, that the four American ice ages were the trans-Atlantic equivalent of the European succession.

In Europe, each ice age was named for a river valley. As a convenience to geologists, who were already overburdened with historical terms, the names were alphabetized: Günz, Mindel, Riss, and Würm. The oldest glaciation (the Günz) was represented by the gravels that composed the highest terrace. The most recent glaciation (Würm) was recorded by the gravels underlying the present river. Günz, Mindel, Riss, Würm—these names, coined by Penck and his colleague Eduard Brückner, would be stamped in the memories of generations of students, and would echo in lecture halls for years to come.

In addition to naming the succession of ice ages, Penck and Brückner were also able to estimate the length of time since the last ice sheet had disappeared from Switzerland. This they accomplished by studying the thickness of postglacial sediments in Swiss lakes, and by estimating how fast these sediments had accumulated. In this way the duration of postglacial time was calculated to be about 20,000 years.

With the 20,000-year estimate of postglacial time as a basis, Penck and Brückner proceeded to estimate the duration of earlier interglacials by comparing the depth of postglacial erosion with the depth of erosion that had occurred during each of the earlier warm periods. In this way they calculated that the interglacial that occurred immediately before the last (Würm) ice age was about 60,000 years long; and that the preceding interglacial—which they called the Great Interglacial—had lasted some 240,000 years. Altogether, they estimated that the Pleistocene was 650,000 years long.

In 1909 Penck and Brückner had published a curve that showed the history of Pleistocene climate (Figure 29). Fifteen years later, when Köppen received Milankovitch's radiation curves in the mail, he realized immediately that he could test the astronomical theory by comparing the radiation curves with

Penck and Brückner's scheme. As noted in Chapter 8, Köppen and Wegener made this comparison in 1924 and concluded that theory matched fact amazingly well. In both the radiation diagrams made by Milankovitch and the climatic diagram drawn by Penck and Brückner, ice ages appeared as short pulses separated by longer warm intervals. Although the timing of the ice ages and the radiation minima did not agree in detail, the general pattern of the two curves was quite similar. Köppen and Wegener were especially impressed by the fact that the interglacial interval between the Mindel and Riss glaciations (the Great Interglacial of Penck and Brückner) was analogous to the long, warm interval predicted by Milankovitch. Finally, the 20,000-year date given by Penck and Brückner for the end of the last ice age matched reasonably well with the date of the last radiation minimum, 25,000 years ago.

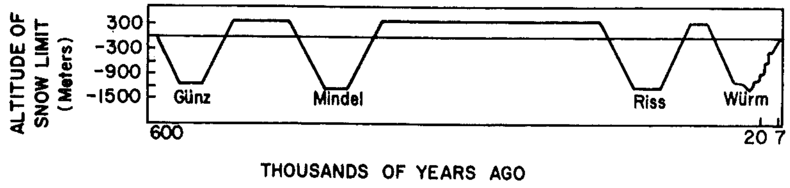

Figure 29. Theoretical succession of European ice ages, according to the climatic history of Europe suggested by the work of A. Penck and E. Brückner in 1909. During four supposed ice ages (named Günz, Mindel, Riss, and Würm), they estimated that the snow extended more than a thousand meters below its present level in the Alps. (Adapted from M. Milankovitch, 1941.)

Satisfied that Milankovitch's astronomical theory had been confirmed by an independent line of research, Köppen passed the good news along to Milankovitch and then published his curves in 1924. During the next fifteen years, the German geologists Barthel Eberl and Wolfgang Soergel restudied the Swiss terraces and discovered that several terraces recognized by Penck and Brückner were actually compound structures made up of more than one gravel deposit. But the revised version of Penck and Brückner's climatic curve seemed to match the details of the radiation curve even better than before; and Milankovitch included a summary of the geological work in his 1941 publication (Figure 30, next page).

