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Chapter 8
Deep ocean sediments and dating the past

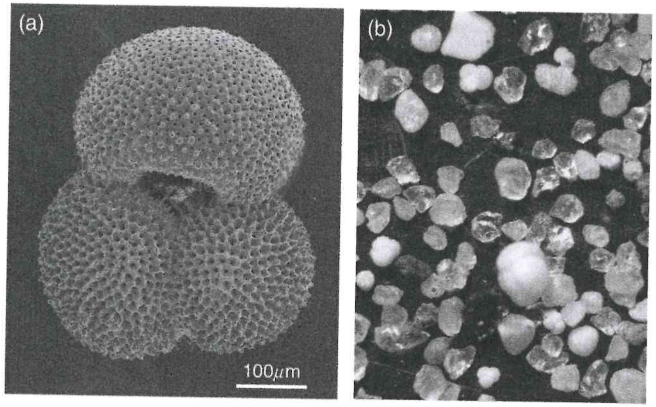
The sea must know more than any of us.

Carl Sandburg (1918)

Away from the continents, in the low energy setting of the deep ocean floor, fine sediments dominated by the shells of tiny marine organisms have accumulated over millions of years to form a thick veneer of soft mud. Marine sediments are especially useful because they form an unbroken record of environmental change that spans the entire Quaternary. Geologists had long speculated that these deposits might tell the full story of the Quaternary ice age. So when the Swedish oceanographer, Börje Kullenberg (1906–91), designed a piston corer in 1947 that could achieve deep penetration into the soft sediments on the ocean floor and recover long undisturbed cores, it heralded a new era in ice age research. In 1968, the Deep Sea Drilling Project began to collect hundreds of long sediment cores. Two aspects of the marine sediment record proved to be particularly instructive for reconstructing the history of the terrestrial ice sheets: the isotope chemistry of foram shells and the incidence of ice-rafted debris (IRD) (Figure 22).

Forams and their shells

Forams are tiny unicellular creatures found at all depths in polar, temperate, and tropical marine environments. Planktonic forams

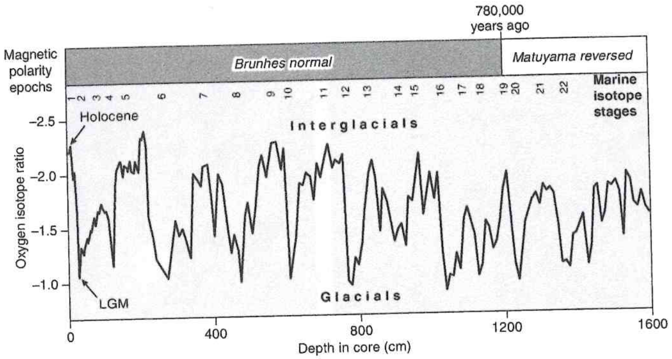


22. a) The fossil shell of the planktonic foram *Globigerinoides ruber* (b) Sand-sized ice-rafted debris with a small number of forams from a North Atlantic sediment core

inhabit the upper part of the water column that is penetrated by sunlight whilst benthic forams live close to the sea floor in the darkness of the deep ocean. Many species build pinhead-sized shells of calcium carbonate ($CaCO_3$) from elements extracted from seawater—these shells record key properties of the waters in which they live. When forams die and sink to the sea bed they contribute to a neatly stacked sedimentary record of changing ocean conditions from the present day to the deep past. Figure 22a shows a fossil foram shell viewed under a scanning electron microscope. In living specimens thousands of thin organic filaments or rhizopodia extend through the holes in the shell to help the foram move and feed. Some rather ingenious approaches have been employed to prise information from foram shells to illuminate aspects of the ice age past. One of these is oxygen isotope analysis.

The marine oxygen isotope record

Quaternary research was transformed in 1973 when the record shown in Figure 23 was published by Nick Shackleton and Neil



23. The oxygen isotope record from core V28-238

Opdyke. This is the oxygen isotope record from marine sediment core V28-238. It is perhaps the most famous plot in ice age research since it revolutionized our understanding of Quaternary ice sheet dynamics and global environmental change. It is therefore worth thinking about how it was derived, what it represents, and why it had profound implications for all of the natural sciences.

Oxygen has three stable isotopes: ^{16}O, ^{17}O, and ^{18}O. The lightest (^{16}O) and heaviest (^{18}O) are widely utilized in the study of past environments. Due to a process known as isotopic fractionation, when evaporation takes places from a body of water (H_2O), more of the isotopically lighter (^{16}O) water molecules are removed from the water surface relative to the isotopically heavy (^{18}O) water molecules because less energy is required to evaporate the lighter isotope. Fractionation operates at all scales: from the surface of the smallest pond to the largest ocean. In the global hydrological cycle, therefore, the ratio of $^{18}O/^{16}O$ in water vapour is less than the $^{18}O/^{16}O$ ratio of the seawater from which it is derived. The differences are very small, just a few parts per thousand, but they can be measured to high precision.

Over many thousands of years, as ice sheets build up during the course of a glacial cycle, enormous volumes of water are abstracted

from the oceans and stored on the continents as glacial ice. The fractionation process creates ice sheets that are isotopically 'light' because they are fed by snow formed from atmospheric water vapour. As the ice sheets on land increase in size, the oceans become increasingly isotopically 'heavy'. When ice sheets melt at the end of a glacial stage, the isotopically light meltwater is returned to the oceans. Thus, over glacial–interglacial cycles, the oxygen isotope ratio of ocean water shifts in response to the waxing and waning of the continental ice sheets. In order to exploit this process to explore the ice age past, we need a long record of changes in the oxygen isotope ratio of ocean water. This is provided by the fossil foram shells recovered from marine sediment cores. We can measure the ratio of $^{18}O/^{16}O$ in these shells using a mass spectrometer.

Figure 23 shows the changing isotopic composition of the oceans for the past million years as measured in forams from core V28-238. The record is divided into Marine Isotope Stages (MIS). The deepest troughs in the curve (even numbers) are glacial maxima with high global ice volume. The highest peaks (odd numbers) represent interglacials with much reduced ice volume. MIS 2, for example, is the global Last Glacial Maximum (LGM) (*c.*22,000 years ago). MIS 1 is the present (Holocene) interglacial. Note that MIS 3 saw a reduction in global ice volume but full

Box 7

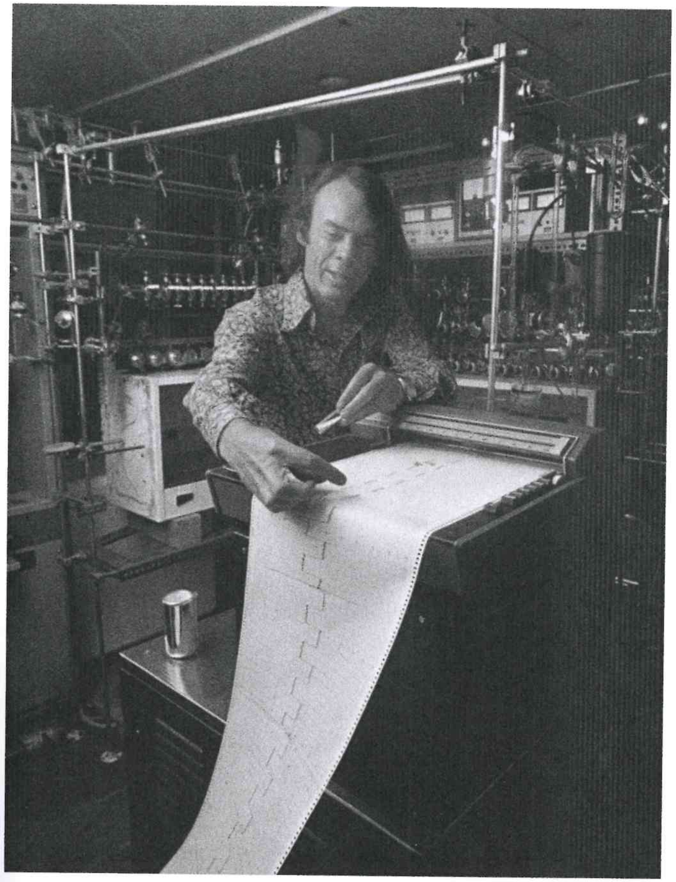
V28-238: This code identifies the 238th sediment core collected on the 28th cruise of the research vessel *Vema*. This core (1,600 cm long) was collected just north of the Equator in the Pacific Ocean in a water depth of 3,120 m. *Vema*, originally built as a luxury iron-hulled schooner (*Hussar*) in 1923 by millionaire New York stockbroker Edward Hutton (1875–1962), was refitted to become the main research vessel of the Lamont-Doherty Geological Observatory of Columbia University. Her crews collected thousands of sediment cores from the ocean floor.

interglacial conditions were not attained and MIS 5 is therefore known as the Last Interglacial.

Ocean temperature or terrestrial ice volume?

