# EARTH AND OCEAN SCIENCES 112

## THE ORIGIN OF THE ICE AGES

### USEFUL REFERENCES:

Covey, C. (1984). Earth's orbit and the ice ages. Scientific American, 250, p.58.
Croll, James (1875). Climate and Time in Their Geological Relations: A Theory of Secular Changes in the Earth's Climate. Appleton and Co., New York. (Available to view in UBC Library by special arrangement)
Imbrie, J. and K.P. Imbrie (1979). Ice Ages: Solving the Mystery. Enslow Publishers, 224 pp.

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### INTRODUCTION:

Between about 75,000 and 18,000 years ago, glacial ice spread from centres near Hudson Bay and eventually buried all of eastern Canada, New England and much of the North American midwest under a sheet of ice, known as the **Laurentide Ice Sheet**, that averaged two kilometres in thickness. At the same time, a second ice sheet, the **Cordilleran**, spread out from centres in the Canadian Rockies and other highlands in western North America to engulf parts of Alaska, all of western Canada, and parts of Washington, Idaho, and Montana. Along the west coast of North America, only the southern Queen Charlotte Islands remained ice free. During this same period, known in North America as the **Wisconsin Ice Age**, much of Siberia and northern Europe was also covered with ice. How is it that the earth could have been plunged into such a period of prolonged cold? Indeed, why have such episodes occupied the *great majority* of the last 2.5 million years? Why did the Wisconsin glacial event end, and the great ice sheets melt away between 19,000 and about 8,000 years ago? Although many questions remain, these major queries have been answered recently, and the explanation is the result of one of the greatest pieces of geological, astronomical and oceanographic detective work seen in the last two centuries.

### HISTORICAL PERSPECTIVE:

By the eighteenth century, geologists explained the blanket of moraines and unsorted, unstratified boulder-bearing sediments which covers much of northern Europe as being the expression of the great flood described in the Bible. But how could floodwaters possibly have transported boulders, sometimes as big as a house, hundreds of kilometres from their source area? On July 24, 1837, **Jean Louis Agassiz** presented a revolutionary and indeed, heretical, paper at the annual meeting of the Swiss Society of Natural Sciences in Neuchatel, and unwittingly precipitated one of the most violent disputes in the history of geology. Agassiz boldly and simply suggested that the abundant scratched and faceted boulders in the Jura mountains of the Swiss Alps, which were composed of rock types found only at distant locations, had been transported to the present sites by moving glaciers. Agassiz was not the first to make this suggestion - it had been advanced as early as 1787 by Bernard Kuhn, a Swiss minister, and seven years later by **James Hutton**, the famous Scottish geologist and author of the landmark book "Theory of the Earth", published in 1795. Agassiz's paper heralded a new age, however, as it launched the previously obscure glacial theory into the public eye.

Over the next few decades, it became clear that there had been multiple episodes of glaciation. Just how many was hard to determine because each glacial advance largely removed the evidence of the pre-existing events. In 1842, **Joseph Adhemar**, a French mathematician, suggested in a book entitled "Revolutions de la Mer" that the prime mover of the ice ages might be variations in the mode of movement of the earth about the sun. Adhemar concentrated on the effect of cyclical changes in the direction in space of the earth's axis, a phenomenon termed **axial precession,** and surmised that long-term changes in the relative length of the seasons in the northern and southern hemispheres would promote a glacial climate in whichever hemisphere had the longest winter, and therefore the coldest average temperature. Although Adhemar was headed along the right track, his reasoning was faulty, as Alexander von Humboldt pointed out in 1852 - one hemisphere could not heat up while the other cooled down because the annual total number of calories received by each hemisphere was the same. A long cold winter is counterbalanced by a short, but hotter, summer. The mechanics of precession are described in more detail below.

In the spring of 1864, a Scot named **James Croll** came across Adhemar's book and, although he realized that there were errors in the mathematician's approach, he became convinced that some astronomical mechanism was responsible for the ice ages. Croll was a deeply philosopical, self-taught "naturalist" who earned a living in various successive professions including millwright, carpenter, shopkeeper, and life insurance salesman! Although he had had to leave school at age 13 to help support his mother, and despite his unsettled career path, he was very inquisitive and an original thinker, and he used every spare moment to teach himself mathematics, mechanics, and philosophy. He began to publish widely on a range of topics, including circulation in the oceans - indeed, the debates that raged between Croll and the Irish scientist, William Carpenter, about the motive forces for deep-sea circulation are legion in the scientific literature of the 1860's through the

