

Internal Forcing of Environmental Change

One of the most perplexing questions is why Earth's climate varies slowly from very warm conditions, "Greenhouse Earth," to those of bi-polar glaciation, "Icehouse Earth" (Figure 17). How are the polar regions kept cold, and how, at other times, is heat transported poleward under conditions of extreme warmth? Why does change occur sometimes gradually and at other times in discrete steps? Answers to these questions include, at least in part, mechanisms internal to Earth's system such as continental assembly and breakup, elevation and erosion of vast plateaus, opening and closing of oceanic gateways, magmatism, and changing concentrations of CO₂ and other greenhouse gases in the atmosphere. Issues related to such internal forcing of climate change include those of the forcing mechanism (what initiates change), feedbacks that may serve to amplify or reduce the effects of both large and small events, and response (which components of the Earth system are most sensitive and why).

- ▶ **Tectonically induced changes:** The uplift of high mountain ranges and plateaus, such as those in the Himalayan-Tibetan region, the Colorado Plateau and the Andes Mountains, contribute to environmental change in a number of ways. The elevations themselves may physically interfere with atmospheric circulation. For example, the uplift of the Himalayan-Tibetan region has altered the path of the northern hemisphere jet stream. It brought monsoons to regions lying south and east of the plateau, and aridity to regions lying to the north. The elevation of the Andes during the Pliocene has resulted in the orographic stripping of moisture from the southern hemisphere tradewinds and the return of that moisture to the Atlantic via the Amazon. Accelerated weathering permitted by the rapid erosion of newly uplifted terranes also draws down atmospheric CO₂ by means of silicate weathering. Furthermore, burial of organic carbon associated with the muds derived from these eroding regions also removes carbon from the climate system. All of these processes lead Earth towards a colder climate. One clear way to evaluate tectonic uplift is to measure the resulting change in terrigenous deposition evidenced in sediment cores recovered by drilling in nearby marine basins. Increases in terrigenous accumulation rates, driven by increased topographic relief and erosion, can be directly tied to a chrono-stratigraphy and to the proxy indicators of climate and unroofing history contained in the relatively complete marine sections recovered by scientific ocean drilling.

A second mechanism for inducing climate change via tectonic processes results from the large horizontal motions of the plates. These motions rearrange the geography of oceans and continents, and may be associated with large-scale volcanism. Especially critical are the opening and closing of oceanic gateways. For example, during Cenozoic time at low latitudes, the Tethyan and Panamanian seaways have closed and the Indonesian passage has been significantly restricted. The Norwegian-Greenland Sea began to open in earliest Eocene (~55 Ma) time. In the Southern Hemisphere, the Tasman and Drake passages began opening in Late Cretaceous (~80 Ma) and mid-Tertiary (~30 Ma) time, respectively, although timing of the deepening of these southern passages is poorly constrained. This changing configuration of barriers and gateways has altered ocean-surface and deep-water circulation and thus global heat transport. The change from latitudinal to meridional flow at low and mid latitudes, and the opening of the circum-Antarctic ocean, have been tied to the long Cenozoic cooling process. The