There are two principal controls on the oxygen isotope ratio of modern marine foram shells: (1) the isotopic composition of the ocean water in which they live; and (2) the temperature of that water. There has been much debate about the contribution of these two factors to the Quaternary isotope record. In the 1940s, at the University of Chicago, Nobel Laureate Harold Urey (1893–1981) was the first to suggest that oxygen isotopes could be used to reconstruct ancient temperatures. Urey encouraged a young colleague, Cesare Emiliani (1922–1995), to apply this principle to the study of the ice age oceans. Emiliani believed that the isotopic fluctuations he observed in planktonic forams in marine sediments were primarily a function of changing ocean *temperature* during glacial and interglacial cycles. He published a classic paper on this work in 1955.

During his PhD research in the mid-1960s Shackleton noticed a fundamental error in Emiliani's work. Shackleton argued that changes in terrestrial ice volume and *not* ocean temperature were the dominant influence on the isotopic variations detected in the foram record. He was able to demonstrate this by analysing benthic forams from the last glacial period. Benthic forams secrete their shells in the dark unchanging environment of the deep ocean where Quaternary water temperatures have always been close to zero. This environment is effectively insulated from the glacial–interglacial shifts in temperature we see on land and in ocean surface waters. This new approach took temperature out of the equation. Shackleton showed that the oxygen isotope record from benthic forams displayed the same fluctuations that Emiliani had observed in planktonic species. The benthic signal must therefore have been controlled by changes in the volume of ice stored on the continents. This was a stunning breakthrough (Figure 24).



24. Nick Shackleton in Cambridge in 1972

Dating the marine record

Using his long isotope records Emiliani attempted to revive the Milankovitch theory, but he was hampered by poor dating control. Developing a reliable timescale for the long marine records was problematic throughout the 1950s and 1960s. Radiocarbon dating had been developed by another Nobel Laureate in the Chicago group, Willard Libby (1908–80), just after the Second World War. This method could be used to date carbonate shells in the top section of cores back to about 50,000 years, but even this was only a small fraction of Quaternary time. Without a reliable timescale it was not possible to establish the tempo of change or the length of glacials and interglacials.

Box 8
Radiocarbon dating

Willard Libby made the first calculation of the half-life of radiocarbon and recognized its potential as a geological dating tool. The unstable isotope of carbon (^{14}C) is present in tiny quantities in all plants and animals. It is produced in the upper atmosphere by cosmic rays and enters the food chain with stable carbon (^{12}C) via the carbon cycle. All living organisms take up ^{14}C. When an organism dies, its radiocarbon stock is no longer replenished. By measuring the residual radiocarbon in fossil material, such as wood, charcoal, peat, seeds, bone, or foram shells, it is possible to estimate when the organism died using the half-life of 5,570 ± 30 years. In the early 1960s, samples of skin and fatty tissues taken from the Adams Mammoth yielded ages of 34,450 ± 2,500 and 35,800 ± 1,200 years BP (Before Present). By convention, the year 1950 is deemed to be the 'present' for radiocarbon dates.

Specialist equipment is needed to measure radiocarbon—for every trillion (10^{12}) atoms of stable carbon in a living organism, there is just one atom of ^{14}C. In theory, the method can provide ages for samples up to 50,000 years old, but beyond six half-lives this involves the accurate measurement of tiny amounts of residual radiocarbon. This can be done, but such very old samples can be susceptible to contamination by more recent radiocarbon and this yields ages that are too young.

Since Libby pioneered this method there have been important advances in sample preparation and in the way radiocarbon is measured. Also, because radiocarbon production in the upper atmosphere is not constant, all dates must be calibrated because radiocarbon years are not equivalent to calendar years. Despite these difficulties, it remains the most widely applied dating method in ice age research even though it can only be used for the Holocene and the second half of the last glacial stage. Libby was awarded the Nobel Prize for Chemistry in 1960.

Shackleton and Opdyke employed a different approach to date their isotope record using reversals in the Earth's magnetic field. Opdyke made systematic down-core assessments of magnetic polarity and located a reversal in V28-238 at a depth of 1,200 cm in MIS 19 (Figure 23). Because the V28-238 record does not contain any obvious breaks in sedimentation, he could be confident that this was the Brunhes-Matuyama reversal—the last time the Earth's magnetic field flipped—780,000 years ago. From this fixed point ages could be interpolated for each level in the core by assuming, quite reasonably, that the sediments had accumulated at a uniform rate. For the first time, reliable ages could be assigned to the glacial and interglacial stages of the Quaternary.

Box 9
Dating using magnetic reversals

Today a compass needle points toward magnetic north. This has not always been the case because magnetic reversals—when magnetic north becomes magnetic south or *vice versa*—are an intrinsic feature of our planet's magnetic field over geological timescales. The last full reversal took place 780,000 years ago—this is known as the Brunhes-Matuyama reversal. Prior to that reversal, the needle of a magnetic compass would point to magnetic south. All sediments deposited in the ocean include a component of minerals that retain information on the Earth's polarity at the time of deposition. We can measure this palaeomagnetic signal in the laboratory to establish if the sediments were deposited during a period of normal polarity (like today) or reversed polarity. Periods of normal polarity are shown in black and periods of reversed polarity in white (Figure 23). A magnetic reversal does not mean—as a student once excitedly asked this author after a lecture—that the Earth itself flips through 180°! It is the magnetic *field* that flips. The causes of reversals are not fully understood, they are probably triggered by the shifting motions of the hot liquid metals that surround the Earth's core.

Implications: global ice sheet dynamics

The oxygen isotope record from V28-238 has been described as the 'Rosetta Stone' of the ice ages. It shows that for most of the last 1 million years, large ice sheets were present in the middle latitudes of the northern hemisphere and sea levels were lower than today. Indeed, 'average conditions' for the Quaternary Period involve much more ice than present. The interglacial peaks—such as the present Holocene interglacial, with its ice volume minima and high sea level—are the exception rather than the norm. The sea level maximum of the Last Interglacial (MIS 5) is higher than today. It also shows that cold glacial stages (*c*.80,000 years duration) are much longer than interglacials (*c*.15,000 years). Ice volume in Antarctica did increase during glacial stages, but the Quaternary marine isotope record is dominated by the much larger changes in ice volume that took place in the northern hemisphere.

Box 10
CLIMAP

A good deal of the ice age research in the marine realm was made possible because of an international collaboration known as CLIMAP (Climate: Long range Investigation, Mapping, and Prediction) established in 1971 by James Hays of Lamont. It was funded by the United States National Science Foundation. John Imbrie of Brown University, Nick Shackleton, Neil Opdyke, and others were prominent members of this team. A key outcome was the reconstruction of the oceans and land surface of the Earth at the LGM.

The steep transitions from even to odd numbered stages indicate that the large ice sheets decayed very rapidly (Figure 23). These rapid deglaciations are known as Terminations. Indeed, planktonic forams in marine cores from the Gulf of Mexico record a distinctive influx of isotopically light water between 20,000 and 15,000 years ago because large meltwater floods travelled some 2,000 km down the Mississippi Valley from the disintegrating Laurentide Ice Sheet. The isotope stages are considered to be globally synchronous with a resolution that is better than 1,000 years—this is the best estimate for the mixing time for any regional changes to be transmitted throughout the global ocean.

Box 11
Rapid deglaciation

Deglaciations are rapid because positive feedbacks speed up both the warming trend and ice sheet decay. As Milankovitch-induced changes in summer insolation warmed the oceans at the end of glacial stages, the oceans released CO_2 into the atmosphere. This strengthened the greenhouse effect and reinforced the warming trend. Rising sea levels further undermined the ice sheet margins.

This process accelerated melting and hastened the sea level rise. Not only do warmer oceans produce greater volumes of atmospheric water vapour (another potent greenhouse gas), they also reduce the extent of sea ice. As both glacial ice and sea ice diminish, the amount of solar energy reflected back into space also falls because they reveal surfaces with much lower albedos. Internal feedbacks combine to amplify warming.

Figure 24 shows Nick Shackleton in his laboratory in 1972 surveying the oxygen isotope data from core V28-238, holding a test tube of precious forams. When the analysis for V28-238 was complete, Shackleton stuck the long sheet of graph paper around the wall of his living room at home in Cambridge and threw a party. He was fully aware that this record signposted a new direction for ice age research. Many of the fundamental questions about the climate system and ice sheet dynamics could now be tackled by studying the sediments on the ocean floor. In 1976, Shackleton and Opdyke published the record from sister core V28-239 which spanned the entire Quaternary. The ice age now had a template showing the *complete* record of glacials and interglacials.

Oxygen isotope analysis quickly became established as a powerful geological tool for correlating marine records around the world. The records from V28-238 and V28-239 were soon replicated in all the oceans. Shackleton and Opdyke had produced the first truly global, well dated, and continuous record of glacial events on the continents and, by inference, sea level change, for the entire Quaternary. The Penck and Brückner model of four glacials and four interglacials was now obsolete.