1880's. In 1867, Croll was offered a position at the Geological Survey of Scotland in Edinburgh, and in 1875, he published a remarkable book entitled "Climate and Time...", in which he outlined in detail his extensions of Adhemar's ideas. Using calculations of orbital variations published by the French astronomer Leverrier in 1855, Croll reasoned that periodic glaciations on earth are controlled by changes in the eccentricity of the earth's orbit around the sun, in addition to variations in precession. Eccentricity is the degree to which the orbit, which is slightly elliptical, deviates from being circular; variations thus affect the absolute amount of sunlight reaching the surface of the planet at a given time. Croll also noted that changes in the obliquity (tilt of the earth's axis) over time would redistribute solar radiation on the globe, but because Leverrier had not determined the timing of the changes in tilt, Croll was unable to relate them directly to his periodicity arguments. Simply summarized, Croll's idea was that decreased solar radiation would foster a colder earth alternately in one hemisphere or the other (Fig. 1) and promote the growth of ice sheets at the appropriate high northern or southern latitudes. Croll's theory created a profound impression in the world of science for, at last, here was a plausible explanation for the origin of the ice ages. For his many and varied contributions, James Croll was made a Fellow of the Royal Society of London in 1876. The great thinker died at age 69, in 1890, shortly after publishing a small book on yet another topic entitled, "The Philosophical Basis of Evolution".

Croll's ideas were debated intensely during the latter part of the 19th century, as the search for geological confirmation of the astronomical theory intensified. Criticism gradually grew as it was realized that the present interglacial must have commenced relatively recently, and not about 80,000 years ago as calculated by Croll (Fig. 1). By the mid-1890's, most North American scientists disbelieved the Croll theory, largely because it became clear that rivers which flowed atop deposits of glacial drift could not have occupied their channels for much more that 6,000 to 10,000 years, based on observed rates of erosion. In Europe too, evidence mounted that the last ice age had ended not 80 kyr ago, but much nearer 10 kyr before the present. Meteorologists also calculated that the variations in solar heating described by Croll were far too small to have much effect on climate. By the end of the century, the astronomical theory had largely been discarded as a geological curiosity.

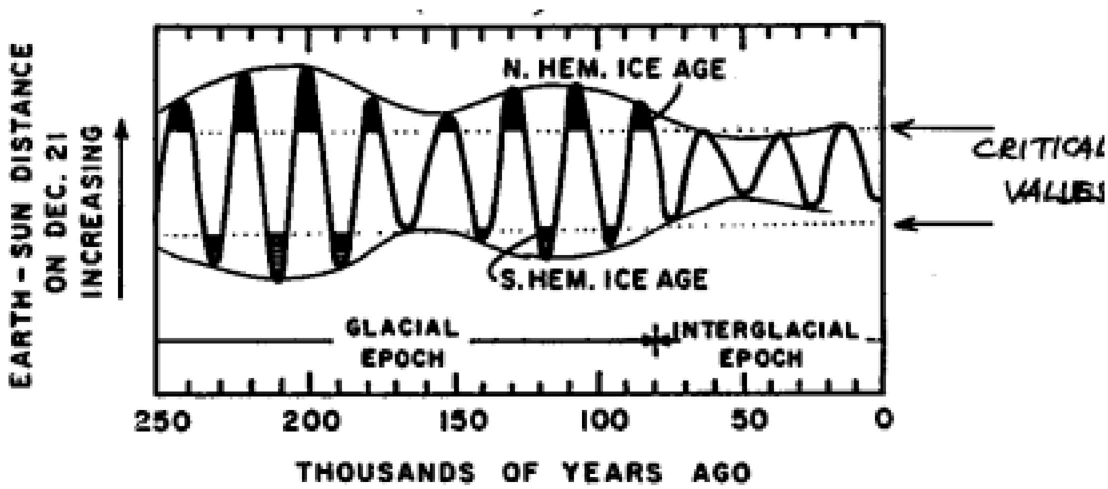


***Figure 1****. James Croll's theory of the ice ages. He believed that glacial periods are caused by changes in the distance between the earth and the sun, as measured on the first day of winter. When this distance exceeds a critical value, winters in the northern hemisphere are cold enough to trigger an ice age; when the distance is less than a critical value, an ice age occurs in the southern hemisphere. According to Croll, orbital eccentricity is so large during glacial epochs that the critical limits are often exceeded (after Imbrie and Imbrie, 1979).*

Some twenty years after Croll's death, a young Serbo-Croatian mathematician at the University of Belgrade named **Milutin Milankovitch** decided to develop a mathematical theory capable of describing the history and future of earth's climate. This was an extraordinary task, and it was to consume Milankovitch for the next thirty years. He began by calculating how solar radiation is distributed over the earth's surface in response to changes in the tilt of the axis, eccentricity and the precession of the equinoxes. **Obliquity or tilt** (the angle between the axis and the normal to the ecliptic, i.e. the orbital plane described by the earth's revolution about the sun) ranges between 22.1 and 24.5° with a period of **41,000** years. At present, the tilt is 23.5°. The degree to which the orbit is elliptical (the eccentricity) is defined as the percentage ratio of the distance between the two foci of the ellipse to the length of the long axis of the ellipse. The earth's orbit is never far from being circular but over the course of one full **103,000** year long cycle, eccentricity does vary from a low of near zero to a high of about six per cent. The precession of the equinoxes has two periods, **19,000** and **24,000** years, which represent a complicated response to cyclical changes in the direction of the axis in space. In order to explain this effect, a digression is in order.