During the 1930s and 1940s, most European geologists were won over to the Milankovitch theory. In fact, as Milankovitch himself noted with obvious pleasure: "A constantly increasing number of scientists undertook to classify the . . . sediments according to the new method, to connect them with the radiation curves and to date them by means of the latter." Subtly but surely, the emphasis had shifted: where once the geological record had been used to test the theory, now the theory was used to explain the record. "In this manner," Milankovitch said, "the ice age was given a calendar." Among those who developed this calendar was Frederick E. Zeuner, Professor of Geochronology at the University of London. In 1946 and again in 1959 he published books in which the Milankovitch calendar was used to date the main events of the Pleistocene Epoch.

Geologists in America, to whom the Alpine terraces seemed

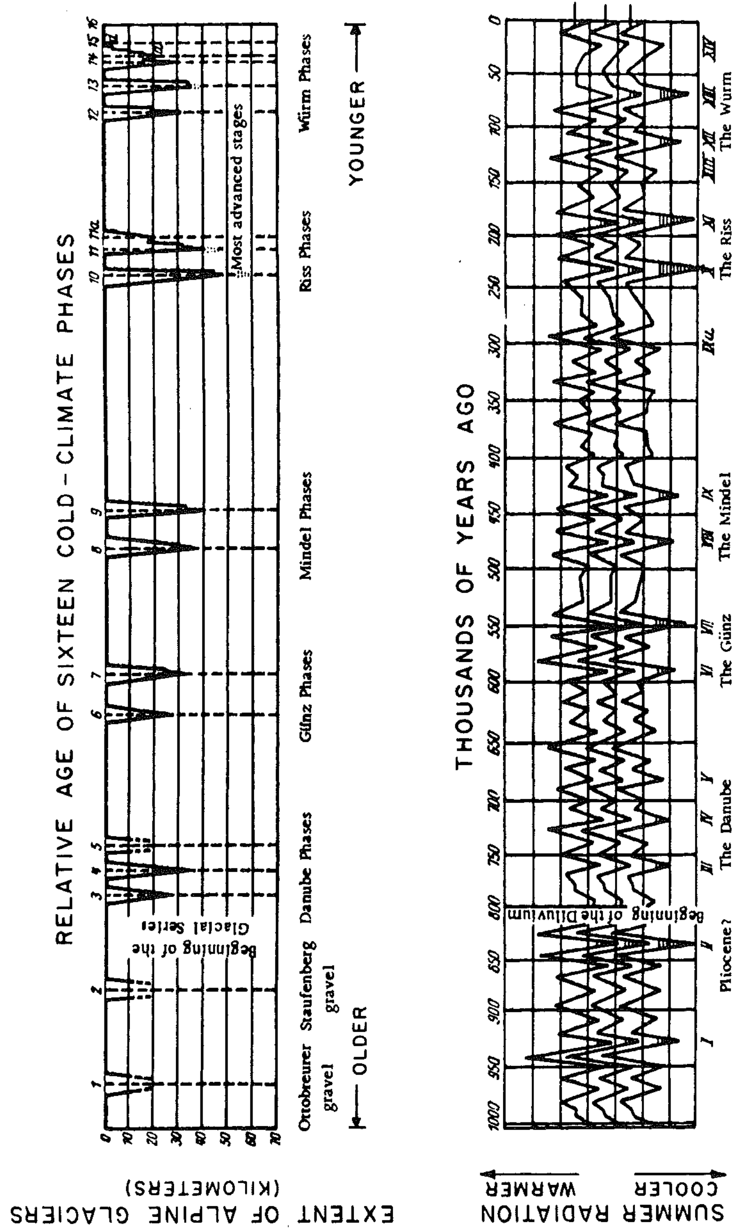

Figure 30. Eberl's test of the Milankovitch theory. Climatic history of Europe, as interpreted by B. Eberl (upper diagram) compared with the Milankovitch radiation curves for 55°, 60°, and 65° North latitude (lower diagram). Although the time scale for Eberl's climatic curve was rather uncertain, Milankovitch regarded the degree of correspondence between the two diagrams as proof of his theory of the ice ages. (Adapted from M. Milankovitch, 1941.)

remote and somewhat puzzling, were more skeptical. Even in Europe the theory was not unanimously endorsed. One man who spoke out against it was the German geologist, Ingo Schaefer. After devoting much attention to the Alpine river terraces, Schaefer became convinced that the fundamental hypothesis of the Penck-Brückner scheme was faulty. For he discovered that some layers of gravel contained fossil molluscs that are found today only in warm climates. How could sediments containing such fossils have been deposited during an ice age? It was a sticky question, threatening to undermine the very foundations of the Milankovitch theory. Most European geologists chose to ignore the problem, dismissing Schaefer's fossils as insignificant exceptions to a general rule.

