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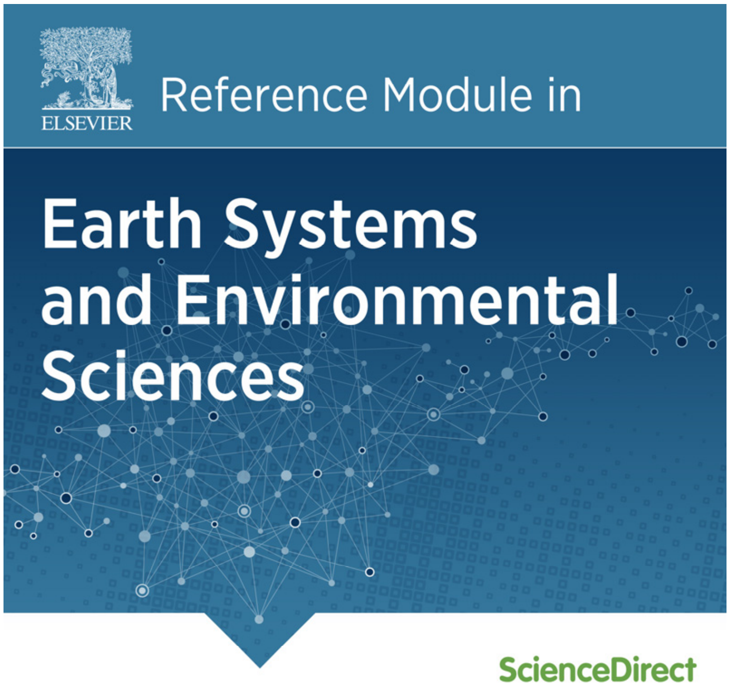

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Paleoceanography☆

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Introduction: The Relevance of Paleoceanography

Paleoceanography encompasses (as its name implies) the study of 'old oceans', that is, the oceans as they were in the past. In this context, 'the past' ranges from a few decades through centennia and millennia ago, to the very deep past, millions to billions of years ago. In reconstructing oceans of the past, paleoceanography needs to be highly interdisciplinary, encompassing aspects of all topics in this encyclopedia, from plate tectonics (positions of continents and oceanic gateways, determining surface and deep currents, thus influencing heat transport) through biology and ecology (knowledge of present-day ecosystems and organisms ranging from microbes through large vertebrates), to oceanography (ocean circulation, fluxes of organic matter) to geochemistry (using various properties of sediment, including fossil remains, in order to reconstruct properties of the ocean waters in which they were formed) to climate, ecosystem and earth system modeling.

Because paleoceanography uses properties of components of oceanic sediments (physical, chemical, and biological) in order to reconstruct various aspects of the environments in these 'old oceans', it is limited in its scope and time resolution by the sedimentary record, because ocean properties cannot be measured directly, but must be derived from proxies, which are present within the sediments. For instance, several types of proxy data make it possible to reconstruct such ephemeral properties as temperature (see Determination of Past Sea Surface Temperatures) and nutrient content of deep and surface waters at various locations in the world's oceans, and thus obtain insights into past thermohaline circulation patterns, as well as patterns of oceanic primary productivity. The information on ocean circulation can be combined with information on planktic and benthic microfossils, allowing a view of interactions between fluctuations in oceanic environments and oceanic biota, on short but also on evolutionary timescales.

Paleoceanography offers information that is available from no other field of study: a view of a world alternative to, and different from, our present world, including colder worlds ('ice ages'; see Plio-Pleistocene Glacial Cycles and Milankovitch Variability) as well as warmer worlds (see Paleoceanography: the Greenhouse World). Paleoceanographic data thus serve climate modelers in providing data on boundary conditions of the ocean–atmosphere system very different from those in the present world. In addition, paleoceanography provides information not just on climate, but also on climate changes of the past, on their rates and directions, and possible linkages (or lack thereof) to such factors as atmospheric pCO_2 levels (see Plio-Pleistocene Glacial Cycles and Milankovitch Variability) and thus on climate sensitivity to changing levels of CO_2, and to the location of oceanic gateways and surface and deep-sea current patterns. Paleoceanography therefore enables us to gauge the limits of uniformitarianism: in which aspects is the present world indeed a guide to the past, in which aspects is the ocean–atmosphere system of the present world with its present biota just a snapshot, providing information only on one possible, but certainly not the only, stable mode of the Earth system? How stable are such features as polar ice caps, on timescales varying from decades to millions of years? How different were oceanic biota in a world where deep-ocean temperatures were 10–12°C rather than the present (almost ubiquitous) temperatures close to freezing? How did ecosystems in the past react to climate change, increased nutrient input, and acidification? Such information is relevant to understanding the climate variability of the Earth on different timescales, and modeling possible future climate change ('global warming') and its effects on Life on Earth, as recognized by the incorporation of a paleoclimate chapter in the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (2007), as well as in the forthcoming (2014) Fifth Assessment.