**DIGRESSION: The effect of axial precession**
(summarized from Imbrie and Imbrie, 1979):

Seasons occur because on short time scales the orientation of the earth's axis remains fixed in space as the earth revolves about the sun. When the North Pole points away from the sun, the northern hemisphere is in winter, and when it points toward the sun, summer prevails. At present, the earth is closest to the sun (the point in its path known as perihelion) on about January 3 and farthest (aphelion) on or about July 4 (see Fig. 11-6 in the text). The earth-sun distance at aphelion is 5 x $10^6$ km greater than at perihelion.

Each season starts at a particular point in the orbit called a cardinal point - the earth reaches these points on or about Dec. 21, Mar. 20, Jun. 21, and Sept. 22. The earth is tipped farthest away from the sun on about Dec. 21 (the winter solstice), which makes it the shortest day of the year in the northern hemisphere and also marks the beginning of the northern hemisphere winter. Six months later, on the first day of summer, the North Pole is tipped maximally toward the sun, making June 21(the summer solstice) the longest day of the year in the northern hemisphere. Twice each year, on March 20 or so and about September 22, the north and south pole are exactly the same distance from the sun. These dates are respectively the vernal and the autumnal equinoxes (from the Greek for "equal nights") when every point on the globe receives equal amounts of daylight and darkness.

A pair of lines drawn between the two solstices and the two equinoxes intersects in a cross at the sun (Fig. 2). The short arm of the cross divides the orbit into two parts of unequal length: at the present time, the distance travelled by the earth between the autumnal and vernal equinoxes (about September 22 and March 20, respectively) is shorter than the arc travelled during the remainder of the year, and the time required for this journey is shorter by several days. Thus, the warm spring and summer seasons are slightly longer in the northern hemisphere than the cool seasons. This contrast in the relative length of the seasons changes with time, however. Because the earth's axis is changing direction in space (precessing) as it carves a circular path with time, the cardinal point on the orbit where the earth is tilted farthest from the sun gradually moves. If the location of the cardinal point representing the winter solstice is compared from one year to the next, by the time the earth has returned to last year's winter solstice point, the axis has very slightly changed its direction in space, so that the point on the orbit at which the axis is now farthest from the sun (marking the first day of winter in the northern hemisphere) is very slightly different than it was the year before. Thus, over thousands of years, the point on the orbital path where the winter solstice occurs steadily migrates. Indeed, all four cardinal points move slowly around the orbital path in this fashion (clockwise if looking down on the North Pole), as shown in Figure 2.