Box 12
Nicholas John Shackleton

Born in 1937, a century on from the Neuchâtel Discourse, the son of an eminent geologist and a distant relative of Ernest Shackleton of the Antarctic, it would seem that Nick Shackleton was destined to work on the ice sheets of the Quaternary. After graduating in Physics in 1961, he was encouraged by the botanist Sir Harry Godwin (1901–85) to work on isotopes in marine sediments for his PhD. Although he spent his entire career in Cambridge, Shackleton was a great collaborator internationally and became a key member of the CLIMAP group of mostly American geoscientists who pooled their expertise to explore the nature of ice age Earth. Shackleton received a bucketful of the most prestigious awards in recognition of the significance and excellence of his work. He was knighted in 1998 and, in 2010, when the Royal Society celebrated its 350th anniversary, he was chosen with ten notable members of the Fellowship (including Isaac Newton, Benjamin Franklin, Ernest Rutherford, and Alfred Russel Wallace) to feature on a special issue of Royal Mail stamps. Shackleton's other passion was music. He was an accomplished clarinettist and an internationally renowned collector and scholar of that instrument. He invariably used the proceeds of his geological prizes to amass the world's largest collection of rare woodwind instruments. He even lectured on acoustics in the Department of Music in Cambridge. Shackleton's many geological achievements would not have been possible without the selfless support of his good friend and laboratory manager *par excellence* Mike Hall. It was he who ensured that the Cambridge mass spectrometers carried out more isotope analyses on forams than any other laboratory.

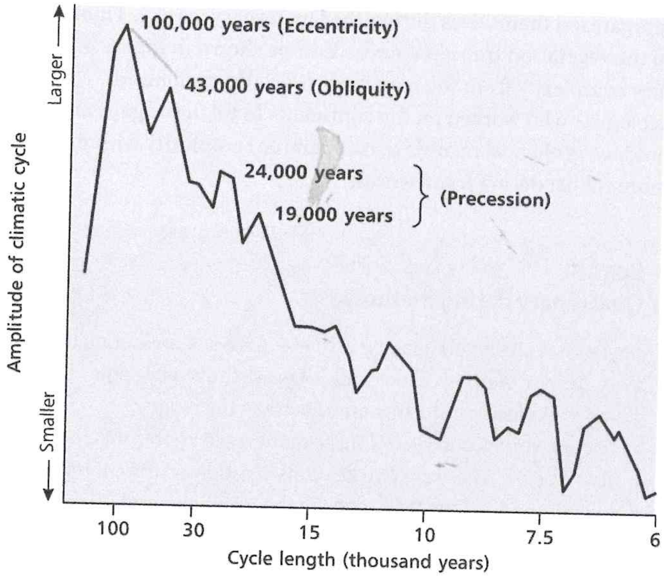
Milankovitch revived: pacemaker of the ice ages

In the late 1960s, a new record of Quaternary sea level change was produced by dating the uplifted coral reefs of Barbados. Because the reefs lay beyond the range of radiocarbon, they were dated using the uranium-thorium decay series. Sea level high stands were identified at 230,000, 170,000, 125,000, 105,000, and 82,000 years ago: the intervals between were times of low global sea level associated with continental glaciation. Significantly, the ages of the high stands coincided with times of maximum solar radiation in the northern hemisphere. These findings sparked a renewed interest in the astronomical theory.

Shackleton's saw-toothed isotope curve also hinted at some degree of cyclicity: the isotopic ratios of the glacial maxima were very similar and they appeared to be evenly spaced (Figure 23). The ice volume record presented a new opportunity to revisit the orbital theory of ice age climate variability and to test the new sea level model from Barbados. To this end, Shackleton collaborated with James Hays (who led the CLIMAP team) and John Imbrie, who had pioneered the use of computers and a statistical tool called spectral analysis to explore trends in long geological datasets. Shackleton's expertise in acoustics and waves also served him well in this analysis.

Spectral analysis of two long oxygen isotope records from the southern Indian Ocean revealed four dominant peaks that matched closely with the cycles computed by Milutin Milankovitch half a century earlier (Figure 25). Hays, Imbrie, and Shackleton had confirmed that long-term changes in the Earth's climate and geological processes were paced by changes in orbital geometry. This has been described as one of the most important geological discoveries ever made. Of course, it also represented an emphatic vindication of the Serbian engineer's life's work. The astronomical theory wasn't hogwash after all.

This breakthrough also created a new problem. Milankovitch Cycles actually generate quite modest changes in insolation, yet the climate shifts of the Quaternary are evidently rather more dramatic. The processes and feedbacks involved in shifting the Earth from glacial to interglacial conditions and back again were yet to be established.



25. Spectral analysis of the marine oxygen isotope record

Shackleton and others went on to produce more detailed oxygen isotope records that extended deep into pre-Quaternary time. In the first decade of the 20th century, Penck and Brückner had proposed four glacial–interglacial cycles for the Quaternary when many were making the case for just one. Figure 26a shows a 2.5-million-year record (with a chronology provided by several magnetic reversals) showing no fewer than 50 such cycles over this period back to MIS 104—it is a quite astonishing demonstration of our planet's propensity for change.

This amount of Quaternary climate variability has profound implications for all of the natural sciences. Not only did geologists have to rethink the speed of ice sheet build up and decay (not to mention sea level change), biologists now had to contemplate an order of magnitude shift in the number of times that ecosystems reorganized themselves during the Quaternary ice age. Think back to the vegetation transects across Europe shown in Figure 4. The new complexity from the marine records also challenged geologists who worked on the continents to fill in the gaps and to produce geological records of comparable complexity with much more robust dating frameworks.

Box 13

Quaternary dating methods

Physics has presented geology with many ways of measuring deep time. Several methods are capable of providing reliable age frameworks for deposits that are older than the range of radiocarbon (>50,000 years). Three of the most important are outlined below. There are two key considerations in the choice of dating method: (1) the time range of the technique; and (2) the composition of sample material.

Uranium-thorium dating

This method is based on the measurement of both the parent (uranium-234) and daughter (thorium-230) isotopes using high precision mass spectrometry. It has a range of about 500,000 years and can be used to date carbonate materials such as corals, stalactites, and bones because they retain both uranium and thorium. With a half-life of 245,000 years, ^{234}U decays to ^{230}Th, which has a half-life of 75,000 years. Over thousands of years, as ^{230}Th builds up in a carbonate sample, it provides a precise measure of age. Under optimum sample conditions its range is an order of magnitude greater than that of radiocarbon dating.

Luminescence dating

All geological deposits are exposed to low level natural background radiation. Grains of quartz and feldspar behave as dosimeters because they absorb this ionizing radiation and store trapped electrons in their crystal lattices (traps). This is a time-dependent process that can be used to establish the length of time since burial. Exposure to sunlight empties these traps and resets the geological clock. When grains of quartz or feldspar are exposed to a light or heat source in the laboratory they emit light; this signal is known as *luminescence*. By measuring the strength of this signal and establishing how much annual background radiation the sediments currently receive, it is possible to calculate the length of time since burial. If the stimulus in the laboratory is a light source, the method is called optically stimulated luminescence (OSL). It can be applied over a very wide time range—from very young deposits (*c.*100 years) to sediments more than a million years old. OSL dating is particularly useful for dating aeolian sediments and fluvial sands deposited on glacial meltwater plains. Such deposits are very often unsuitable for radiocarbon dating because they contain little or no organic material. OSL has also been widely employed to date dune fields and flood deposits in deserts.

Cosmogenic isotope dating

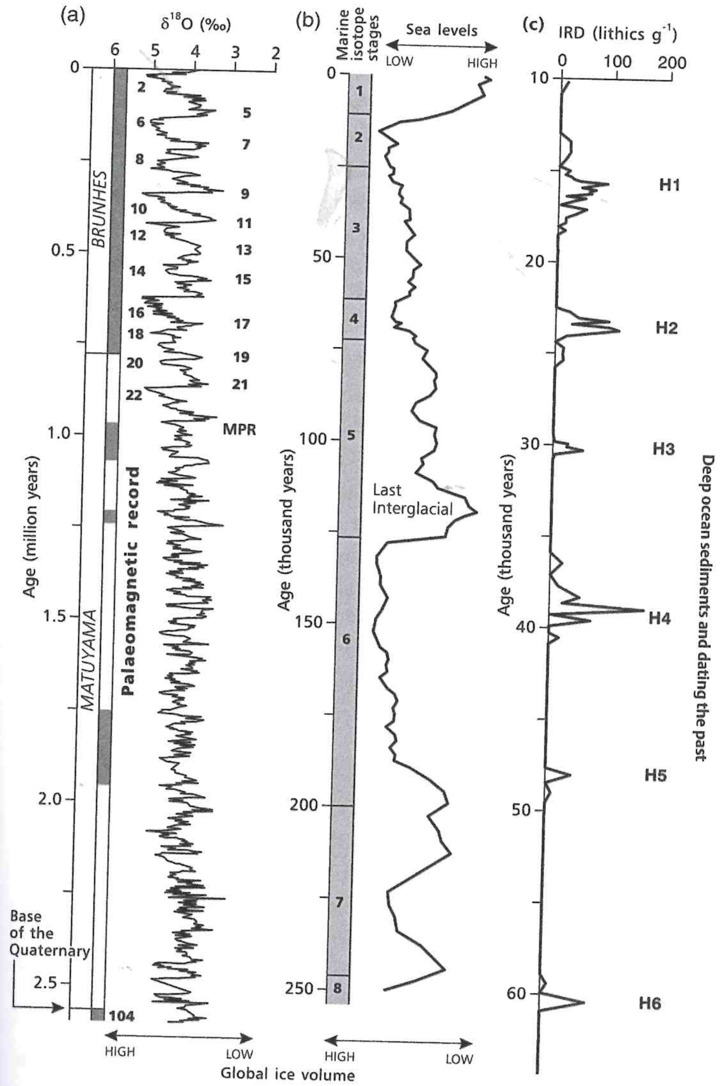
This is a relatively new dating method that utilizes another time-dependent geological process: the build-up of cosmogenic nuclides in rocks and soils exposed at the Earth's surface. These nuclides are created when high energy particles bombard rocks and sediments. Over time, cosmogenic isotopes such as beryllium-10, aluminum-26, and chlorine-36 accumulate in the upper metre or so of the Earth's surface. The duration of exposure can be determined by measuring their concentration. This method has been widely applied in glaciated mountains to date large boulders on moraines. It has a range of about 200,000 years. Many of the moraines and erratic boulders in the Alps that were first mapped in the 19th century have now been dated using cosmogenic isotopes. It has also been used to date bedrock surfaces to establish the timing of ice sheet retreat in Greenland and Antarctica.

