PALEOCEANOGRAPHY

Overview

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Relevance of Paleoceanography

Paleoceanography encompasses (as its name implies) the study of 'old oceans', i.e. the oceans as they were in the past, including the very deep past. It is a relatively young, highly interdisciplinary field of study, encompassing aspects of all topics in this encyclopedia. Paleoceanography uses properties of oceanic sediments (physical, chemical, biotic) in order to reconstruct various aspects of the environments in these 'old oceans'. Therefore, paleoceanography is limited in its scope by the properties for which proxies from the sediments can be used: ephemeral ocean properties cannot easily and/or directly be studied, although recently the time resolution in some sediment studies has come close to decades. In thinly laminated (varved) ocean sediments an annual resolution is possible and in studies using corals seasonal signals can be deciphered.

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. Several types of proxy data make it possible, for instance, to reconstruct the temperature and nutrient content of deep and surface waters at various locations in the world's oceans at various times, 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 benthic and planktic microfossils, allowing a view of interactions between fluctuations in oceanic environments and oceanic biota, on short and evolutionary timescales.

Paleoceanographic data serve climate modelers in providing data on boundary conditions of the ocean–atmosphere system which are very different from those in the present world. Paleoceanography provides information 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 and the location of oceanic gateways and 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 ubiquitous temperatures close to freezing?

In providing this information, paleoceanography 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 since 1983, and the locations of these meetings reflect the international character of the paleoceanographic research community: ICP1 was held in Zürich (Switzerland, 1983), ICP2 in Woods Hole (USA, 1986), ICP3 in Cambridge (UK, 1986), ICP4 in Kiel (Germany, 1989), ICP5 in Halifax (Canada, 1992), ICP6 in Lisbon (Portugal, 1998). ICP7 (Japan, 2001).

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 its first 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 the journal 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 data generated on material of the sedimentary record in the oceans (*see* **Authigenic Deposits, Calcium Carbonates, Clay Mineralogy, Ocean Margin Sediments, Pore Water Chemistry, Sediment Chronologies**), including such materials as carbonates, clays, and authigenic minerals, as well as carbonate secreted by colonial or individual corals (*see* **Past Climate From Corals**). As indicated above, sediments recovered from now-vanished oceans as well as sediments recovered from the present oceans are included, but paleo-oceanography 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 still is in existence in the oceans (has not yet been subducted), i.e., the last 200 million years or so of Earth history (*see* **Propagating Rifts and Microplates, Mid-ocean Ridge Geochemistry and Petrology, Seamounts and Off-ridge Volcanism**).

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 initiation of modern oceanography with the *Challenger* expedition (1872–1876). Little research was conducted on deep-sea sediments between this time and the 1950s, although some short cores had been collected by the German South Polar expedition (1901–1903) and the Dutch *Snellius* expedition (1929–30). The lack of information on oceanic sediments is documented clearly by the statement in the book *The Oceans*, by H. Sverdrup, N. Johnson, and R. Fleming (1942):

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

The situation quickly changed in the post-war years, with increased funding for geology and geophysics, and major expansion occurred in the US oceanographic institutions, specifically Woods Hole Oceanographic Institution (Woods Hole, Massachusetts), Scripps Institution of Oceanography (La Jolla, California), and the Lamont Geological Observatory of Columbia University (Palisades, NY), now the Lamont-Doherty Earth Observatory. At the latter institution, extensive sediment coring expeditions with the R/V *Vema*, instigated by M. Ewing, led to the establishment of large collections of cores, mainly of lengths of several meters.

Cores collected by R/V *Vema* were the basis for seminal papers in paleoceanography, such as the 1956 paper in which D.B. Erickson and G. Wollin used information on pelagic oceanic microorganisms (foraminifera, *see* **Protozoa, Planktonic Foraminifera**) to reconstruct the oceanic pelagic biogeography (*see* **Pelagic Biogeography**) over the last ice ages. The development of the oxygen isotope method to reconstruct past oceanic temperatures using carbonate sediments by Harold Urey, first outlined in a paper in *Science* in 1948, was used on oceanic microfossils by C. Emiliani (1955), in order to reconstruct ocean surface temperatures during the Pleistocene ice ages. It turned out that the oxygen isotope record was more complex and combined signals of temperature change as well as ice volume (*see* **Cenozoic Climate — Oxygen Isotope Evidence**), but the method has become widely established since those early days, and is still one of the 'workhorses' of paleoceanographic research.