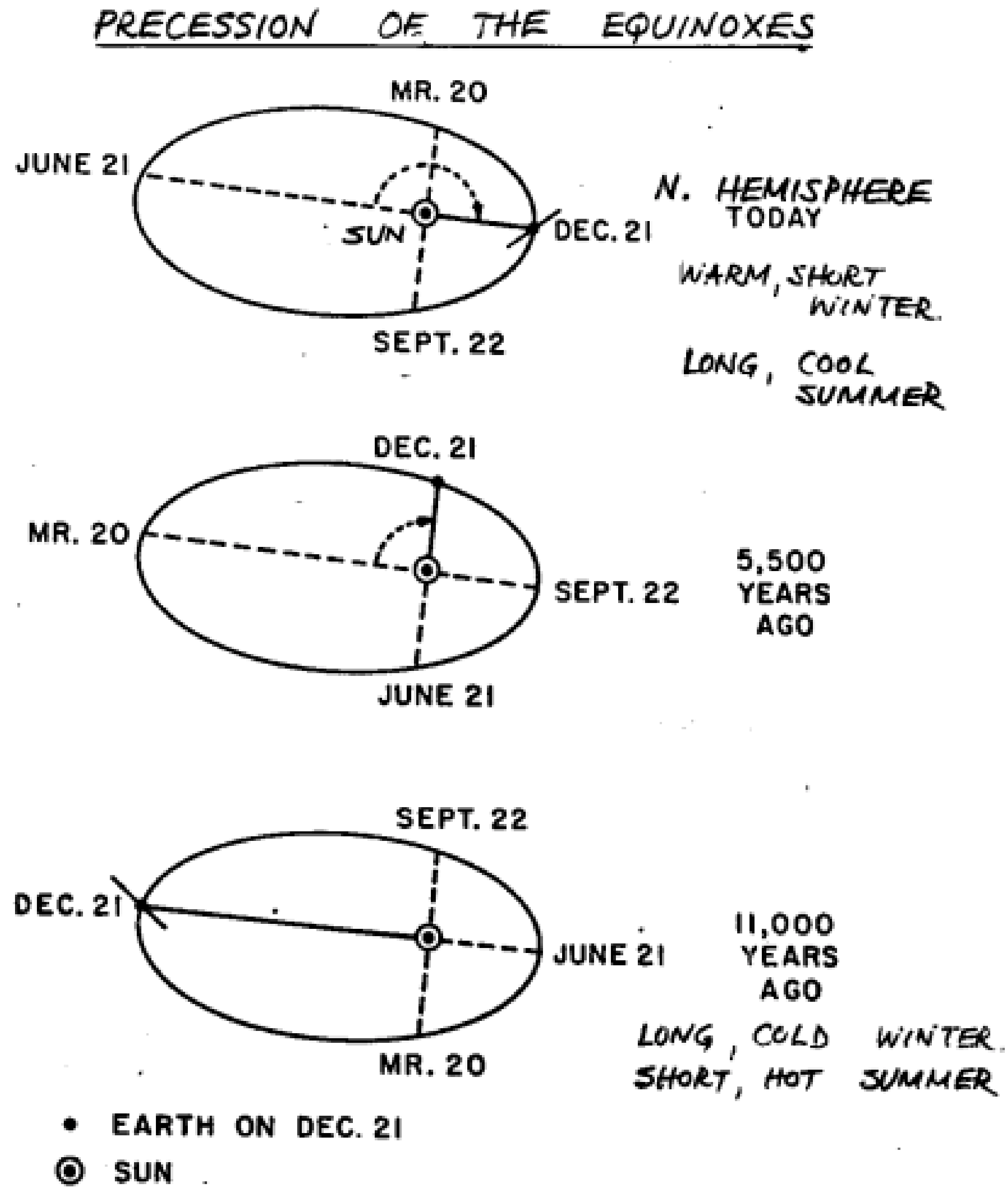


***Figure 2**. The precession of the equinoxes. Owing to axial precession and the rotation (precession) of the ellipse, the positions of equinox (about March 20 and Sept. 22) and solstice (June 21 and December 21) shift slowly around the perimeter of the orbit, completing one full cycle about every 22,000 years. Eleven thousand years ago, the winter solstice occurred near one end of the orbit, but today*

*occurs at the opposite end. As a result of this migration we have today relatively short, warm winters in the northern hemisphere and relatively long, cool summers.11,000 years ago, the precession effect would have yielded relatively long, cold northern hemisphere winters and short, hot summers.*

Because the orbital path is elliptical rather than circular, the distance the earth travels between equinoxes varies with time as the cardinal points migrate. Today the northern hemisphere warm seasons are slightly longer than the colder autumn and winter; 11,000 years ago the opposite was true (see Figure 2). This is the principal manifestation of the precession of the equinoxes - the relative length of the seasons varies cyclically with time. The effect is further complicated by the fact that the ellipse also rotates slowly and independently. This is not shown in Figure 2 in the interests of maintaining simplicity, but the very slow counterclockwise rotation of the ellipse modulates the precession effect. The net result of these different motions is that the relative length of the seasons varies with two periods rather than one: 19,000 and 24,000 years. The precession effect is often reported as a precession index, which is a relative measure of the earth-sun distance at the winter solstice (i.e. on or about Dec. 21).

Milankovitch used the obliquity, eccentricity, and precession periodicities to calculate the distribution of insolation (solar radiation) on earth as a function of time. Such calculations took an incredibly long time in the days before computers, but he persisted and eventually published a series of insolation curves for various latitudes in each season. The next step required facing a critical question - at what latitude and during what season was the received insolation most likely to foster the growth of ice sheets? Following a suggestion by the famous German climatologist Wladimir Köppen, Milankovitch decided that the critical factor was the diminution of heat during the summer half-year. Köppen noted that changes in winter radiation could hardly have any effect on the annual snow budget because temperatures in Arctic regions are cold enough for snow to accumulate even in modern times. During the summer, however, modern snow cover melts at high latitudes. Thus, a decrease in summertime insolation at the high latitudes would inhibit melting of the previous winter's accumulation of snow, and could lead to glacial expansion. The increased albedo (reflectivity) of the white snow cover would act as a positive feedback and further enhance summertime cooling. A key realization here is that it is the insolation at high latitudes in the **northern** hemisphere that is important because most of the land that can support expanded ice accumulation is in this hemisphere - at high southern latitudes there is little land other than the relatively small Antarctic continent.

