

11.1 Background

11.1.1 The *Albatross* and the Rise of Paleooceanography

Paleooceanography, that is, the study of ocean history, emerged with the investigation of the record of the ice ages in cores from the deep seafloor. Initial efforts by W. Schott (1905–1989) in the 1930s were based on very short cores. Thus, it was the Swedish Deep Sea Expedition (1947–1949) that launched the new science, thanks to long cores retrieved from many parts of the world. In essence, the Swedish expedition played the same role in launching the science of ocean history that the British *Challenger* Expedition had played some 70 years earlier for deep-sea sediment types. The Swedish expedition, led by the radiochemist and physicist Hans Pettersson (1888–1966), took the four-masted research vessel *Albatross* from Gothenburg all around the world, bringing back several hundred long cores taken with a device developed by the oceanographer Börje Kullenberg, who invented the original version of modern “piston corers” for the *Albatross* Expedition.

Kullenberg’s device typically recovered cores of a length of 7 m or so, with the oldest sediment commonly having ages between 0.3 million and 1 million years. Many of the cores unfortunately were disturbed, the sediments showing signs of having been “sucked” into the barrel taking the sample by the powerful forces invoked by the piston that facilitated the entry of sediments into the coring tube. Many of the cores turned out perfectly usable, however. They opened up an entirely new way of looking at geologic history, with remarkable time resolution. Devices modified from Kullenberg’s invention but retaining the piston principle became the workhorse instrument for gathering ice-age sediments from the deep seafloor (Fig. 11.1). Developments include coring by the drilling ship (coring ahead of drilling) thus ensuring the long-lasting contribution of Kullenberg’s engineering.

The scientists reporting on the *Albatross* cores became the founders of paleooceanography. In this fashion paleoceanography became linked to piston coring. The *Albatross* pioneers defined fundamental questions about



Fig. 11.1 Recovering the Pleistocene record by piston coring. The corer is a wide-diameter model; note the white sediment in the core nose. Other equipment seen on deck: deep-sea camera frame (with protective grid), hydrophone for seismic profiling (wrapped on a spool), and box corer (aft) (SIO Eurydice Expedition, 1975; photo Tom Walsh; taken at night)

the Pleistocene history of the ocean. The questions included ice-age fluctuations in productivity (G.O.S. Arrhenius, then Stockholm), ice-age changes in plankton distributions and surface currents (F.B. Phleger and F.L. Parker, then Massachusetts), ice-age changes in surface water temperatures and in ice volume (C. Emiliani, then Chicago), and ice-age changes in deep circulation patterns (Eric Olausson, Göteborg). Since then the questions raised by the pioneers, as well as related ones, have been pursued vigorously at the major oceanographic institutions in several countries. Perhaps the most significant early contributions to deep-sea-based ice-age lore were by scientists working on a large number of cores raised on Lamont's research vessel *Vema* (Columbia University).

The outstanding pioneer working on the ice-age record of the deep seafloor was Cesare Emiliani (1922–1995). Emiliani (not a member of the *Albatross* Expedition, but a scientist who used *Albatross* samples he obtained from H. Pettersson) was an Italian-American Chicago-trained nuclear chemist who introduced isotopic studies to deep-sea research. In addition, he was a paleontologist familiar with foraminifers, with a relevant doctoral degree from the University of Bologna, Italy. For much of his career, he worked in the Caribbean, from Miami, Florida.

11.1.2 Support for Milutin Milankovitch (1879–1958)

The cyclic variations of isotopic composition of foraminifers that Emiliani discovered provided crucial support for Milankovitch Theory, that is, the notion that ice ages are the planet's climate response to solar forcing linked to orbital variation (Figs. 1.2 and 11.2). Such variations are strictly cyclic, and their timing can be calculated with great precision. In pursuing such calculations, the Serbian civil engineer and astronomer Milutin Milankovitch (1879–1958) faced formidable obstacles, though. In the geologic record first studied on land, the ice-age sequence was poorly defined and not readily recognized as related to Earth's orbit. The available astronomical background calculations were unsatisfactory by today's standards. Also, Milankovitch's calculations, unaided by computing equipment, were extremely time-consuming.

To show that the course of the ice ages owed to Milankovitch forcing, reliable sequences of deep-sea sediments needed to be reliably dated. Radiocarbon dating (often cited as an important ice-age tool) was poorly suited for the long-term dating necessary to document Milankovitch cycles. Appropriate long-term dating was (eventually) achieved by radiochemical dating of volcanic products on

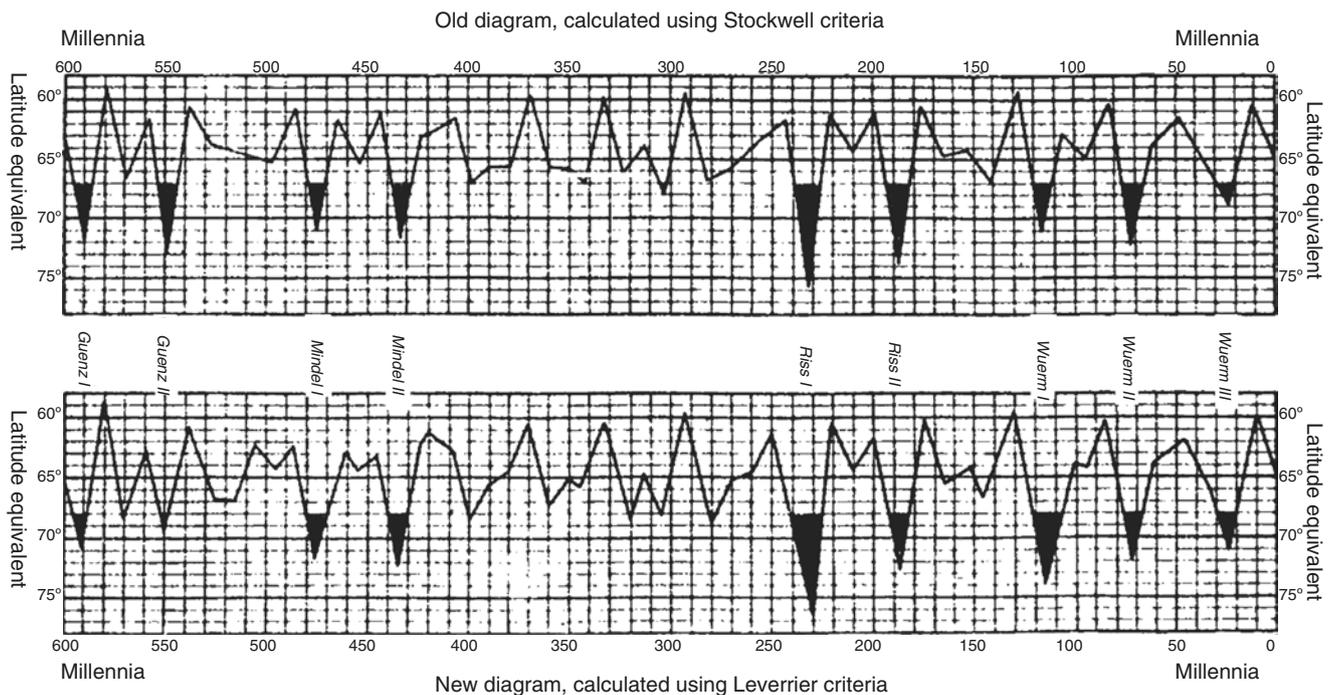


Fig. 11.2 Milankovitch diagram using solar input in high northern latitudes (y-axis) as the driver of major climate change in the ice ages (cold periods: filled valleys in the graph). [The data were sent to the Russian-

born German botanist and climatologist Wladimir Köppen by Milankovitch and were soon published by Bornträger (in 1924) (See Schweizerbart web site for "Bornträger")]

land and correlation of such dating into deep-sea sequences with the aid of magnetic stratigraphy (Fig. 6.10). Emiliani's original time scale turned out to be quite incorrect, illustrating the difficulties encountered by the pioneers. The task of refining orbital forcing was tackled by the Belgian astronomer and climatologist André Berger and his associates who reconstructed the various wobbles of planet Earth and its orbit in detail. The template he provided greatly facilitated the matching of deep-sea records to Milankovitch forcing, even bringing the entire Neogene into the range of millennial resolution. Matching the oxygen isotope record to astronomical forcing (Milankovitch "tuning") was the favorite dating tool of the British geophysicist N.J. Shackleton (1937–2006). Shackleton made much use of oxygen isotope stratigraphy in Pleistocene research, usually isotope sequences that were produced in his own laboratory. The third problem, the great labor of making appropriate calculations, was resolved by the rapid development of computing devices and the application of Fourier mathematics (Fourier methods are available since Napoleon but were not routinely used in ice-age research until the 1960s).

Beginning in 1968, the year when the drilling vessel *Glomar Challenger* left port in Galveston (Texas) to initiate scientific drilling in the deep ocean, many new dimensions in the interpretation of marine sediments were bound to emerge in paleoceanography. For once, the length of time that became available for detailed study increased from about 1 million years to the past 100 million years! But more to the point for ice-age studies: thanks to the technical advances in coring on the *JOIDES Resolution* (the drilling vessel that took over from the *Glomar Challenger* in 1985), ever more detailed studies could be done on the full 2 million-year ice-age record of the deep sea, taking advantage of a new (millennial) time resolution based on Milankovitch tuning (i.e., using Milankovitch Theory as a dating tool).