Paleoceanography thus enables us to use the past in order to gain information on possible future climatic and biotic developments: the past is the key to the future, just as much and maybe more than the present is the key to the past.

Paleoceanography: Definition and History

Paleoceanography is a relatively recent, highly interdisciplinary, and strongly international field of science. International Conferences on Paleoceanography (ICP) have been held every 3 years since 1983, and the locations of these meetings reflect the

☆*Change History:* April 2013. E Thomas updated the text, Table 1, the references and her biography.

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Table 1 International paleoceanographic conferences (ICP meetings.)

Meeting	*Year*	*Location*
ICP1	1983	Zurich, Switzerland
ICP2	1986	Woods Hole, USA
ICP3	1989	Cambridge, UK
ICP4	1992	Kiel, Germany
ICP5	1995	Halifax, Canada
ICP6	1998	Lisbon, Portugal
ICP7	2001	Sendai, Japan
ICP8	2004	Biarritz, France
ICP9	2007	Shanghai, China
ICP 10	2010	La Jolla, USA
ICP 11	2013	Barcelona, Spain

international character of the paleoceanographic research community (Table 1). The flagship journal of paleoceanographic research, Paleoceanography, was first published by the American Geophysical Union in March 1986. In the editorial in its first volume, its target was defined as follows by founding editor J.P. Kennett:

Paleoceanography publishes papers dealing with the marine sedimentary record from the present ocean basins and margins and from exposures of ancient marine sediments on the continents. An understanding of past oceans requires the employment of a wide range of approaches including sedimentology; stable isotope geology and other areas of geochemistry; paleontology; seismic stratigraphy; physical, chemical, and biological oceanography; and many others. The scope of this journal is regional and global, rather than local, and includes studies of any geologic age (Precambrian to Quaternary, including modern analogs). Within this framework, papers on the following topics are to be included: chronology, stratigraphy (where relevant to correlation of paleoceanographic events), paleoreconstructions, paleoceanographic modeling, paleocirculation (deep, intermediate, and shallow), paleoclimatology (e.g., paleowinds and cryosphere history), global sediment and geochemical cycles, anoxia, sea level changes and effects, relations between biotic evolution and paleoceanography, biotic crises, paleobiology (e.g., ecology of 'microfossils' used in paleoceanography), techniques and approaches in paleoceanographic inferences, and modern paleoceanographic analogs.

Perusal of the volumes of the journal published since demonstrates that it indeed covers the full range of topics indicated above.

What is the shared property of all these papers? They deal with various aspects of data generation or modeling using information generated from the sedimentary record deposited in the oceans (see Authigenic Deposits, Calcium Carbonates, Clay Mineralogy, Ocean Margin Sediments, Pore Water Chemistry and Sediment Chronologies), including such materials as carbonates, clays, and authigenic minerals, as well as organic matter produced by organisms, and carbonate, phosphate, and opaline silica secreted by marine organisms, including for instance the calcium carbonate secreted by corals (see Past Climate from Corals). Sediments recovered from now-vanished oceans as well as sediments recovered from the present oceans are included, but paleoceanography as a distinct field of study is tightly linked to recovery of sediment cores from the ocean floor, deposited onto oceanic basement. Such sediments represent times from which oceanic crust is still in existence in the oceans (i.e., has not been subducted), which is about the last 200My of Earth history (seeMid-Ocean Ridge Geochemistry and Petrology, Propagating Rifts and Microplates, Seamounts and Off-Ridge Volcanism and Sediment Chronologies).

Paleoceanography is a young field of scientific endeavor because the recovery of oceanic sediments in cores started in earnest only in the 1950s, long after the *Challenger* Expedition (1872–76), usually seen as the initiation of modern oceanography and the first large datasets on deep-sea organisms. Little research was conducted on ocean sediments until the late 1940s and 1950s, although some short cores were recovered by the German South Polar Expedition (1901–03), the German *Meteor* Expedition (1925–27), the English *Discovery* Expedition (1925–27), and Dutch *Snellius* Expedition (1929–30). This lack of information on oceanic sediments is documented by the statement in the authoritative book for its time, *The Oceans* by H. Sverdrup, N. Johnson, and R. Fleming published in 1942:

From the oceanographic point of view, the chief interest in the topography of the seafloor is that it forms the lower and lateral boundaries of the water.

