Paleoceanographic Musings

BY CHERYL LYN DYBAS

From the moment a strange Icelandic parchment is discovered in an old bookseller's shop, to an eventual descent into the "dark hollow heart" of Earth itself, Jules Verne's novel *A Journey to the Center of the Earth* is a tale of pioneering exploration of new worlds.

In the novel, Professor Hardwigg and his precocious nephew uncover a secret passageway into Earth's interior by translating Runic characters in an old manuscript. And so begins a hazardous, at times frustrating, but ultimately fantastic, journey to the center of the Earth.

Today, sediment cores retrieved by drilling into Earth's oceanic crust—through efforts like the former Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), and current Integrated Ocean Drilling Program (IODP)—are the equivalent of Verne's Icelandic parchment.

As Professor Hardwigg struggles to decipher the meaning of the manuscript's mysterious letters, his nephew has a "Eureka!" moment: "I had got the clue," he exults. "All you had to do to understand the document was to read it backwards."

Similarly, to understand ocean and climate history, paleoceanographers "read sediment backwards": the story's latest chapters are preserved at the beginnings (tops) of sediment cores, and its opening chapters are at the cores' ends (bottoms).

In hundreds of thousands of meters of sediment recovered by drilling are keys to some of Earth's most elusive mysteries.

PALEOCEANOGRAPHY'S SERENDIPITOUS START

Answering many worldwide climatic, oceanic, and geologic questions began with the study of micropaleontology. The fossil skeletons of some of Earth's tiniest oceanic life forms—protozoans like foraminifera ("forams") and radiolarians ("rads"), the former made of calcium carbonate, the latter of opaline silica—contain chemical information that records environmental change.

As geologist Cesare Emiliani and chemist Harold Urey of the University of Chicago (Emiliani later moved to the University of Miami) found in the early 1950s, the ratio of the stable isotopes of oxygen in a fossilized microscopic shell reflects the temperature of the water in which the shell grew.

"Paleoceanography originated in an almost casual remark," remembered Emiliani years later, recalling a lecture of Urey's in which he advanced the notion that saline waters in the ocean should be richer in the heavier isotopes of oxygen than fresh waters.

"From a piece of uranium-bearing rock we can estimate the age of the earth; from a sliver of bone we can date a prehistoric camp site," wrote Emiliani, considered the father of modern paleoceanography, in a 1958 paper. "The clocks that make such dating possible are radioactive isotopes of the elements. Isotopes have provided us with another tool for looking into a distant past—a 'thermometer' that tells the temperatures of ancient seas."

In paleoceanographic terms, Urey had translated the Runic code in Jules Verne's ancient Icelandic manuscript. Forams were the characters.

When forams and other planktonic life forms die, their skeletons rain down upon the ocean floor. Mixed with silt and clay, they form oozes that carpet vast areas of the deep sea. The oozes accumulate very slowly, averaging 1 to 3 centimeters every 1,000 years. Over millennia they pile up to great thicknesses.

In the interval between 200 and 65 million years ago, especially from 100 to 65 million years ago, the abundance and diversity of microscopic plankton in the oceans greatly increased. During the Cretaceous Period, sea level was high, and shallow seas lapped onto continents. The environment was favorable for an explosion in numbers of species of

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forams, radiolaria, and coccolithophores.

At the end of the Cretaceous, many of Earth's life forms suddenly became extinct, including many microscopic marine species. Comparatively few survived.

The long snowfall of material to the ocean floor was "suddenly" less biogenic. Clays temporarily became more widespread, forming a centimeters-thick layer and marking a boundary in time.

Ocean sediment cores would thus shed light on questions left unanswered by evidence on land, Emiliani believed.

DESCENT INTO THE UNKNOWN

Emiliani was right: seafloor sediment cores allowed scientists to make discoveries from confirmation of the catastrophic impact of a meteorite 65 million years ago, to the opening and closing of gateways between continents and their effect on global climate.