11.1.3 Milankovitch Cycles Explained

A brief explanation of Milankovitch Theory is in order. Unsurprisingly, when the disk of the sun is large in the sky (whenever our planet is close to the sun, i.e., in "perihelion" position), more sunlight is received than when the sun appears small. According to Milankovitch, if the disk is large in summer in high northern latitudes (i.e., perihelion in northern summer), melting of northern ice masses can occur, but if small (i.e., perihelion in northern winter), northern ice buildup proceeds. The seasons migrate along the orbit (relative to perihelion), completing a cycle roughly every 21,000 years; this defines the climate-relevant *precessional cycle*. Thus, precession is a matter of the *eccentricity* of the orbit discovered by Johannes Kepler

(1571–1630). In addition, the tilt of the Earth's axis changes through a range of somewhat less than three degrees on a cycle near 41,000 years (the present tilt is intermediate, at $23^{\circ}27'$). The tilt (*obliquity* of the rotational axis) determines how high the sun can rise during noon, in northern summer. A higher position translates into higher insolation in high latitudes, adding to any precession effect.

And that is all that is to it: the "precession" effect controls the apparent size of the sun through the seasons, and the obliquity or tilt of the Earth's axis determines how high the sun rises at noon at the different latitudes. One more thing: the precession effect has opposite signs in the northern and the southern hemisphere, while the orbital tilt effect is the same in both hemispheres (the sign of seasons being opposite).

The ice-age fluctuations in both hemispheres being parallel (more or less) and the available record apparently mainly reflecting northern irradiation patterns, we must assume with Milankovitch that the northern hemisphere takes the lead in pacing the ice ages. There is more land at crucial latitudes in the northern hemisphere (affecting land albedo from snow cover), and ice buildup is farther from the pole than in the south. As a result, northern ice masses are a lot more sensitive to change (positive albedo feedback) and vulnerable to destruction by solar variation than southern ice. The climate information of the northern ice ages is readily made global by changes in sea level and in carbon dioxide content of the atmosphere. Neither effect is restricted to one hemisphere, but the northern one is taken as dominant in originating changes.

It is obvious that the presence of Milankovitch forcing in the ocean's climate should be reflected in appropriate cycles of sedimentary particles in deep-sea sediments, and this is indeed the case, according to a study by the Lamont geologist J. Hays and colleagues, in 1976. For clarity, the study did show that Milankovitch forcing is extant; it did not document that this forcing is the only one at work.

11.1.4 Melting Not Ice Buildup

As the time scale for the ice ages evolved, it supported Milankovitch's emphasis on summer insolation in high northern latitudes (i.e., melting) in preference to earlier ideas that focused on the building of ice caps. The climatologist Wladimir Köppen, who advised and supported Milankovitch, had been right. His intuition in backing the thoughts of the confident young Serbian proved correct. Milankovitch was right on when he implied that the problem is *not* how to make ice, as assumed earlier by the brilliant geologist James Croll and various other scientists linking astronomy and ice ages; instead, it is how to *get rid of the ice in an unusually cold world*. Contrary ideas on this point still surface on occasion, for example, in the hypothesis of the UC physicists R. Muller

and G. MacDonald; a hypothesis that purports to explain the 100-kyr cycle of the ice ages by rhythmically obscuring the sun, a notion that answers the ancient question about cooling and buildup of ice mass, rather than worrying about melting, as did Milankovitch.

11.2 A Search for Lessons

11.2.1 The Ice Ages as Information Resource

We live in a period of northern ice ages, that is, a succession of periods of enormous ice buildup in northern latitudes, especially on the North American continent. The great extent of the ice here during the last glacial maximum was mapped by R.A. Daly in the first half of the last century and subsequently by R.F. Flint in the 1950s. One of the most appealing compilations is from the second half of the last century, done under the tutelage of the late John Imbrie of Brown University (Fig. 11.3). The book by J. Imbrie and his daughter K.P. Imbrie (published in 1979) is a special treat in this context. Our current situation is characterized as “postglacial.” The last glacial period ended about 15,000 years ago with vigorous melting setting in. Sea level ceased rising some 7000 years ago. It did rise for nearly 10,000 years and by some 125 m. Remnant ice near the North Pole (foremost on Greenland; Fig. 11.4) represents but a small fraction of the former northern ice mass.

Albedo feedback is crucial in ice age theory. Ice forms largely in high latitudes. At sea, the formation of sea ice (itself reflective and a base for snow) provides for sudden and large albedo change. In the mountains elevation is of prime importance for ice formation, so that the time since unloading continental crust and letting it rise is clearly of great relevance to ice growth. Lately, mountain glaciers the world over have been shrinking. Examples are seen throughout the Rocky Mountains of western America (some rangers fear the disappearance of glaciers in Montana’s Glacier Park on the scale of



Fig. 11.4 Our place in geologic time: remnant ice in Greenland (Air photo W.H.B)

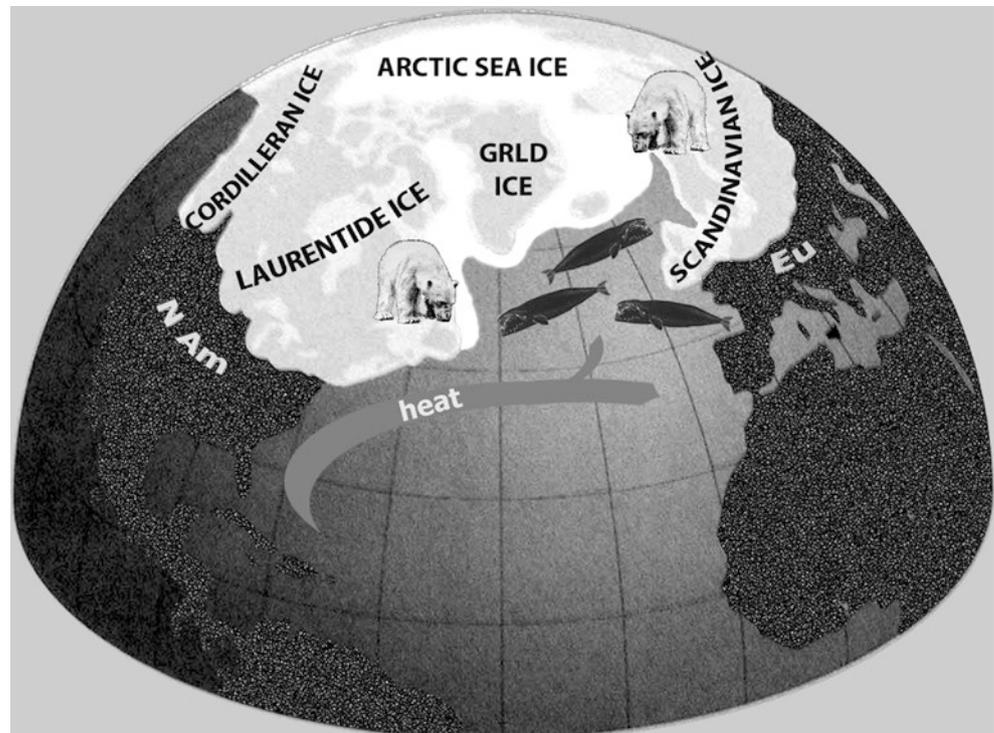


Fig. 11.3 Sketch of the northern hemisphere (Atlantic and Arctic) in the last ice age. Note the asymmetric distribution on both sides of the Atlantic (Map after J. Imbrie and associates. See J. Imbrie and K.P. Imbrie, 1979. *Ice Ages, Solving the Mystery*. Enslow, Short Hills, N.J. Polar bears from a drawing by F. Nansen; whale shadow-grams (placement hypothetical) after US NOAA)

decades). Such developments, and the ongoing rise in sea level, have motivated increasing interest in the history of the northern ice ages with a view to lessons obtainable for generating expectations and hence for planning.

11.2.2 Ice Ages and Positive Feedback

The ice ages do have interesting information on climate change, of course, some of which is relevant to present concerns and discussions of the topic, despite the great difference in time scale between ice-age history and human life (factor of 100). Regarding geologic history, the ice-age time scale (measured in millennia) is more than a hundred times more refined than the regular geologic scale, with important implications for understanding rapid change. The ice ages have geological lessons, because an appreciation of positive feedback (mainly albedo and carbon dioxide, perhaps methane) is crucial for understanding abrupt climate change. Positive feedback in the climate system is implied in Milankovitch Theory in the first place. When using rather subtle changes in the distribution of solar energy to drive major climate change, the question of albedo change becomes paramount. Snow reflects sunlight and snow-free areas do much less so; thus, small changes in solar forcing are readily magnified wherever snow is seasonal, that is, mostly in high and in moderately high latitudes (sea ice included) and in high elevations (Fig. 11.5).

