Paleoceanography: Sea Floor Clues to Earlier Environments

In seeking to understand climate change and other environmental transformations, investigators are increasingly looking to the record of past environments, especially to the huge reservoir of data in sea floor sediments. There they are finding evidence of remarkable changes in the earth's climate over the past 100 million years, changes that appear to be inextricably linked to the evolution of the oceans during this period. Oceanic history was, until recently, sparsely known, so much so that geologists and geochemists often treated the ocean basins as an "infinite sink," postulating that they contain whatever detrital materials theories of continental erosion needed to get rid of.

But the cores of sea floor sediments now available from the Deep Sea Drilling Project (see box) have stimulated new interest in paleoceanography and have made possible more quantitative studies. What is emerging is not only a novel picture of past climates and climate mechanisms, but also entirely new information on oceanic circulation patterns, geochemistry, biological productivity, and other aspects of the changing environments of the earth's surface. The investigations have a distinctly practical aspect as well, in that the linking of marine and continental data seems likely to improve geochemical understanding of petroleum resources on the continental shelves and how they were formed.

Paleontologists have long known that the world was much warmer and the climate more uniform 100 million years ago. Since then, the distribution of continents and the configuration of the oceans have changed dramatically through the process of continental drift. These tectonic changes now appear to have played a major role in the deterioration and dramatic cooling of the earth's climate and particularly in the formation, relatively recently in the earth's history, of permanent polar ice caps. In fact, the course of events leading to the colder, latitude-dependent, and fluctuating glacial-interglacial climates of the past million years is a story of the interaction of the solid earth, the oceans, and the atmosphere. The details and even the broad outlines of these environmental changes are only now beginning to be well enough understood to allow a tentative new synthesis.

As the motion of the underlying crustal plates split up the ancient supercontinent of Pangaea, it apparently disrupted the existing global circulation patterns, the chemistry, and the stabilizing climatic influence of the ancestral Pacific Ocean. At first, the new ocean basins forming between the separating land masses were narrow and open to the larger ocean on one end only. Like modern proto-oceans such as the Red Sea, the narrow basins with their restricted circulations seem to have acted as chemical sinks, removing salt and other materials from the seawater and bury-

Deep Sea Drilling: Entering a New Phase

For seven years, the *Glomar Challenger* has been drilling and collecting samples of deep sea sediments. In the process it has had a major impact on the acceptance of plate tectonic theories and has opened new fields of research. Now the ship is beginning a new phase of the Deep Sea Drilling Project in which the nature of the basaltic rock underlying the sediments will be explored.

Geologists compare their present knowledge of the oceanic crustal rock to their knowledge of the sea floor sediments when the drilling program first began—scanty, based on a few samples, indirect geophysical measurements, and inference. Hence they believe that they are poised to learn a lot from the more systematic sampling of the deeper layers of the crust now planned, which will involve drilling to unprecedented depths in the sea floor. Also planned is more drilling and coring of sediments, especially along the margins of the continents, where the sediments are thicker.

If the results from the first seven years of the drilling project are any guide, the new phase of the venture will prove fruitful indeed. These results are now beginning to appear at a rapid rate, as investigators in fields ranging from geophysics to paleoceanography to petroleum geochemistry turn increasingly to the sediment data.

Those data, despite some gaps introduced by coring techniques that have since been abandoned, seem to be of very high quality. According to William Hay of the University of Miami, the cores recovered constitute "such a good sample that we probably know the average composition of sediments in the deep sea better than the average composition of what's on land." This fortuitous circumstance is all the more remarkable in that drill sites were chosen more to answer questions of tectonics than for sediment-sampling purposes.

The sediment cores have become a main source of information on the environment at the earth's surface and in the oceans over the past 100 million years (see accompanying article). Indeed, sedimentologists and paleontologists have dominated the scientific crews on board the *Challenger*, although geophysicists have also played a major role. In addition to the basic studies that the deep sea data have stimulated, their relevance to such timely subjects as climate and petroleum resources has also attracted interest from academic and industrial scientists alike. Maps of earlier sea surface temperatures, models of organic carbon accumulation on the continental shelves, atlases of past populations of microorganisms, and charts of oceanic current systems and their development over time are all in preparation.