This situation quickly changed in the years after the World War II, when funding for geology and geophysics increased, and new technology became available to recover material from the seafloor. Sediment cores collected by the *Challenger* in 1873 reached a maximum length of 2ft (Figure 1), and little progress in core collection was made in more than 50 years, so that cores collected by the *Meteor* (1925–27) reached only 3ft, as described by H. Petterson in the *Proceedings of the Royal Society of London* in 1947. In 1936, the American geophysicist C.S. Piggott obtained a 10-ft core using an exploding charge to drive a coring tube into the sediment, and in the early 1940s H. Petterson and B. Kullenberg developed the prototype of the piston corer. Piston corers were first used extensively on the Swedish Deep-Sea Expedition (1946–47) using the *Albatross*, the first expedition to focus "on the bottom deposits, their chemistry, stratigraphy, etc.," and thus arguably the first paleoceanographic expedition.

A major expansion occurred in US oceanographic institutions in the postwar years, and piston corers were used extensively by Woods Hole Oceanographic Institution (Woods Hole, Massachusetts) with its research vessel *Atlantis*, the first American ship built for sea research (1931–66), Scripps Institution of Oceanography (La Jolla, California) with the *E.W. Scripps* (1937–55), and the

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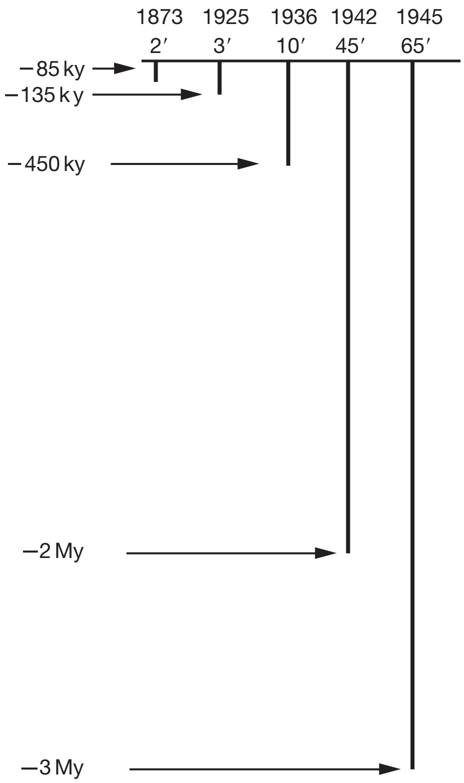

Figure 1 Lengths of sediments cores (in ft) obtained by the *Challenger* (1873), the *Meteor* (1925), Piggott's explosive-driven coring device (1936), and piston cores obtained by corers constructed by H. Petterson and B. Kullenberg, Institute of Oceanography, Göteborg, Sweden (1942–45). Adapted from Petterson H (1947) A Swedish deep-sea expedition. *Proceedings of the Royal Society of London*, *Series B*: *Biological Sciences* 134(876): 399–407, figure 5.

Lamont Geological Observatory of Columbia University (Palisades, New York), now the Lamont-Doherty Earth Observatory, with the *Vema* (1953–81). In 1948, only about 100 deep-sea cores existed, and by 1956 the *Vema* alone had collected 1195 cores.

Before the Swedish Deep-Sea Expedition, only limited estimates of the sedimentation rates in the deep ocean were available, described by H. Petterson in 1947 as "the almost unknown chronology of the oceans" (Figure 1). The development of radiocarbon dating of carbonates (seeSediment Chronologies) in combination with geochemical determination of the titanium content of sediments as a tracer for clay content led to estimates of sedimentation rates by G. Arrhenius, G. Kjellberg, and W.L. Libby in 1951, and of differences in sedimentation rates in glacial and interglacial times by W.S. Broecker, K.K. Turekian, and B.C. Heezen in 1958.

