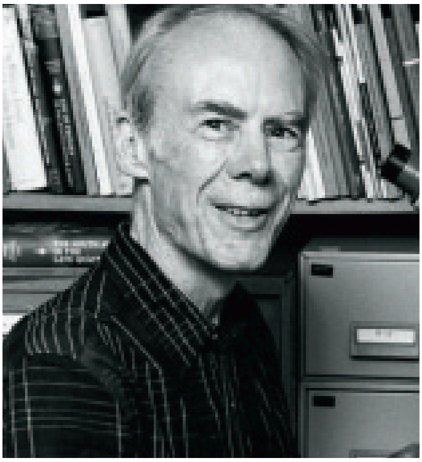
2005

Blue Planet Prize

Professor Sir Nicholas Shackleton (U.K.)

Emeritus Professor, Department of Earth Sciences, University of Cambridge
Former Head of Godwin Laboratory for Quaternary Research



Dr. Gordon Hisashi Sato (U.S.A.)

Director Emeritus, W. Alton Jones Cell Science Center, Inc.
Chairman of the Board, A&G Pharmaceutical, Inc.
President, Manzanar Project Corporation

The Sign:
The earth is engraved with the wisdom of nature, leaving its impression in the changes of the weather, and in the behavior of animals giving them life. Humans have forgotten to listen to the suffering earth, or to notice the state of living creatures. The 2005 opening film touched on the signs in the earth's history that pointed towards the future and the creatures that live there.

His Imperial Highness Prince Akishino congratulates the laureates

Their Imperial Highnesses Prince and Princess Akishino congratulate the laureates at the Congratulatory Party

The prizewinners receive their trophies from Chairman Seya

Dr. Gordon Hisashi Sato

Prof. Sir Nicholas Shackleton

Dr. Jiro Kondo, chairman of the Presentation Committee makes a toast at the Congratulatory Party

J. Thomas Schieffer, Ambassador of the United States of America to Japan and Graham Fry, Ambassador of the United Kingdom to Japan, congratulate the laureates

Blue Planet Prize Commemorative Lectures

Profile

Professor Sir Nicholas Shackleton

Emeritus Professor, Department of Earth Sciences, University of Cambridge
Former Head of Godwin Laboratory for Quaternary Research

Education and Academic and Professional Activities

1937	Born on June 23, in London
1961	B.A. University of Cambridge
1965-1972	Senior Assistant in Research, University of Cambridge
1967	Ph.D., University of Cambridge
1972-1987	Assistant Director of Research, Sub-department of Quaternary Research, Cambridge
1974-1975	Senior Visiting Research Fellow, Lamont-Doherty Geological Observatory, Columbia University
1975-2004	Senior Research Associate, Lamont-Doherty
1985	Fellow of The Royal Society
1987-1991	Reader, University of Cambridge
1988-1994	Director, Sub-department of Quaternary Research, Cambridge
1990	Fellow, American Geophysical Union
1991-2004	*Ad hominem* Professor, University of Cambridge
1995	Crafoord Prize, Royal Swedish Academy of Science
1995-2004	Director, Godwin Institute of Quaternary Research, Cambridge
1998	Knighthood (for services to the Earth Science)
2000	Foreign Associate, US National Academy of Sciences
2002	Ewing Medal, American Geophysical Union
2003	Urey Medal, European Association of Geochemistry
2003	Royal Medal (Royal Society of London)
2004	Vetlesen Prize, Columbia University
2004	Emeritus Professor, University of Cambridge
2005	Founder's Medal, Royal Geographical Society
2006	Deceased, January 24

It is important to know and understand climatic change over the past in order to simulate future climate change more reliably.

After graduating from Cambridge University with a B.A. in physics, Professor Shackleton received a Ph.D. with a thesis titled "The Measurement of Palaeotemperatures in the Quaternary Era" in 1967, and focused his attention on the geologically most recent period in the earth's history, the Quaternary which covers about the last 1.8 million years.

During the ice age when ice sheets up to 3 km thick covered North America and Scandinavia, lighter oxygen isotope ^{16}O was trapped in the ice sheets and the remaining ocean water have been enriched in ^{18}O by a measurable amount. He developed a high-resolution analysis method for oxygen isotope ratios in the tiny fossil shells of foraminifera from the oceans globally and devised a method to analyse more accurately the fluctuations in size of ice sheets which developed many times during the period, and made contributions to palaeoclimatology.

In 1973, he analysed a core from the western tropical Pacific that contained evidence of the most recent reversal of the Earth's magnetic field that occurred about 780,000 years ago. It was obvious that the ice-volume cycles that he reconstructed occurred roughly every 100,000 years, and he established a method for assigning an age scale for a core, based on the 100,000-year cycles from the core.

Further work on the cyclicity in the sediment cores revealed that the major cyclice was in sync with the major changes in the eccentricity of the earth's orbit, and a paper was published in 1976 together with Drs. J. D. Hays and J. Imbrie, which validated the "Milankovitch hypothesis" that hypothesized the idea that cyclical changes in the three elements, earth orbit eccentricity, angle of its rotational axis (obliquity) and precessional changes, caused the glaciation that had occurred during that time.

In the 1990s, after French and Swiss scientists measured the carbon dioxide in air bubbles trapped in ice from the Vostok ice core in central Antarctica and revealed the atmospheric carbon dioxide concentration for the last 420,000 years, he used the carbon isotope ratios in fossil foraminifera to reconstruct past carbon dioxide concentrations. His reconstruction was surprisingly similar to the first record obtained by French and Swiss scientists. In a later study he showed that carbon dioxide was a major contributor to past global climate change during the period and that in fact the main features of climatic variability over the past million years can be explained taking account of earth's orbital changes as well as natural carbon dioxide changes.

Recently he worked on the detailed record of the last glacial cycle. He showed that a drastic warming and cooling, such as, temperature difference of 10 degree within 30 years which the earth had experienced known from the study of ice cores from Greenland can also be found in sediment cores from the North Atlantic.

Professor Shackleton had major influence on the development of Palaeoceanography and Palaeoclimatology, and served central roles in several international research projects. He published more than 200 papers including highly renowned ones, taught and brought up many young researchers, and was major thrust in these field with his highly positive attitude. Besides serving as Director of the Godwin Institute for Quaternary Research, he served many key positions such as the President of the International Union for Quaternary Research.