The term “ice age,” incidentally, is used in various somewhat confusing ways. The sense in which the term is used in any given situation has to arise from the context. One convention applies the term to the entire period since the buildup of large ice masses on the northern hemisphere, that is, roughly the last 3 million years (here referred to mainly as “the (northern) ice ages”). Another type of use restricts the

label “ice age” to periods of glaciation, as defined by the ice covers in Canada and in Scandinavia. Finally, there is a third use of the word train. It is employed, on occasion, as an abbreviation for the term “last ice age,” which had its peak some 20,000 years ago. Many prefer the expression *last glacial maximum* (LGM) for that particular concept. The “ice age” that is congruent with the “Quaternary” (yet another use) is here taken as comprising the last 2 million years. If the last 10,000 years (the “Holocene”) are exempted from the “Quaternary,” one obtains the “Pleistocene,” which is a formal technical term and hence avoided here.

The study of the ice ages cannot but improve one’s understanding of climate change. However, expectations for elucidation of relevant processes are easily exaggerated. As geologists we are largely in the dark about the future. The future in fact has no analog in the past, as far as this can be determined. We are moving from an unusually warm interval within a long succession of ice-dominated times into a period of ever greater warming, a movement of a type that is without precedent in the last several million years. Also, at present it presumably occurs at a highly unusual speed. Geologic history reliably defines what is possible (what *can* happen) in the future, that is, in the attempt to predict, based on observation and experience. It is not a reliable source of information about what *will* in fact happen.

11.2.3 Useful Insights

Among the firm insights that emerge from the study of ice ages is the one that albedo feedback is a prime mover in rapid climate change. The behavior of snow and ice (including sea ice) matters. A second fundamental insight – this one from polar ice core studies rather than from marine geology – is



Fig. 11.5 Albedo feedback from ice and snow. *Left:* Sierra Nevada; peaks are higher than 4000 m. Note brightness of snow, darkness of forests, implying large seasonal change in albedo. *Right:* Svalbard 80°N. Note reflective snow on ice; relatively *dark water*

that warming and cooling over the last million years was invariably accompanied by a natural increase or a decrease in the concentration of carbon dioxide in the atmosphere. To what degree this change in concentration of greenhouse gas is a driver of the change in climate and to what degree it is merely an expression of the climate change is a famous chicken-or-egg problem and a topic for much interesting academic debate.

Actually, any postulated either-or scenario may not address what is happening. Effects can develop into causes – a situation highly relevant in all of geology and well appreciated by all scientists and engineers working with evolving systems. When studying the ultimate cause for the appearance (or elimination) of an ice age, we come up against the problem of evolving systems, that is, systems whose change produces more change. The link is called “feedback,” and it works both for the onset of ice ages and the subsequent cycles (which characterize the transitions from being ice-free to having eternal ice and vice versa).

Traditionally the question about the origin of ice ages has been about the cooling that is necessary to make lots of ice. Geologists commonly proposed at least one central force resulting in cooling: mountain building and uplift of the land. Uplift can increase the reflectivity of the ground rather suddenly, as when a large area goes above the snow-line or a shelf emerges, exposing white carbonate rock. Also, uplift and warming have for more than half a century been recognized as a control of volcanogenic carbon dioxide, some of which is used up in weathering, by becoming a component of carbonate. Deep mechanical weathering (fostered by the buildup of ice) can enhance uplift by unloading mountains, that is, leaving the upward push by mountain roots less opposed by materials covering the mountain. There is a reason why one of the modes of elevation (Fig. 2.1) is well above sea level. It suggests that uplift is ubiquitous. It is up to geologists to document the underlying process. Another important insight derives from the observation that whenever fast melting occurred during deglaciation, much of the required energy appears to have been delivered by the gravitational instability of the ice itself, rather than solely from the heat in the surrounding environment.

11.3 The Last Glacial Maximum in the Sea

11.3.1 General Patterns

It is generally agreed that *surface currents during glacial periods were stronger than now*. It is obvious why this should be so: surface currents are driven by winds, and the strength of relevant winds depend on horizontal temperature gradients at sea level. With the ice rim and polar front

much closer to the equator, the temperature difference between ice rim (0 °C) and the high tropics (25–30 °C) was compressed into a much shorter distance than now. Hence, the temperature gradients were greater, winds were stronger, and so were the ocean currents generated. As a consequence of stronger surface currents, *equatorial upwelling* was intensified (as first suggested by G. Arrhenius during the Swedish Albatross Expedition), as was *coastal upwelling* (as seen, e.g., in the benthic foraminifer sequence off Namibia). Thus, despite the fact that the productivity of the sea must have decreased in very high latitudes because of growth of sea ice cover, the LGM likely led to an overall increase in production owing to an increase in mid- and low latitudes because of intensified mixing and upwelling. In consequence of increased meridional temperature gradients, we must assume that winds during glacial periods were more zonal, that is, more predictable than in warm periods.

Also, it is generally accepted that the glacial-time *ocean surface was cooler*, on the whole, than today. With a substantial part of northern continents covered by ice and with sea ice greatly extended, the Earth reflected the Sun’s radiation more readily (had a higher *albedo*) than today. As a result, it absorbed less of the incoming radiation, and its atmosphere was cooler. In addition, concentrations of the greenhouse gas carbon dioxide were lower during the last glacial maximum (a fact documented by laboratories in Grenoble and in Berne, in polar ice cores). Carbon dioxide in the last glacial maximum was but 2/3 of the postglacial natural background concentration. As a result, the lower atmosphere held less water vapor (the most potent common greenhouse gas) than now. Other possible feedbacks have to be considered also when discussing a cooling of the planet, for example, from changes in plant cover on land affecting albedo and from changes in chlorophyll content in surface waters at sea (also affecting albedo, as variously pointed out by professional students of plants on land and at sea).

An attempt to precisely determine the amount of cooling on an ocean-wide scale (as in the 18 k map by the CLIMAP group), while confirming the concepts mentioned (e.g., strengthening of surface currents), turned out to be an extremely difficult task, involving plankton ecology. An attempt to precisely reconstruct ocean temperatures from fossils in cores may easily fail in finding the correct historical drop over large areas. An overall cooling of around 5 °C for tropical surface waters (roughly twice the general CLIMAP value) now seems acceptable to many workers in the field. True, the difference of past to present temperature seems to change considerably with latitude. However, when using organic remains for reconstruction of precise temperature history, one must be aware of the ability of organisms (especially tiny ones with rapid reproduction cycles) to adapt to climate change on a millennial scale and thus for fossils to

show less change than might seem appropriate for differences in conditions. In addition, organisms may react to elements in the changing conditions that are quite different from those assumed to be controlling the fossil abundances. These types of problems of fossils are pervasive in all of historic reconstruction.

A fourth agreement among students of the ice ages is particularly important: a substantial *drop in sea level* results from the buildup of glacial ice. Roughly 125 m or so is the generally accepted range for the last 20,000 years, for which changes in sea level are dated and documented in great detail (Fig. 6.5). These changes represent a phenomenon with an enormous number of important implications for geology and for climate change (including changing the sites of deposition of carbonate: shelf seas tend to trap carbonate; dry shelves cannot do so).

11.3.2 A Millennial Perspective and the Task of Correct Dating

A millennial perspective is appropriate when discussing ice-age climates: the resolution of many of the available deep-sea records is limited roughly to a thousand years. The ice record may offer greater resolution, but what can be cored to great depth is restricted to high latitudes (or high elevations). The record on the seafloor is not so restricted, but it has other problems. The ocean mixes on a time scale of about one millennium, and great ice masses take millennia to build and also to melt. Even the timing of the last glacial maximum is in some doubt on the millennial scale.

A resolution focused on one millennium might seem a bit coarse for many purposes. However, for many geologists an ability to separate one millennium from a neighboring one is commonly referred to as “high resolution.” It took some time to get there, actually. Dating used to be quite fuzzy even a few decades ago, with geologic age estimates routinely off by some 10 or 20% (i.e., by tens of thousands of years or even by millions, depending on the age being discussed). Absolute dating (assigning ages in terms of years before present) using radioactive isotopes other than radiocarbon (mainly certain types of *uranium* and its decay products, or “daughters”) has brought relief from the contamination problems.

The exploration of paleomagnetic sequences and their introduction to deep-sea cores has fundamentally changed the earlier limitations on dating deep-sea sediments by correlation to widely used time scales on land. These developments have allowed expansion of millennial assignments to the million-year scale, based on Milankovitch tuning. Orbital cycles can serve as guides back to many millions of years ago because – according to experts concerned with the history of the solar system – the planets of our solar system

seem to retain their current patterns of travel over many millions of years.