The Mid-Pleistocene Revolution

Another key discovery in the long marine records is a marked shift in the *amplitude* of climate change around 900,000 years ago when the duration of glacial–interglacial cycles increased from 41,000 years (paced by obliquity) to 100,000 years (paced by eccentricity). This shift in the length of glacial–interglacial cycles has been termed the Mid-Pleistocene Revolution (MPR) (Figure 26a). The MPR heralded an era of more intensive glaciation when the size of the ice sheets in the northern hemisphere increased significantly. The cause of this striking tempo shift has generated much debate because eccentricity has the weakest influence on insolation. This has been termed the 100,000 year problem. This mismatch between stimulus and outcome suggests there must be internal mechanisms that amplify the response of the climate system. Some researchers have argued that the ice sheets became thicker and perhaps less responsive to the obliquity and precession cycles that previously enhanced summer melting. Glacial stages therefore became longer and terminations only took place when these cycles were strengthened by the eccentricity cycle. It is also likely that other internal mechanisms such as albedo feedbacks and atmospheric greenhouse gas concentrations were important in this remarkable shift in the pacing of glacial cycles.

Ice-rafted debris and Heinrich Events

Where glaciers reach the coast, calving bays produce sediment-laden icebergs. The sediment they transport is known as IRD. In the mid-1980s a young German marine geologist named Hartmut Heinrich found six distinctive spikes in IRD in the North Atlantic marine record for the last glacial stage (Figure 26c). Just a few centimetres in thickness, the Heinrich layers (H1 to H6) can be traced in sediment cores over large sectors of the North Atlantic. They become thinner moving south and east from the Labrador Sea. The IRD is angular, predominantly sand-sized sediment with



26. Marine oxygen isotope records for (a) the last 2.5 million years and (b) the last 250,000 years; (c) Heinrich Events in the North Atlantic during the last glacial. Note the different timescales for each record

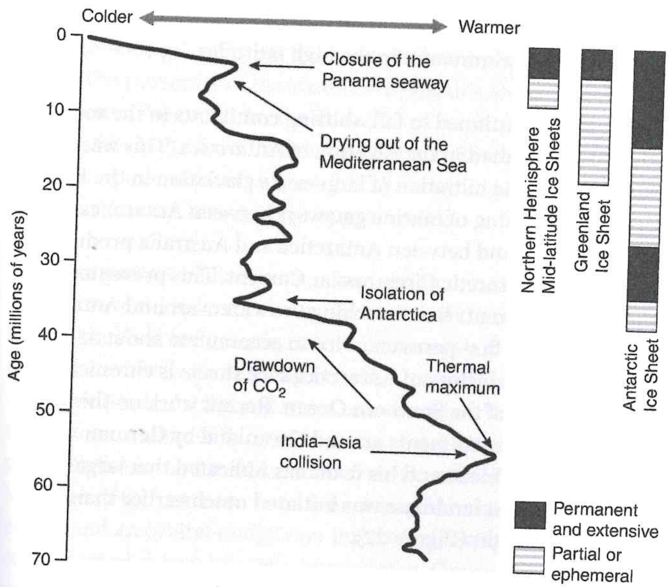
a mix of rock types from the glaciated interior of North America (Figure 22b). Each particle is a tiny erratic that has been transported in glacial ice and set afloat from a calving bay. Heinrich layers form a dramatic record of terrestrial ice sheet instability. Each IRD layer was deposited by an armada of melting icebergs that calved from the Laurentide Ice Sheet and travelled down the Hudson Strait—they represent truly colossal discharges of glacial ice from land to sea. These are known as Heinrich Events.

Mechanisms both internal and external to the Laurentide Ice Sheet have been put forward to account for Heinrich Events. It has been suggested that once the ice sheet reached a critical size, it became unstable and shed mass catastrophically via large-scale sliding and calving. This is the so-called '*binge-purge*' model. Rises in sea level and earthquakes triggered by crustal rebound have also been implicated in undermining the margins of the ice sheet. The identification of Heinrich Events shattered the long held notion that the large ice sheets were fairly stable throughout a glacial period. Indeed, the globally averaged marine isotope curve from tropical latitudes does not show any dramatic change between 60,000 and 10,000 years ago (Figure 26b).

The vast armadas of drifting ice chilled the surface of the Atlantic and checked the influence of the Gulf Stream. Melting icebergs created a layer of isotopically light, low salinity surface water that is clearly recorded in the few planktonic forams found within the Heinrich layers (Figure 22b). Heinrich Events were rather short-lived—lasting for about 750 years. They do *not* represent a revival of the Lyell drift ice hypothesis—they were associated with the collapse of mid-latitude ice sheets and very severe Arctic climates. They produced the coldest and driest conditions in Europe during the last glacial stage. The reduction in evaporation from the cold Atlantic produced widespread droughts that led to collapses in tree populations in southern Europe and dramatic falls in the level of the Dead Sea.

The Cenozoic glacial epoch: the last great cooling

Marine sediments also provide an extended record of global change that has allowed us to gain a deeper understanding of Earth's steady shift from greenhouse to icehouse over the past 55 million years. At the end of the Cretaceous, around 65 million years ago (Ma), lush forests thrived in the Polar Regions and ocean temperatures were much warmer than today. This warm phase continued for the next 10 million years, peaking during the Eocene thermal maximum (Figure 27). From that time onwards, however, Earth's climate began a steady cooling that saw the initiation of widespread glacial conditions, first in Antarctica between 40 and 30 Ma, in Greenland between 20 and 15 Ma, and then in the middle latitudes of the northern hemisphere around 2.5 Ma. Several key events have been implicated in this last great



27. Global temperature change and ice sheet development over the last 70 million years

cooling in Earth history (Figure 27) and these are briefly reviewed next.

The uplift of the Himalayas was underway by 50 Ma after the initial collision between India and Asia. The high rainfall and steep relief in this region created a global hot spot for both physical and chemical weathering. The big rivers that drain the Himalayas transport very high loads of fine sediment and material dissolved in solution. As the rocks of the Himalayas are broken down and transported to the sea, the CO_2 from rainwater combines with the weathering products to form new compounds such as the calcium carbonate ($CaCO_3$) shells of marine creatures. As uplift continued, more and more carbon from the atmosphere became sequestered in the fossils of creatures deposited on the ocean floor. It took a very long period of weathering (about 20 million years) to sufficiently weaken the Earth's greenhouse effect to bring down mean global temperature so that large-scale glaciation could commence in the high latitudes.

As CO_2 levels continued to fall, shifting continents in the southern hemisphere resulted in the isolation of Antarctica. This was a crucial step in the initiation of large-scale glaciation in the Polar South. The opening of marine gateways between Antarctica and South America and between Antarctica and Australia produced the powerful Antarctic Circumpolar Current. This prevented warm ocean currents from reaching the waters around Antarctica and allowed the first permanent ice to accumulate about 35 Ma (Figure 27). The history of Antarctica's ice sheets is chronicled in the IRD record of the Southern Ocean. Recent work on the IRD record in marine sediments around Greenland by German geologist Jörn Thiede and his team has indicated that large-scale glaciation on that landmass was initiated much earlier than previously thought (Figure 27).

At the end of the Miocene, between 5.5 and 5 Ma, the Mediterranean Sea dried out and refilled many times as its

connection with the Atlantic was disrupted by tectonic movements at the Straits of Gibraltar. The Mediterranean became an enormous salt pan as the basin's waters evaporated during times of isolation. These salt deposits can exceed 2 km in thickness. The end result was a *c.*6 per cent fall in the salt load of the global ocean so that sea water became easier to freeze. It has been argued that the extent and thickness of sea ice increased in high latitudes after this period. The enhanced albedo effect that this created would have augmented the long-term trend of Late Cenozoic global cooling.

Finally, in the Late Pliocene, sometime after 4 Ma, the formation of the Isthmus of Panama joined the continents of North and South America and closed the connection between the Atlantic and Pacific Oceans. This strengthened the Gulf Stream and increased the supply of moisture to the land masses around the North Atlantic. The final closure preceded the earliest evidence for large-scale glaciation in the northern hemisphere south of 60°N. The proximity of these events makes this an attractive hypothesis (Figure 27) for the initiation of ice sheet growth in the high middle latitudes of North America and Europe although some computer models suggest that the warming influence of the Gulf Stream may have had the opposite effect.