Cores collected by the *Albatross* during the Swedish Deep-Sea Expedition as well as the many later expeditions of the *Atlantis* and *Vema* were used extensively in seminal paleoceanographic studies of the Pleistocene ice ages, including those of the variation of calcium carbonate accumulation by G. Arrhenius and E. Olausson, and of the variations in populations of pelagic microorganisms (foraminifera; see Protozoa, Planktonic Foraminifera) by F. Phleger, F. Parker, and J.F. Peirson published in 1953, as well as D.B. Erickson and G. Wollin published in 1956. The oxygen isotopic method to reconstruct past oceanic temperatures using carbonate sediments, as outlined by H. Urey in a paper in *Science* in 1948, was first applied to oceanic microfossils by C. Emiliani, in order to reconstruct ocean surface temperatures during the Pleistocene ice ages, which has revolutionized the study of ice ages as conducted on land-based materials.

It turned out that the oxygen isotope record combined signals of temperature change as well as ice volume and is more difficult to interpret than first hoped (see Cenozoic Climate – Oxygen Isotope Evidence and Determination of Past Sea Surface Temperatures), but the method has become widely established since those early days. Oxygen isotope analysis was the major tool in the first attempt to look at paleoclimate globally, in the CLIMAP (Climate/Long Range Investigation Mappings and Predictions) project in the early 1970s, which led to the documentation that major, long-term changes in past climate are associated with variations in the geometry of the Earth's orbit, as described by J. Hays, J. Imbrie, and N.J. Shackleton in 1976 in *Science* (seePlio-Pleistocene Glacial Cycles and Milankovitch Variability). Oxygen isotope analysis is still one of the 'workhorses' of paleoceanographic research, as documented in the review of global climate of the last 65My by J.C. Zachos and others in *Science* (2001). New methods, such as the use of various trace element to Calcium ratios in marine carbonates (e.g., Mg/Ca) and clumped isotope analysis may assist in deconvolving the record of temperature and ice volume. The research on orbital control of global climate, thus oceanic sediments worldwide, has led to a revolution in geochronology through the development of orbitally-tuned age models for earlier parts of Earth History, now close to encompassing the full Cenozoic.

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Most material older than the last few hundred thousands of years became available in much longer cores which could be recovered only after the start of drilling by the Deep Sea Drilling Project (DSDP) in 1968, an offshoot of a 1957 suggestion by W. Munk (Scripps Institution of Oceanography) and H. Hess (Princeton University) to drill deeply into the Earth and penetrate the crust–mantle boundary. In 1975, various countries joined the United States of America in the International Phase of Ocean Drilling, and DSDP became a multinational enterprise. Between 1968 and 1983, the drill ship *Glomar Challenger* recovered more than 97km of core at 624 drill sites. Cores recovered by DSDP provided the material for the first paper using oxygen isotope data to outline Cenozoic climate history and the initiation of ice sheets on Antarctica, published in the *Initial Reports of the Deep Sea Drilling Project* in 1975 by N.J. Shackleton and J.P. Kennett.

DSDP's successor was the Ocean Drilling Program (1983–2003), which recovered more than 222km sediment at 652 sites with its vessel *Joides Resolution*. These two programs were succeeded by the Integrated Ocean Drilling Program (IODP; ending in 2012), and its present successor the International Ocean Discovery Program (IODP), which have greatly expanded the reach of the previous programs by using multiple drilling platforms, including riser drilling by the Japanese-built vessel *Chikyu*, riserless drilling by a refitted *Joides Resolution*, and mission-specific drilling using various vessels (seeDeep-Sea Drilling Methodology), which has made it possible to recover paleoclimate records from the Arctic Ocean.

Paleoceanographic Techniques

Over the last 30 years there has been an explosive development of techniques for obtaining information from oceanic sediments (Figure 2). One of the limitations of paleoceanographic research on samples from ocean cores is the limited size of each sample. However, a positive result of this limited availability is that researchers from different disciplines are forced to work closely together, leading to the generation of independent proxy records on the same sample set, thus integrating various aspects of chemical and biotic change over time. Proxies are commonly measured on carbonate shells of pelagic and benthic microorganisms (see Benthic Foraminifera, Coccolithophores and Protozoa, Planktonic Foraminifera), thus providing records from benthic and several planktonic environments (surface, deep thermocline), but in more recent years various proxies based on organic compounds (biomarkers) have become more commonly used and made it possible to obtain data on non-carbonate materials.