One of the limitations of paleoceanographic research using samples from ocean cores is obviously 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, and information became available from many independent proxies on the same sample set.

Material older than the last few hundred thousand of years became available only in much longer cores which could be recovered only after the start of the Deep Sea Drilling Project (DSDP) in 1968, an outflow of a suggestion by W. Munk (Scripps Institution of Oceanography) and H. Hess (Princeton University) in 1957 to drill deeply into the earth and penetrate the crust/mantle boundary. In the mid-1970s, various countries joined the USA in the International Phase of Ocean Drilling, and DSDP became a multinational effort. Between 1968 and 1983 the drill ship *Glomar Challenger* recovered more than 97 km of core; the program was followed by the Ocean Drilling Program (ODP) with its drilling vessel *Joides Resolution* (*see* **Deep-sea Drilling Methodology, Deep-sea Drilling Results**). Cores recovered by DSDP provided the material for the first paper which used oxygen isotopes to outline the Cenozoic climate history and the initiation of the Antarctic ice sheets, published in the *Initial Reports of the Deep Sea Drilling Project* in 1975 by N.J. Shackleton and J.P. Kennett.

Paleoceanographic Techniques

Over the last 25 years there has been an explosive development of techniques for obtaining information from oceanic sediments. Methods used since the first paleoceanographic core studies include micropaleontology, with the most commonly studied groups including pelagic calcareous (*see* **Protozoa, Planktonic Foraminifera**) and siliceous-walled (*see* **Protozoa, Radiolarians**) protists as well as calcareous-walled and siliceous-walled pelagic protist algae (calcareous nanoplankton and diatoms), benthic protists (*see* **Benthic Foraminifera**), and microscopic metazoa, Ostracods (Crustaceans). Micropaleontology is useful in biostratigraphic correlation, as well as in its own right, providing information on evolutionary processes and linkages to climate change, as well as on changes in patterns of oceanic productivity (*see* **Sedimentary Record, Reconstruction of Productivity from the**).

Classic stable isotopes used in paleoceanography include those of oxygen (*see* **Cenozoic Climate – Oxygen Isotope Evidence**) and carbon (*see* **Cenozoic Oceans – Carbon Cycle Models**). Carbon isotope records proved to be of prime interest in investigations of oceanic circulation and of oceanic productivity (*see* **Sedimentary Record, Reconstruction of Productivity from the**). In addition to these 'classic' paleoceanographic methods, many new methods of investigation are being developed using different geochemical proxies. Proxies are commonly measured in the carbonate shells of pelagic and benthic microorganisms, thus providing records from benthic and pelagic environments. Many more proxies are in development and can be expected to come online in the next few years, to investigate many aspects of global biogeochemical cycles, biotic evolution and productivity, and thermohaline (*see* **Thermohaline Circulation**) circulation patterns (**Figure 1**).

Techniques to correlate sediment records recovered at different locations, and to assign numerical ages, are clearly of the utmost importance to derive age models for sediments, and to be able to estimate rates of processes. Correlation between sediment sections is commonly achieved by biostratigraphic techniques, which cannot directly provide numerical age estimates. Techniques used in numerical dating include the use of radionuclides (*see* **Sediment Chronologies**), the correlation of