Early findings were about the causes of Earth's ice ages. "Current research," wrote Emiliani in 1950s scientific papers, "supports the theory worked out in the 1920s by Serbian physicist Milutin Milankovitch: fluctuations in the Earth's orbit and in its axis of rotation periodically change the pattern of reception of heat from the sun, so that there are long periods when the summers are cool and the winters mild, alternating with periods of hot summers and cold winters."

In cool Northern Hemisphere summers, during which most winter snow stays frozen, ice covers a much larger part of Earth. Milankovitch calculated that the coolest summers would arrive at intervals some 40,000 years apart. "The analysis of the microfossils in cores indicates that the low points in ocean temperatures indeed occurred at 40,000-year intervals," said Emiliani. "If Milankovitch's theory [of cycles] is correct, about 10,000 years from now there will be another advance of the glaciers, burying Chicago, Berlin, and Moscow under thousands of feet of ice."

Emiliani based his deductions on sediments retrieved with an early piston corer developed in the 1940s. With the advent in the late 1960s of DSDP's more advanced coring technology, and the refinement of isotopic analyses, paleoceanography entered a new era. Some would say that's when the field really began.

"The first attempt to take a global look at paleoclimate in the oceans occurred in the CLIMAP [Climate/Long Range Investigation Mappings and Predictions] project in the 1970s," said paleoceanographer Nick Pisias of Oregon State University. "CLIMAP showed the value of the ocean sediment record in understanding the history of ocean circulation and its influence on Earth's climate."

Results from CLIMAP led to a turning point in paleoceanography. Geologists James Hays of Columbia University, John Imbrie of Brown University, and Nick Shackleton of Cambridge University published a paper based on CLIMAP data in the December 10, 1976, issue of *Science*. They advanced the idea that major long-term changes in past climate are associated with variations in the geometry of Earth's orbit; these changes, stated Hays, Imbrie, and Shackleton, are linked to orbital variations with periods of 20,000 years and longer. Their paper—"Variations in Earth's Orbit: Pacemaker of the Ice Ages"—led to major acceptance of the Milankovitch hypothesis.

"After CLIMAP, the field essentially split into two parts," said Bruce Malfait, former Director, Ocean Drilling Programs, at the National Science Foundation. "Sediment retrieved in short piston cores [obtained from conventional research vessels] became used primarily in paleoclimatology, while material from DSDP's and ODP's much longer cores fostered the development of paleoceanography as we know it today."

Added Pisias, "With the development of the hydraulic piston corer in DSDP and the advanced piston corer in ODP [which provided high-quality core materials] parts of the two communities of scientists were reunited."

Hence, the terms paleoclimatology and paleoceanography are often used interchangeably. Paleoceanography is defined, however, as the study of all features of the past oceans—temperature, salinity, ocean circulation, biogeochemistry, carbon cycling, and others.

Paleoceanographer James Kennett of the University of California at Santa Barbara has identified three paradigm shifts in the history of the field: the first, from the mid-1960s to mid-1970s, concentrated on plate tectonics through evidence retrieved by rotary coring; a second from the late 1970s to early 1990s, in which undisturbed sediment could be recovered through newer coring methods, led to a focus on understanding the basic tenets of paleoceanography; then finally an evolution from 1990 to the present of an integrated global view of the planet, as the study of Earth system history.

"We've gone from studying the lithosphere to the hydrosphere, from the atmosphere to the cryosphere to the biosphere," said Kennett. "Now we're trying to understand the whole picture in the 'anthrosphere,' which includes our effects on the globe."

Rapid progress in paleoceanography happened in the past few decades, he believes, as a result of engineering advances that enabled recovery of continuous deep-sea sediment cores; development of biostratigraphic correlations, which provided a temporal framework for interpreting the cores; confirmation of the concept of plate tectonics, which gave a context for interpreting paleogeography; and development of new geochemical, mineralogical, and other techniques that allowed for interpretations of the paleoenvironmental conditions under which sediments were deposited.