Professor Shackleton had an idea that by knowing the past global climate and eventually the earth's environment through the research in geology, this would enable us to find a way to tackle the issue of global environmental change in the future, and thus contribute to society. He poured in his enthusiasm into understanding global climate change during the Quaternary which was also considered as the human era, and he sounded a warning that we should be aware that increase in global warming gas may possibly trigger a rapid climate change that had happened in the past again in the future, and urged that the human race must make efforts to control the release of greenhouse gases.

Professor Sir Nicholas Shackleton passed away on 24 January, 2006. May he rest in peace.

Lecture

Geological Deposits, Geological Time and Natural Changes in Climate

Professor Sir Nicholas Shackleton

What are geological deposits?

A geologist who is examining material hundreds of millions of years old with the aid of a geological hammer, might use the expression 'geological deposits' as synonymous with 'rocks'. However as one becomes interested in younger material one has to consider deposits which have not yet experienced sufficient time, pressure and temperature to be converted to rocks. In addition, one can consider deposits such as the ice in the Greenland ice cap that remains a geological deposit until such time as it melts. In my interpretation, even the bubbles of air that are trapped in this ice constitute geological deposits. The annually ringed trunk of an ancient tree may be thought of as a geological deposit, whether or not the tree is living today.

Two very important descriptors of a geological deposit are accumulation rate and time resolution. On a cut cross-section of a tree, one can see every yearly increment so the resolution is described as annual. The accumulation rate, or radial growth rate, may be of the order 1mm/year. In reality it may be possible to distinguish spring growth from summer growth but it is not possible to extract monthly information. On the other hand, a mollusc might accumulate a similar thickness per year but might preserve a weekly resolution provided a suitable sampling method is used. On the other hand a muddy, estuarine sediment might accumulate at a similar rate but might only offer a resolution of a hundred to a thousand years due to the prevailing mixing by burrowing organisms on the sea floor (bioturbation) and mixing by bottom currents.

If funding and time permits, I believe that a scientist should sample a geological section at close enough depth intervals to achieve the temporal resolution required for his/her project, or as close as the resolution of the deposits allows, whichever is the smaller. People often ask me what are the secrets of my success, and I believe one of them is that I have always preferred to sample as closely as circumstances permit. In contrast, many of my friends would prefer to sample as long a record as possible, sacrificing resolution. It could be argued that the benefit of my approach is purely aesthetic; the closely-sampled record looks nicer. But undoubtedly the densely sampled record gives the reader greater confidence in the data, because it is easier to see just how reliable the measurements are.

What have I measured? stable isotope ratios

The Chicago scientist Harold Urey was awarded the 1934 Nobel Prize for discovering Deuterium, the heavier isotope of hydrogen. In 1947 he published a seminal paper[1] on fractionation between the stable isotopes of a variety of elements. Here “fractionation” refers to a process in which some matter is separated in such a manner that on fraction contains proportionately more of the heavy isotope, while the remainder has proportionately more of the light isotope. For example, in nature it is observed that when water evaporates the water vapour is depleted in the heavy isotope of oxygen ^{18}O and the remaining liquid is slightly enriched in ^{18}O. The reason is that it requires slightly more energy to hold a heavier water molecule in the vapour phase. In his 1947 paper Urey calculated the magnitude of this effect both for the case of the evaporation of water and for many other phase transitions and chemical reactions. One example involves the crystallization of calcite (calcium carbonate) from water, and here not only did Urey calculate the ^{18}O fractionation between the water and the calcite, but he also calculated the effect of temperature on this fractionation. He then suggested that if this fractionation could be measured at different times in the geological past, it would be possible to estimate the palaeotemperature at the time of crystallization.

Together with a team of brilliant colleagues Urey set about developing this idea into a viable tool. This entailed: 1. developing a sufficiently precise mass spectrometer for measuring the isotope ratios; 2. developing a method for extracting CO_2 from carbonate without introducing additional fractionation; 3. demonstrating that the fractionation exhibited during calcite crystallization is as predicted by theory; 4. demonstrating that biogenic calcite undergoes the same ^{18}O fractionation during shell growth as does calcite that grows inorganically; and 5. demonstrating that the method does actually give reasonable results for fossils. All this was achieved in a remarkable series of papers published in the early 1950's[2].

One additional scientist was needed to set the scene for my entry into the field. Cesare Emiliani came to Chicago already fortified by a PhD in micropalaeontology (the study of microscopic fossils) from the University of Bologna in Italy. Using the techniques that Urey's team had developed he set out to measure palaeotemperatures in a range of deep-sea sediment cores and rock outcrops. His outstanding publication (1955)[3] was entitled "Pleistocene Palaeotemperatures". In this paper Emiliani gave palaeotemperature measurements in cores that covered over half a million years (as we now know) in cores from the deep Caribbean, equatorial Atlantic, and North Atlantic.

After the second World War Dr (later Sir Harry) Godwin formed a Sub-Department of Quaternary Research as a small research unit within the Botany School in Cambridge. He was an all-round botanist and the founder of pollen analysis in Britain. He set up this group because together with the archaeologist Graeme Clarke he was working on vegetational change in Britain in relation to the prehistoric humans. Godwin set up the first radiocarbon dating laboratory in Britain in the 1950's and so was able to put the human and vegetational changes in a reliable time frame for the first time. About 1960 Dr (later Sir Edward) Bullard suggested that Godwin should seek funding to set up a laboratory for stable isotope analysis. The idea was that in Eastern England marine deposits exist that contain pollen from the nearby land mass as well as marine fossils; Bullard suggested that the combination of palaeotemperature analysis using ^{18}O, and pollen analysis would make a unique contribution. Godwin's grant application was successful and through a series of random events I was the person who he selected to get the project under way.