The drilling program has continued to uncover evidence of interest to geophysicists as well. The question of whether hot spots fixed in the mantle have been the source of island chains and seamounts, for example, seems to have been answered in the negative, although the evidence is not conclusive. These linear volcanic chains, it had been proposed, were formed as the crustal plate moved horizontally over the hot spot—a model that seems to hold up for the Hawaiian chain. But drilling near the Line Islands in the Pacific and the chain of oceanic volcanoes known as the New England Seamounts in the Atlantic failed to find that these features were of hot spot origin. The New England volcanoes, for example, appear to have been active along the length of the chain simultaneously, rather than one after the other.

Another complication for plate theorists is evidence of vertical motions within the supposedly rigid plates. Subsidence—of oceanic ridges, of large pieces of continental crust, and of whole basins—seems to have been a not infrequent phenomeing them. As the global water mass divided into the modern Pacific, Atlantic, and Indian oceans and the smaller tributary oceans and seas, what had been a relatively homogeneous body of water was broken up and each part isolated to some degree. The major connecting flow among the oceans, a current system that moved along the equator through a nearly circumglobal seaway, the Tethys, was shut off as the seaway closed. Eventually a new current system, the circumpolar flow around Antarctica, became the major link. As the climate cooled, presumably in part because of the new circulation patterns, ice formed at the poles. The effect of the ice on the world oceans was dramatic, forming much colder bottom water and increasing the temperature gradient from the poles to the equator and the climatic differentiation of ocean bodies.

Deducing these and other results from the sea floor sediments is not a little complex. The primary sources of data on oceanic history are the geographical distribution and time sequence of different sediment types and the shells of foraminifera and other tiny ocean-dwelling organisms. Knowledge of the various species and their habitats can give some insight into temperature and circulation patterns of the past oceans, and measurements of the rate at which biogenic sediments are formed reflect the amounts of nutrients available. But the horizontal motions of the oceanic plates, the depth of the sea floor where the sediment was deposited, the relative abundance or scarcity of calcium carbonate and oxygen in the water when the sediment was formed, and the action of deep sea currents can all affect the core samples. As a result, painstaking work with huge amounts of information is required to extract a detailed historical picture.

In addition, measurements of the $^{16}O/^{18}O$ ratio in the fossil sediments can provide information about ice formation and, possibly, water temperatures. The lighter isotope evaporates preferentially, and so precipitation and hence ice in glaciers and polar caps is enriched in ^{16}O relative to seawater. Hence, fluctuations in the amount of water locked up as ice can be determined from variations in the oxygen isotope ratio of fossils locked up in the deep sea sediments. This ratio also varies with the temperature of the water in which the fossil organisms lived, a source of some confusion in the past. Recently, N. J. Shackleton of Cambridge University has shown that the temperature effect is much smaller than the ice effect and hence that temperature fluctuations tend to be masked by ice fluctuations. He believes that the isotope evidence can still be used to determine temperatures before the polar caps were formed, although not all investigators agree. Because the mixing time of the oceans, a few hundred years, is short on the time scale of major climatic changes, the isotopic variations provide a globally consistent signal upon which to base a paleoceanographic chronology, and there is considerable interest in this technique.

The isotope technique has proved useful in determining when significant amounts of ice first formed at the poles. According to James Kennett of the University of Rhode Island, the Antarctic ice cap formed only about 16 million years ago, after Australia had split off and moved away from Antarctica, leaving that continent isolated at the pole and surrounded by the fast-moving circumpolar current. But

non. A submarine ridge at a depth of about 4.6 kilometers near the Grand Banks, for example, was found to contain reef material that must once have been at the sea surface.

The new phase of the drilling project will cover less ground than the earlier phase, in part simply because of the difficulty of drilling as much as 2000 meters into volcanic rock. The first such deep hole, now being attempted, will require nearly four months of drilling if all goes well. As a result, fewer holes will be drilled, and considerable effort is being put into choosing the correct site and getting as much information from the hole as possible. The latter is especially important because of concern as to how typical of the crust in a given area one sample is, in light of growing evidence of the extreme variability of the sea floor over distances of a kilometer. Thus on some holes temperature, levels of radioactivity, and other quantities will be measured continuously during drilling. Experiments deep within the holes are also being contemplated. Setting off small charges, for example, would make possible seismic studies of the structure of surrounding rock out as far as 10 kilometers.