11.4 The Pleistocene Cycles

11.4.1 Background

It is commonly safe to start any essay on pioneers in any geological subject whatever with the British barrister Charles Lyell (1797–1875), erstwhile vice-president of the Geological Society of London and prolific textbook writer. His opus “Principles of Geology” (first published in the 1830s) provided a scientific framework for doing geology at a time when the Holy Bible was still widely used as a geology text even by some scientists. In later editions of his work (e.g., Lyell, 1868), we find that what he had to say about the ice ages, though appropriately vague in places, is quite interesting. For example, he quotes John Herschel (1792–1891), son of the famous astronomer William H., as invoking changes in the brightness of the sun as a possible cause for climate change on Earth – an early version of change of radiation balance. More in line with later reasoning, John Herschel already invoked effects of orbital elements on climate, notably eccentricity. Almost of equal interest is what Lyell does not say, implicitly dismissing various early notions regarding the origin of ice ages.

It was the brilliant self-taught Earth scientist James Croll (1821–1890), member of the Geological Survey of Scotland, who followed up with astute calculations on the notion of orbital forcing floating about within the scientific community of the time. He argued that the effects of changing eccentricity of Earth’s orbit on climate would be substantial. Obviously, such change would affect the contrast between seasons as Earth changed its distance to the sun, with the closest approach sometimes in northern summer and sometimes in northern winter. Croll’s theories (summarized in a book published in 1875) bravely addressed the challenge posed by multiple ice ages. Unfortunately for Croll, multiple ice ages were not yet generally recognized as a reality of geological history. They were proposed by his colleague, the distinguished Scottish geologist James Geikie (1839–1915) at the time Croll pondered the matter, and practically by no one else.

Multiple ice ages were a tremendous discovery, of course. The origins of this discovery are not entirely clear. Albrecht Penck, the leading ice-age geologist of his time at the start of the last century, gave credit to James Geikie. Penck himself (with his associate E. Brückner) postulated four large glaciations, which he labeled with the names of rivers draining the Alps, rivers that bore rubble in their banks from ancient floods presumed to have been associated with glacial activity (i.e., the melting of ice). The postulated reasoning was

acceptable at the time, but Penck-Brückner assignments are in doubt since the 1960s and have been abandoned decades ago. Instead, there is the Milankovitch scheme of orbital forcing of climate change, a scheme that Penck thought bound for failure. However, the isotopic geochemistry introduced by Cesare Emiliani attained its prominence because of its relevance for Milankovitch Theory. The Theory attempted to explain the sequence of multiple ice ages. And thanks to Emiliani, Pleistocene geology acquired a multitude of numbered climate excursions, many more than Penck's measly four.

Milankovitch triumphed. Ironically, his goal was to explain the multiple glaciations as interpreted by Penck and Brückner (see Fig. 11.2). The success of his theory (well after his death) in fact stems from observations on deep-sea sediments, observations that suggested that Penck's scheme could be misleading when applied globally. The chief problem arising with Milankovitch, though, has to do not with the Penck target he pursued. Rather, it has to do with the observed prominence (in deep-sea sediments) of a cycle near 100,000 years, a climate cycle that dominates the time period studied by Milankovitch and apparently was not identified by him. The origin of the long cycle is still not clear.

However, regardless of the doubts arising with respect to the 100,000-year cycle, Milankovitch Theory is now the most valuable part of the toolbox of ocean historians, as

emphasized by Nicholas Shackleton of the UK; André Berger of Louvain, Belgium; Lamont's James Hays; and Brown's John Imbrie, among other ice-age experts of the last several decades. In fact, Milankovitch Theory has achieved textbook status. It is a tool without peer when the task is to date ice-age sediments from the deep seafloor or to determine sedimentation rates of such sediments. Apparently the theory works for sediments that were deposited well before the onset of the northern ice ages but carry information from orbital cycles, even in ancient Cretaceous deep-sea sediments (Chap. 13). Milankovitch Theory has profound implications for all of climatology and the Earth sciences in general, because of its emphasis on solar system astronomy, which provides for known forcing (although not feedbacks!). The theory is a revolutionary force in natural philosophy: it successfully emphasizes external astronomical factors in the determination of geologic processes on the surface of the planet.

11.4.2 Carbonate and Productivity Cycles

The first hint from deep-sea sediments that there was a long succession of cycles (as called for by Milankovitch Theory) was delivered by the carbonate cycles of the eastern equatorial Pacific (Fig. 11.6, left panel). The cycles were described

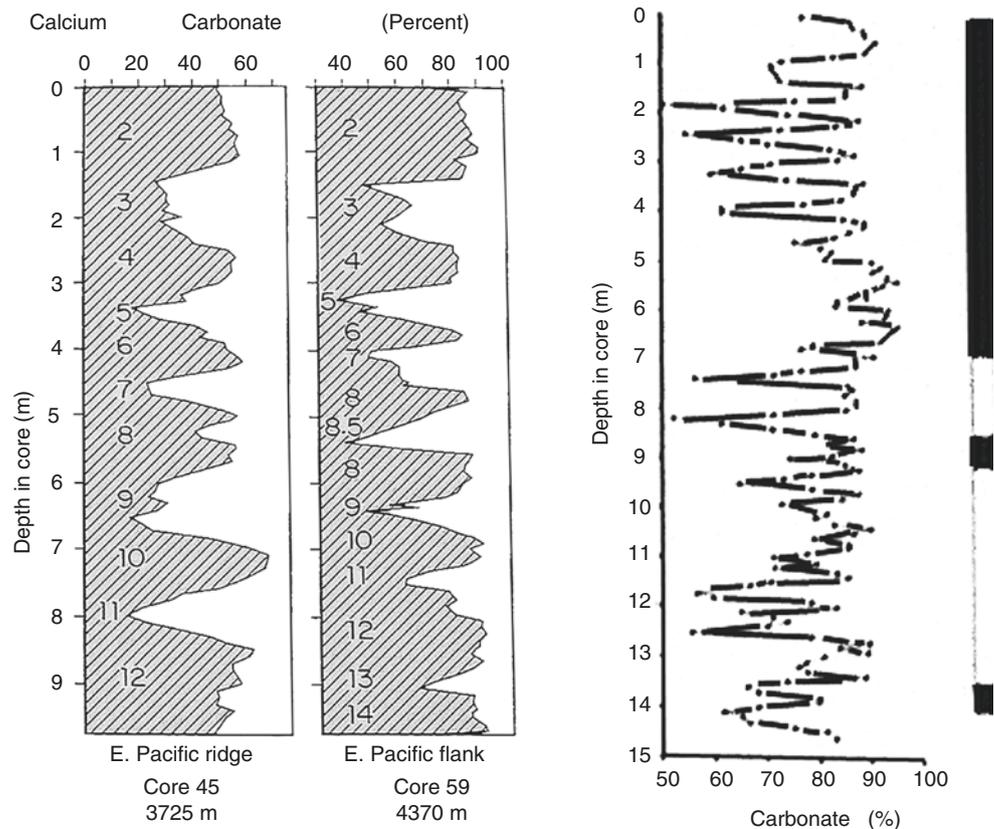


Fig. 11.6 Carbonate cycles of the eastern tropical Pacific. *Left:* cycles as recorded in the Albatross report (After G.O.S. Arrhenius, 1952. Reports of the Swedish Deep Sea Expedition). *Right:* dated cycles as reported by Lamont scientists (J.D. Hays et al., 1969. Geol. Soc. Am. Bull. 80:1481). Note the control of timing by paleomagnetism

by the Swedish-American geochemist G.O.S. Arrhenius, member of the *Albatross* Expedition. How the cycles are made has been the subject of much academic discussion. The cycles are now commonly interpreted as *dissolution cycles*, with high dissolution of carbonate in interglacial time intervals (low carbonate values) and low dissolution in glacial periods (high carbonate values), rather than chiefly as evidence for varying production in the equatorial zone of the Pacific, as originally suggested.

That the carbonate cycles are in fact Pleistocene in age and therefore represent conditions in the ice ages is readily seen in a long piston core studied at Lamont by the paleoceanographer-geologist J. Hays and the magnetism expert N. Opdyke (then Lamont, now in Florida) and colleagues (Fig. 11.6, right panel). The Lamont core is dated by several magnetic reversals. The first one (going down in the core) is the Brunhes-Matuyama reversal, the date of which is roughly 780,000 years, as confirmed by radiochemistry on land. The patterns suggest that the *Albatross* cores end in the earliest part of the Brunhes Chron, making the sedimentation rates come out near 1.3 cm/millennium. A cycle length of 1–1.5 m consequently suggests a carbonate cycle close to eccentricity, when assuming Milankovitch forcing.

Even though the carbonate cycles may not chiefly result from variations in production, this does not mean that they cannot run parallel to such variations. That plankton productivity is higher during glacials than during interglacials in the equatorial Pacific now appears well established, and the associated variation in carbonate output must therefore contribute to the carbonate cycles observed. Whether the change is large enough to explain most or all of the observed range of variation of carbonate ooze, however, is another question and is seriously doubted by many geologists.

Convincing evidence on Arrhenius-type productivity variations along the eastern Pacific equator was presented by A. Paytan and collaborators, using barite concentrations in ice-age sediments. H. Perks and R. Keeling found evidence on Ontong-Java Plateau in the western equatorial Pacific that glacial-time production exceeded interglacial production. Foraminiferal composition in a long core studied by M. Yasuda and unpublished box core results from that area point in the same direction (Fig. 11.7). Thus, effects of productivity cycles along the Pacific equator on deep-sea carbonate sedimentation are well established. Obviously, the question, when discussing effects from dissolution cycles versus effects from productivity variation in making carbonate cycles, is one of proportional importance. It is not a question of the either-or type.