Urey's team had not been limited as regards sample size because they worked with relatively large fossils. Emiliani worked with the same equipment – indeed when he moved to a permanent position in the University of Miami he took one of the Chicago mass spectrometers with him. He was obliged to pick up to 400 foraminifera for each analysis in order to make up the 5 mg of carbonate that was needed. I soon realised that if I was to set up a successful laboratory without the need to rely on a team of assistants, it would be necessary to have a mass spectrometer that was about ten times more sensitive than this. The means by which I accomplished this are only of historic interest today[4]. However it is important to realise that at the time this was a considerable achievement and for many years my reputation was mainly as "the person who can analyse ^{18}O in tiny samples of foraminifera." I had devoted the last year of my undergraduate studies to physics, absolutely essential training given that my first task was to rebuild a commercial mass spectrometer such that it could attain the specifications that I needed. Over the next years I learned a great deal about the disciplines with which I would interact as well as keeping up with Emiliani's work, and one of the areas that I covered was glaciology (aided by the existence in Cambridge of the Scott Polar Research Institute). Hence I discovered a fatal weakness in Emiliani's brilliant papers. Emiliani had appreciated that it was necessary to make a correction for changes in the isotopic composition of the ocean when huge ice sheets accumulated on North America and Fennoscandia. This is because the removal of isotopically depleted water to form the ice sheets must have left the ocean slightly enriched in ^{18}O. However when I started to calculate this effect more carefully I realized that Emiliani had seriously underestimated it and indeed that it must have been the dominant cause of the variations in ^{18}O in many of the cores that he analysed[5].

At first sight this discovery appeared to weaken the attraction of the field, but I was able to see it in a different light and to offer two entirely new contributions. First, it would be extremely valuable to be able to generate a record of global ice volume through time. By selecting cores from areas where temperature variability might be small, I could optimise the value of the measurements from the ice volume point of view. Second, subject to the limitations of each individual core, I could use the ^{18}O record to correlate any core to a master curve. As it happens the second contribution gained me a large group of high-level colleagues and this enabled me to achieve the first. John Imbrie, Andrew McIntyre and a number of others had embarked on an ambitious project named CLIMAP, to generate a map of the surface temperature of the ocean at the time of the last glacial maximum. They had already achieved one task that would be needed for this endeavour; they had found a means for mathematically analyzing quantitative faunal data from each sample going down the core so as to estimate a record of changing sea surface temperature. However they were stymied by the other problem: how to locate the horizon in each core that corresponded to glacial maximum. When I said that that would be easy with my method they were amazed and immediately invited me to joint the CLIMAP team (which up to that point was an exclusively American venture). The publication in 1976 of the CLIMAP map of sea-surface temperature during the last ice age maximum [6] was huge accomplishment for the reason (among others) that it provided sufficient data for numerical atmospheric modellers to reconstruct atmospheric circulation in glacial times. One of the many scientists who was stimulated by this opportunity was Syukuro Manabe, winner of the first Blue Planet Prize.

Working with the CLIMAP community, and spending many months in the USA, gave me access to two incredibly exciting ventures. First, I wanted to analyse a long Pacific core. My friend Jim Hays taught me to look at deep-sea sediment cores and showed me the cores from the East Pacific that he had worked on with Neil Opdyke and others. However the pattern of cyclic carbonate dissolution that he had worked on was a disadvantage from my point of view, because I wanted to analyse calcite Foraminifera that had not been subject to dissolution on the sea floor. I then turned to the West Pacific and with the assistance of Neil Opdyke I found what I wanted; a core that appeared uniform from top to bottom. Its reference number is V28-238; number 238 of the cores collected during the 28th cruise of the Vema. Neil Opdyke had already located a reversal in the direction of magnetization of the sediment at twelve metres in the sediment; the last time the direction of the Earth magnetic field reversed was about 730 (now known to be 780) thousand years ago. This is known as the Brunhes-Matuyama boundary. With Mike Hall to assist me, we worked steadily down the core (Mike Hall has worked with me for forty years starting as a junior technician). Each day I plotted the measurements on graph paper, gluing on extra pieces when necessary. Any suspect measurement I would try to replicate three more times. The excitement was palpable as we saw all the features of the Caribbean records published by Emiliani, and then continued into unknown territory. I could see nothing wrong with the core (Though I looked forward to being the first person to replicate it). I could also see that with the benefit of the Brunhes-Matuyama boundary fixed at 12 metres in what I called Isotope Stage 19, the time scale that Emiliani has set up, extrapolating from very shaky dates near the top of his cores, was too short. There were many important conclusions to be drawn and I wrote what has proved to be a very influential paper[7] that has been cited well over a thousand times.

Soon after that I saw the opportunity to analyse another long core. An Englishman named David Parkin had developed a method for estimating changes in the vigour of the wind that blows dust out into the Atlantic Ocean from the Sahara Desert. He had a long record that included the Brunhes-Matuyama boundary and since the data showed most vigorous winds near the top of the core he concluded that winds were weaker during glacial times. I persuaded him to delay publishing his conclusions until I could develop an oxygen isotope record and establish whether greater wind vigour was consistently associated with lighter ^{18}O values. It turned out that David Parkin had missed the very short Holocene and that in general more vigorous winds were consistently associated with the glacials. This study[8] confirmed the importance of my oxygen isotope stratigraphy; suddenly a method existed by means of which a record of variations in an important palaeoclimate parameter (in this case, wind) could be directly linked to a standard stratigraphy and associated time scale. Soon after this, Neil Opdyke suggested that I should work on another core V28-239 that extended about two million years into the past. The accumulation rate of this core was lower but by analysing it every 5cm instead of every 10cm I was able to obtain a nice record of the whole Pleistocene[9].

When I first showed the data from core V28-238, my colleague John Imbrie immediately wanted to perform a spectral analysis of the data, in order to test the long-standing “Milankovitch Hypothesis”. In the 1920’s Milutin Milankovitch has hypothesised that the ice ages were caused by changes in the distribution of the sun’s energy over the earth, which in turn arise due to changes in the geometry of the earth-sun system. It had never been possible to test this because continuous records of changing climate were not available until Emiliani published his ^{18}O records, and because these could not be used because of the lack of age control. We started working of the spectral analysis but then it emerged that Jim Hays was working on cores from the subantarctic Indian Ocean that had several advantages over my core. Most important, they had twice the accumulation rate of core V28-238. Jim Hays generated records of sea-surface temperature in the Southern hemisphere, while I generated a Northern hemisphere record from the ^{18}O measurements, since the fluctuating ice sheets accumulated on the Northern hemisphere continents. We showed[10] that the three periodicities with which the orbit changes (100,000 years, 40,000 years and 21,000 years) were all present in the data, just as Milankovitch theory predicted.