Before long, however, other voices were raised against the Milankovitch theory. Some meteorologists pointed out that the theory dealt only with the earth's radiation balance, and ignored the role played by the atmosphere and the ocean in the transport of heat. Others found inconsistencies in some of the calculations published by Milankovitch. In theory, temperatures during an ice-age summer would have been 6.7° C colder than today. Milankovitch's calculations here seemed quite reasonable. But winter temperatures were calculated to have averaged 0.7° C *warmer* than today—a value that many scientists found difficult to believe. Milankovitch himself was untroubled by these criticisms: "I do not consider it my duty to give an elementary education to the ignorant, and I have also never tried to force others to accept my theory, with which no one could find fault."

In spite of the theoretical objections raised by meteorologists and the damaging field evidence found by Schaefer, the majority of scientists continued to favor the astronomical theory as late as 1950. But the early 1950s saw a dramatic about-face. By 1955, the astronomical theory was rejected by most geologists. The downfall of the theory was the development of a revolutionary new approach to the problem of dating Pleistocene fossils.

The new technique was the radiocarbon dating method, developed between 1946 and 1949 by Willard F. Libby at the University of Chicago. Libby discovered that a radioactive form of carbon (radiocarbon) is produced in small quantities in the atmosphere by cosmic rays. Eventually, the radiocarbon atoms in the atmosphere are absorbed into the bodies of all living plants and animals. But organisms continue to acquire radiocarbon only as long as they live. After death, the radiocarbon atoms in the organic tissues disintegrate, changing into inert atoms of nitrogen at a rate that can be measured. Libby reasoned that it should be possible to use this rate to calculate the time of death for any fossil: all that was necessary was to measure what proportion of carbon atoms in the fossil were still radioactive. Libby tested his idea extensively and found that the radiocarbon dating method worked remarkably well. The only hitch was that the dates calculated were accurate only for fossils that were less than about 40,000 years old.

When the radiocarbon dating method became available to geologists in 1951, they lost no time in launching a worldwide effort to discover the true chronology of the last ice age—or that part of it which was within the radiocarbon dating range. Radiocarbon laboratories were installed in many institutions, including Yale University, Columbia University, the U.S. Geological Survey, and the University of Groningen in the Netherlands. Pioneering geochemists such as Hans Suess, Meyer Rubin, and Hessel DeVries stood ready to analyze the anticipated avalanche of material. They did not have long to wait. Samples of wood, peat, shells, and bones were gathered from drift sheets, terrace gravels, and lake beds all over the world. "If it's organic, collect it and date it," was the rule of the day. So many dates were obtained that a special periodical, *Radiocarbon*, was established to make the results widely available.

One of the first American geologists to advocate the systematic use of the radiocarbon method in the study of Pleistocene drifts was Richard F. Flint at Yale University. After collecting a large number of datable materials from the Wisconsin drift of the eastern and central United States, Flint sent them off to Meyer Rubin for radiocarbon analysis. Flint's results showed that the drift actually recorded at least two glaciations—perhaps more. Previously, it had been supposed that a single glaciation was responsible for the Wisconsin drift, but the radiocarbon results made it clear that this hypothesis could no longer be maintained. The older tills in the drift were, for the most part, beyond the range of radiocarbon dating; but the youngest till was well within the datable range, and Flint and Rubin were able to show that the great ice sheet had reached its maximum extent 18,000 years ago. Then, about 10,000 years ago, it rapidly disappeared.

For a time it seemed that the results of the radiocarbon revolution were consistent with the Milankovitch theory. Although it

was true that the 18,000-year date for the last glacial maximum was 7000 years younger than the 25,000-year date calculated by Milankovitch for the last radiation minimum, such a discrepancy could easily be explained as the time needed for a sluggish ice sheet to respond to a change in the earth's radiation budget. In fact, Milankovitch himself had predicted that just such a lag should occur, and estimated its duration as about 5000 years.