A modern computer-generated insolation curve for 65°N latitude in June is shown in Figure 11-9 in the text (uppermost panel). This is nearly identical to the type of curves that Milankovitch produced by hand calculation. The theory of orbital control of the ice ages, now known as the **Croll-Milankovitch Theory**, would predict that at times of northern hemisphere insolation minima, growth of ice sheets should occur, although with some lag, since as Milankovitch and subsequent investigators realized, such expansion could not be instantaneous. Note that the curve shown in Figure 11-9 is the resultant of four periods, 100 kyr (the eccentricity cycle), 41 kyr (the obliquity cycle), and ~24 and ~19 kyr (the precession of the equinoxes).

Milankovitch's reestablishment of a controlling astronomical influence on glacial-interglacial cycling was lauded into the early 1950's. However, a new development in 1951 was to provide a major setback to the theory. Willard Libby developed the technique of radiocarbon dating during the late 1940's at the University of Chicago, and it became generally available to the geological community in 1951. Large numbers of radiocarbon dates made on organic remains recovered from glacial deposits over the next several years suggested that there had been multiple advances of ice sheets over the last several tens of thousands of years. This result conflicted with the Milankovitch curves, which defined only two insolation minima during the last 100,000 years. Thus, the astronomical theory gradually fell out of favour, and by 1965 it had lost most of its supporters. The conflict between the terrestrial record of ice advances provided by $^{14}C$ dating and the astronomical theory arose to a large extent because of limited, and in many cases poor, information. This is because the land-based clues were very patchy in time - succeeding episodes of ice sheet growth destroy or distort previously-deposited evidence.

The phoenix was to rise from the ashes once more, however, when new evidence for the cyclicity of glaciations was obtained from the record held in deep-sea sediments. What was badly needed to test the Croll-Milankovitch Theory properly was a continuous record of changes in the amount of ice on the continents over the last several hundred thousand years. Fortunately, the oceans contain recording secretaries that have kept an accurate tally of the global ice volume through time. The secretaries are the humble foraminifera and oxygen isotopes.

## OXYGEN ISOTOPES AND ICE VOLUME

There are two principal stable isotopes of oxygen, $^{16}O$ and $^{18}O$, only 0.2% of which is the heavy isotope. When water evaporates from the ocean, molecules containing the light isotope evaporate preferentially because the vapour pressure of $H_2{}^{16}O$ is higher than that of $H_2{}^{18}O$. At equilibrium, the ratio of $^{18}O/^{16}O$ in the water vapour is less by about 10 parts per thousand than the ratio in the source water from which it evaporated. As the air masses carrying the water vapour cool as they move through the atmosphere, isotopically heavy water (i.e. $^{18}O$ enriched) condenses preferentially and precipitates out - this reflects the lower vapour pressure of $H_2{}^{18}O$. The remaining water vapour thus becomes increasingly depleted in $^{18}O$ - i.e. it becomes isotopically lighter. Thus, rain or snow falling at high latitudes far from the point where the water vapour initially evaporated typically has an $^{18}O/^{16}O$ ratio some 30 to 50 parts per thousand less than the ratio in mean ocean water.

During a glacial period, more of the isotopically-light precipitation which falls on the continents remains as ice rather than returning to the sea as surface runoff. Not only does sea level fall in response, but the $^{18}O/^{16}O$ ratio of the water remaining in the ocean rises. During the last glacial maximum, for example, the ocean was enriched in $^{18}O$ by 1.2 per mille. The per mille notation, known as the **delta notation**, is a convenient way to report isotopic compositions relative to a standard, and is defined by the following equation:

$$\delta^{18}O = \frac{[(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}]}{(^{18}O/^{16}O)_{standard}} \times 1000$$

Thus, glacial periods are characterized by increases in the $^{18}O$ content of the oceans. As the ice sheets waxed and waned in the past, the $\delta^{18}O$ of seawater must have risen and fallen in parallel. Fortunately, we have an excellent history of such variations because foraminifera growing in the sea secrete their calcium carbonate skeletons in near isotopic equilibrium with the water in which they are growing. Therefore, it is possible to derive a detailed history of ice volume changes on the planet in the past (certainly over the last 2.5 million years) by picking foram shells from deep-sea cores and measuring the $^{18}O$ content of the calcite by mass spectrometry. This method works so well because dissolved inorganic carbon species in seawater readily exchange oxygen atoms with water molecules – oxygen atoms in the $CO_3^{2-}$ ions used by forams to make their calcite are always in isotopic equilibrium with the $^{18}O$ in seawater.

One complication with measuring ice volume in this way is that the extent of incorporation of $^{18}O$ in calcite shells is sensitive to temperature. At low temperatures there is some discrimination in favour of $^{18}O$ incorporation; this fractionation decreases in importance at higher temperatures. The problem is that if surface water temperatures varied in response to glacial-interglacial cycles, then the $\delta^{18}O$ record given by planktonic foraminifera preserved in deep-sea cores will include a temperature signal in addition to the ice volume signal. One way to get around this is to analyse benthic foraminifera, the rationale being that the deep ocean is always cold, and therefore the temperature could not have decreased much during a glacial period. Thus, any variation in the $\delta^{18}O$ of benthic forams can be attributed mostly to changes in global ice volume.