We realised while finalising the publication that it was possible to fine-tune the time scale by aligning the cycles in a core with those calculated by astronomical theory, by the early 1980's we had constructed an astronomically tuned and averaged stable isotope record known as the SPECMAP stack[11], which has been incredibly valuable as a template for workers to place their data on a highly detailed common time scale. In 1991 I improved this with new data and was able to show that the age of the Brunhes-Matuyama reversal was 780,000 years rather than 730,000 years as had been believed[12]; I also recalibrated several earlier reversals. Surprisingly, these recalibrations were very soon accepted because new laboratory measurements also suggested that the published ages required correction. I was able to carry the work further back in time, ultimately calibrating the geological time scale back to about 30 million years[13].

In 1975 I was invited to a meeting in Hawaii concerned with carbon dioxide, and I decided to think about the isotopes of carbon. Every day that I collected ^{18}O data I also collected ^{13}C data but up to that time I had only used them to make a small correction to the ^{18}O measurements. The most important process that gives rise to variations in ^{13}C in nature is photosynthesis; plants, and organic matter that derives from them, contain about two percent less ^{13}C than the CO_2 from which they grew. When I saw in my collection of ^{13}C data that the ocean has undergone systematic variations in the ^{13}C content I reasoned that the only plausible explanation had to be was that the mass of organic matter on planet Earth had fluctuated on a glacial-interglacial time scale. Investigating the literature I found that the area that is covered by tropical rainforest was reduced during glacial times because it was drier. At the same time large areas of terrain that are now vegetated, were then covered by ice sheets. It seemed that I had stumbled across a method for estimating changes in the mass of organic matter covering the continents. When the continental biomass (including soil) diminished, the organic carbon that was released must have oxidised and ended up in the ocean[14].

Soon after this, two reports appeared claiming that the concentration of carbon dioxide in "fossil" air bubbles from the glacial part of the Antarctic ice sheet is less than that of pre-industrial air. Wallace Broecker (another past Blue Planet Prize winner) gave a talk which I was lucky enough to hear before he published it[15]. He explained that the only mechanism capable of reducing the carbon dioxide in the atmosphere from 280 to 200 parts per million by volume was one that transferred it to the deep ocean, and he described the working of the "biological pump" that controls the equilibrium pressure of carbon dioxide over the ocean. In the ocean surface layer photosynthesis removes some of the dissolved carbon dioxide by converting it to organic matter, which sinks to the deep ocean and oxidises there. The proportion that can be photosynthesised is limited by the concentration of nutrients in the surface water. This process leads to an enrichment in ^{13}C in the remaining dissolved carbon dioxide that is available for Foraminifera to build their calcite shells with. Meanwhile the rare genera of Foraminifera that live on the sea floor build their shells from average ocean carbon dioxide, so that the strength of the "biological pump" can be monitored by the ^{13}C difference between the shells of the planktonic (floating near the surface) foraminifera and the benthonic (living on the sea floor) foraminifera. I sought a suitable core and carefully selected benthonic and planktonic specimens to get the best record. Sure enough there was a larger ^{13}C difference between surface water and bottom water in the glacial part of the core, consistent with the published data from the ice cores that showed a lower carbon dioxide concentration in the air bubbles from glacial times. I continued and obtained a record that predicted similar values to today in the last interglacial. My glaciologist friends in France were shocked when they saw this record published in the journal *Nature*[16] because they had already analysed ice from the Antarctic ice core at Vostok, and saw at once the similarities between their real carbon dioxide record and my reconstruction.

I have reviewed for you some of the work I have done which may give you an idea why I have been selected for this wonderful award. Each publication was based on a lot of new analytical data, and indeed much of my success has depended on the fact that I and my assistant Mike Hall have always had the philosophy that to justify the support of my funding agents, the lab ought to be generating data all the time. However five years ago I wrote a paper that contains no new data and instead is based on combining data from my lab with different data published by Robert Petit and his colleagues in the French ice core community. In some ways I regard it as my best paper[17] and of course it is far too complicated to explain to a general audience. Nevertheless I will explain some of its importance. The key was the fact that there is a record from the Vostok ice core of the changing isotopic composition of the atmospheric oxygen that is trapped in bubbles in the ice. The trapping occurs at the point where that accumulating snow on the ice surface becomes sufficiently packed down that the air can no longer exchange with the overlying atmosphere (this trapping happens tens of metres below the surface). Now atmospheric oxygen equilibrates with ocean water through global photosynthesis with many complex steps, but if everything else is assumed not to change, the atmospheric oxygen would follow changes in the isotopic composition of the ocean with a lag of about a thousand years. By comparing this record with the deep-sea oxygen isotope record from carbonate microfossils, I was able to separate the ice-volume component of the many deep-sea records I had published from the temperature component, something that we have never previously been able to do. Thus I found that the ice volume component does indeed lag (i.e. it responds with a delay) behind the carbon dioxide record. Some people have argued that changes in the ice sheets caused the changes in atmospheric carbon dioxide; I believe these data show the reverse; carbon dioxide was a major player in causing the glacial cycles.

Ultimately if we claim to be able to explain past climate, we want to be able to take the carbon dioxide record and the orbital variations and model the resulting climate record, and to compare this model result with the geological observations. I believe that at the very simplest level we can actually do that.

The natural range of variation in atmospheric carbon dioxide during the ice ages, which had such a dramatic effect on the earth's climate, was about 80 parts per million by volume. This range has already been exceeded by the man-made increase over the past century. The geological record is very important in ramming home the message, that it is imperative that we stop the carbon dioxide rise that is causing global warming.