Evidence that ice-age productivity fluctuations were global in nature comes from a record in the central Atlantic (Fig. 11.8). P.J. Müller and E. Suess used organic matter as an indicator in their reconstruction. Such effects can be difficult to assess, due to problems arising from changes in dilution with inorganic matter and in preservation of organic

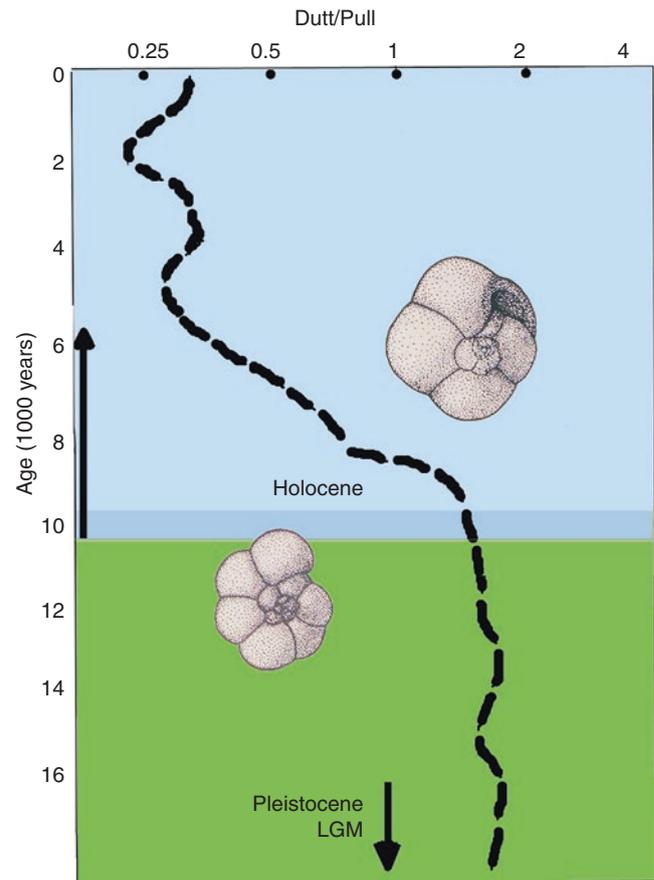


Fig. 11.7 Evidence for a sharp decrease in productivity in the Holocene in the western equatorial Pacific, on Ontong-Java Plateau, based on a drop in abundance of the planktonic foraminifer *N. dutertrei* (a high-production indicator) and a rise in the species *P. obliquiloculata* (a low-production species) in a box core bearing a well-preserved fossil assemblage. The indication is that productivity was considerably higher during the last glacial maximum than within the interglacial period following deglaciation (Drawings of foraminifers by F.L. Parker, S.I.O., here shaded. Data: unpublished notes of W.H.B.; ages based on radio-carbon determinations)

matter. Regarding glacial productivity, Müller and Suess suggested that it exceeded the interglacial one by a factor of 2.3, very similar to the factor of 2 determined for the eastern tropical Pacific by A. Paytan and colleagues. Increased glacial productivity in coastal upwelling regions, presumably thanks to increased winds (in agreement with the Arrhenius mechanism), seems to hold true in many places all over the world.

Productivity cycles imply faunal and floral cycles, which are indeed pervasive in the ice ages. These fossil cycles invite reconstruction of temperature changes, given present biogeographic patterns. The most striking result of the effort to link eupelagic fossils mathematically to surface water temperatures is the famous 18 k map of ice-age surface temperatures, a map that was widely used as a target for computer modeling of ice-age conditions of the sea.

Fig. 11.8 Ice-age variation in productivity off NW Africa, based on organic matter content in Meteor Core 12,392 (P.J. Müller and E. Suess, 1979. *Deep-Sea Res.* 26A:1347; also P.J. Müller et al., 1983. In: J. Thiede and E. Suess, *Coastal Upwelling*, Part B, Plenum Press, New York)

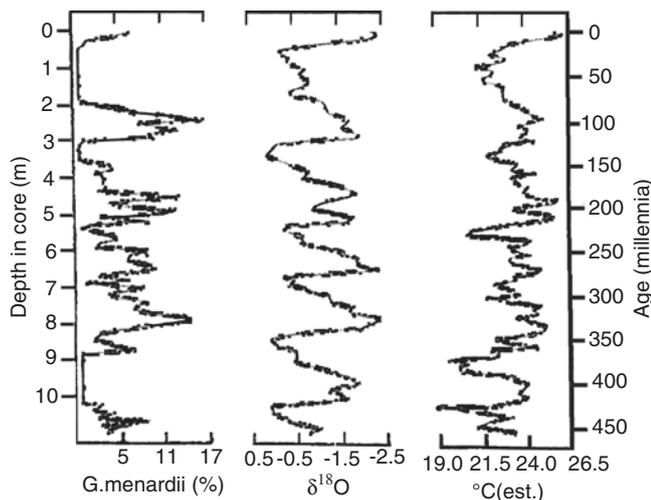
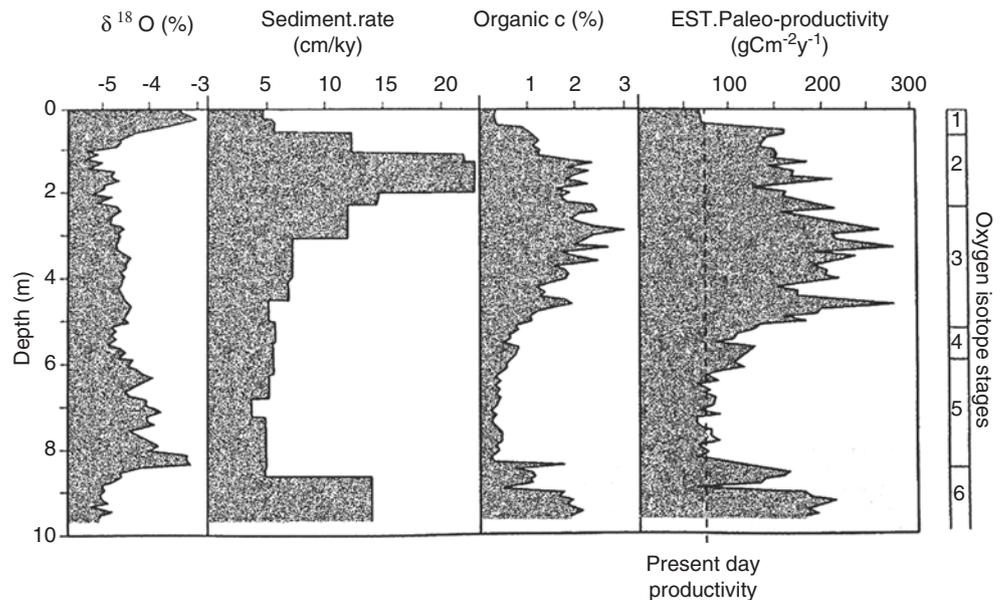


Fig. 11.9 Ice-age cycles in the deep-sea sediments of the Caribbean Sea. Left: pulses of *Globorotalia menardii*, a warm-water planktonic foraminifer that disappeared entirely from the central Atlantic during the last glacial period and also 400,000 years ago (not a cold spell); middle, oxygen isotopes in foraminifers; right, temperature estimates from abundance distributions of planktonic foraminifer shells (Imbrie et al., 1973. *J. Quat. Res.* 3:10)

11.4.3 Faunal and Floral Cycles and Some Open Questions

That some species are not particularly reliable as recorders of paleotemperature was established early in the experiments involving planktonic foraminifers (Fig. 11.9). In a record from the Caribbean Sea, the foraminiferal cycles (reflected in temperature estimates) rather closely follow the associated oxygen isotopes, but without duplicating them, supporting the notion that a comparison of the two curves

(temperature estimate from faunal composition and from oxygen isotopes) might be useful when attempting to separate the various controlling factors. In some disagreement with expectations, one important tropical species (*G. menardii*) is missing from the Atlantic both during the last cold period and also during Emiliani Stage 11, a warm interval 400,000 years ago. Evidently there are controls still to be discovered; temperature alone seems a fickle guide to faunal change.

11.4.4 Walvis Silica Cycles

A strong worldwide increase in glacial production apparently left its mark on the chemistry of the sea: in many places glacial output of opaline shells (diatoms and radiolarians) was diminished rather than increased by high production (the *Walvis Paradox*, first described by the marine geologist L. Diester-Haass, Saarbrücken, Germany). Major changes in the chemistry of the sea also are in evidence in the variation of carbon dioxide in the atmosphere. The first description of the Diester-Haass effect was from sediments off Namibia. It was confirmed by drilling there, during ODP Leg 175, as being valid for older Pleistocene sediments studied, as well as the younger ones assessed by Diester-Haass. Apparently, productivity increased, while the supply of diatoms did not, calling for different controls on the two types of phenomena, productivity and diatom abundance.