A typical profile of $\delta^{18}O$ in foraminifera deposited in deep-sea sediments over the last half million years is shown in Fig. 11-9 in the text (lowermost panel). The cycles represent periodic variations in continental ice volume. Note that five major glaciations, about one every 100,000 years, have occurred on earth during this period. In order to use such records to assess the veracity of the Croll-Milankovitch Theory, it is critical to have a well-constrained time scale. In the original test of the theory less than 30 years ago, the time scale was provided by choosing a core from the Indian Ocean which included the last major reversal of the earth's magnetic field, known to have occurred 780,000 years ago. The age of this important event was originally determined by using the potassium-argon method to date successive terrestrial lava flows, which respectively were reversely and normally magnetized relative to today's magnetic field.  The 780 kyr reversal is readily detectable in deep-sea cores which are long enough to extend back to that point in history. The Indian Ocean core was also dated in the upper part by $^{14}C$ measurements made on the carbonate fraction. Because the half-life of $^{14}C$ is relatively short, however, the radiocarbon method is only useful for dating sediments deposited within the last 40 or 45 kyr. Isotopic analysis of foraminifera from the core revealed the same type of cycles shown in the lowermost panel of text Figure 11-9.

Time series measurements of the type shown in Fig. 11-9 suggest that multiple cyclicities of different frequencies are embedded in the data. Such series can be deconvolved into their constituent cycles using Fourier transform techniques (spectral analyses). This is illustrated in Figure 11-9.

When the component  frequency of the oxygen isotope cycles shown in Figure 11-9 were determined using spectral analysis, it became apparent that four major periods were recorded by the $^{18}O$ profile (Fig. 3): 100 kyr, 41 kyr, 24 kyr and 19 kyr. These are almost exactly the "Milankovitch" frequencies! Thus, about 100 years after Croll published "Climate and Time..." and 50 years after Milankovitch had collaborated with Köppen, the astronomical theory was confirmed. As Imbrie and Imbrie (1979) point out, much remains to be learned. We do not yet know the exact mechanism(s) by which changes in insolation trigger glaciations or deglaciations. It is clear that although insolation changes are the pacemaker of earth's climate, there are myriads of internal feedbacks, many of which are modulated by various response times, and many of which are poorly understood. Hypotheses abound, however, and the area remains one of intense research.