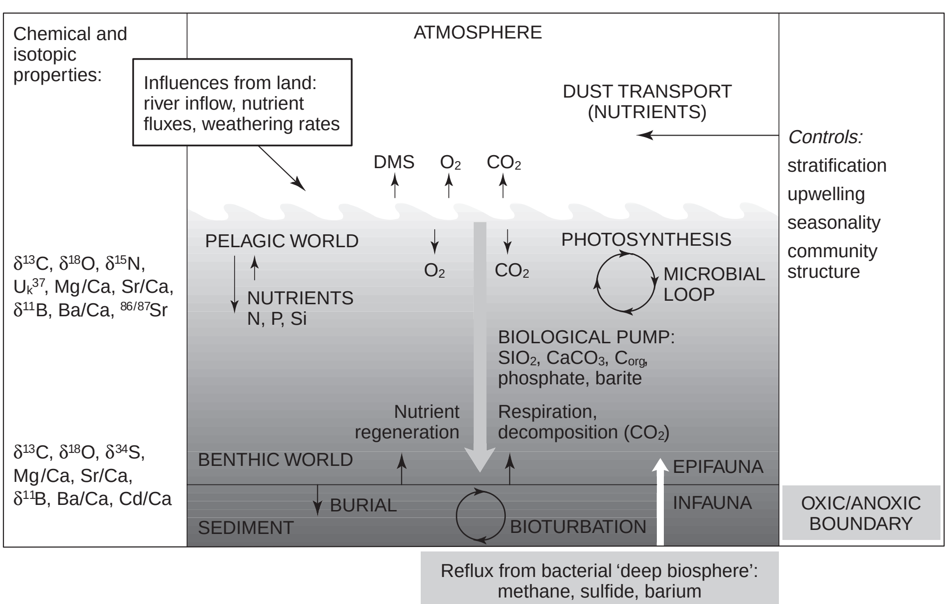

Figure 1 Linkages between the marine biosphere and global biogeochemical cycles in the oceans, as well as to various proxies used in paleoceanographic studies. The proxies include particular isotope measurements (indicated by lower case deltas, followed by the elements and the heavier isotope), organic geochemical finger prints (e.g. Uk^{37}, which is an alkenone ratio, in which the 37 refers to the carbon number of the alkenones of interest), and elemental ratios. DMS is dimethylsulfide, a sulfur compound produced by oceanic phytoplankton. These 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 and Delaney, 1999.)

sediment records to the geomagnetic polarity timescale (*see* **Geomagnetic Polarity Timescale**), and the more recently developed techniques of linking variability in sediment character (e.g. color) to pacing in climate supplied by changes in the Earth's orbit and thus energy supplied by the sun at specific latitudes (*see* **Orbitally Tuned Timescales**). 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 for laboratory studies (*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 todays', and that changes have occurred on many different timescales. Evidence from paleoceanographic studies has been instrumental in establishing that climate change occurred rapidly, stepwise rather than gradually, whether in the establishment of the Antarctic ice cap on timescales of tens to hundred thousands rather than millions of years, or the ending of a Pleistocene ice age on a timescale of decades rather than ten thousands of years.

Unexpected paleoceanographic discoveries over the last few years include that of large amounts of methane hydrates (clathrates), methane stored in ice in sediments along continental margins, in amounts considerably larger than the total global amounts of fossil fuels (*see* **Methane Hydrates**). Gas hydrates may become a new source of energy, but destabilization and dissociation of methane hydrates occurs as a result of changes in sea level (*see* **Sea Level Variations Over Geologic Time, Sea Level Change**). Changes in thermohaline circulation and subsequent changes in deep-ocean temperature (*see* **Methane Hydrates and Climatic Effects**) may have caused major slumps on continental margins and possibly tsunamis. Such dissociation and subsequent oxidation of methane in the atmosphere has been speculated to end ice ages, or to cause major upheaval in the global carbon cycle and global warming (*see* **Methane Hydrates and Climatic Effects**). The influence of the large methane hydrate reservoirs with their inherent capacity to dissociate on timescales of a few thousand years at most on global climate on various timescales and on the global carbon cycle functioning still must be elucidated.

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 buried deep in sediments. Fundamental issues such as the conditions that support and limit this biomass are not yet understood and neither are its linkages to the remainder of the oceanic biosphere, and the importance, now and in the past, of chemosymbiosis as a part of the deep-oceanic food supply, and thus in the global carbon cycling.

In contrast to these unexpected discoveries, paleoceanographers of a decade ago could have predicted our increased knowledge of climates of the past, on various timescales, although the suddenness and common occurrence of rapid events 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. We do not understand what drives long-term climate processes such as the Cenozoic cooling; possible drivers include atmospheric CO_2 levels, and opening and closing of oceanic gateways which direct heat transport by the oceans.