11.4.5 Oxygen Isotope Cycles: H.C. Urey, Sam Epstein, and C. Emiliani

Oxygen isotopes, determined for the calcareous shells of planktonic and benthic foraminifers, have become the master

signal of ocean history and especially of ice-age history, comparable in importance to the ocean's temperature distributions in oceanographic studies.

Aware of the central importance of temperature in the reconstruction of oceanic conditions, Cesare Emiliani introduced a concept to deep-sea studies he labeled *isotopic temperature*. It is based on the discovery by the physical chemist Harold Urey (then Chicago) that calcite (CaCO_3) in shells precipitated in equilibrium with seawater are enriched in ^{18}O relative to seawater but less so at higher temperatures. The equation relating temperature of precipitation to the oxygen isotopic composition of shells was found for mollusks by the Canadian-US geochemist Sam Epstein (1919–2001) and his coworkers in Chicago, including H.C. Urey. It was adopted by Emiliani for the foraminifers. The measure reported is the δ -value. It is the difference in the isotope ratios of sample and standard, as permil of the standard (“permil” is ten times percent). The standard usually is taken as “PDB,” named for a now vanished belemnite from the Pee Dee formation in South Carolina that was originally analyzed by Urey's group. For the correct interpretation of the changes in δ -value, one needs to know the δ of the seawater within which the shell was precipitated. This value is usually not known and must be guessed at, before the temperature of precipitation can be calculated.

Emiliani was well aware of this effect, as well as of other complications in pursuing his measure of “isotopic temperature.” In his initial studies, he carefully listed the various problems that interfere with reading the oxygen isotope record in terms of the history of temperature (the ice effect, geographic variation in isotopic composition of seawater, vital effects, seasonal growth of shells, and growth of foraminifers at various depths in the water). But once he settled on the two preferred planktonic species for analysis (*G. rubra* and *G. sacculifer*), he presented his data as indices of “isotopic temperature” in his graphs. Thus, he implied that the various other interfering factors can be captured by a single proportion. His assessment that the ice effect (and others) may be taken as a constant proportion of the overall change in oxygen isotopes was widely adopted. However, his estimate of the ice effect was too low, making his guesses for temperature differences automatically too high. The correct value for the ice effect was first suggested by the Swedish marine geologist Eric Olausson (1923–2010) and subsequently confirmed by the British geophysicist N. Shackleton (1937–2006). The delta value for the sea is taken to be near 1 permil (Fig. 1.5).

Emiliani's studies introduced fundamentally new ways of reconstructing ocean history. Unfortunately, however, the time scale he employed was quite incorrect, just like his guess on the ice effect was. Valid cycles with a (nearly) correct interpretation were first presented not by Emiliani using samples obtained from Hans Pettersson (leader of the *Albatross* Expedition) but by Nicholas Shackleton and

the Lamont geophysicist Neil Opdyke, who used a core taken by Lamont's research vessel *Vema* and employed paleomagnetism for dating by correlation (Fig. 6.10).

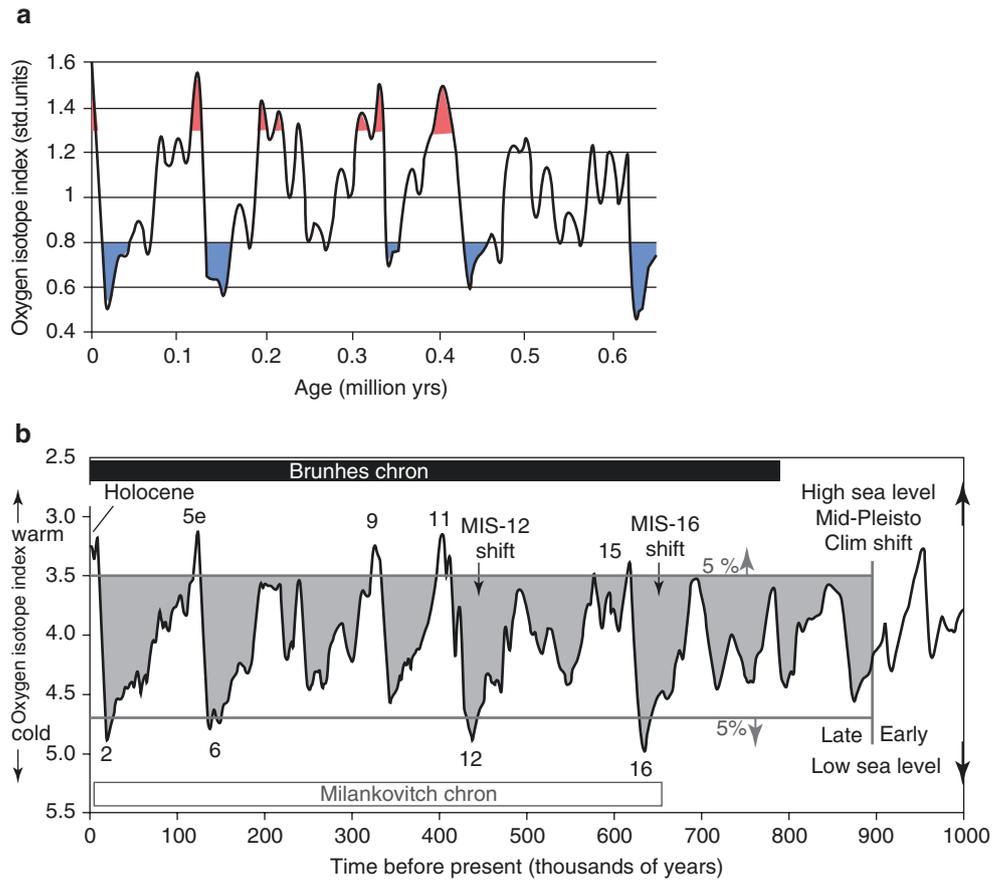
The link to Milankovitch Theory that emerged once the time scale for the oxygen isotope variations became a lot closer to the truth than the one offered by Emiliani represented strong evidence for the theory and invited its use for precise dating. Milankovitch Theory, by providing accurate wavelengths for the climate cycles contained in the deep-sea record, delivered a standard sequence based largely on averages of oxygen isotope series in several cores from the deep Atlantic that has remained useful for Pleistocene sediments back to 650,000 years since first proposed in 1984 by John Imbrie and associates (Fig. 11.10a). Subsequently, it was shown (by N. Shackleton, A. Berger, and R. Peltier) that Milankovitch Theory is applicable in finding an age for the Brunhes-Matuyama magnetic reversal. In a very convincing demonstration, these scientists produced an age for the beginning of the Brunhes Chron identical to one obtained by radiochemistry. The discovery allows for revision and extension of the standard isotope curve for the Quaternary ice-age fluctuations (Fig. 11.10).

Despite the successful application of Milankovitch Theory, it is important to realize that the theory is not in fact capable of describing all of the observed variations in ice mass and temperature in simple fashion. For clarity: the Theory may be unexcelled as a dating tool, but it is incomplete as a mechanism for explaining ice ages.

11.4.6 Sea-Level Cycles and Limiting Feedbacks

Assuming that phase shifts between forcing and response are constant, we can use the detailed information from the timing of the forcing to reconstruct rates in sea-level change. One typically obtains maximum rise rates between 2 and 3 m per century (the 3 m/century value being extremely rare). Falling sea level moves more slowly than rising one, suggesting a contribution to (fast) sea-level rise from instability in the ice (see also Chap. 6). The fastest sustained rises of sea level are seen within the times of glacial *termination* (= *deglaciation*; = major melting), that is, whenever the large northern ice masses on North America and Scandinavia were melting vigorously (see section on *deglaciation*). The last one of these ice-age events ended about 7000 years ago and took almost 10,000 years. The rise of sea level was approximately 125 m, that is, the average rise rate, sustained for many millennia, was just above 1 m per century (Fig. 11.5). For any one millennium within that set, of course, an average rise per century could have been much greater than the typical millennial value. Likewise, for any one century, within the ten centuries making up a millennium within *deglaciation*, the rise rate could have greatly exceeded the average. The available data do not show such short-term pulses.

Fig. 11.10 Quaternary isotope standards based on Milankovitch dating. (a) Useful portion of the Imbrie et al. (1984) data (“SPECMAP”; red, warm peaks; blue, cold peaks); the Holocene appears to be missing. (b) . Revision and extension (to 1 million years) of the “SPECMAP” standard based on subsequent isotope data. (Holocene added from box-core information.) Numbers are Emiliani stages. Large ice-age events are followed by shifts in climate systems



In evaluating the confidence to be placed in the results of this statistical exercise (and others like it), it is well to remember that the Milankovitch Chron (the time span studied by Milankovitch, the last third of the Pleistocene) has plenty of major melt events. There are only very few of those in the earlier portion of the ice-age record.