In addition to information on igneous rock forms and the geological structure of the crust, the magnetization of the crust will be of particular interest to many geophysicists. Magnetic anomalies presumably frozen into the sea floor as it was formed have been a prime source of data in reconstructing the motions of the crustal plates. But calculations indicate that only 500 meters of magnetized rock will produce the observed anomalies, leading to questions about the magnetic state of the lower rock and the causes of the phenomenon.

Over and above its scientific goals, the Deep Sea Drilling Project has become a significant arena of international cooperation. West Germany and the Soviet Union have contributed financially to the project for the last two years. Japan and Britain have now joined too, and France is reported to be on the verge of signing. At the going rate of $1 million per country per year, the foreign contribution to the $50 million budget of the project over the next three years is still small compared to the U.S. share. But participation has extended far beyond money, bringing together on shipboard scientists from all over the world. Even tiny Switzerland, for example, has had 19 scientists aboard. Many younger U.S. scientists believe that service on the *Challenger* has been a rare opportunity to work with distinguished foreign investigators they would not normally have a chance to meet.

There is some controversy over how to best use the resource that the *Challenger* represents, largely because the current drilling plans do not call for any more holes at high latitudes. The argument pits paleoenvironmentalists against scientists interested in the crust and the continental margins. The paleoenvironmentalists point out that events controlling climatic and oceanographic development of the earth for much of the past 40 million years seems to have occurred in the polar regions. But, they say, there are huge gaps in the data—the date of the opening of the Drake Passage between Antarctica and South America, for example, is still unknown—and no relevant drilling is scheduled. The crust and continental margin people, many of whom have been eagerly awaiting drilling opportunities for years, reply that it just worked out that way in the logistics of scheduling, and besides, the *Challenger* is not really equipped for drilling in hazardous, ice-filled waters. But they admit that the critics have a point.

Despite the dispute, there seems to be wide support for the drilling program within the scientific community. Interest in the cores as a source of data continues to grow. More than 50,000 samples have been distributed to researchers, half of them in the past two years, and the volume of requests received at the core repositories at Scripps Institution of Oceanography and the Lamont-Doherty Geological Observatory is rising. There is every indication that this particular investment in big science is paying off more handsomely than even its supporters had hoped.—A.L.H.

ice may have played a crucial role even earlier, about 38 million years ago, at the boundary between the Eocene and Oligocene geological time zones. Kennett and Shackleton find evidence from that time of a sharp drop in the temperature of the oceans' bottom water, from about 10° to 5°C, in what they believe to have been a major paleoceanographic event. They find that most of the temperature change occurred within 100,000 years or less—nearly instantaneously on a geological time scale. They argue that it probably reflects the first occurrence of extensive sea-ice around Antarctica as the isolation and cooling of that continent reached a critical point. The colder, denser water in contact with the ice sank to the bottom, becoming a new source of bottom waters for the world oceans that has continued to the present. The subsequent cooling of the Arctic Ocean to freezing temperatures has provided another source of cold bottom waters.

The sudden temperature change at the sea bottom killed many bottom-dwelling organisms, eliminating many species altogether and reducing the total population substantially. A simultaneous but less dramatic drop in sea surface temperature also reduced the diversity of sea life in the upper layers of water. Currents associated with the new bottom water circulation appear to have been the cause of widespread erosion on the sea floor and the resulting gaps in the deep sea sediment records about 38 million years ago. Oceanic chemistry was also affected. A shift in the oceanic equilibrium involving calcium carbonate, for example, resulted in the deposition of much more carbonate-rich sediments after 38 million years ago than before.

The development of ice on the continents came more recently, according to Shackleton and Kennett, with the first appearance of a thick Antarctic ice sheet about 16 million years ago as an essentially permanent feature. The formation of a substantial northern hemispheric ice sheet, including that in North America, occurred about 3 million years ago. As the equator to pole temperature gradient intensified, the geographical distribution of surface-dwelling organisms assumed a distinct warm to cold pattern of latitudinal bands.