We have learned much about the nature of this warm 'greenhouse world': a world characterized by low latitudinal and depth temperature gradients in the oceans, and the possible occurrence of widespread anoxia. An unexpected observation was the occurrence of short-term episodes of extreme warmth, such as the one that occurred at the end of the Paleocene period (about 55 Ma). Episodes of extreme warmth may have been triggered on timescales of a few millions of years by CO_2 emissions from large igneous provinces (*see* **Igneous Provinces**), on a timescale of thousands of years by dissociation of methane hydrates. Use of climate models (*see* **Paleoceanography, Climate Models in**) has helped in understanding the 'greenhouse world', but has also demonstrated that we lack understanding of mechanisms to transport heat to high latitudes efficiently at extremely low latitudinal temperature gradients. We have also learned much about the patterns of changes in sea level at various timescales (*see* **Sea Level Variations Over Geologic Time**), in times at which large polar ice sheets were present and at which they were absent.

Paleoceanographic research has provided information on the major biogeochemical cycles over time (*see* **Cenozoic Oceans – Carbon Cycle Models**); geochemical models of the carbon cycle rely on carbon isotopic data on bulk carbonates in order to evaluate transfer of carbon from one reservoir (e.g. organic matter) to another (e.g. limestone). Information on pelagic carbonates and their microfosssil content as well as stable isotope composition have assisted in delineating the rapidity and extent of the extinction at the end of the Cretaceous in the pelagic realm. Data on sediment character at many sites have been used to reconstruct the large-scale failure of the North Atlantic western margin, with slumps covering up to half of the basin floor in the North Atlantic, following the meteorite 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 (*see* **Cenozoic Climate – Oxygen Isotope Evidence**). The east Antarctic ice sheet became established, after a prolonged period of cooling in the middle to late Eocene, by the earliest Oligocene (about 33.5 Ma), during a period of about 100 000 years of rapid ice sheet growth. The Antarctic ice sheet expanded, and the west Antarctic ice sheet started to grow in the middle part of the Miocene, with a major expansion at about 14 Ma. Northern Hemispheric glaciation started much later, with expansion of the Northern Hemispheric ice sheets starting in the late Pliocene at about 3 Ma. As noted above, causes of these long-term intensifications of global cooling and increased polar ice volume are not yet clear. Changes in atmospheric CO_2 level as a result of changes in volcanic output rates, changes in weathering intensity and take-up of CO_2, as well as changes in oceanic gateways (such as the opening of Drake Passage and the closing of Panama Straits) and thus passages for heat transport through surface currents have been mentioned most commonly.

Another success story of paleoceanographic research is the enormously increased understanding of the Plio-Pleistocene ice ages as being driven by changes in Earth's orbital parameters (*see* **Orbitally Tuned Timescales**), and the correlation of the data from oceanic sediment cores to records from ice cores on land. Although we know that orbital forcing is the 'pacemaker of the ice ages', we do not yet understand which feedback processes work in magnifying the effects of the small changes in insolation into the major climatic swings of the Plio-Pleistocene. We do not yet understand why the amplitude of these orbitally driven climate swings increased at about 0.9 Ma, and why the dominant periodicity of glaciation switched from 40 000 (obliquity) to 100 000 (eccentricity) years at that time, the so-called mid-Pleistocene revolution. In addition, effects of the high-latitude glaciation at low latitudes, and changes in upwelling, productivity, and monsoonal activity during these climatic fluctuations, are only beginning to be documented (*see* **Monsoons, History of**). Recognition of orbital-frequency signals in much older sediments (back into the Paleogene) has led to the expectation that precise correlation of such older sequences will prove to be possible in the near future (*see* **Orbitally Tuned Timescales**).