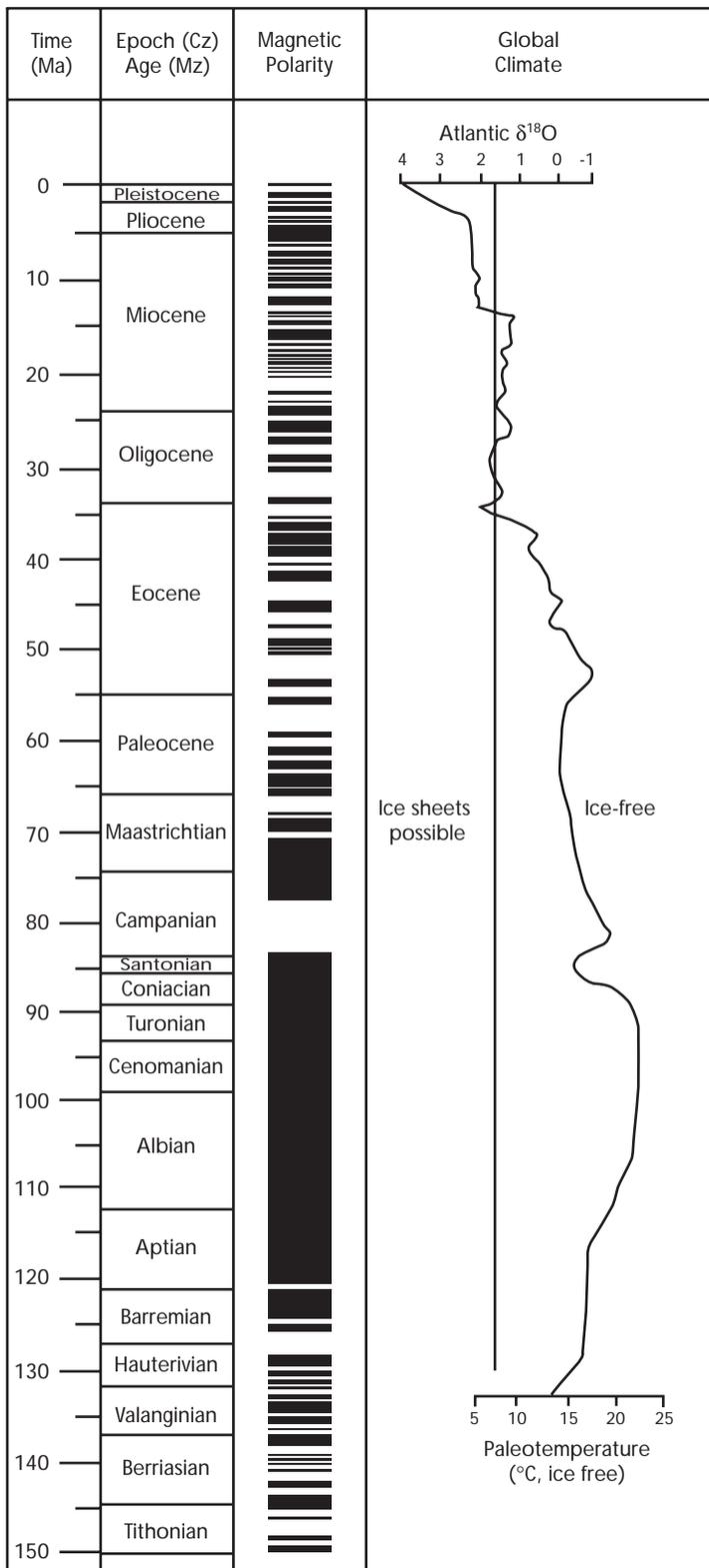


Figure 17. The past 150 m.y. of Earth surface temperatures as indicated by the $\delta^{18}\text{O}$ values of marine calcareous sediments. Note the transition from a “Greenhouse” Earth during the Cretaceous to an “Icehouse” Earth today. See also comparison between longer term changes in climate and major tectonic and igneous processes in Figure 28. Figure compiled by Millard F. Coffin, The University of Texas at Austin.

clearest way of defining the timing and the oceanographic impact of these gateway changes is by way of paleoceanographic indicators of deep- and surface-water conditions found in scientific ocean drilling sites that lie within regions affected by these changes.

Another tectonic process that may influence the global environment is plate-boundary rearrangements, especially those occurring along ridge-transform systems. When a new spreading center breaks through older lithosphere, seafloor hydrothermal activity increases by one to two orders of magnitude. Greatly increased rates of seafloor spreading, such as those characterizing mid-Cretaceous time, may also result in enhanced seafloor hydrothermal activity. Significantly enhanced seafloor hydrothermal activity would have a pronounced effect on ocean chemistry, including the silica budget, and possibly on climate. The long-term history of hydrothermal activity is the least well-understood, yet critically important, aspect of the global geochemical budgets of many elements, such as strontium, iron, manganese, silica, magnesium and potassium. Development of better proxy indicators of hydrothermal activity and their use in recovered sections from a variety of ages and locations should allow IODP to better develop this crucial history.