Over the past 55 million years, a succession of processes driven by tectonics combined to cool our planet. It is difficult to isolate their individual contributions or to be sure about the details of cause and effect over this long period, especially when there are uncertainties in dating and when one considers the complexity of the climate system with its web of internal feedbacks. The tipping point for the initiation of ice sheet formation in the high middle latitudes of the northern hemisphere may have been albedo effects and an orbital nudge that intensified the long-term cooling trend driven by tectonic processes. Once set in glacial mode, the length of glacials and interglacials was paced by the Milankovitch Cycles.

The ice age transformed

The study of marine sediments utterly transformed ice age research in ways that no one could have imagined. The discoveries of the 1970s were so profound and their implications so far-reaching that at least one leading Professor of Quaternary Science, David Bowen, ranked them in significance alongside the plate tectonics revolution. The oxygen isotope record provided a powerful proxy for long-term changes in *global* ice volume. The marine record of IRD allowed the geography of ice sheet development and decay to be reconstructed in both hemispheres with much greater spatial resolution.

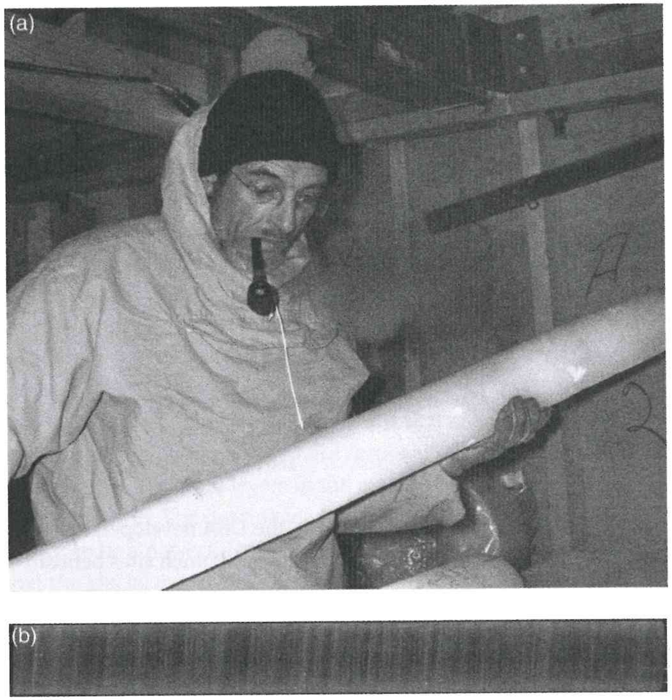
It was then established in the late 1980s that catastrophic releases of icebergs from calving bays were responsible for the deposition of distinctive Heinrich layers in the marine record across the North Atlantic. The floating ice that deposited them was also shown to be a powerful agent of climate change. It became clear that the glacial stages were themselves punctuated by abrupt climate shifts. This kind of ice sheet behaviour could not be detected in the first isotope records from the tropical oceans. Rapid climate change triggered by ice sheet–ocean–atmosphere interactions was now firmly on the agenda. At about the same time that Heinrich Events were discovered in the North Atlantic, new data from the study of Greenland ice cores became available. In a remarkable twist, the ice sheets themselves would soon provide the most finely resolved records of glacial stage climate and shed new light on the causes of ice age climate change.

Chapter 9
Ice cores, abrupt climate shifts, and ecosystem change

> ...ice contains no future, just the past, sealed away...clear and distinct.
>
> Haruki Murakami (1995)

In 1958, at the height of the Cold War, the USA developed a secret plan for a network of mobile nuclear missile launch sites beneath the Greenland ice sheet. It was codenamed Project Iceworm. Feasibility studies, involving experimental ice drilling and tunnelling, took place at Camp Century (77°N) in the northwest corner of Greenland. Sub-glacial living quarters were constructed for 250 personnel. It soon became apparent, however, that the motion of the ice was crushing the tunnels. The project was abandoned in 1966: but not before drilling trials retrieved the first long ice cores from a polar ice sheet. By drilling ice cores and melting the layers of ice for analysis, it is possible to obtain remarkably detailed records of the ice age past.

Willi Dansgaard (1922–2011) (Figure 28) was the first scientist to demonstrate that the ice sheets themselves provided an extended record of Earth's climate history. In the early 1960s, when Nick Shackleton was perfecting the measurement of oxygen isotopes on benthic foram shells in Cambridge, Dansgaard was setting up his own isotope laboratory in Copenhagen, but with very different kinds of samples. Dansgaard was interested in oxygen isotope



28. **(a) Willi Dansgaard in Greenland in 1979 (b) Annual banding in a 1m section of ice core from Greenland from a depth of 1837 to 1838 metres**

ratios in rainfall, snow, and ice. He made the landmark discovery that the oxygen isotope profile in ice cores provided a long-term record of changing air temperature in the Polar regions. He was able to show that as air temperature falls, more molecules of H_2O containing the heavy (oxygen-18) isotope condense and are lost from clouds as rain and snowfall. Thus atmospheric water vapour becomes more and more depleted of ^{18}O in a poleward direction. Dansgaard analysed rainfall samples and temperature data from around the world to test this idea—he even collected samples in beer bottles in his back garden in Copenhagen.

Rapid climate change

In 1966, the Americans obtained a 1,390 m ice core from Camp Century—the first ice core to penetrate the Greenland ice sheet down to bedrock. Greenland ice cores typically have very clear banding (Figure 28b) that corresponds to individual years of snow accumulation. This is because the snow that falls in summer under the permanent Arctic sun differs in texture to the snow that falls in winter. The distinctive paired layers can be counted like tree rings to produce a finely resolved chronology with annual and even seasonal resolution. The section of ice core shown in Figure 28b was produced by snow that fell around 16,250 years ago. Recent work on Greenland ice cores has allowed the end of the Pleistocene epoch and the onset of the Holocene interglacial to be dated very precisely to 11,700 years before AD 2000.

By sampling each layer of ice and measuring its oxygen isotope composition, Dansgaard produced an annual record of air temperature for the last 100,000 years. He had produced the first annual weather report for the last glacial stage. Perhaps the most startling outcome of this work was the demonstration that global climate could change extremely rapidly. Dansgaard showed that dramatic shifts in mean air temperature (>10°C) had taken place in less than a decade. These findings were greeted with scepticism and there was much debate about the integrity of the Greenland record, but subsequent work from other drilling sites vindicated all of Dansgaard's findings.

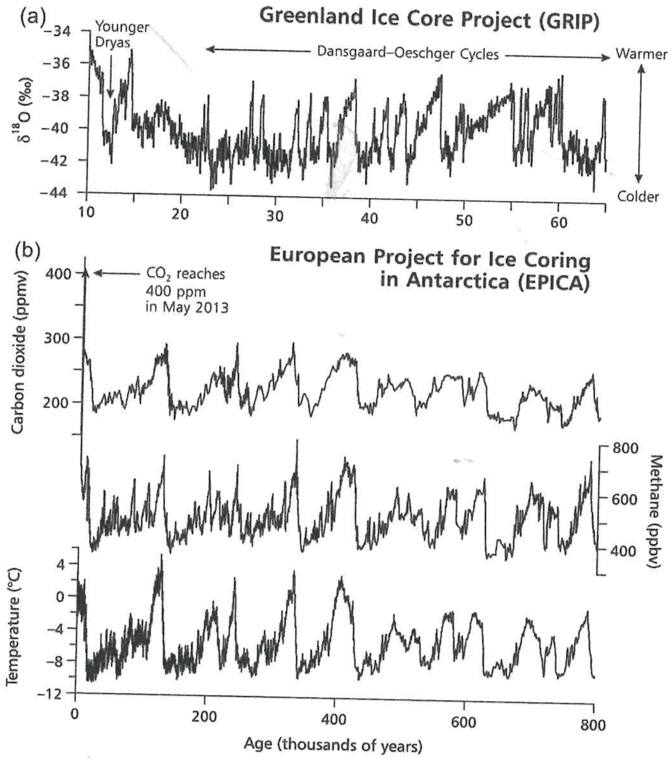
Dansgaard was to ice core research what Shackleton was to the study of marine sediments. It was therefore fitting when, in 1995, the Royal Swedish Academy of Sciences awarded its prestigious Crafoord Prize (widely regarded as the equivalent of a Nobel Prize) jointly to Shackleton and Dansgaard for their work on isotopes in geoscience.

The ice age atmosphere

As layers of snow become compacted into ice, air bubbles recording the composition of the atmosphere are sealed in discrete layers. This fossil air can be recovered to establish the changing concentration of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). The ice core record therefore allows climate scientists to explore the processes involved in climate variability over very long timescales.

A Swiss physicist, Hans Oeschger (1927–98), made fundamental contributions to our understanding of ice age climate change. He pioneered the measurement of greenhouse gases in the bubbles trapped in ancient ice. In his laboratory at the University of Bern, Oeschger analysed many thousands of samples from Greenland and Antarctica. In 1979 his team was the first to show that CO_2 concentrations during glacial stages were almost half those of the present. Oeschger showed that atmospheric CO_2 concentrations were about 180 ppm (parts per million) during glacials, but around 280 ppm during interglacials.