Much is being learned from the study of the fossil sediments themselves. In the central Pacific, for example, a detailed history compiled by Tjeerd van Andel of Oregon State University and by Theodore Moore, Jr., and Ross Heath, now of the University of Rhode Island, shows that the oceanographic evolution of this region over the past 50 million years has been dominated by the changing configuration of continents and seaways and the progressive glaciation of Antarctica. The influence of the latter has been so great, the investigators conclude, that "events in the Antarctic have been the engine that drove and drives the evolution of the equatorial Pacific." Before this glaciation, van Andel believes, the distribution of water and of nutrients between the deep oceans and the shallower regions of sea and continental shelves may have been the most controlling factor.

The investigators computed accumulation rates of carbonate and carbonate-free sediment in million-year increments along the sediment cores, using a chronology developed by dating the stratigraphic divisions within the sediments. For each sample interval, they determined the depth of the sea floor and the position at the time the sediment was deposited. Depth was found by estimating the rate at which the ocean floor subsides as it moves away from the mid-ocean ridge, and position by backtracking the generally northward movement of the Pacific plate across the equator. The accumulation rates can thus be placed within an accurate environmental context, but their interpretation involves still more detective work on the chemistry of the oceans.

Carbonate Chemistry Unraveled

Calcium carbonate, the main constituent of the shells of foraminifera and many other species of microfauna, dissolves in seawater at a rate that increases with depth. Below a certain point, known as the carbonate compensation depth or CCD (a depth that, to the surprise of geochemists, has fluctuated markedly depending on such things as the overall supply of carbonate and the corrosiveness of bottom water), the sediments that are deposited are free of carbonate. The dissolution of silica, on the other hand, does not depend on depth. And, although much of it does dissolve and is recycled within the water column as a nutrient, the fossils of radiolaria and other species that produce silica-rich shells more often survive in deep water sediments. But the siliceous sediments have proved difficult to measure quantitatively, and paleontologists have so far used carbonate as a tracer for nutrients and biological productivity.

In the period between about 70 and 38 million years ago, van Andel and his colleagues find, the CCD was very shallow, about 3000 meters as compared to 5000 meters in the Pacific today. Most of the deep sea sediments from this time are free of carbonate, except in shallow areas near the mid-ocean ridge. The investigators propose that a very low input of calcium carbonate into the deep oceans was the primary cause. Other evidence that the continents were extensively flooded at this time supports the hypothesis that shallow seas and the continental shelves trapped most of the carbonate and other nutrients emanating from the continents. Thus, van Andel believes, the deep oceans were an underprivileged environment for life, especially considering the relatively high input of nutrients throughout most of the Mesozoic era (from 225 to 70 million years ago).

Beginning about 38 million years ago, however, the supply of carbonate abruptly increased and the CCD retreated to much greater depths. The investigators attribute this change both to the gradual rise of the continents, which ended their flooding and released more nutrients to the oceans, and to a new, Antarctic source of bottom water that was higher in oxygen content and hence less corrosive of the forming sediments. Later, after 32 million years ago, the accumulation of carbonate sediments increased still further, probably reflecting an increase in upwelling that would bring nutrients to the surface in the equatorial regions. The upwelling may have been due to diminution of the old equatorial current system as the Tethys seaway gradually closed. With the permanent glaciation of Antarctica around 16 million years ago and the establishment of a thin layer of very cold, very salty, and more corrosive bottom water, which is characteristic of the present, carbonate dissolution increased and the CCD rose toward its present level.

A recent summary of research on the history of the Atlantic by W. A. Berggren and C. D. Hollister of Woods Hole Oceanographic Institution also shows the interaction of geography, currents, and climate. The Atlantic is in many ways an ideal ocean for sedimentologists because, having no oceanic trenches, it contains a complete sedimentary record from its earliest origins. Berggren and Hollister point out that there is evidence in both the North and South Atlantic of stagnant conditions when the oceans were young and narrow. By about 100 million years ago, however, the North Atlantic had widened enough that an early version of the Gulf Stream flowed northward into the Labrador Sea, and a westward equatorial current flowed through the Tethys, across the Atlantic, and into the equatorial Pacific via the Straits of Panama. Both of these currents persisted essentially unchanged until the last 20 million years and controlled the biogeographic patterns in the North Atlantic. The South Atlantic, which opened from the south, established communication with the North Atlantic about 95 million years ago, although faunal evidence indicates that there was no deep water circulation between the two until later. The researchers find no sign of active bottom water movements until 50 million years ago.