What is intriguing is that there seems to be strong resistance in the ice-age climate system to sea level dropping below a certain maximum low-level zone (Fig. 11.11; also see Fig. 6.10). Upward boundaries are less well defined, but there does seem to be a resistance for late Pleistocene sea level to climb above a certain high level zone, here interpreted as evidence for negative feedback at the boundary for the “normal” range. The suggestion is that the onset of strong negative feedback at both lower and upper boundary zones kept ice mass variations within more or less regular limits in the last million years. To what degree such observations can be applied to present concerns is unknown, of course. The ice ages offer illustrations of response to millennial-scale changes in solar forcing; one cannot assume that they also reflect fast response (on the human scale) to fast changes in external forcing. Applying findings in one-time scale to another always involves much guesswork unless all details are known and amenable to calculation.

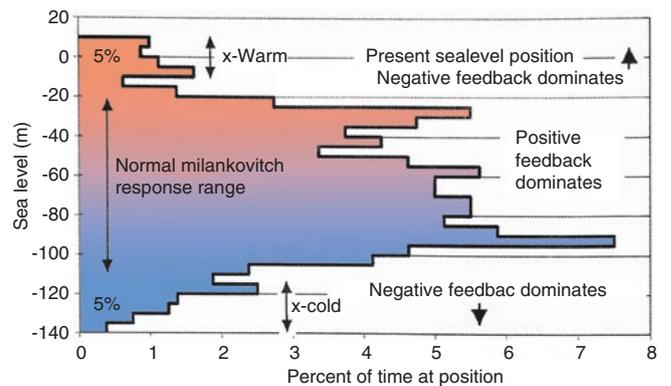


Fig. 11.11 Histogram of estimated sea-level positions for the last million years, based on oxygen isotope measurements in foraminifers of deep-sea sediments. Note maximum position near -100 m (W.H.B., 2008. *Int. J. Earth Sci.* 97:1143; color here added)

11.4.7 Carbon Cycles

It may seem obvious that ice-age cycles should generate carbon cycles. The link is implied in the propositions re the Arrhenius carbonate cycle and in the Mueller-Suess measurement of variations in productivity (the latter measured as grams C per square meter per year). (The marine component in the variations of organic matter within sediments in

principle is accessible through *biomarkers*, that is, organic substances bearing on the origin of the organic carbon within sediment.) In addition, there are the carbonate cycles, presumably strongly influenced by the changing availability of shelves, the preferred sites of carbonate deposition. A move of carbon back and forth between organic matter dominance in glacial periods and carbonate dominance on a shallow seafloor during warmish interglacials must influence changes in atmospheric carbon dioxide (although to determine the size of the signal independent of ice core data is extremely difficult and yields unreliable information).

Small changes in the chemistry of the sea, leading to a small proportional change of carbon chemistry in the ocean, can potentially have large effects on the atmosphere, since the ocean reservoir available for exchange with the air is relatively very large. The question is how to track such changes in the marine realm. One commonly used proxy is the $\delta^{13}\text{C}$ signal, describing the changing ratios between the isotopes ^{12}C and ^{13}C . The $\delta^{13}\text{C}$ signal emerges together with $\delta^{18}\text{O}$ when analyzing carbonate. Biological pumping tends to remove the ^{12}C slightly more efficiently from the photic zone than ^{13}C , because ^{12}C is more readily incorporated into organic matter during photosynthesis than is ^{13}C .

The effect of the slight difference in reactivity is that *carbon-13 (or ^{13}C) is enriched in surface waters* relative to deep waters. Thus, the $\delta^{13}\text{C}$ (which is recorded in carbonate plankton) is a measure of the intensity of the pumping, as pointed out by the Lamont geologist and chemical oceanographer W.S. Broecker several decades ago. The maximum $\delta^{13}\text{C}$ value in any period depends on the nutrient content of deep-ocean waters, which controls the amount of isotopic fractionation that can be achieved.

11.5 Deep-Ocean Drilling and the Ice-Age Target

11.5.1 Advantages of Drilling

While much of the material recovered for ice-age studies in deep-sea sediments was recovered by piston coring, the contributions from drilling were momentous. Technically, they involved obtaining excellent records after piston coring was adapted to drilling by taking cores ahead of the rotating pipe end, before the sediment was touched by the drill. There are several additional reasons that drilling became central to ice-age studies. One is that drilling allows the sampling of the entire ice-age sequence, starting with the onset in the middle of the Pliocene. In areas of high sedimentation rate, where the record is potentially very promising, plain piston coring may retrieve a record that falls short of completeness. Any

drilling into the seafloor, of course, likely has to penetrate ice-age sediments to get to a target older than the ice ages. Thus, ice-age sediments became the chief product of deep-sea drilling, not necessarily with explicit intent.

The main result of studying ice-age sediments was a deeper understanding of climate change and the role of the ocean in it. This type of understanding became ever more desirable as the importance of climate models gained momentum in the discussion of global warming.

A rather pragmatic approach to the advantages of drilling was illustrated by Cesare Emiliani. He pointed out that on land confusion is likely to reign with regard to ice-age history thanks to the prevalence of erosion and especially owing to the fact that subsequent ice-age cycles tend to destroy the evidence left by previous ones. In contrast, in the deep sea, one might expect a long undisturbed record of the ice ages, with drilling even recovering the evidence for the onset of ice ages in routine fashion. The onset, of course, follows a general cooling. It is part of Cenozoic history therefore, and will be discussed in the chapter that follows.

11.5.2 The Mid-Pleistocene Revolution and Milankovitch Theory

As mentioned, a long ice-age record is a common product of drilling. One implication is that the study of lengthy time series from the deep seafloor ceased to be a privilege of successful piston coring and became routine instead. Through such routine work, it was confirmed in the western equatorial Pacific that some 900,000 years ago, the ice-age cycles changed rather drastically (Fig. 11.12). While the nature of the ice-age cycles changed, that of the astronomic forcing remained as before. In addition to the appearance of seemingly unforced long cycles arising near 700,000 years ago, there is another enigma: variations in the quality of response to forcing, which may be addressed as changes in the quality of listening of Earth's climate system to Milankovitch forcing in general. There seem to be periods of defective listening, and they are as yet poorly documented or understood.

The Mid-Pleistocene Climate Shift (*MPR* in Fig. 11.10) that separates late Pleistocene long climate oscillations larger than 70,000 years from shorter ones before about 900,000 years ago, dominated by obliquity cycles (41,000 years), should be seen in acoustic profiles, since the echo structure is bound to change at that level within the sediment. There are indeed indications that this is so, in slope sediments off Angola and Namibia (cf. Fig. 3.6). The phenomenon fitting expectation was discovered during preparations for drilling during ODP Leg 175. Quite generally, drilling has had benefits through expanding the need for preparation (and thus exploration of poorly known seafloor conditions).

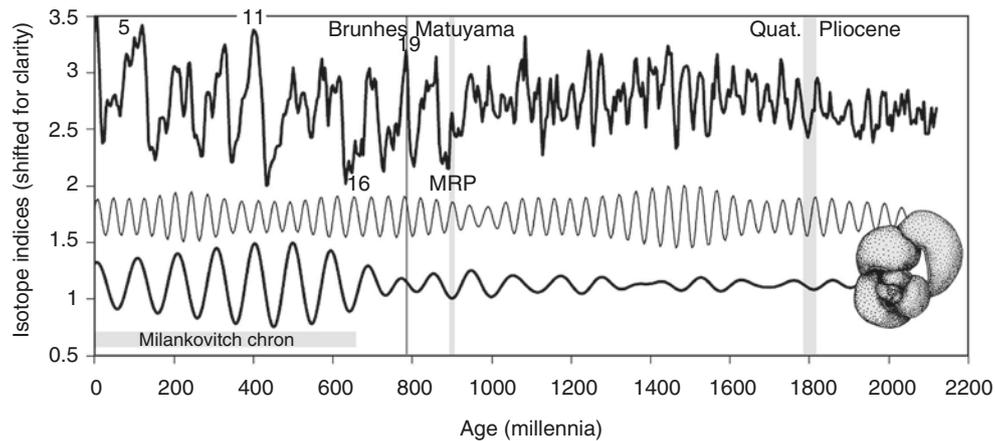


Fig. 11.12 Oxygen isotope record of the planktonic foraminifer *G. sacculifer*, ODP Site 806, western equatorial Pacific, 41,000 y- and 100,000 cycles extracted by Fourier mathematics. 5, 11, 16; Emiliani isotopic stages. The Milankovitch Chron starts with Stage 16 (Marine

Isotope Stage 16). It is dominated by 100,000-year cycles, as shown. The Brunhes Chron starts with Stage 19. The *MPR* (mid-Pleistocene Revolution) is at Stage 22, apparently the first very large glaciation in the Quaternary (W.H. B. and G. Wefer, 1992. *Naturwissenschaften* 79:541)

11.6 Deglaciation

11.6.1 Background

The discovery of the relatively young age of the last glacial maximum implied a short time span for moving from glacial conditions into postglacial ones (Fig. 6.5). It is an achievement that owes much to radiocarbon dating of deep-sea sediments during pioneer time (1930s–1980s), with strong connections into the study of oxygen isotopes in foraminifers. Naturally, the great mass of meltwater delivered during transition time (some in tremendous floods such as the famous Columbia River Flood studied by the U. Washington geologist Harlan Bretz in the 1920's) had implications for the ocean's stratification and circulation, which stimulated much discussion and speculation. Discussions on this topic may have lost vigor in the past few years, with other issues taking center stage, but the problems identified half a century ago are by no means solved.