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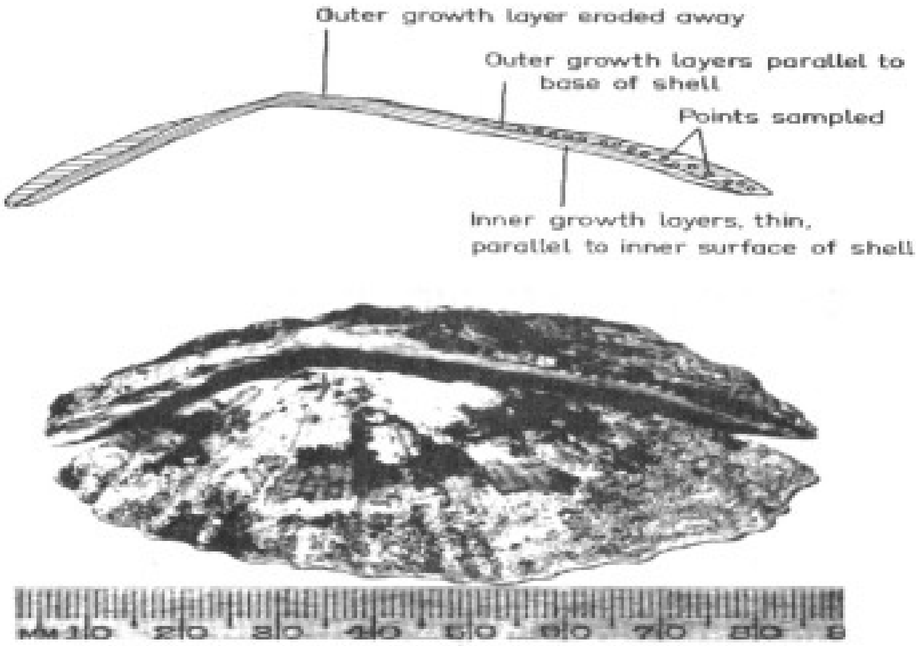

Figure 1. Photograph of a limpet from the South African coast, cut in half and sampled with a small drill for oxygen isotope analysis.

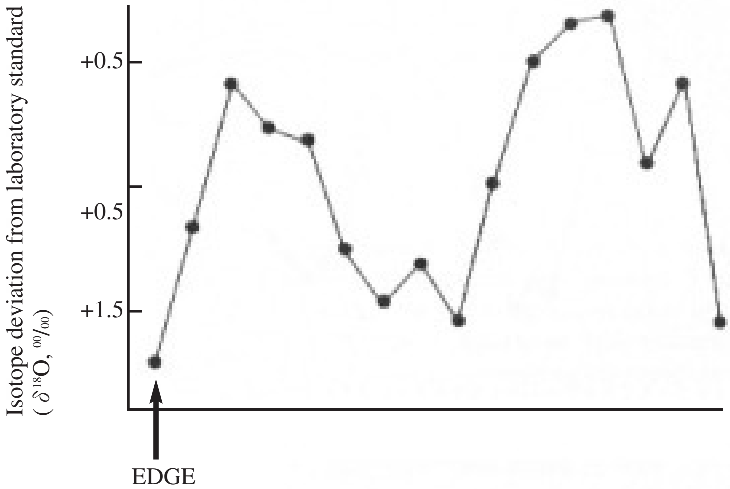

Figure 2. Oxygen isotope record for shell in Fig. 1, covering two years of growth. This crude sampling is good enough to determine the season during which prehistoric people were eating shellfish (winter), but it would be technically possible with modern methods to sample at weekly intervals. This is an example of geological measurements on a very fine time scale.

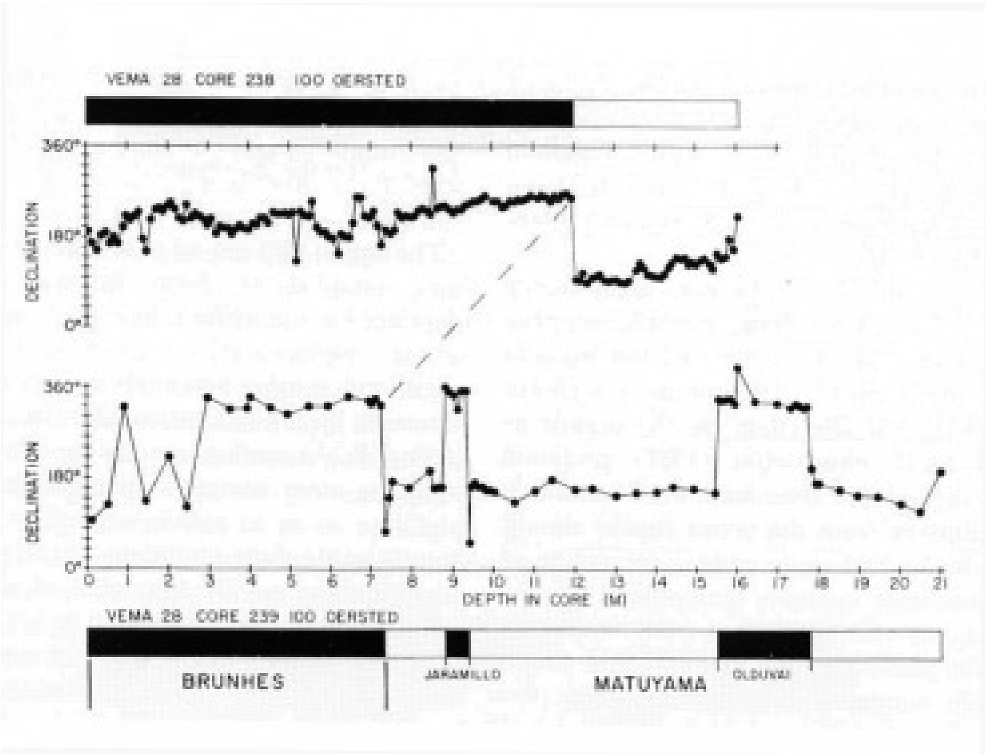

Figure 3. The magnetic measurements that were carried out by Neil Opdyke in core V28-238 (upper part of figure) before I sampled the core. It is apparent that the direction of magnetization of the sediment switches by 180 degrees at 12 meters depth in the core. We know that the last time the field was consistently oriented in the reverse direction was about 780,000 years ago.