Ice accumulation is generally much slower in Antarctica, so the ice record takes us much further back in time. The lower part of Figure 29 shows an 800,000-year Antarctic ice core record that spans eight glacial–interglacial cycles. This was produced by the European Project for Ice Coring in Antarctica (EPICA). Note how the changes in temperature closely track the changes in methane and CO_2. Methane is a potent greenhouse gas—it is stored in large volumes in the frozen biomass of the permafrost and as methane hydrate within sediments beneath the ocean floor. Ice core data have been fundamental in demonstrating that changes in the composition of the atmosphere played a key role in the shifting climates of the Quaternary, but there is still much debate about the processes involved and the leads and lags. CO_2 exchange between the oceans and atmosphere is the key link between the Milankovitch Cycles and the glacial and interglacial shifts of the



29. (a) Temperature fluctuations in the Greenland ice core record between 65,000 and 10,000 years ago (b) An 800,000-year record of CO_2, methane, and air temperature from Antarctica. Note the different timescales for the Greenland and Antarctic records

Quaternary. A key challenge, however, is to develop a better understanding of the processes that lead to marked shifts in atmospheric greenhouse gases during the course of glacial and interglacial cycles.

The ice age does not give up its secrets easily. Ice coring involves huge logistical challenges—pushing equipment and people to the limit. The Icelandic geophysicist Sigfús Johnsen (1940–2013) designed the specialist ice drilling equipment for the later Greenland projects. Bone chilling temperatures and powerful winds make the elevated interiors (where the ice is thickest) of the polar ice sheets some of the most inhospitable places on Earth. The lowest temperature ever measured at the Earth's surface (−89.2°C) was recorded at the Vostok Station in the middle of the East Antarctic Ice Sheet on 21st July 1983. Vostok also holds the record for the longest ice core. In late 2012, a Russian team drilled 3,768 m to reach Lake Vostok: the largest of the sub-glacial lakes in Antarctica and the third largest lake by volume in the world.

Dansgaard-Oeschger Events

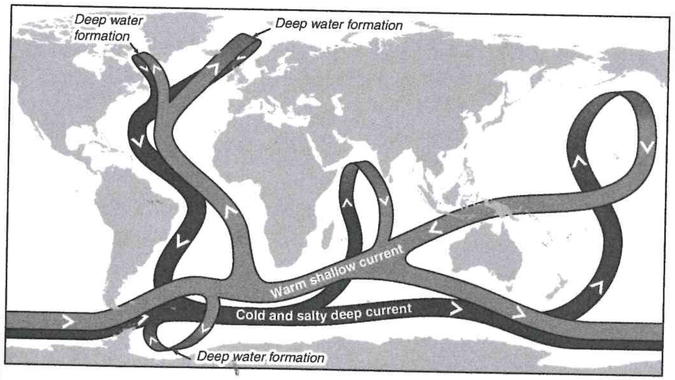
The ice core records from Greenland reveal a remarkable sequence of abrupt warming and cooling cycles *within* the last glacial stage. These are known as Dansgaard-Oeschger (D-O) cycles. The upper part of Figure 29 shows a series of D-O cycles between 65,000 and 10,000 years ago when mean annual air temperatures on the Greenland ice sheet shifted by as much as 10°C. Twenty-five of these rapid warming events have been identified during the last glacial period. This discovery dispelled the long held notion that glacials were lengthy periods of stable and unremitting cold climate. The ice core record shows very clearly that even the glacial climate flipped back and forth.

There has been much discussion about the cause of these D-O cycles and their relationship to the Heinrich Events. Changes in ocean circulation triggered by influxes of freshwater from the continents have been implicated. D-O cycles commence with a very rapid warming (between 5 and 10°C) over Greenland followed by a steady cooling (Figure 29). The most pronounced coolings are associated with Heinrich Events when severe glacial climates with extreme cold and aridity characterized many parts of the northern hemisphere.

The great ocean conveyor

Figure 30 shows the circulation system linking the world's oceans that moves vast quantities of heat around the globe. This circulation includes warm, shallow currents and deeper flows of denser, colder water. It is known as the thermohaline circulation because it is driven by contrasts in water temperature (thermo) and salinity (haline). These properties control the density of seawater. It takes about 1,000 years for a body of water to complete a full cycle. This circulation has been called the great ocean conveyor—it plays a fundamental role regulating global climate.

There are strong thermal gradients in both hemispheres because the low latitudes receive the most solar energy and the poles the least. To redress these imbalances the atmosphere and oceans move heat polewards—this is the basis of the climate system. In the North Atlantic a powerful surface current takes warmth from the tropics to higher latitudes: this is the famous Gulf Stream and its northeastern extension the North Atlantic Drift. Two main forces drive this current: the strong southwesterly winds and the return flow of colder, saltier water known as North Atlantic Deep



30. Ocean currents: the thermohaline circulation

Water (NADW). The surface current loses much of its heat to air masses that give maritime Europe a moist, temperate climate. Evaporative cooling also increases its salinity so that it begins to sink. As the dense and cold water sinks to the deep ocean to form NADW, it exerts a strong pull on the surface currents to maintain the cycle. It returns south at depths >2,000 m.

The Younger Dryas cooling

The thermohaline circulation in the North Atlantic was periodically interrupted during Heinrich Events when vast discharges of melting icebergs cooled the ocean surface and reduced its salinity. This shut down the formation of NADW and suppressed the Gulf Stream. The warming at the time of the last deglaciation also stalled abruptly around 12,800 years ago bringing Arctic conditions back to much of the northern hemisphere for about 1,200 years. This rapid cooling is known as the Younger Dryas after the arctic/alpine evergreen dwarf shrub (*Dryas octopetala*) whose pollen is common in European vegetation records from this period. The mean annual temperature at the summit of the Greenland ice sheet may have been about 15°C colder than present during the Younger Dryas. This cold snap lasted long enough to allow glaciers to advance in many parts of the world. Glaciers reformed in the uplands of Scotland, England, and Wales. Arctic birds, insects, mammals, and fish headed south once again.

Cause of the Younger Dryas cold snap

The Younger Dryas cooling may have been triggered by huge volumes of freshwater flowing into the high latitude North Atlantic from glacier-lake outburst floods. One of the largest glacial lakes formed by the melting Laurentide ice sheet is known as Lake Agassiz. When it emptied catastrophically around 12,800 years ago it created a freshwater cap on the ocean surface that halted the formation of NADW and the Gulf Stream stalled. This cooling

event shows up very clearly in the GRIP ice core record (Figure 29). Many of the ideas about the linkages between ocean circulation and abrupt climate change have been shaped by Wally Broecker of Columbia University's Lamont-Doherty Earth Observatory.

Box 14
Glacial Lake Agassiz

The existence of this great lake was first postulated in 1824 by the American geologist William Keating (1799–1844). It was named Lake Agassiz in 1879, six years after the death of the celebrated Harvard professor who had become the most famous scientist in America. At its maximum extent it was the largest lake on the North American continent (>500,000 km^2) with a volume greater than all of the modern Great Lakes combined. It extended across parts of Manitoba, Saskatchewan, and Ontario in Canada, and North Dakota and Minnesota in the USA. Fed by the wasting Laurentide ice sheet, it rose and fell repeatedly during its 4,500-year existence at the end of the last glacial stage. At times, the present location of Winnipeg was submerged beneath more than 200 m of water. From time to time, rapid outflows produced catastrophic floods and there is currently a lively debate about whether the floodwaters that triggered the Younger Dryas cooling flowed northwards down the Mackenzie River into the Arctic Ocean or directly into the North Atlantic via the St Lawrence.