"Ocean drilling has resulted in spectacular paleoceanographic and geologic revelations," said Margaret Leinen, a paleoceanographer and NSF Assistant Director for Geosciences.

FIVE OUTSTANDING CONTRIBUTIONS

Gateways: Opening and Closing of Seaways Led to Ocean Circulation and Climate Changes

Paleoceanographers discovered that rapid (decadal to centennial scale) climate shifts are a global phenomenon, and documented climate extremes, including ocean-wide anoxic events, said Leinen. "They confirmed that a 'hothouse world' existed some 55 million years ago, when warm subtropical climates prevailed even at the polar regions."

Millions of years later, a passageway formed between Australia and Antarctica, found Kennett and colleagues, setting up a situation in which the hothouse era ended and a 40-million-year cooling of the Earth began. Kennett and others initially made the discovery on DSDP Leg 29, then re-confirmed it on the later ODP Leg 189.

"During the Cenozoic Era," said Kennett, "Australia separated from Antarctica and 'drifted' northward, which opened the Tasmanian Gateway and allowed the Antarctic Circumpolar Current to develop. This current began to isolate Antarctica from the influence of warm surface currents from the north, and an ice sheet started to form."

Eventually, conduits led to deepwater circulation between the southern Indian and Pacific Oceans and ultimately to "ocean conveyor belt" circulation. "Continuing Antarctic thermal isolation caused by this continental separation," said Kennett, "contributed to the evolution of global climate from relatively warm early Cenozoic 'greenhouse' to late Cenozoic 'icehouse.'"

Sediments Off New Jersey Tell Tale of Long-Ago Ice Sheet Formation

Sediments recovered off the New Jersey coast on ODP Leg 150 tell a long-ago tale of sea-level rise and fall. Ken Miller, a geologist at Rutgers University in New Jersey, was among scientists on ODP Leg 150 who studied the sedimentary record of sea-level changes extending back 35 million years. Reading the sediment layers, he gained clear insights into how large, rapid global sea-level change results from the waxing and waning of Northern Hemisphere ice sheets.

The New Jersey continental margin underwent a dramatic change during Earth's transition from hothouse to icehouse. Miller and colleagues found calcium carbonate chalks from a warmer climate lying beneath sands and muds deposited by glacial activity. About 22 million years ago, surface waters in this region became unusually productive, resulting in blooms of diatoms and an abundant supply of organic carbon to the seafloor. Another sharp change happened about 14 million years ago, when increasing sediment, wood fragments, and organic matter were deposited from adjacent land masses. Sedimentation took yet another turn about 600,000 years ago when large continental ice sheets advanced to and retreated from New Jersey.

In a later ODP leg, 174AX, an onshore extension of an offshore expedition, Miller found that sea-level changes during the Late Cretaceous Period were huge, more than 25 meters, and rapid, occurring on timescales of thousands to less than a million years. Ice formation in Antarctica likely caused these sea-level changes—in a period previously thought to be ice-free. Ice sheets confined to the continent's interior would explain the finding, Miller believes. Although the ice would not have reached the coast, it would have been enough to alter global sea-level significantly.

The Eocene: Rads Ruled

"Radiolaria ruled the Eocene," said Ted Moore, a paleoceanographer at the University of Michigan, "if the stratigraphic record from that time is any indication." Moore has conducted paleoceanographic research on DSDP and ODP legs, including ODP Leg 199 in the central equatorial Pacific. There he and others found that the path of plate motions carried a trace of equatorial upwelling and productivity northward—in radiolarians preserved in sediments. The sediments contain a carbonate and siliceous interval from the Holocene through the base of the Oligocene. But through the Eocene and Paleocene, the section is composed primarily of radiolarian ooze and red clay, giving scientists a rare look at this important zone of upwelling through time.