However, the discovery of a 25,000-year-old peat layer in Farmdale, Illinois, finally shattered belief in the Milankovitch theory. Such a deposit could only have been formed during an interval of relatively warm climate. Exactly how warm was uncertain, but the date for that warm interval coincided exactly with the date of a radiation minimum. When deposits of the same age and type were found at other locations in the Midwest, in eastern Canada, and in Europe, the geological evidence against the astronomical theory seemed to be overwhelming.

The program of radiocarbon dating allowed more and more geologists to fix their field observations on a firm time scale. This led to the development of a new method for constructing a climatic curve that could be directly compared with the radiation curve. Geologists accomplished this by finding dates for a large number of till and loess samples along some convenient north-south line. This till-loess boundary could then be graphically represented as a function of time. The resulting jagged line showed the position of the southern margin of the ice sheet as it advanced and retreated at that particular longitude over the course of thousands of years.

The temptation to use radiocarbon dates beyond the reliable range of the method (40,000 years) was hard to resist. By the mid-1960s, several teams of researchers had drawn diagrams showing how the southern margin of the ice sheets fluctuated back and forth during the past 70,000 or even 80,000 years. One of the most detailed of these diagrams, produced by Richard P. Goldthwait, Aleksis Dreimanis, and their colleagues was based on observations of till and loess along a line between Indiana and Quebec (Figure 31). These results revealed a pattern of climatic change that was at variance at almost every point with the astronomical theory. About 72,000 years ago, for example, the glacial margin was located in southern Quebec, far to the north of its position during the maximum advance. Yet this was the time of an important radiation minimum. Moreover, the diagram indi-

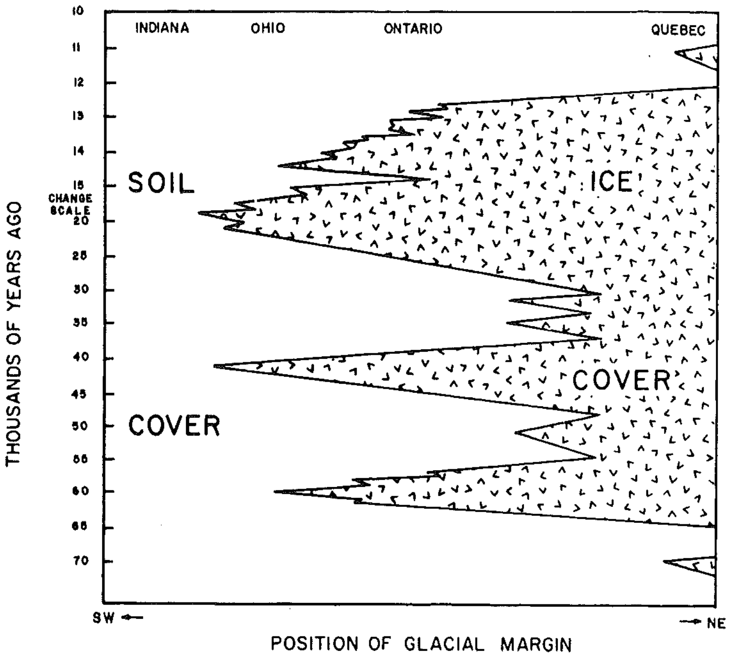

Figure 31. Fluctuations of the ice-sheet margin between Indiana and Quebec. The geographic position of the margin of the North American ice sheet is recorded as a fluctuating boundary between soil deposits and glacial drift. The supposed chronology of these fluctuations, provided by radiocarbon dates as old as 70,000 years, is at variance with the Milankovitch theory. (Adapted from R.P. Goldthwait et al., 1965.)

cated that major glacial advances occurred 60,000, 40,000, and 18,000 years ago. Only the youngest of these advances had been predicted by Milankovitch.

Wherever geologists used the radiocarbon dating method to study the older drift deposits, the result was the same. There were more glacial advances during the past 80,000 years—or at least during an interval of time they believed to the the last 80,000 years—than could be explained by the Milankovitch theory. By 1965, the astronomical theory of the ice ages had lost most of its supporters.