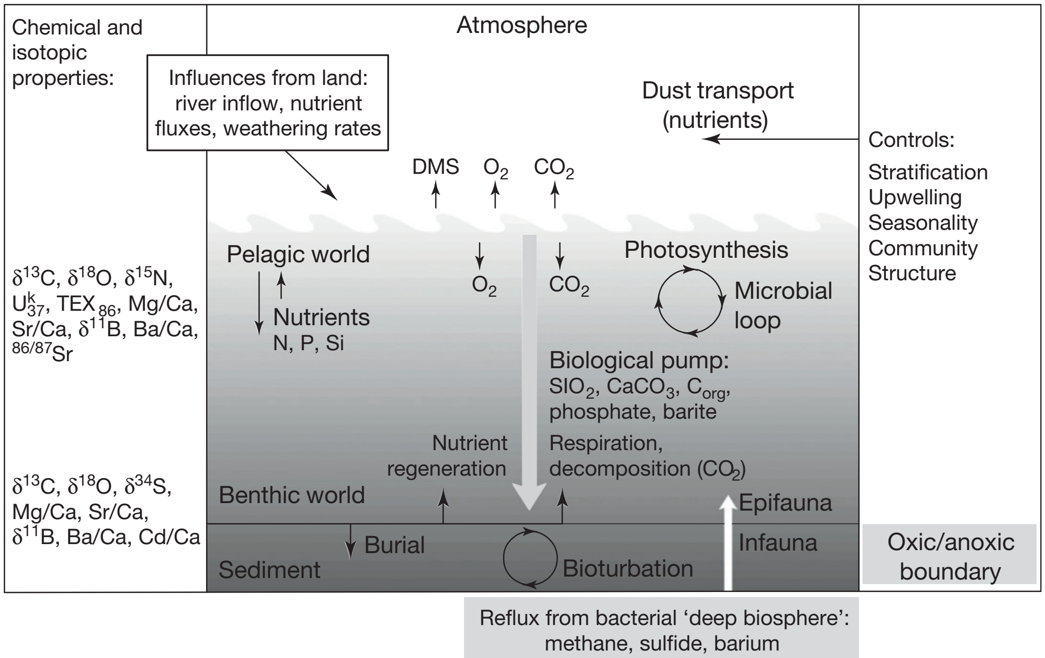

Figure 2 Linkages between the marine biosphere and global biogeochemical cycles, as well as to various proxies used in paleoceanographic studies. The proxies include isotope measurements (indicated by lower case deltas, followed by the elements and the heavier isotope), elemental ratios, and organic geochemical temperature proxies (e.g., U^k_{37}', an alkenone ratio in which the 37 refers to the carbon number of the alkenones; TEX_{86}, a proxy based on the number of cyclopentane rings in sedimentary membrane lipids derived from marine crenarchaeota). DMS is dimethylsulfide, a sulfur compound produced by oceanic phytoplankton. The various proxies can be used to trace changes in ocean chemistry (including alkalinity), temperature, and productivity, as well as changes in the reservoirs of the carbon cycle. Adapted from Pisias NG and Delaney ML (eds.) (1999)*COMPLEX*: *Conference of Multiple Platform Exploration of the Ocean*. Washington, DC: Joint Oceanographic Institutions.

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Methods used since the first paleoceanographic core studies include micropaleontology, with the most commonly studied fossil groups including pelagic calcareous (see Protozoa, Planktonic Foraminifera) and siliceous-walled (see Protozoa, Radiolarians) heterotroph protists, organic-walled and calcium carbonate cysts of heterotroph and autotroph dinoflagellates, siliceous-walled (Diatoms) and calcareous-walled autotroph protists (see Coccolithophores), benthic protists (see Benthic Foraminifera), and microscopic metazoa, Ostracods (Crustacea), as well as small fish teeth. Micropaleontology is useful in biostratigraphic correlation as well as in its own right, providing information on evolutionary processes and their linkage (or lack thereof) to climate change, the history of oceanic diversity and latitudinal diversity gradients under changing climates, as well as the effect of climate change on oceanic productivity and the ecosystem-wide effects of ocean acidification event (see Sedimentary Record, Reconstruction of Productivity from the).