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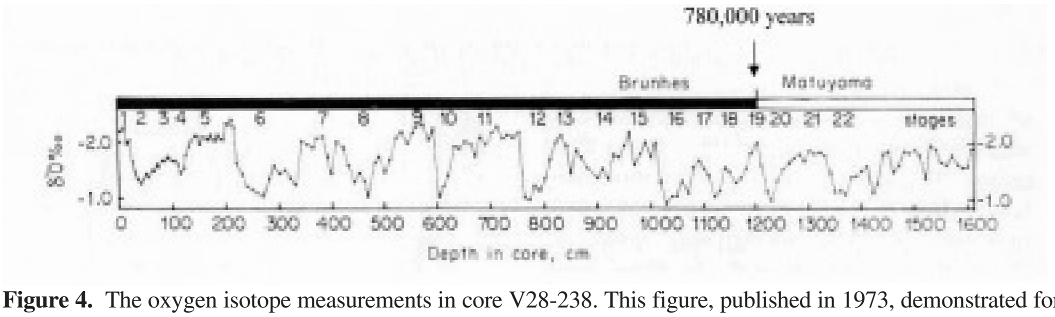

Figure 4. The oxygen isotope measurements in core V28-238. This figure, published in 1973, demonstrated for the first time the existence of 100,000-year cyclicity of glaciations over the past million years and has been described as a "Rosetta Stone" for the ice ages.

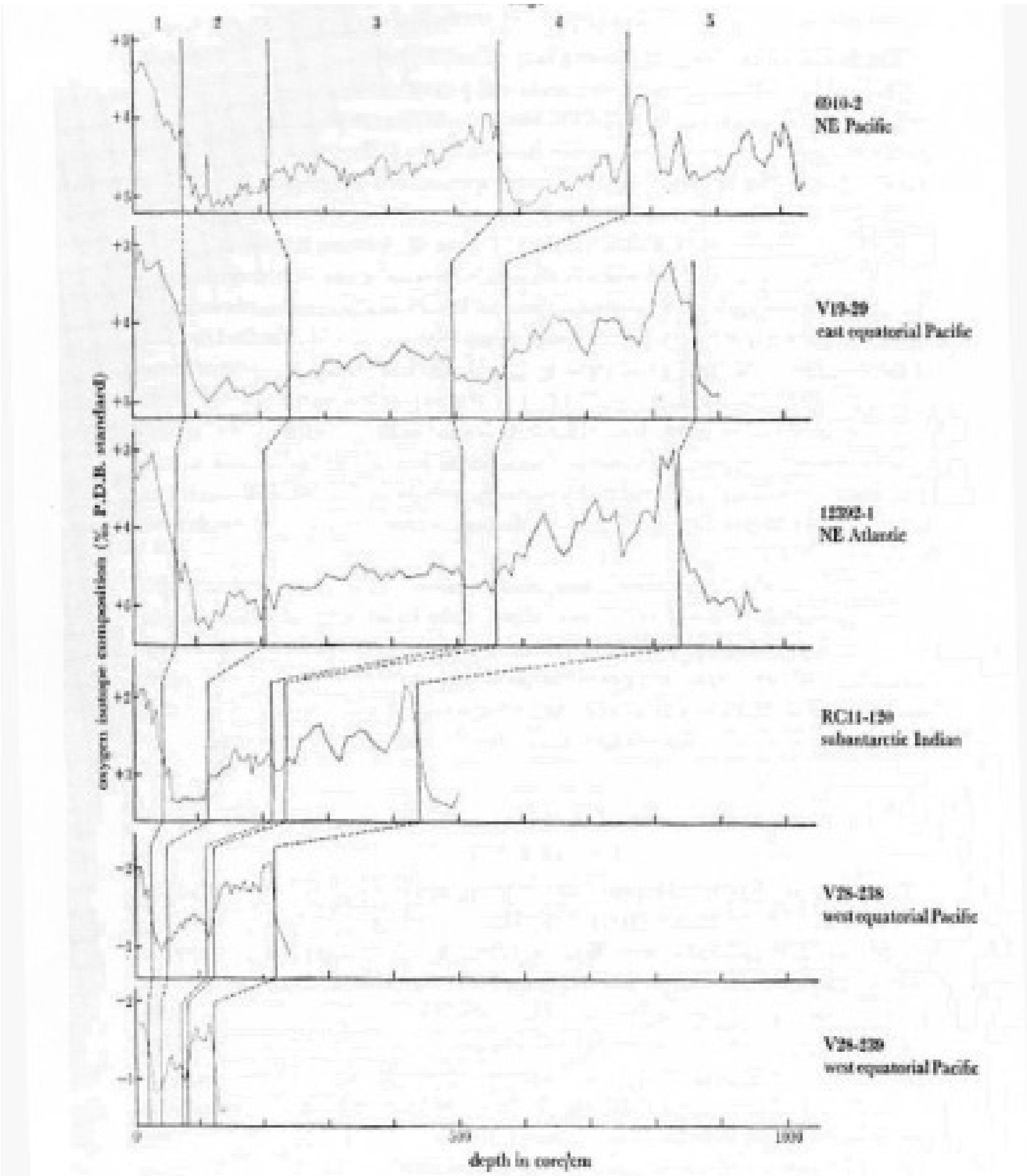

Figure 5. This figure illustrates the effect of sediment accumulation rate on the character of the record obtained by oxygen isotope analysis. At the bottom 100,000 years is compressed into only a meter of sediment and all the fine detail is lost. As the accumulation rate increases in cores toward the top of the figure the last 100,000 years are revealed in four to ten meters and the important details of the last glacial cycle are reproducibly revealed.