"Biostratigraphy, based on the presence of particular assemblages of foraminifera, coccoliths, radiolaria. and diatoms, has been critical to understanding what sediments in cores have to tell us," said Moore. "When DSDP got underway, knowledge of the taxonomy and stratigraphy of radiolarians blossomed. Rads are very useful in paleoceanography, especially in regions where calcium carbonate in forams isn't preserved well or at all, such as in high-latitude oceans." Dozens of species of radiolaria are present in Arctic and Antarctic seas, and in areas of the oceans where there is strong upwelling, such as the equatorial Pacific.

On ODP Leg 199, Moore and colleagues used accumulation rates of biogenic debris (such as fossilized rads) to determine the position and strength of upwelling zones in the early Paleogene, a time of unexplained very warm temperatures.

Oceans Warmer than a Hot Tub

Tropical Atlantic Ocean temperatures between 100 million and 84 million years ago reached 42°C—about 14°C higher than today. These temperatures are off the charts when compared to what was previously known, according to paleoceanographer Karen Bice of the Woods Hole Oceanographic Institution. To determine these ancient ocean temperatures, Bice and others analyzed sediment cores retrieved from the seafloor off Suriname in South America on ODP Leg 207. They used core samples to estimate both ocean temperatures and atmospheric carbon dioxide levels: when the ocean was hot-tub-hot, atmospheric carbon dioxide levels may have been 1,300 to 2,300 parts per million (ppm). Today's level is about 380 ppm, and rising.

Bice's research suggests that future ocean warming from the build-up of greenhouse gases may be much greater than predicted.

Global Signals...

During January 2006, paleoceanography lost one of its greatest scientists and also announced one of its most far-reaching discoveries.

Paleoceanographer Nick Shackleton died on January 24, 2006 at age 69. Shackleton discovered that oxygen isotope variations recorded in foram shells are dominated by changes in Earth's ice-volume.

"This insight," wrote paleoclimatologist William Ruddiman of the University of Virginia in a tribute to Shackleton published in the journal *Science*'s May 5, 2006, issue, "meant that a common ice-volume signal is present in all carbonate-bearing sediments, and that oxygen-isotopic signals can be used to correlate ice-age marine records on a nearly global basis."

When Nick Shackleton began his research, wrote Ruddiman, "the investigation of past climatic changes was an area of 'academic' interest only. Four decades later, his lifetime achievements define the emergence of our understanding of the operation of Earth's natural climate system. This understanding of the past is now central to efforts to predict the future climate we have begun to create."

Indeed, those comments echo research results published in the journal *Nature* on January 4, 2006, by Flavia Nunes and Richard Norris, both of Scripps.

Nunes and Norris looked at forams preserved in DSDP and ODP sediment cores from 14 sites around the world. Fifty-five million years ago, deep-ocean circulation in the Southern Hemisphere abruptly stopped the conveyor belt-like process known as "overturning," in which cold, salty water in the depths "switches" with warm water on the surface. But overturning became active in the north, even as it was shutting down in the south. This shift, the paleoceanographers believe, drove unusually warm water to the deep sea, likely releasing stores of methane from gas hydrates, which led to further warming.

The heat-up of 55 million years ago happened in less than 5,000 years, a blip on geologic timescales. "Overturning is very sensitive to surface ocean temperatures," said Norris. "This may be one of the best examples of global warming triggered by the massive release of greenhouse gases. It gives us a perspective on what the long-term impact is likely to be of today's human-caused warming."

In Jules Verne's *A Journey to the Center of the Earth*, Professor Hardwigg's nephew catches a glimpse of what lies ahead on their journey into the unknown: "We followed an extraordinary spiral staircase down into a fissure in the earth. What I see is incredible. My descent into the interior of the earth is rapidly changing all preconceived notions, and day by day preparing me for the marvelous."

The very definition of the sediment record…and of paleoceanography.

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