- ▶ **Igneous processes and environmental change:** Large igneous province (LIP) formation is characterized by massive basalt extrusion on continents, such as the Siberian, Deccan and Columbia River flood basalts, on nascent continental margins, such as the North Atlantic volcanic margins, or in the oceans, such as Kerguelen Plateau-Broken Ridge and the Ontong Java Plateau. The formation of these LIPs is accompanied by the release of heat, hydrothermal fluid, volatiles and particulates to the environment, which is in turn likely to affect oceanic and atmospheric chemistry, hence the climate and biosphere. The formation of several large Cretaceous (~140~65 Ma) oceanic plateaus and of the North Atlantic volcanics—marking the opening of the North Atlantic at the end of Paleocene (~55 Ma) time—are accompanied by high sea-level stands and unusually warm climate, perhaps resulting from CO₂ emissions associated with this enormous amount of observed volcanism. Warming that began at the end of Paleocene time led to the early Eocene warm period, the only time during the Cenozoic as warm as the predicted “Greenhouse” world of the near future. This warming may have played a role in the initiation of the Late Paleocene Thermal Maximum event, a relatively short-lived spike in the global temperature record, thought to have resulted from a destabilization of gas hydrates on the continental margins (see Gas Hydrates Initiative). The unusual characteristics of a very warm global climate are of pressing interest to the modern world; the paleoceanographic record of warm climates will be an important early IODP focus (see Extreme Climates Initiative).

In contrast to the environmental effects hypothesized for the bulk of LIP emplacements, the explosive eruptions that characterize subduction zone volcanism may be associated with climatic cooling. ODP has documented significant episodes of volcanic activity in the Caribbean region in late Paleocene (~56 Ma) time and in Central America in earliest Oligocene (~34 Ma) time. Although the former accompanied early Eocene warming, the latter was at the time of early Oligocene cooling. DSDP and ODP drilling has also revealed that during the Neogene, volcanic episodes occurred in the Pacific Rim every five million years or so. A particularly intense volcanic period in the North Pacific began at about 2.6 Ma, at the same time as the sudden onset of major northern hemisphere glaciation. Whether the vol-

Initiative: Extreme Climates

Understanding the mechanisms by which climatic extremes develop, are maintained and end is fundamental to a quantitative description of global change. Earth is now in one of those extremes, the geologically unusual situation of bi-polar glaciation. Our knowledge of how Earth's system operates to maintain the current climate is relatively good, but we are still debating how the climate has reached this state. Changing gateway configuration, elevation of mountains and plateaus, and CO₂ drawdown by chemical weathering are all factors that may contribute to the answer.

Continued global warming could become a serious problem, but the case of extreme global warmth presents a challenge that is beyond human experience. The last time the world was as warm as it is hypothesized to be in the year 2150 was during early Eocene (~50 Ma) time. Such warm climates must be engendered by some combination of an increase in greenhouse gas coupled with changes in atmospheric and oceanic heat transport. In the past, extended periods of naturally warm climate began slowly, over two or three million years, as in the case of late Paleocene to early Eocene (~55~49 Ma), and possibly longer during the warm climate regime of the Cretaceous (~140~65 Ma), implying underlying long-term tectonic causes. A question of fundamental importance is how, once established, Earth's climate system operated to maintain the low thermal gradients indicated by warm, high-latitude climates. The paradox in this case is the apparent requirement to transport the great amount of heat needed to warm the poles, versus the sluggish oceanic and atmospheric circulation suggested by low pole-to-equator thermal gradients. The mechanisms for ending periods of extreme warmth are also poorly known, and may involve a combination of both step-wise and gradual change associated with fluctuations in ocean circulation and removal of atmospheric CO₂ by weathering or carbonate deposition.

Much of the inherent climatic variability during "Icehouse" extremes is related to changing ice volume in response to Earth's orbital variability. Neogene (~24-0 Ma) oceans are generally well-ventilated, physical and chemical fluxes of materials from continents to oceans are high, and the calcite compensation depth (CCD) is relatively deep. During extremely warm climate intervals, it is less clear how orbital cycles influenced climate. Oceans may have been less well-ventilated, fluxes of materials from continents to oceans may have been reduced, and the CCD was relatively shallow.

To investigate the nature of fundamentally different conditions on Earth during times of past extreme climate, IODP will drill at locations that will yield critical information about the nature of past oceanic and atmospheric circulation, such as equatorial and sub-polar regions. The Arctic Ocean, which is thought to have been ice-free in Paleogene and Cretaceous times, is also critical to our understanding of these climatic extremes, and will be drilled accordingly. Sites with higher sediment-accumulation rates in Cretaceous or early Eocene times, coupled with reduced overburden, such as are found on some oceanic rises and plateaus, are particularly desirable drilling targets because such sediments will not have been subjected to significant diagenesis and primary isotopic and geochemical signals may still be preserved.