J Harlen Bretz (1882–1981)

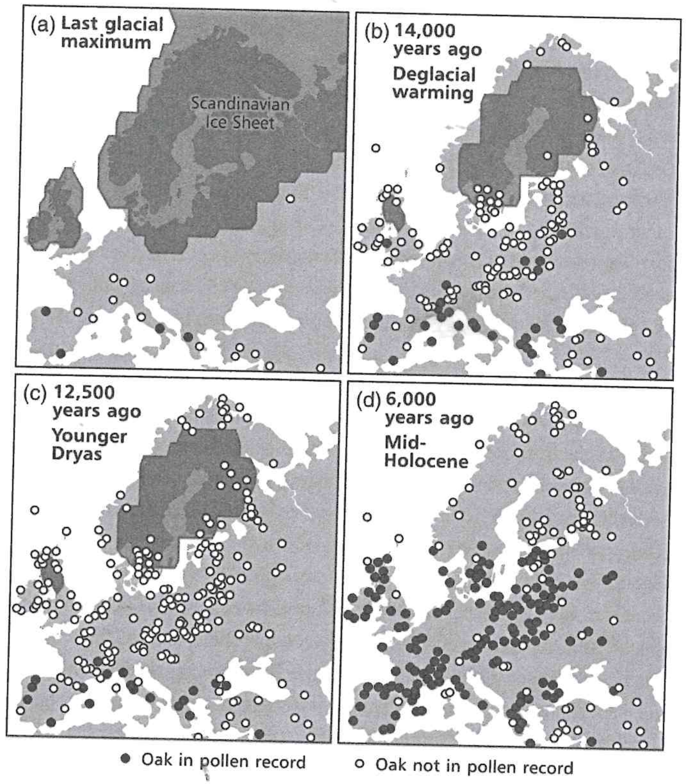
J Harlen Bretz was a geologist who discovered evidence for truly catastrophic floods that took place at the end of the last glacial stage on the Columbia River Plateau in eastern Washington State. Bretz described large-scale erosion features including the enormous basalt canyons of the Columbia River gorge that he named the Channeled Scablands. He published his great flood theory in 1923 exactly 100 years after William Buckland's

Reliquiae Diluvianae. Perhaps this coincidence was not lost on members of the American geological establishment, who were vehemently opposed to what they saw as a new deluge theory. It was Joseph Pardee (1871–1960) of the United States Geological Survey who suggested that the floodwaters originated from Glacial Lake Missoula in western Montana where a southern lobe of the Cordilleran ice sheet created an ice dam over 25 km wide and more than 600 m high. This dam periodically failed, releasing about 2,100 km^3 of raging floodwater—the equivalent of half the volume of today's Lake Michigan. Time and again the Missoula floods swept through the Scablands and on to the Pacific Ocean as the ice dam reformed and failed. Recent research has suggested that there may have been about 40 of these outburst floods at the end of the last glacial stage between c.15,000 and 13,000 years ago. Bretz has been hailed as a pioneer of neocatastrophism: the movement that recognized the importance of very high magnitude events in landscape evolution. His pioneering work on palaeofloods inspired a much later generation to consider catastrophic meltwater discharges as a potential cause of abrupt climate change.

The ice core records heralded a new era in climate science: the study of abrupt climate change. Most sedimentary records of ice age climate change yield relatively low resolution information—a thousand years may be packed into a few centimetres of marine or lake sediment. In contrast, ice cores cover *every* year. They also retain a greater variety of information about the ice age past than any other archive. We can even detect layers of volcanic ash in the ice and pinpoint the date of ancient eruptions. New questions have emerged: how did ecosystems and humans respond to these abrupt changes? Were they regional or global phenomena? What role did they play in the demise of the ice age megafauna?

Late Pleistocene ecosystems and extinctions

Figure 31 illustrates the major ecosystem reorganizations that took place across Europe during the rapid environmental changes of the last glacial to interglacial transition. The maps show the presence or absence of deciduous oak from a large number of vegetation records obtained from sediment cores collected from lakes and peat bogs across the continent. Fossil pollen has been extracted from these cores and counted, layer by layer, to build up a picture of long-term



31. The dispersal of oak across Europe since the Last Glacial Maximum

vegetation change. Four time slices are given: from the Last Glacial Maximum (LGM) to the middle of the present Holocene interglacial. The open circles in central and northern Europe indicate the presence of pioneer species such as birch, juniper, and pine as well as open ground or steppe plants like grasses and sedges. The records have been dated using radiocarbon.

At the LGM the Arctic tundra that fringed the ice sheets was dominated by a landscape of permafrost, frost-shattered rocks, thin soils, and a low vegetation adapted to brief, cold, growing seasons. The upper layer of permafrost thawed in the glacial summer creating shallow wetlands and boggy soils where grasses, mosses, herbs, sedges, and other flowering plants briefly flourished. These shallow-rooting plants clustered together to conserve warmth and resist attack from strong winds and blowing snow. Arctic willow (*Salix arctica*), the northernmost woody plant on Earth, is found in central European pollen records from the last glacial stage. It was an important food source for muskox, mammoth, bison, and arctic hare. Arctic plant communities and permafrost returned to many parts of central Europe during the Younger Dryas cooling. Relics of this flora are found today in the far north and in high mountains.

In the Mediterranean, far to the south of the erosive power of the ice sheets, several lakes are very ancient indeed, with unbroken sedimentary records than span multiple glacial–interglacial cycles. These very long records of vegetation change show Milankovitch cyclicity as well as clear responses to Heinrich and Dansgaard–Oeschger events during the last glacial stage. Deciduous oak is a key indicator of warm and moist interglacial conditions. It is absent from central and northern Europe during glacial stages. At the LGM it is only recorded at sites in the Mediterranean (Figure 31a). Southern Europe contains zones of high biodiversity where species of plants and animals have survived throughout the Quaternary ice age. These zones are called *refugia*: they are crucial for the long-term survival of Europe's forest ecosystems. Oak, along with other temperate

interglacial tree species such as beech, elm, and alder (Figure 4), survived the glacial stages at intermediate elevations in the wetter parts of the Mediterranean mountains.

The lakes and peat bogs of northern Europe formed after the recession of the last ice sheets, so their sediment records are much shorter than those in the south. By 14,000 years ago, a large number of vegetation records are available for central and northern Europe (Figure 31b) because meltwater streams and thawing permafrost produced extensive wetlands where pollen and plant macrofossils were readily preserved. The vegetation records from these settings track the return of pioneer plants as the ice sheets receded. The last deglaciation was well underway by 14,000 years ago and the ice sheets were much reduced in size (Figure 31b). Under a rapidly warming climate, oak had spread northwards from its southern refugia as far as the latitude of northern Germany. By 12,500 years ago, however, in the middle of the Younger Dryas cooling, this expansion had halted—oak is only found south of the Alps at this time (Figure 31c). By the middle of the Holocene, some 6,000 years later, oak had expanded its range as far as southern Scandinavia and a full interglacial flora with mature soils was well established across temperate Europe.

The return of the forests to central and northern Europe at the end of glacial stages is dependent upon migration from southern refugia. If trees fail to survive in the Mediterranean they become extinct. The marine record tells us that glacial periods last for about 80,000 years and interglacials about 15,000 years. For most of the Quaternary deciduous forests have been absent from most of Europe. The D–O warmings were too brief for significant forest expansion to take place. All this means that the interglacial forests of temperate Europe that are so familiar to us today are, in fact, rather atypical when we consider the long view of Quaternary time. Furthermore, if the last glacial period is representative of earlier ones, for much of the Quaternary terrestrial ecosystems were continuously adjusting to a shifting climate.

Box 15
Pleistocene megafauna

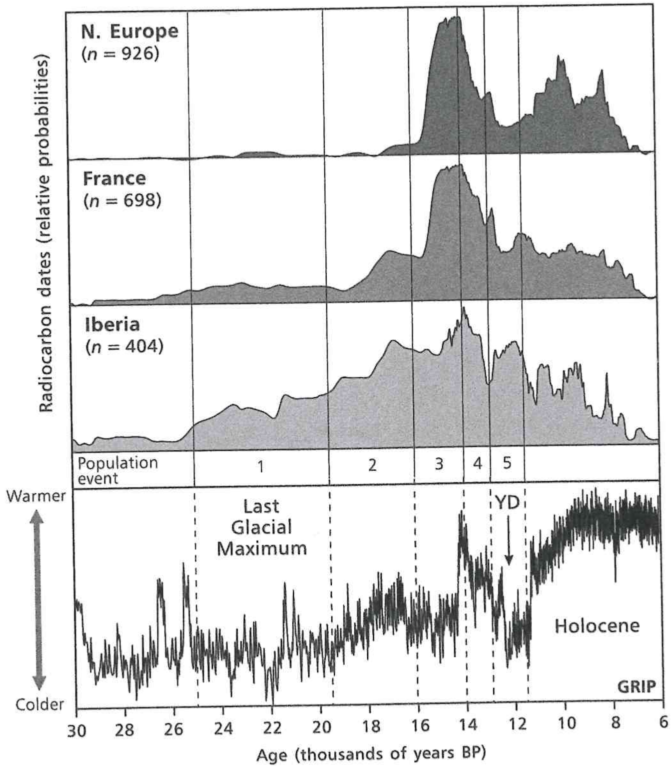
Figure 31b shows how rapidly the vast tundra steppe biome contracted as it was colonized by pioneer woodland species (open circles) at the end of the last glacial period. The close of a glacial was always a stressful time for mammoths and other large mammals in northerly latitudes because their habitats shrank and populations became increasingly fragmented and isolated. The demise of the Pleistocene megafauna (including the mammoth, Irish elk, woolly rhino, and others) is a hotly disputed topic but their extinction cannot be attributed to a single cause. Contrary to earlier ideas that the megafauna died out at roughly the same time at the end of the last glacial, we now know that some of these animals persisted in isolated refugia for several thousand years into the present Holocene interglacial. Populations of mammoth, for example, survived on Wrangel Island in the East Siberian Sea until about 4,000 years ago. They outlived the last mammoths on the Siberian mainland by about 6,000 years. The Irish elk (*Megaloceros giganteus*) persisted in western Siberia until about 7,700 years ago.