Great interest has been generated by the information on climate changes at much shorter timescales, the millennial-scale climate change of the glacial periods (*see* **Millenial Scale Climate Variability**), and the climate fluctuations of lesser amplitude during the Holocene (*see* **Holocene Climate Variability**). These research efforts are beginning to provide information on timescales that are getting close to the human timescale, on such topics as abrupt climate change (*see* **Abrupt Climate Change**), and the intensity and occurrence of such climatic variations as the El Niño-Southern Oscillation (*see* **El Niño Southern Oscillation (ENSO)**) and the North Atlantic Oscillation (*see* **North Atlantic Oscillation (NAO)**) during overall colder or warmer periods than today.

The Future of Paleoceanography

Past progress in paleoceanography has been linked to advances in technology. In the early to mid-1980s, paleoceanographic studies appeared to reach a plateau, with several review volumes published, e.g. Pleistocene Ice Ages (CLIMAP), the oceanic lithosphere, and the global carbon cycle, as well as a textbook. New technology, however, spurred major activity until the present day, and research benefited from the results of present ocean-observation programs such as the Joint Global Ocean Flux Studies (JGOFS).

The extensive use of the hydraulic piston corer by DSDP/ODP led to recovery of minimally disturbed soft sediment, making more high-resolution studies a possibility. The development of the Global Positioning System led to more precise determination of a ship's location at sea. The development and miniaturization of computers led to 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 possible detection of more isotopes and trace elements in very small samples, such as those recovered in deep-sea cores, so that new proxies could be developed. Many of these newer ideas have not yet been compiled into review volumes. Some reviews are available in various documents prepared to review achievements and plan for paleoceanographic research in the twenty-first century.

The Ocean Drilling Program is scheduled to end in 2003; it may be followed by the Integrated Ocean Drilling Program (IODP). IODP drilling activities may be integrated with drilling of long (up to 30 m) piston cores by the French research vessel *Marion Dufresne*, which in its present international phase of drilling (IMAGES) provides most material for studies covering the last few hundred thousands of years or less. International drilling efforts may incorporate drilling by alternative vessels, such as drilling in the Arctic Ocean, one of the frontiers in ocean science, and drilling from platforms in shallower ocean regions than are accessible to the present drilling vessel. If these ambitious programs are indeed carried out, we can expect to learn much more about the working of the Earth's system of lithosphere–ocean–atmosphere–biosphere, specifically about the sensitivity of the climate system to changes, about the controls on the long-term evolution of this sensitivity, and about the complex interactions of the biospheric, lithospheric, oceanic, and atmospheric components of the Earth system at various timescales.

See also

Abrupt Climate Change. Authigenic Deposits. Benthic Foraminifera. Calcium Carbonates. Cenozoic Climate – Oxygen Isotope Evidence. Cenozoic Oceans – Carbon Cycle Models. Clay Mineralogy. Deep-sea Drilling Methodology. Deep-sea Drilling Results. El Niño Southern Oscillation (ENSO). Geomagnetic Polarity Timescale. Holocene Climate Variability. Igneous Provinces. Methane Hydrates and Climatic Effects. Methane Hydrates. Mid-ocean Ridge Geochemistry and Petrology. Millenial Scale Climate Variability. Monsoons, History of. North Atlantic Oscillation (NAO). Ocean Margin Sediments. Orbitally Tuned Timescales. Paleoceanography, Climate Models in. Past Climate From Corals. Pelagic Biogeography. Pore Water Chemistry. Propagating Rifts and Microplates. Protozoa, Planktonic Foraminifera. Protozoa, Radiolarians. Sea Level Variations Over Geologic Time. Sea Level Change. Seamounts and Off-ridge Volcanism. Sedimentary Record, Reconstruction of Productivity from the. Sediment Chronologies. Thermohaline Circulation.

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PALEOCEANOGRAPHY, CLIMATE MODELS IN

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Introduction

Climate models have been applied to the investigation of ancient climates for about 25 years. The early investigations used simple energy balance models, but since the 1970s increasingly more elaborate atmospheric general circulation models (AGCMs) have been applied to paleoclimate problems. It is only within the last decade that climate model results have been used to drive ocean circulation models to simulate the behavior of ancient oceans. Similarly, increasingly more complex ocean models have been used since the 1970s to explore the effects of changing boundary conditions on