Classic stable isotopes used widely and commonly in paleoceanographic studies include those of oxygen (see Cenozoic Climate – Oxygen Isotope Evidence) and carbon (see Cenozoic Oceans – Carbon Cycle Models). Carbon isotope records are of prime interest in investigations of deep oceanic circulation (see Ocean Circulation: Meridional Overturning Circulation) and of oceanic productivity (see Sedimentary Record, Reconstruction of Productivity from the and Tracers of Ocean Productivity). In addition to these classic paleoceanographic proxies, many new methods of investigation have been and are rapidly and continuously being developed using different geochemical (stable isotope, radioisotope, trace element, organic geochemical) proxies for many different environmental parameters (see Determination of Past Sea Surface Temperatures). Many more proxies are in development, including proxies on different organic compounds, to investigate aspects of global biogeochemical cycles, ocean oxygenation, biotic evolution and productivity, input of various land-derived organic molecules and thermohaline circulation patterns (see Ocean Circulation: Meridional Overturning Circulation) (Figure 2).

Techniques to correlate the age of features in sediment records recovered at different locations and to assign numerical ages to sediment samples are of the utmost importance to be able to estimate rates of deposition of sediments and their components. Correlation between sediment sections is commonly achieved by biostratigraphic techniques, which cannot directly provide numerical age estimates, and are commonly limited to a resolution of hundreds of thousands of years. Techniques used in numerical dating include the use of various radionuclides (see Sediment Chronologies), the correlation of sediment records to the geomagnetic polarity timescale (see Geomagnetic Polarity Timescale), and the more recently developed techniques of linking high-resolution records of variability in sediment character using core scanners (e.g., color, magnetic susceptibility, density, and sediment composition) to variability in climate caused by changes in the Earth's orbit and thus energy supplied by the sun to the Earth's surface at specific latitudes (see Paleoceanography: Orbitally Tuned Timescales). Such an orbitally tuned timescale has been fully developed for the last 40 My of Earth history, with work in progress for the period of 65–23Ma. Remote sensing techniques are being used increasingly in order to characterize sediment in situ in drill holes, even if these sediments have not been recovered (see Deep-Sea Drilling Methodology), and to establish an orbital chronology even under conditions of poor sediment recovery.

Contributions of Paleoceanographic Studies

Paleoceanographic studies have contributed to a very large extent to our present understanding that the Earth's past environments were vastly different from today's, and that changes have occurred on many different timescales. Paleoceanographic studies have been instrumental in establishing the fact that climate change occurred rapidly and stepwise rather than gradually, whether in the establishment of the Antarctic ice cap on timescales of tens to hundreds of thousands of years rather than millions of years, or in the ending of a Pleistocene ice age on a timescale of decades rather than tens of thousands of years (see Abrupt Climate Change and Millennial-Scale Climate Variability).

Unexpected paleoceanographic discoveries over the last few years include the presence of large amounts of methane hydrates (clathrates), in which methane is trapped in ice in sediments along the continental margins (see Ocean Margin Sediments), in quantities potentially larger than the total global amount of other fossil fuels. The methane in gas hydrates may become a source of energy, with drilling advanced furthest in the waters off Japan and India. Such exploration and use of gas hydrates might, however, lead to rapid global warming if drilling and use of methane hydrates inadvertently led to uncontrolled destabilization. Destabilization of methane hydrates may have occurred in the past (see Methane Hydrate and Submarine Slides) as a result of changes in sea level (see Sea Level Change and Sea Level Variations Over Geologic Time) and/or changes in thermohaline circulation and subsequent changes in deep-ocean temperature (see Methane Hydrates and Climatic Effects). Dissociation of gas hydrates and subsequent oxidation of methane in the atmosphere or oceans have been speculated to have played a role in the ending of ice ages, and in a major upheaval in the global carbon cycle and global warming (see Methane Hydrates and Climatic Effects). The influence on global climate and the global carbon cycle of methane hydrate reservoirs (with their inherent capacity to dissociate on timescales of a few thousand years at most) is as yet not well understood or documented (see Carbon Cycle and Ocean Carbon System, Modeling of).

Most methane hydrates are formed by bacterial action upon organic matter, and another unexpected discovery was that of the huge and previously unknown microbial biomass in seawater, also found buried deep in the sediments (see Bacterioplankton and Microbial Loops). Fundamental issues such as the conditions that support and limit this biomass are still not understood and neither are their linkage to the remainder of the oceanic biosphere and the role of chemosynthesis and chemosymbiosis in the deep oceanic food supply and the global carbon cycle.