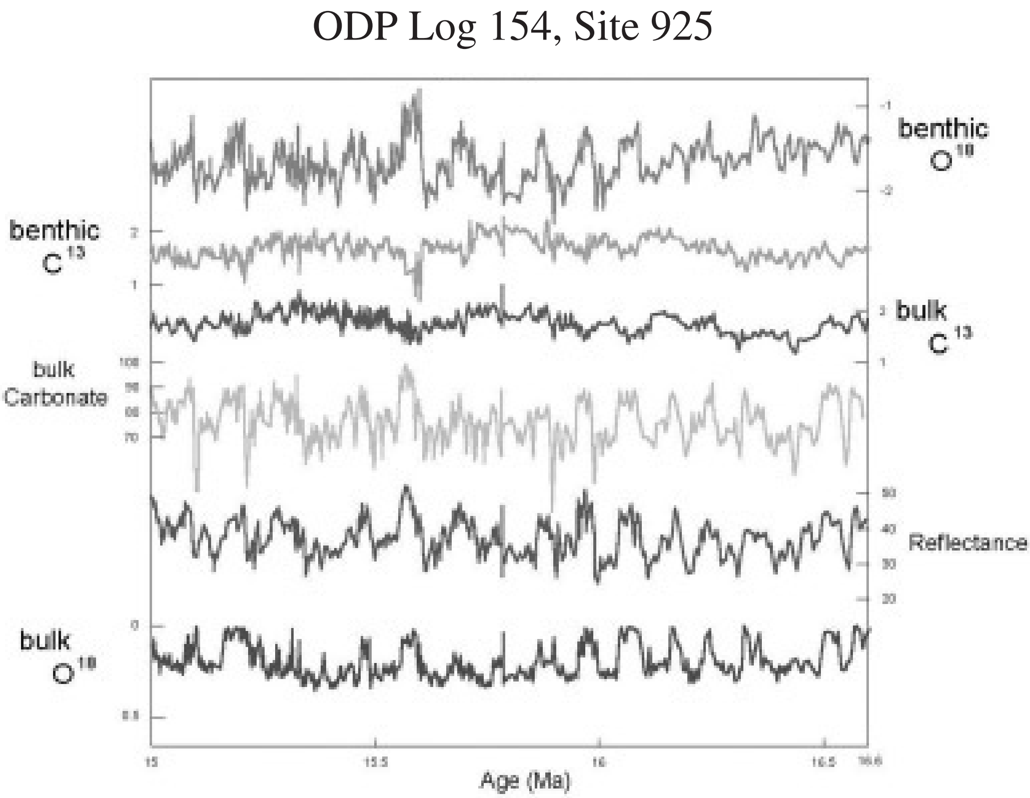

Figure 6. Climate cycles (probably including cyclic appearance and disappearance of the Antarctic ice sheet) between 15 million and 16.6 million years ago are illustrated. Many different climate-sensitive parameters were measured, and it is apparent that all display approximately the same cyclicity.

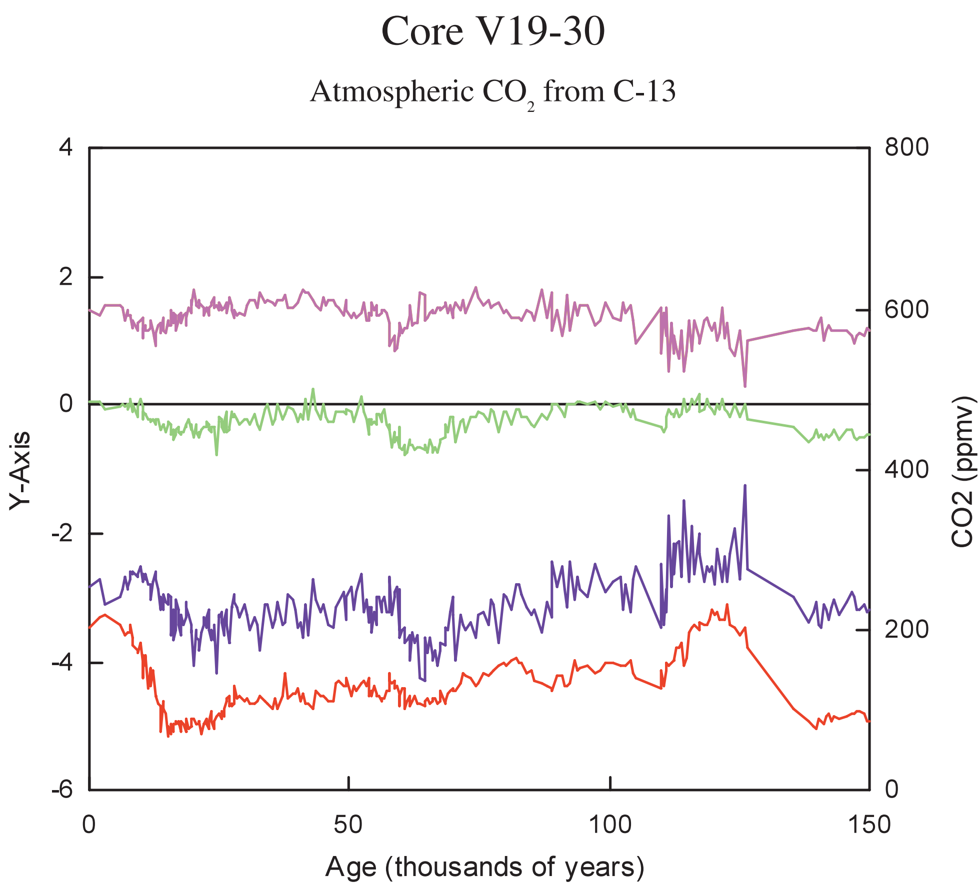

Figure 7. The top two records in this figure show carbon isotope records from the surface waters, and from the water bathing the sea floor, in the Eastern equatorial Pacific. The next record shows the carbon isotope gradient between the surface and deep water as a function of time (obtained by subtracting the second record from the first). To a first approximation this provides an estimate of changing carbon dioxide in the atmosphere. The bottom record shows the oxygen isotope record of the core. From this it can be concluded that carbon dioxide was higher during interglacials and lower during glacials.