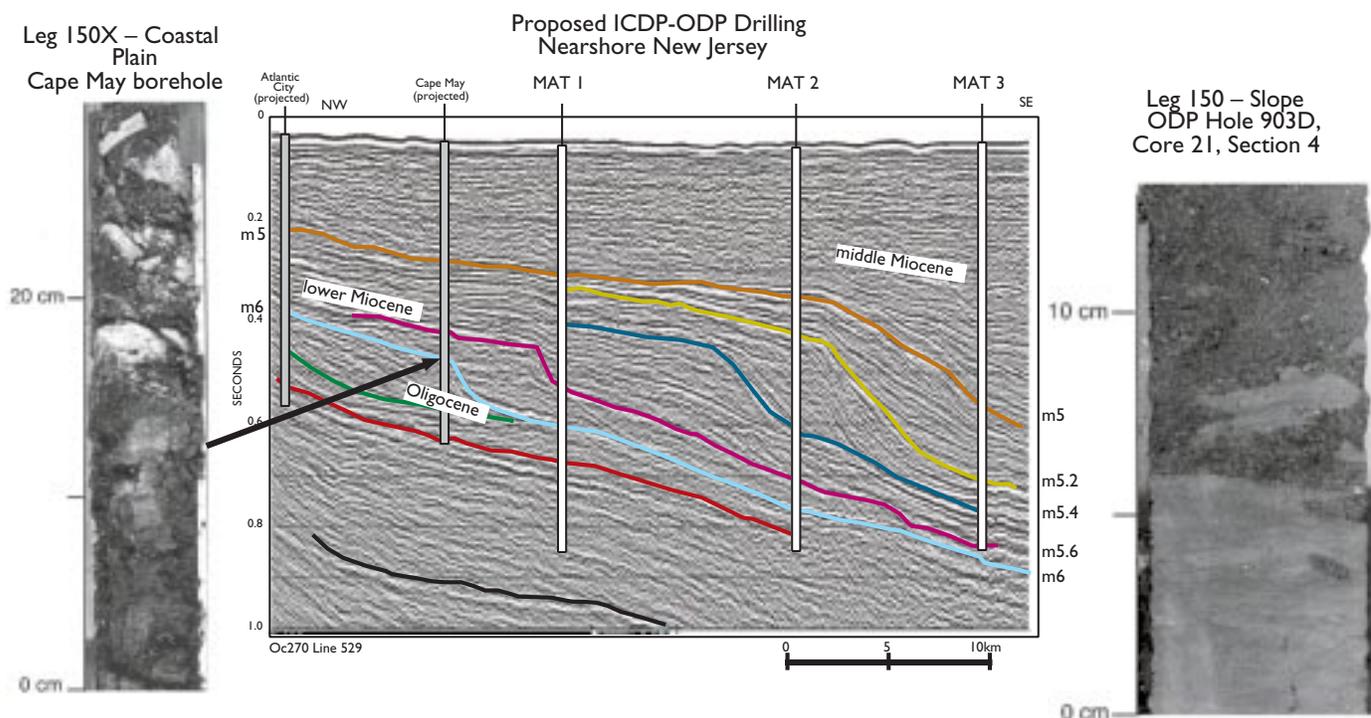


Figure 18. Early Miocene seismic sequences sampled onshore (Leg 150X Cape May) and on the continental slope (Leg 150) of New Jersey showing core and seismic expressions of a basal Miocene (m6) sequence-bounding unconformity. Note that the region most critical to sea-level and sedimentary three-dimensional structure studies (around proposed sites MAT 1-3) has not yet been drilled because the shallow water depths involved require mission-specific drilling platforms. Figure courtesy of Kenneth G. Miller, Rutgers University, and Gregory S. Mountain, Columbia University.

canism is related to the onset of glaciation is unknown. To establish whether there was a volcanic output-climate link then, and at other times throughout Earth's history, IODP will drill downwind from important volcanic centers, and then integrate the information from the drill cores into climate models.