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In contrast to these unexpected discoveries, paleoceanographers of a few decades ago could have predicted at least in part our increased knowledge of aspects of climate change such as the patterns of change in sea level at various timescales (see Sea Level Variations Over Geologic Time). The suddenness and common occurrence of rapid climate change events in Earth history, however, was unpredicted. On timescales of millions of years, the Earth's climate was warm globally during most of the Cretaceous and the early part of the Cenozoic (65–35Ma), and the Earth had no large polar ice caps reaching sea level (see Paleoceanography: the Greenhouse World). Drilling in the Arctic Ocean, for instance, established that average summer surface water temperatures might have reached up to 18°C. The use of climate models has assisted in understanding such a warm world (see Paleoceanography, Climate Models in), but the models still cannot fully reproduce the necessary efficient heat transport to high latitudes at extremely low latitudinal temperature gradients.

Paleoceanographic research has provided considerable information on the major biogeochemical cycles over time (see Cenozoic Oceans – Carbon Cycle Models). Geochemical models of the carbon cycle rely on carbon isotope data on bulk carbonates and on planktonic and benthic foraminifera in order to evaluate transfer of carbon from one reservoir (e.g., organic matter, including fossil fuel; methane hydrates) to another (e.g., limestone, the atmosphere, and dissolved carbon in the oceans). Information on pelagic carbonates and their microfossil content as well as stable isotope composition has assisted in delineating the rapidity and extent of the extinction at the end of the Cretaceous in the marine realm. Sedimentological data at many locations have documented the large-scale failure of the western margin of the Atlantic Ocean, with large slumps covering up to half of the basin floor in the North Atlantic as the result of the asteroid impact on the Yucatan Peninsula.

One of the major successes of paleoceanographic research has been the establishment of the nature and timing of polar glaciation during the Cenozoic cooling (see Cenozoic Climate – Oxygen Isotope Evidence and Paleoceanography: the Greenhouse World). After a prolonged period of polar cooling in the middle to late Eocene, the East Antarctic Ice Sheet became established during a period of rapid ice volume growth (<100ky) in the earliest Oligocene, *c.* 33.5Ma. This establishment was followed by times of expansion and contraction of the ice sheet, and the West Antarctic Ice Sheet may have started to grow at *c.* 14Ma. Until recently it was argued that the Northern Hemispheric Ice Sheets formed much later: these ice sheets increased in size around 3Ma (in the Pliocene), and ever since have contracted and expanded on orbital timescales (see Plio-Pleistocene Glacial Cycles and Milankovitch Variability). There is now considerable evidence that the polar ice sheets in the Northern Hemisphere also became established, at least in part, in the earliest Oligocene or even in the middle Eocene, that is, at a similar time as the Southern Hemisphere ice sheets.

The cause(s) of the long-term Cenozoic cooling are not fully known. Possible long-term drivers of climate include the opening and closing of oceanic gateways, which direct oceanic heat transport (see Heat Transport and Climate). Such changes in gateway configuration include the opening of the Tasman Gateway and Drake Passage which made the Antarctic Circumpolar Current possible (see Antarctic Circumpolar Current), and closing of the Isthmus of Panama, which ended the flow of equatorial currents from the Atlantic into the Pacific (see Atlantic Ocean Equatorial Currents and Pacific Ocean Equatorial Currents). Evidence has accumulated, however, that changes in atmospheric CO_2 levels may have been considerably more important than changes in gateway configuration. For instance, long-term episodes of global warmth (in timescales of millions of years) may have been sustained by CO_2 emissions from large igneous provinces (see Igneous Provinces), and short-term global warming (on timescales of ten to one or two hundred thousands of years) could have been triggered by the release of greenhouse gases from methane hydrate dissociation or burning/oxidation or organic material (including peat), or degassing of CO_2 from the oceans, or permafrost decomposition. Decreasing atmospheric CO_2 levels due to decreasing volcanic activity, or change in dominant mode of subduction, and/or increased weathering intensity have been implicated in the long-term Cenozoic cooling. High-resolution paleoceanographic records show that climate change driven by changes in atmospheric CO_2 levels may have been modulated by changes in insolation caused by changes in orbital configuration. Recognition of variability in climatic signals in sediments at orbital frequencies has led to major progress in the establishment of orbitally tuned timescales throughout the Cenozoic (see Paleoceanography: Orbitally Tuned Timescales).