The last deglaciation is but one example (albeit the closest one in time) of a dozen rapid climate change events associated with major melting in the last million years. The appearance of these events (called “terminations” by W. Broecker; Fig. 11.13) presumably signaled an increase in potentially unstable ice mass. In any case, W. Broecker and his student J. van Donk in 1970 boldly drew the fast deglaciation events (“terminations”) on top of Emiliani's isotope stratigraphy, thus introducing this very fruitful concept into the thinking about the ice ages.

11.6.2 The Younger Dryas

One major enigma arising in the last deglaciation is the problem of the Younger Dryas cold episode (the name is taken from a plant fossil, an Arctic flower, Fig. 11.14). The episode

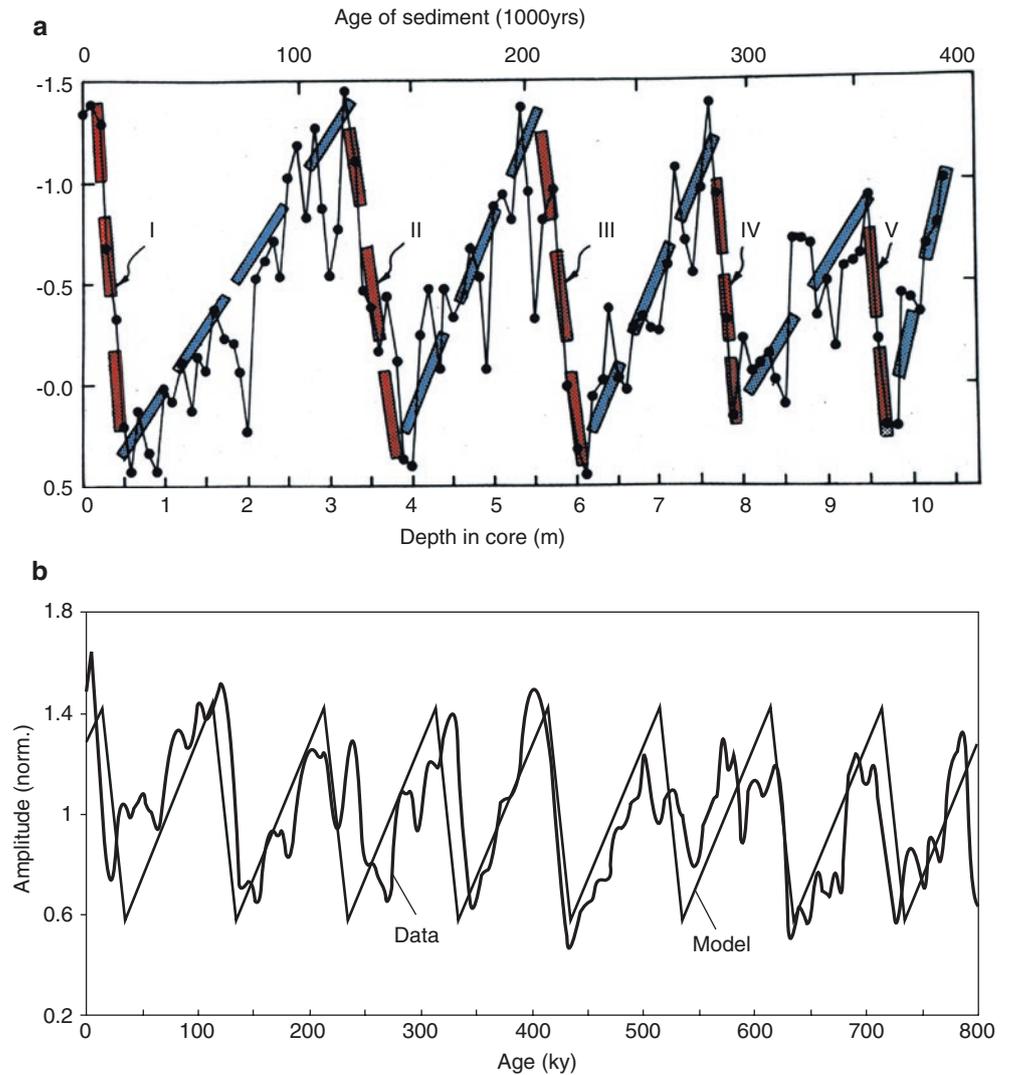
is a 1000-year relapse into glacial conditions in the northern hemisphere first seen in Greenland ice cores studied by the Danish physicist Willi Dansgaard (1922–2011). The Younger Dryas occurred in the middle of the last deglaciation interval, which followed considerable warming. The reversal of post-glacial warming and its halt during the Younger Dryas has led to much discussion, including speculations about changes in deep circulation. Many of the suggestions regarding the effect of the Younger Dryas on the deep-sea environment are based on information from the chemical stratigraphy of benthic foraminifers (the shells of which carry clues about ventilation of deep waters in their chemistry). Other constraints are based on modeling of climate change and inferred responses of the circulation.

In recent years the problem of the Younger Dryas cold spell has been linked to a postulated impact from space some 12,800 years ago. An impact event could perhaps explain drastic change at the time of the onset of the Younger Dryas, including megafauna extinctions, which have been linked to both climate change and to human over-hunting. But an impact too (like so many other possible explanations) would leave unexplained the preceding drastic warming of the first melting step (the “Alleroed” warm spell that presumably started the melting and thus the “deglaciation” process). As long as the Alleroed warming is unexplained, it seems difficult to claim that the deglaciation record is “understood.”

11.6.3 On Sudden Mammoth Extinction and Other Unexplained Deglaciation Topics

Discussions of possible reasons for the extinction of the mammoth and other large mammals (also large birds) have

Fig. 11.13 (a): Terminations I to V in the sawtooth interpretation of Emiliani isotope data by W.S. Broecker and J. van Donk, in 1970. [Rev. Geophys. Space Phys. 8:169] Red: fast melting; blue: buildup of ice; colors here added. (b): Remarkable agreement between data series (ODP Site 804) and a simple termination model with a period of 100 ky (W.H.B., presentation in Berne, 1999) Phase difference between data series and termination model was set to zero at an age of 400 ky



been vigorous among geologists after Baron Cuvier showed that the mammoth is extinct (i.e., that extinction is for real).

In this context (as well as other ones related to abrupt change in climate) climatologist geologists would like to know why the melting of the last deglaciation started when it did and what precisely controlled the rate of destruction of glacial period ice masses. The assumption is that a rise in temperature, while important, is unlikely to be the whole story. The fact that *terminations* exist suggests that large ice masses can become unstable. Dansgaard-Oeschger Oscillations and Heinrich Events with their evidence for sudden cooling appear to have a similar message. The notion of unstable ice is not new, actually: regular instability of ice has been urged by the US glaciologist T. Hughes (University of Maine) for many decades. “Heinrich Events” (pulsed IRD delivery), among other evidence, seem to bear him out.

Modern concerns revolve around the striking presence of methane ice, much of it below sea level, in high-latitude

northern regions (known as “permafrost” and in the past stable enough on land for bearing houses and roads and telegraph poles). Melting such ice releases the powerful greenhouse gas methane (exceeding effects from CO₂ on a century scale by more than 25 times). Some of the methane may escape destruction by oxidation for a number of years. In historical marine geology, the methane problem appears when discussing an uncommonly strong spike of ¹²C-rich carbonates at the end of the Paleocene, a time of maximum warmth, within the early Cenozoic. The Cenozoic is the topic of the chapter that follows.

11.6.4 Mediterranean Sapropels

The Swedish *Albatross* Expedition retrieved a large number of cores in the Mediterranean Sea, many of which contain the black organic-rich layers called *sapropels*. Black sediments commonly are addressed as “sapropels,” a term



Fig. 11.14 *Dryas octopetala*, the Arctic flower that gives its name to the 1000-year cold spell during the last deglaciation, the “Younger Dryas” (implying the existence of an “Older Dryas”) (Photo W. H.B., taken near Joestedal Glacier, Norway)

related to the Greek word for rotteness and thus presumably referring to a disagreeable smell involving hydrogen sulfide and related compounds that can be associated with an oxygen-free environment. Burrowing commonly was suppressed when the dark layers were deposited (Chaps. 8 and 13).

The debate about origins of these sapropel layers has focused largely on the question of whether the organic-rich layers in the Mediterranean reflect a lack of oxygen (at depth) or a marked spike in production (within surface layers). There is some doubt that these are separable causes. The responsible factors may be aspects of the same change in overall circulation within the basin, that is, a shift from anti-estuarine to estuarine deep circulation lasting several thousand years. Identifying climate change (precipitation, freshwater influx) as the main factor links the sapropel origin there to the oceanography of deglaciation. The spacing of sapropel layers provides a base for an astronomical time scale back into the Pliocene, as documented by the stratigrapher Frederik Hilgen in Utrecht. Drilling recovered material there that allowed extending the sapropelic orbital time scale deep into the Tertiary.

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