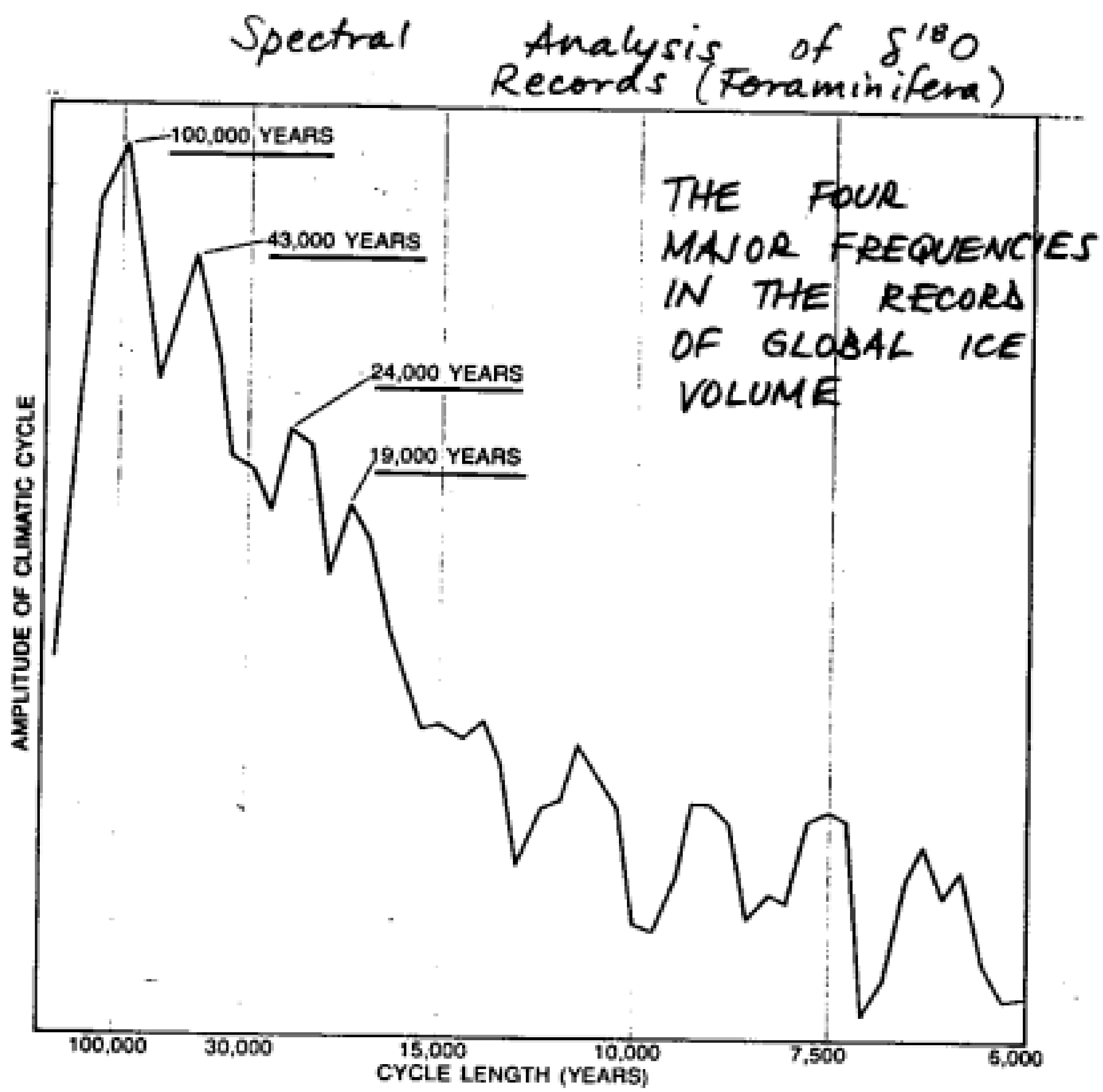


***Figure 3.*** *Results of spectral analysis of a well-dated, benthic-foram oxygen-isotope record. The four principal Milankovitch frequencies are clearly represented. The 100 kyr cycle has the largest amplitude, despite the fact that eccentricity has only a minor effect on insolation. The reason for dominance of the 100 kyr cycle is not entirely clear, but it may reflect a natural frequency in the operation of the earth's climate which is "paced" by the orbital variations.*

Two questions remain. First, why is it that ice ages have been common during the last 2.5 million years but were absent for the previous 240 Ma? The answer appears to be related to continental drift. The earth has cooled steadily since the Cretaceous period ended 65 million years ago. About 3 million years ago, the

Isthmus of Panama formed when a volcanic arc drifted eastward from the Pacific and became welded into the opening between northwestern South America and the southern extremity of what was then Central America. This blocked the flow of warm Atlantic equatorial waters into the Pacific and would have diverted the flow northward, probably strengthening the Gulf Stream. The increased delivery of warm water to the North Atlantic is thought to have promoted the accumulation of ice sheets on the continents at high latitudes. Although this seems paradoxical, it simply reflects the fact that the major limitation on the rate of accumulation of snow and ice in the continental interiors at high latitudes is lack of precipitation, not temperature. Enhanced evaporation from a slightly warmer ocean at high latitudes therefore would increase the precipitation rate and allow ice sheets to grow in the continental interiors, given otherwise favourable conditions such as low summertime insolation.

Second, why do ice ages end rather suddenly (as can be seen in the ice volume record shown in Figure 11-9 in the text) after building to a maximum so gradually? The answer to this question is not clear, but a major influence appears to be changes in the $CO_2$ concentration in the atmosphere which are remarkably well correlated with ice volume variations. In 1987 an extraordinary data set was published in Nature (Barnola et al., Nature 329, pp. 408-414) which showed that the $CO_2$ content of the atmosphere has varied cyclically over the last 160,000 years in close sympathy with high southern-latitude temperature. In 1999, these data were expanded to span the last 420,000 years (Figure 4). These data were obtained by collecting glacial ice samples from drill core collected continuously from a 3,400 m deep hole bored by the Russians through the Antarctic Ice Cap at Vostok Station, not far from the South Pole (incidentally, the Guiness Book of Records lists this as the coldest place on earth - the **mean** annual temperature is -55.5°C!). The ice was melted under vacuum in a laboratory in France, which released air bubbles originally trapped when the ice first formed. The $CO_2$ content of the air samples was then measured by gas chromatography, yielding the detailed long-term record shown in the figure. Note that the relative temperature data shown in Fig. 4 were determined by measuring the deuterium ($^2H$, or D. also known as heavy hydrogen) concentration in the water from the melted ice samples collected from the Vostok site. High deuterium/hydrogen (D/H) ratios in water reflect condensation of water vapour at relatively high temperatures whereas low (i.e. more negative) D/H ratios indicate a lower temperature of condensation. The magnitude of the isotopic fractionation is essentially proportional to temperature change.