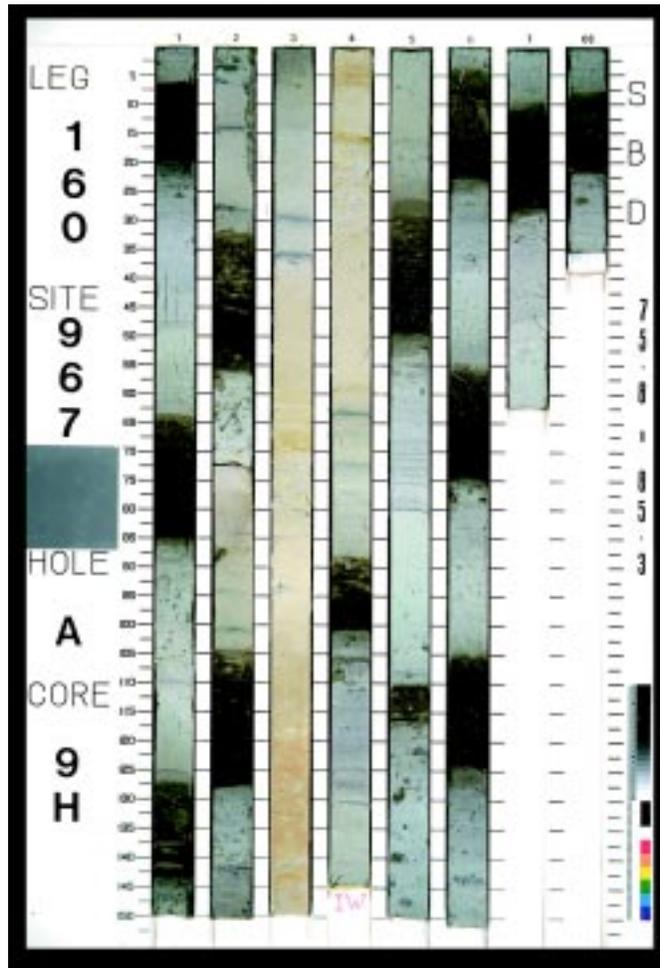
- ▶ **Sea-level change:** Sea level divides our planet into fundamentally contrasting realms, land and sea. Change in the position of this dynamic boundary has occurred throughout geologic time, affecting nearshore ecosystems, material and chemical balances between the land and sea, and the global climate system. Sea-level variation has exerted a major control on the three-dimensional sedimentary architecture of continental margins, with important consequences for the occurrence and migration of fluids, including both hydrocarbon and water resources. ODP drilling has provided a chronology of baselevel lowerings for the past ~42 m.y., linked these lowerings to global sea-level drops caused by the growth of ice sheets (glacioeustasy), and has made progress toward estimating the rates of eustatic change.

Despite these advances, amplitudes of sea-level change remain poorly constrained, mechanisms that control sea level globally and regionally are contentious, and the response of sedimentary architecture to sea-level change has been determined only for short time intervals on selected margins. Amplitudes can best be estimated by locating boreholes in critical nearshore locations that have proved difficult to drill with the *JOIDES Resolution*. This inability to drill in shallow water has hampered efforts to evaluate sequence stratigraphic architecture under a variety of tectonic, eustatic and sedimentary settings (Fig-

ure 18). Though ODP proved that many sea-level changes have a glacioeustatic origin, the causes of large, rapid global sea-level change prior to ~42 Ma remain speculative. Available data cannot determine whether pre-42 Ma variations occurred synchronously around the globe (implying a mechanism driving planetary sea level) or were the result of local processes (tectonism, sediment supply, etc.). Various studies suggest that tectonism, not ice volume, is the most important control on global and regional sea-level change. Evaluating causal mechanisms requires dating margin sequences in different tectonic and sedimentary settings, a goal that has not been attained because of drilling platform limitations. To address these fundamental scientific issues, IODP will use the non-riser drilling vessel in outer shelf-slope settings and, most importantly, use mission-specific platforms to drill on shallower parts of continental shelves.

- ▶ **Organic, carbon-rich sediments and greenhouse anoxia:** Understanding the factors that lead to the development of sediment- and water-column anoxia and the origins of associated organic, carbon-rich sediments has long been a goal of scientific ocean drilling. DSDP and ODP drilling results have provided insights into the influence of climate on marine eutrophication and into the origins of petroleum source rocks. Central to these studies has been a debate as to the relative importance of high marine productivity versus water column stratification and stagnation. Many Mesozoic black shales and

Figure 19. Regular sapropel intervals (black) in background pelagic sediments (white-gray) from eastern Mediterranean ODP Leg 160, Site 967. Photo courtesy of Ocean Drilling Program.



younger anaerobic deposits, such as the sapropels of marginal basins (e.g., the Mediterranean Sea), appear to originate from a combination of enhanced nutrient input, consequent elevated productivity of organic-walled plankton, and water column stratification (Figure 19). A major concern in the modern marine environment is the anthropogenically driven eutrophication of coastal and shelf areas. These conditions lead to anoxia, death of the benthic biota, and significant deterioration of water quality (e.g., anoxia in the Adriatic driven by Po River effluent, and in the Gulf of Mexico resulting from Mississippi River effluent).