Such extinctions are now viewed in terms of prolonged periods of decline rather than abrupt terminations of species by climate change or hunting. The polar bear may well be the next one to go. The latest research is attempting to identify the precise timing and geography of last glacial and Holocene extinction patterns for each species by compiling large databases of radiocarbon-dated fossils. This information is being integrated with genetic data and with high resolution records of vegetation and climate change to better understand the ecology of extinction. A role for human hunters sending isolated populations over the edge of viability cannot be discounted. Indeed, this ice age menagerie had successfully negotiated previous glacial to interglacial transitions. The last one, however, was very different in one key respect: modern humans were present across Europe, Siberia, and North America for the first time.

Humans in the last glacial

The Neanderthals were another casualty of the last glacial period and numerous theories have been advanced to account for their demise. Pinning down the timing of their final disappearance is problematic because many Neanderthal fossils lie close to the limit of radiocarbon dating and this can increase the chances of sample contamination from more recent radiocarbon. Anatomically modern humans (*Homo sapiens*) spread rapidly across Europe between 50,000 and 35,000 years ago from their original homeland in Africa. This placed them in direct competition with Neanderthal groups. The latest research indicates that Neanderthals did not survive much beyond 35,000 years ago. It has been suggested that this new competition and the very severe climatic conditions of Heinrich Event 4 (just after 40,000 years ago; Figure 26c) may have been enough to sink the final nails into the Neanderthal coffin. There are clear parallels here with the megafaunal extinctions: we need more reliable dates and a better understanding of the geography and ecology of the Neanderthal demise.

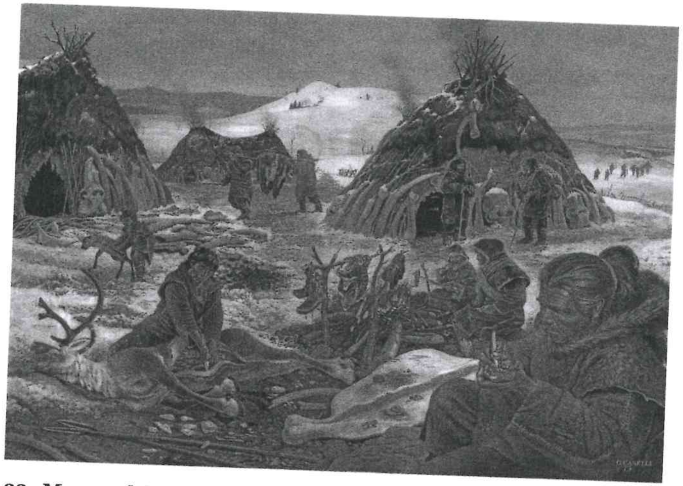
Palaeolithic archaeologist Clive Gamble and colleagues at the University of Southampton have used >2,000 radiocarbon dates from archaeological sites across western Europe as a proxy for ice age population change after the Neanderthal extinction. They have explored population dynamics for modern humans in relation to the Greenland ice core temperature record for the period from 30,000 to 6,000 years ago (Figure 32). This analysis indicates that the dispersal of modern humans across Europe took place within a wide range of climatic tolerances. Whilst southern Europe was an important refuge around the time of the LGM, it also points to tolerance of extreme cold in the northern regions. The number of archaeological sites with reliably dated evidence of human presence increases rapidly in France and northern Europe between 16,000 and 14,000 years ago. The Younger Dryas event



32. Ice age population dynamics in Europe

sees a decline in these regions at this time but an increase in Iberia. This novel approach to the study of humans in the ice age is based on several assumptions and there are issues surrounding the differential preservation of archaeological sites, but it does allow us to view the big picture of social change and human–environment interaction at a continental scale.

Modern humans were able to develop very effective strategies to seek out resources and cope with extreme cold in the barren



33. Mammoth hunters in the last glacial period

tundra biomes of ice age Europe, Asia, and North America. Heinrich Events would have posed especially harsh challenges in the northern regions. Figure 33 shows a group of mammoth hunters—it is a faithful reconstruction by Giovanni Caselli based on archaeological data from the Upper Palaeolithic site of Dolní Věstonice in the Czech Republic. This wonderful image captures the social complexity, sophisticated division of labour, and inventive use of resources that was needed for humans to thrive in the rapidly shifting environments of the last glacial period.

Epilogue

The history of ice age research reveals a good deal about the history of geology and the changes that have taken place in the way we think about the Earth. Lyell's uniformitarian straitjacket was loosened in the second half of the 20th century so that most geologists now take the view that Earth history involved extended periods of gradual change punctuated by infrequent catastrophic events. The last glacial stage was an especially eventful period—great floods and floating ice are very much back on the agenda.

The modern era of debating climate change can be traced back to the discovery of the Adams Mammoth in 1799. But the discourse of the early and mid-19th century was dominated by those who denied the existence of climate change in the recent geological past. The context, of course, was very different from today but powerful individuals with vested interests made their voices heard. The case for the glacial theory and ice age climate change succeeded because its advocates presented a huge body of irrefutable evidence. Winning this argument took the best part of 60 years.

A view then emerged in the last century that glacials were few in number and Quaternary climate change was a slow process paced over many thousands of years. Even for the glacial–interglacial

cycles of the Quaternary, there was nothing to suggest that anything other than a sensible uniformitarian notion of gradual change was needed. These ideas were crushed by the marine and ice core records. The traditional view of grand climate rhythms with smooth, orderly transitions from warm to cold and back again was no longer tenable.

If big bones and boulder clay were the staples of 19th-century ice age research, microfossils and isotopes came to dominate the next, and the scale of analysis went global. The Milankovitch revival and the development of scientific methods of dating stand out as key advances. Modern Quaternary science involves many disciplines and a bewildering array of approaches to retrieve information about the past. The woolly mammoth is now the first extinct mammal to have its DNA sequence decoded. Hair from the Adams Mammoth has been used to retrieve a complete mitochondrial genome along with DNA sequences from the nuclear genome. There is currently much excited speculation about cloning the mammoth but much less critical reflection on the whereabouts of a viable long-term habitat for this ice age beast.

The Quaternary is a unique natural laboratory with a remarkable variety of exceptionally well preserved records. This invites us to ask fundamental questions about the natural world and how its components interact at global, regional, and local scales. These records also provide a meeting place for geology and archaeology. Key chapters in the story of human evolution and dispersal took place during the shifting environments of the Quaternary ice age. We now know that ice age ecosystems were rapidly and repeatedly transformed as plants, animals, and humans reorganized their worlds.

The ice cores yielded stunning datasets that forced all disciplines to rethink their understanding of ice age change. A new tier of climate variability was revealed. The Heinrich layers in the North

Atlantic demonstrated the connections between ice sheets, oceans, and atmosphere: icebergs could change the climate. It became clear that the climate system is finely tuned and prone to abrupt change. A new agenda was forged—not only for all aspects of ice age research, but for global climate science. In many respects the scientific community and its climate modellers are still coming to terms with the reality of rapid climate change. The search for the underlying causes and key feedback processes is still very much in progress.

Hans Oeschger was one of the first scientists to warn of the dangers of an enhanced greenhouse effect driven by anthropogenic increases in carbon dioxide (CO_2). It would be impossible to overstate how deeply this work has penetrated the mainstream of present-day debate. As one of the lead authors of the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Oeschger made the bold leap from ice core science to global climate policy. Because continuous measurements of atmospheric CO_2 from the Mauna Loa Observatory in Hawaii only go back to 1958, it was the ice core records for the last few centuries that first showed the striking rise in greenhouse gases following the Industrial Revolution. The ice core data allowed climate scientists to place recent trends in long-term context. These trends are, quite literally, off the Quaternary scale. The baseline CO_2 value for interglacials is *c.*280 parts per million (ppm). On 9th May 2013 the concentration of atmospheric CO_2 exceeded 400 ppm for the first time since the balmy conditions of the Pliocene when sea level was more than 20 m higher than today.

We still need to better understand the processes involved in rapid climate warming—especially the interactions between ice, oceans, and atmosphere. A deeper understanding of the interactions between landscapes, ecosystems, and shifting climates is also needed. Paradoxically, in an era of warming climate, the study of the ice age past is now more important than ever.

Publisher's acknowledgements

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Chapter 1: The Quaternary ice age

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Time it does not matter
But time is all we have
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Chapter 3: Monster glaciers

...it seemed as if Nature was stepping out of its normal course, and the glaciers expanded rapidly...
Bernhard Friedrich Kuhn (1787)

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Some useful websites

Keith Montgomery at the University of Wisconsin (Marathon County) maintains an excellent series of web resources entitled: 'Debating Glacial Theory 1800–1870': <http://www1.umn.edu/ships/glaciers/

Earthguide is part of the Geosciences Research Division at Scripps Institution of Oceanography in California. The following website contains links to a rich assortment of ice age materials:
<http://earthguide.ucsd.edu/>

In 2008, the Linda Hall Library in Kansas City, Missouri, held an exhibition of rare books and journals entitled 'Ice: A Victorian Romance'. It documented the 19th-century exploration of the polar world and the origins of the glacial theory:
<http://www.lindahall.org/events_exhib/exhibit/exhibits/ice/index.shtml>

Portraits of key figures in the development of British geology can be found in *The Oxford Dictionary of National Biography*:
<http://www.oxforddnb.com/>

Most researchers who delve into the Quaternary ice age are affiliated to the International Union for Quaternary Research (INQUA):
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Further reading

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