Fifty million years ago, however, the

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separation of Greenland and Spitzbergen formed the Norwegian Sea and thus opened the Atlantic to the Arctic regions for the first time. The event precipitated major changes in the oceanic environment, transforming what had been a tranquil regime into what Berggren and Hollister describe as "commotion in the ocean." Before 50 million years ago, calcium carbonate sediments were deposited throughout the latitudinal range of the Atlantic in what apparently was a relatively homogeneous environment. Since then, however, the sediment patterns reveal an environment characterized by latitudinal and vertical temperature gradients, upwelling, and vigorous bottom currents that eroded and transported sediments over large distances on the sea floor.

More recently, the elevation of the Isthmus of Panama about 3.5 million years ago severed the marine connection to the Pacific and may have contributed to a more vigorous Gulf Stream. Shortly thereafter the initiation of Northern Hemisphere glaciation helped to form the cold Labrador current, displacing the Gulf Stream southward to its present position south of latitude 45°N. And during the subsequent ice ages, there appear to have been repeated invasions of cold polar water into the Atlantic.

A somewhat different type of environmental change discovered in the sea floor sediments is the temporary drying up of the Mediterranean Sea, an event so surprising to many scientists that they refused to believe the initial reports, which have subsequently been confirmed. The Mediterranean is a deep basin, the remnant of the Tethys seaway, which was apparently closed off at the eastern end by the intersection of Africa and Eurasia about 18 million years ago. Then about 6 million years ago the western opening to the Atlantic was also closed off for about 1 million years. Because the rate of evaporation from the sea is so high—more than can be supplied by river inflow—the sea dried up until all that was left was a series of lakes. In the process, huge beds of salt and other evaporites were precipitated. (The beds are so thick that they have not yet been drilled completely through.) Then, according to Kenneth Hsü of Technical University of Zurich, Switzerland, the Gibraltar gate opened again, initiating what must have been the world's most spectacular waterfall as the sea filled again. The episode not only dramatically altered the climate of the surrounding region, but also withdrew a substantial amount of salt from the world oceans. Similar processes during the early history of the Atlantic, according to William Ryan of the Lamont-Doherty Geological Observatory, may have withdrawn as much as 10 percent of the salt in the world oceans, forming huge salt beds off the coast of Africa.

Although much of the research on the deep sea sediments has focused on biogenic materials, currents often carry eroded continental materials some distance from land. Ash from explosive volcanism can be distributed even further. Kennett and Robert Thunell, also of the University of Rhode Island, find that the amount of volcanic ash in sediments from the past 2 million years is at least four times as high as the average for the past 20 million years. The increase was observed over wide areas of the oceans. The finding is significant because the period of exceptionally intensive volcanism coincides closely with the period of the earth's climatic history that has been most unstable, marked by repeated ice ages and alternating interglacial climates. Which is cause and which is effect is still uncertain, but the investigators believe that the association is not coincidental.

Cause and effect for most of the other environmental changes described earlier also remain somewhat speculative, especially the causes for major extinctions of life forms such as mark many of the geological time-zone boundaries. The most sweeping of these changes, at the boundary between the Mesozoic and the present Cenozoic era, is still a mystery. But the deep sea sediments are in many ways a good place to look for important environmental changes in the past, since they are so stable that only really global changes show up. According to William Hay of the University of Miami, the areal distribution of major sediment types has not changed significantly over the last 100 million years. He finds, for example, that sediment patterns in the past are similar to those of the present as measured either by maps of the dominant types or by the content of calcium carbonate, corrected for sedimentation rate.

With such a good data base for the deep sea, Hay believes, it will be easier to tackle the problem of the continental shelves and margins, where the sediment columns are much thicker and largely unsampled. It should be possible, for example, to make estimates of the amount of organic carbon—and hence possibly oil—trapped on the ocean shelves. Hay foresees working from what was on land and what is measured in the deep sea to do an element-by-element mass balance and thus to model a closed geochemical system.

The oceans, no longer a blank spot on geological and geochemical maps, are becoming one of the most active areas of research directed at understanding the planet we live on.—ALLEN L. HAMMOND