Analysis of marine sediments provides information on how anoxic events affect the ocean biota and how areas recover when oxygenated conditions return. The most pervasive of the Cretaceous anoxic events (at 120 and 93 million Ma) were global in extent and imply a whole-ocean process that impedes the breakdown of organic matter and results in abnormally high carbon burial. The most extreme event at the Cenomanian-Turonian boundary (93 Ma) appears to have coincided with maximum Cretaceous temperatures, the highest of the last 115 m.y., and with a positive carbon-isotope excursion associated with excess biogenic carbon burial. Cooling immediately postdating this event was probably initiated by the drawdown of CO₂ associated with this sequestration of organic carbon. These periods of enhanced carbon burial represent extreme behavior of the ocean-atmosphere system during times of exceptional global warmth. IODP will complete a global array of drill sites that sample anoxic events in depth transects, allowing scientists to evaluate their character and cause. IODP samples and analyses will provide needed information about the sensitivity of Earth's system to extreme climate and the processes that drove the world's oceans to anoxia during warm intervals (see Extreme Climates Initiative).

- ▶ **Transient climate episodes:** High-resolution climate records obtained from analysis of marine sediments have revealed extreme, "transient" (hundreds to hundreds of thousands of years in duration) climate episodes that likely result from rapid shifts in the climate system in response to an internal feedback or external forcing mechanism. The extreme warm transients include the late Paleocene Thermal Maximum (LPTM, ~55 Ma) and perhaps several events associated with the Cretaceous anoxic events. The cold transients include the early Oligocene (~34 Ma) and Oligocene/Miocene boundary (23.7 Ma) glacial maxima. In several of these cases, these brief climate extremes appear to have triggered major evolutionary pulses in the biota.

At least some of the warm transients appear to have been the result of geochemical feedbacks involving marine carbon reservoirs. For example, the LPTM, which is characterized by a global warming of 2-3°C and 5-7°C of high-latitude warming, was accompanied by a global carbon isotope excursion of -3 per mil over a period of less than 20,000 years. Ocean carbon-isotope values returned to normal in about 170,000 years, approximately the residence time of carbon in the ocean. Methane is greatly depleted in ¹³C relative to the ocean or atmosphere, and one explanation for the very large isotopic signature of this event is the injection of an immense quantity of CO₂, derived from the oxidization of methane gas hydrates or other hydrocarbon sources, at rates approaching (or exceeding) those of fossil fuel inputs at present. Evidence from benthic foraminifera indicates that at least part of the methane was oxidized within the oceans, causing depletion of dissolved oxygen and the largest deep-ocean extinction event of the Cenozoic.

Regardless of source, such large and sudden inputs of carbon into the ocean/atmosphere system should have profoundly affected both atmospheric CO₂ content and ocean carbon chemistry. In particular, geochemical models show that with such a sudden pulse of CO₂, initially the ocean's pH would drop and calcite shells would dissolve at shallower depths. The ocean pH and alkalinity balance would recover within 170,000 years via chemical weathering of silicate rocks and deposition of inorganic and organic carbon. Part of IODP's Extreme Climates Initiative will seek a better definition of this particular event as well as similar events thought to have occurred in the Cretaceous, as well as a more complete evaluation of their global impact.

External Forcing of Environmental Change

- ▶ **Climate system interaction with orbital forcing:** A major ODP achievement has been to document a distinct orbital influence on the oceanic environment through much of the Cenozoic. One new use of this knowledge will be to develop an orbitally tuned time scale for the entire Cenozoic that will significantly enhance the temporal resolution of Earth history and aid in studies of paleoclimate, geochemical cycling and biologic evolution. The importance of this cannot be overstated. Despite a significant and growing understanding of how orbital variability affects the various Earth systems, important questions remain.