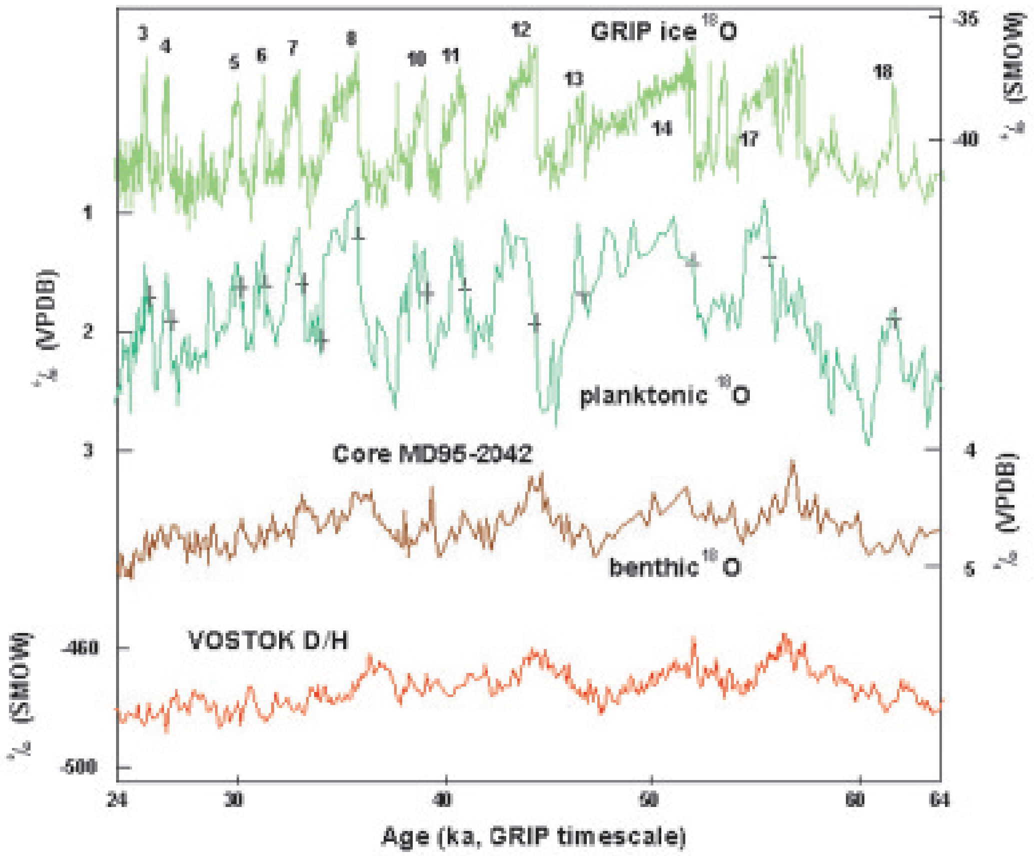

Figure 8. The top and bottom records on this figure show stable isotope records (roughly proportional to air temperature when the snow was falling) from Greenland ice (measured by Johnsen and co-workers in Copenhagen) and from Antarctic ice (measured by Petit and co-workers in Grenoble). The middle two records are stable isotope records (proxies for water temperature) in surface water and in deep (3000 m) water near Portugal, both measured in the same samples. All four records are on a consistent age scale covering the interval from 25,000 to 65,000 years ago during the last ice age. On the scale of rapid events during the last ice age it appears that while the temperature of the surface of the North Atlantic changed in synchrony with Greenland, the temperature of the deep waters varied in synchrony with the high southern latitudes.

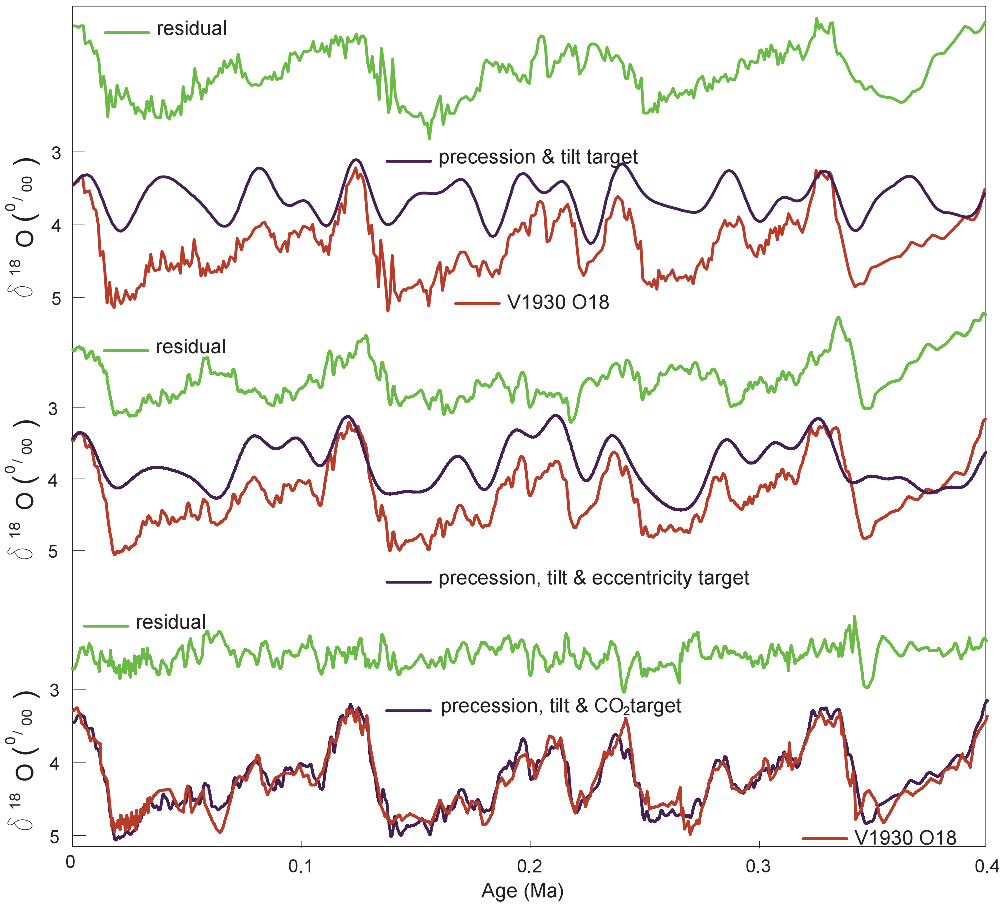

Figure 9. Each panel includes the same oxygen isotope record from a deep-sea core, superimposed on a model that partly simulates the record; each covers 400,000 years. Above each pair is a plot of the residual (obtained by subtracting the model from the data). The upper two panels use different versions of a model using only data for the variations in the Earth's orbital parameters and have quite a large-amplitude residual. The model for the lowest panel incorporates the record of atmospheric carbon dioxide concentration as measured in bubbles from the Vostok Antarctic ice core (from Petit and colleagues) and has a much smaller residual.

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Professor Sir Nicholas Shackleton

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