The temperature change and $CO_2$ concentration profiles in Figure 4 show that high carbon dioxide concentrations are associated with relatively warm conditions and vice versa. Note that the changes in both variables are sudden at the terminations of both the Wisconsin glaciation, about 15,000 years ago, and the previous glacial about 140,000 years ago. Because $CO_2$ is an effective greenhouse gas, the implication of these data is that the increases of the carbon dioxide concentration seen at the glacial termini may have promoted rapid ice retreat via a deglacial greenhouse warming effect which would have provided a positive feedback to astronomically-induced warming.  Similarly, low $CO_2$ levels during glacials would have reinforced global cooling.

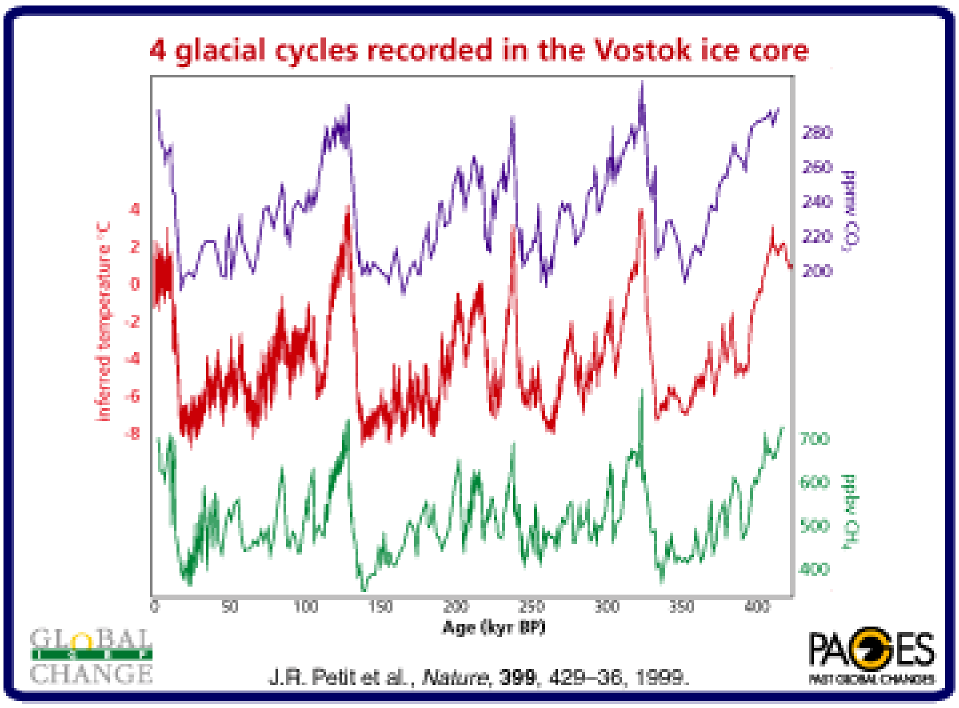


***Figure 4****. The Vostok ice core record of the global atmospheric $CO_2$ concentration (purple line, top), the relative change in temperature at Vostok Station (red line, centre), and the methane concentration (green line, bottom) over the last 420,000 years. The time scale is derived by estimating ice accumulation rates and modelling the flow of the Antarctic Ice Cap at this location. Note the very close correspondence between inferred temperature (in red) and the concentrations of the greenhouse gases, CO2 and methane. Central Antarctica was coldest when the greenhouse-gas concentrations were lowest, and warmest when the greenhouse-gas concentrations were highest. Each major cold episode marks a glacial stage in earth climate. After Petit et al., Nature, 399, 1999. Available for viewing on the PAGES website (http://www.PAGES-IGBP.ORG/) by following the links under the "Products" button.*

Remember from earlier in the course that the ocean contains 60 times more inorganic dissolved carbon than occurs in the atmosphere as $CO_2$. In this context, the magnitude of the variations in the atmospheric $CO_2$ inventory indicated by the Vostok data are such that they could only have been produced by changes in oceanic $\Sigma CO_2$. A rather small oceanic burp or a gulp would have done the trick. How and why such changes occur is not yet clearly known, but they must involve alterations in the carbon cycle in the oceans.

Over the last several years, this has become an area of intense enquiry, partly because an unprecedented perturbation of the carbon cycle is currently being carried out by mankind. Fossil fuel burning and deforestation have already added some 85 ppm of additional $CO_2$ to the atmosphere over the last century, about the same amount as was added during the last glacial-interglacial transition. The continuing exponential growth in $CO_2$ content is predicted to lead to significant global warming over the next century or two – as you know, whether or not such warming has already arrived is currently being hotly debated. Constraining, refining or illuminating such projections are objectives of present research efforts that are attempting to determine how the ocean-atmosphere system has behaved in the past. Milankovitch's ideas, oxygen isotope measurements, and data collected from ice cores are just a few of the many tools used in this search.