Paleoceanographic research has led to greatly increased understanding of the Plio-Pleistocene Ice Ages as being driven by changes in the Earth's orbital parameters (see Paleoceanography: Orbitally Tuned Timescales and Plio-Pleistocene Glacial Cycles and Milankovitch Variability), and the correlation of data from oceanic sediments to records from ice cores on land. Orbital forcing is the 'pacemaker of the ice ages', but it is not yet fully understood how feedback processes magnify the effects of small changes in insolation into the major climate swings of the Plio-Pleistocene. Ice-core data and carbon isotope data for marine sediments show that changes in atmospheric CO_2 levels play a major role, and these data are used in estimating climate sensitivity to varying levels of atmospheric CO_2. We also do not yet understand why the amplitude of these orbitally driven climate swings increased at *c.* 0.9Ma, and why the dominant periodicity of glaciation switched from 40000 (obliquity) to 100000 (eccentricity) years at that time, the 'mid-Pleistocene revolution'. Effects of glaciation at low latitudes, including changes in upwelling, productivity, and monsoonal activity, are only beginning to be documented (see Monsoons, History of).

Great interest has been generated by the information on climate change at shorter timescales than 20ky, the duration of the shortest orbital cycle, precession. Such climate variability includes the millennial-scale changes that occurred during the glacial periods (see Millennial-Scale Climate Variability) and the climate variations of lesser amplitudes that have occurred since the last deglaciation (see Holocene Climate Variability). These research efforts are beginning to provide information on timescales that are close to the human timescale, on such topics as abrupt climate change (see Abrupt Climate Change), and the fluctuations in intensity and occurrence of the El Niño–Southern Oscillation (see El Niño Southern Oscillation (ENSO)) and the North Atlantic Oscillation (NAO) (see North Atlantic Oscillation (NAO)), during overall colder and warmer periods of the Earth history. Both microfossil and geochemical proxies are used more and more to evaluate and monitor the effect of human actions on coastal environments.

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The Future of Paleoceanography

Past progress in paleoceanography has been linked to advances in technology since the invention of the piston corer in the 1940s. In the early to mid-1980s, paleoceanographic studies appeared to reach a plateau, with several review volumes published on, for example, Plio-Pleistocene ice ages (CLIMAP), the oceanic lithosphere, and the global carbon cycle, as well as a textbook *Marine Geology* by J.P. Kennett. Paleoceanographic research, however, has benefited greatly from research programs in the present oceans (such as the Joint Global Ocean Flux Program, JGOFS), and new technology has spurred major research activity. The extensive use and improvement of the hydraulic piston corer by DSDP/ODP/IODP led to recovery of minimally disturbed soft sediment going back in age through the Cenozoic, making high-resolution studies possible, including paleoceanographic and stratigraphic studies of sediment composition using the X-ray fluorescence (XRF) scanner. Progress in computing led to strongly increased use of paleoceanographic data in climate modeling, and to increased possibilities of remote sensing in drill holes. Developments in mass spectrometry led to the possibility to measure isotopes and trace elements in very small samples, such as those recovered in deep-sea cores, and new proxies continue to be developed, including proxies (e.g., on levels of oxygenation and temperature) using organic geochemical methods.

In 2008, the IODP started drilling with three different platforms, and in 2013 the latest phase will initiate. Drilling activity has become integrated with that of the French research vessel *Marion Dufresne*, which has recovered many long piston cores (several tens of meters) for studies covering the last few hundred thousand years of the Earth history, in the International Marine Global Change Study (IMAGES) program. Examples of drilling by alternative platforms include the drilling in the Arctic Ocean, one of the frontiers in ocean science, and drilling in shallower regions than accessible to the drilling vessel *Joides Resolution*, such as coral drilling in Tahiti for studies of Holocene climate and rates of sea level rise. If these ambitious programs can be carried out, we can expect to learn much about the working of the Earth system of lithosphere–ocean–atmosphere–biosphere, specifically about the sensitivity of the climate system, about the controls on the long-term evolution of this sensitivity, and about the complex interaction of the biospheric, lithospheric, oceanic, and atmospheric components of the Earth system at various timescales.

Further Reading

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Relevant Websites

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ecord.org http://www.ecord.org; – European Consortium for Ocean Research Drilling (ECORD).
iodp.org http://www.iodp.org; – International Ocean Discovery Program (IODP).
ipcc-wg1.ucar.edu http://www.ipcc-wg1.ucar.edu; – Intergovernmental Panel on Climate Change, Working Group 1: The Physical Basis of Climate Change.
ngdc.noaa.gov http://www.ngdc.noaa.gov; – National Geophysical Data Center (Marine Geology and Geophysics).
images-pages.org http://www.images-pages.org; – The International Marine Past Global Change Study (IMAGES).