About 750,000 years ago, Earth's climate system changed dramatically from a regime of dominant 41,000-year cycles to one of much larger amplitude, 100,000-year cycles (Figure 20). Curiously, the orbital parameters thought to pace climate change (eccentricity, tilt and precession) do not vary significantly across this transition in the climate system. The cause of the observed change in the response

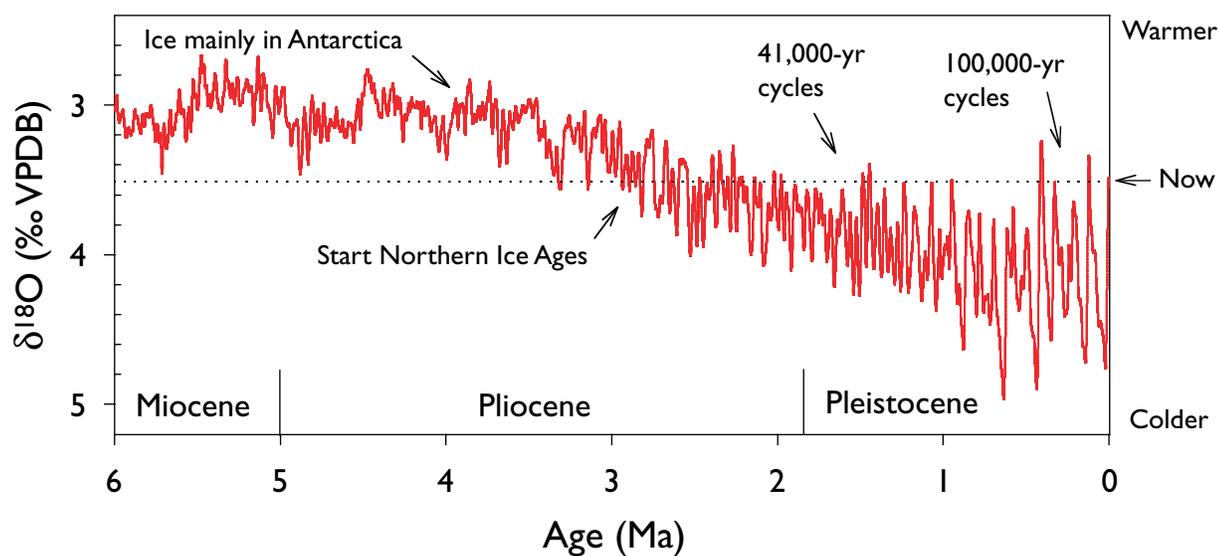


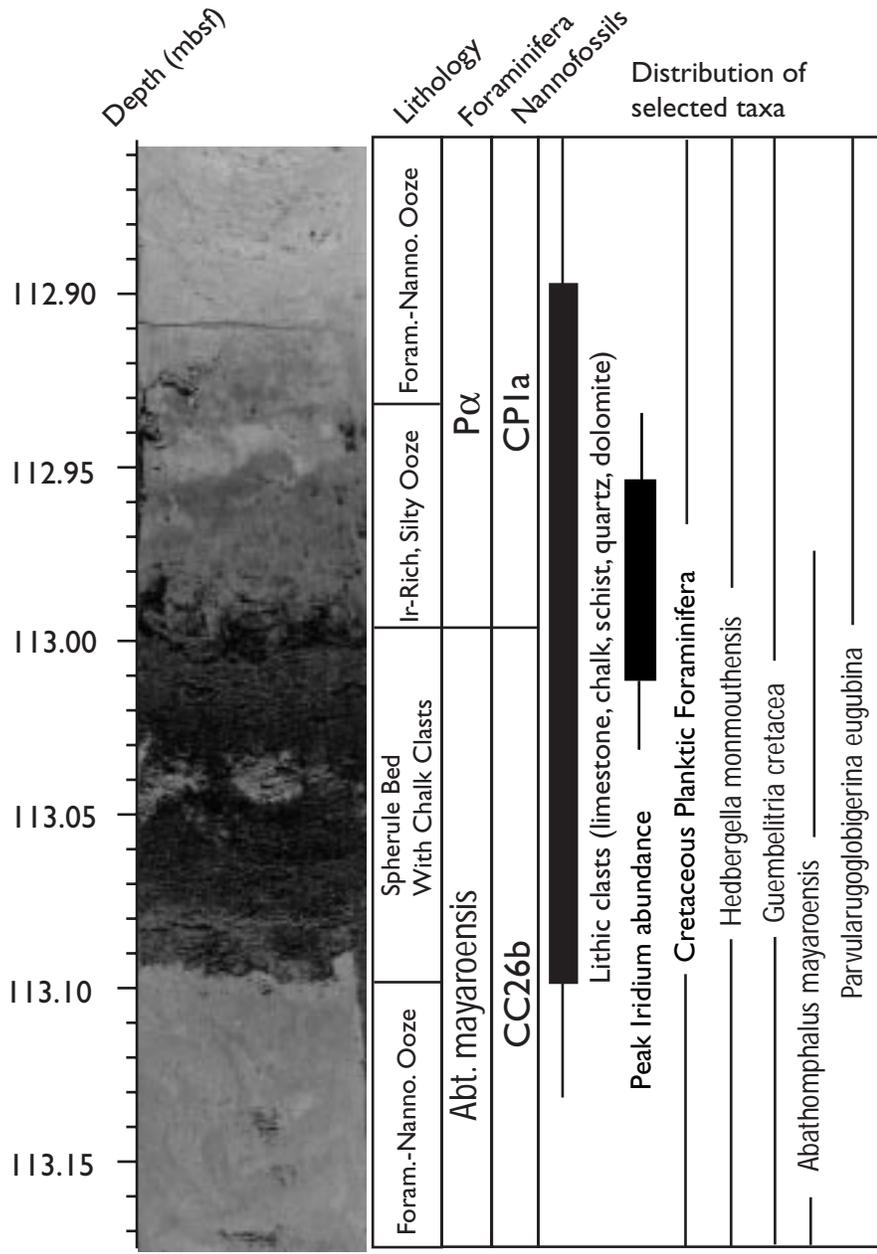
Figure 20. Benthic foraminiferal oxygen isotope record from an eastern equatorial Pacific site (ODP Site 849) for the past 5 m.y. Note the overall trend to more positive values (colder or more ice volume) starting about 4.2 Ma. Changes in the character of variation occur at several places through the record, but especially at about 0.75 Ma. Figure courtesy of Alan C. Mix, Oregon State University.

of Earth's system to orbital forcing remains a mystery, but it must involve a change in sensitivity of, or feedbacks within, the climate system. Thus, this event, in addition to similar ones within the Cenozoic, serve as a natural experiment to help us determine the controls of orbitally induced climate change. Each shift in climate's spectral character represents a separate experiment under differing boundary conditions. Several possible explanations for such spectral shifts have been proposed. When the ice sheets exceeded a certain size, they might have amplified orbitally forced climate oscillations at longer periods. Perhaps other parts of the global system were involved, such as tectonic changes that altered the sensitivity of the system, or changes in the deep sea that modified either the carbon cycle or Earth's heat distribution. IODP will test these hypotheses by using newly developed time-scales, and recovering more complete sections globally.

The earlier Cenozoic record of climate change provides a specific opportunity to test models of climate with and without large polar ice sheets, as well as with substantially different oceanic, atmospheric and orographic boundary conditions. These several different worlds offer a key to understanding how orbital variations interact with a wide range of surface boundary conditions to produce a climatic "state." IODP will recover the continuous sequences of deep-sea sediments from these ancient times that are needed for such tests.

- ▶ **Impact Events:** Over 150 impact craters of varying size have been identified on Earth; the largest is the 180-km diameter Chicxulub crater beneath Yucatán. The Cretaceous/Tertiary (~65 Ma) boundary impact event that created this extremely large crater has been intensively investigated (Figure 21), but considerable uncertainty remains as to the environmental and biological perturbations caused by it. We have even less understanding of the environmental effects of smaller events, such as the late Eocene (~35 Ma) Chesapeake Bay impact. Understanding the environmental and biotic effects of impact events must involve investigation on a variety of temporal scales over which the Earth system responds.

There are many related and outstanding questions about the effects of impacts. We do not understand the exact "killing" mechanism for impact events. Why are some species more sensitive to extinction than others? Extinction of a given species could result directly from the environmental perturbation caused by the impact itself, or perhaps that species was just more susceptible to extinction at the time of the impact. Large impacts clearly cause a major change in oceanic and terrestrial biogeochemical cycling that can last for millions of years, but we need to constrain the exact primary and secondary effects of impacts on oceanic nutrient cycling and how these influence the recovery of faunal and floral groups. The highest quality records of these events reside in the ocean. IODP plans to recover the continuous records needed to document the changes in the environment and in marine life forms that occur in response to impact events.



ODP 1049C BX-5

Figure 21. Cretaceous/Tertiary (~65 Ma) boundary at ODP Site 1049 on South Carolina's Blake Nose, ODP Leg 171B. Illustration shows lithology, planktic foraminiferal and nannofossil zones, distribution of impact-derived materials and ranges of critical planktic foraminiferal taxa. This interval represents a well-preserved record of one of the most dramatic events in Earth history. Figure courtesy of Richard Norris, Woods Hole Oceanographic Institution.