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1. LEG 154 INTRODUCTION[1]

Shipboard Scientific Party[2]

INTRODUCTION

During the last decade, a coring and drilling strategy has been employed by the Ocean Drilling Program (ODP) to recover bathymetric transects of advanced hydraulic piston corer (APC) and extended core barrel (XCB) cores so as to reconstruct the Cenozoic history of deep-water chemistry, carbonate production and dissolution, and deep-water circulation. It invokes the same successful strategy used during pioneering Deep Sea Drilling Project (DSDP) transects for reconstructing Neogene and Paleogene sedimentation history (e.g., DSDP Leg 74) and for reconstructing late Quaternary deep-water chemistry and sedimentation history (e.g., Curry and Lohmann, 1982, 1983, 1985, 1986, 1990; Johnson, 1984; Jones et al., 1984; Peterson and Prell, 1985a, 1985b; Farrell and Prell, 1989).

The reasons for invoking the depth-transect strategy lie in the interaction between the carbonate chemistry of deep water and the underlying lithology of the sediment. The bathymetric distribution of physical and chemical properties in the ocean results from large-scale circulation processes and affects the lithological character of sediments and the chemical composition of the benthic microfossils preserved in the sediments. For instance, the net flow of deep water from the Atlantic to the Pacific oceans and the mineralization of organic carbon cause a horizontal gradient in the preservation of calcium carbonate that is recorded in the sediments. The Pacific Ocean today is much more corrosive to carbonate and has a different carbon chemistry than the Atlantic as a direct result of the modern circulation pattern. These gradients are reflected in the carbonate content of the sediments and in the carbon isotopic chemistry of benthic microorganisms. By reconstructing past gradients in both the depth distribution of the carbonate facies and the chemistry of benthic-dwelling microfossils, we are able to infer the history of deep-water chemistry and circulation in the geologic record. This approach works well in depth transects because carbonate dissolution is depth dependent and because bathymetric gradients of deep-water chemistry are important clues to water-mass origin and flow direction.

A basic assumption of the research strategy is that the principal source of carbonate in the sediments is from surface-water production, with little or no downslope or lateral input. If true, then carbonate accumulation in the least dissolved, shallowest sites approximates the carbonate productivity of the overlying surface waters. For sites located close together, the carbonate productivity overlying all sites in the bathymetric transect should be equal. Then, the difference in carbonate accumulation between shallow and deep sites is a quantitative measure of the amount of carbonate lost to dissolution. These mass balances of carbonate supply and burial provide the means to reconstruct past carbonate productivity and dissolution rate. With the same bathymetric transects, gradients in deep-water chemistry can be inferred from the chemistry of benthic microfossils. Thus, from a single suite of cores located on the slopes of an aseismic rise, we can determine past changes in carbonate productivity and carbonate dissolution as well as important aspects of deep-water chemistry and circulation.

The purpose of Leg 154 was to sample a bathymetric transect in the western equatorial Atlantic at the Ceara Rise (Fig. 1) that would complement the global array of depth transects acquired during the last decade (ODP Leg 108, eastern equatorial Atlantic; Leg 113, Maud Rise; Leg 115, Madingley Rise; Leg 130, Ontong Java Plateau; and Leg 145, Detroit Seamount) and which would make a contribution to our understanding of the Cenozoic history of deep-water chemistry. In addition, the Ceara Rise is located beneath the warm surface waters of the western tropical Atlantic, making it ideal for reconstructing the history of tropical sea-surface temperatures, the evolution of tropical calcareous microfossils, and the chemistry of nutrient-depleted surface waters.

Deep-water circulation in the Atlantic (and to a great extent, in the whole world ocean) is controlled by the mixing between deep-water masses in the western basins of the South Atlantic and Southern oceans. The Atlantic contains the source regions for the two major water masses in the deep oceans today, and in the past this ocean likely contained the source area for other water masses. Mixing between water masses in the South Atlantic and Southern oceans produces the initial chemical and physical characteristics of the deep water that flows through the Indian Ocean and into the Pacific. Thus, no reconstruction of Cenozoic deep-water circulation and chemistry can be complete without a full understanding of the history of deep-water circulation in the western Atlantic. On the basis of location, present oceanographic setting, and continuity of high sedimentation rates, the Ceara Rise certainly provides one of the best target locations for reconstructing this paleoceanographic history.

STUDY AREA

The Ceara Rise is a bathymetric high that formed at the Mid-Atlantic Ridge about 80 Ma, along with its conjugate, the Sierra Leone Rise, in the eastern equatorial Atlantic. The Ceara Rise reaches a minimum depth of about 2600 m; it is surrounded by seafloor that has an average depth of about 4500 m. It is draped with a thick sequence (>1000 m) of relatively undisturbed lithogenic and biogenic sediments. DSDP Site 354, the only previous drilling site on the Ceara Rise, was located on its northern flank at a depth of about 4000 m. Although only spot cored, a generalized history of the area was reconstructed from this investigation (Supko, Perch-Nielsen, et al., 1977).

Bathymetry and Physiographic Setting

The rise consists of a series of platform-shaped shoals oriented in a northwest-southeast direction (Fig. 2). The platform tops of the rise reach about 3200 m below sea level and are punctuated with small, sedimented features that extend upward to minimum depths of about 2800 m. The shallowest portions of the Ceara Rise are located in the southern half of our study area. Two areas (4°30′N, 43°40′W and 4°20′N, 43°30′W) reach depths of 3000 m and are well-sedimented targets for coring. One shallow pinnacle reaches a depth of 2600 m, but it contains little evidence of sediment accumulation on its peak or steep slopes.

The Ceara Rise is asymmetric in cross section (Fig. 3). Slopes along the southwest side are in excess of 5.7°, whereas those on the northeast side are much gentler (ca. 1.4°). It is bounded on the north-

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[2] The Shipboard Scientific Party is as given in the list of participants preceding the Table of Contents.

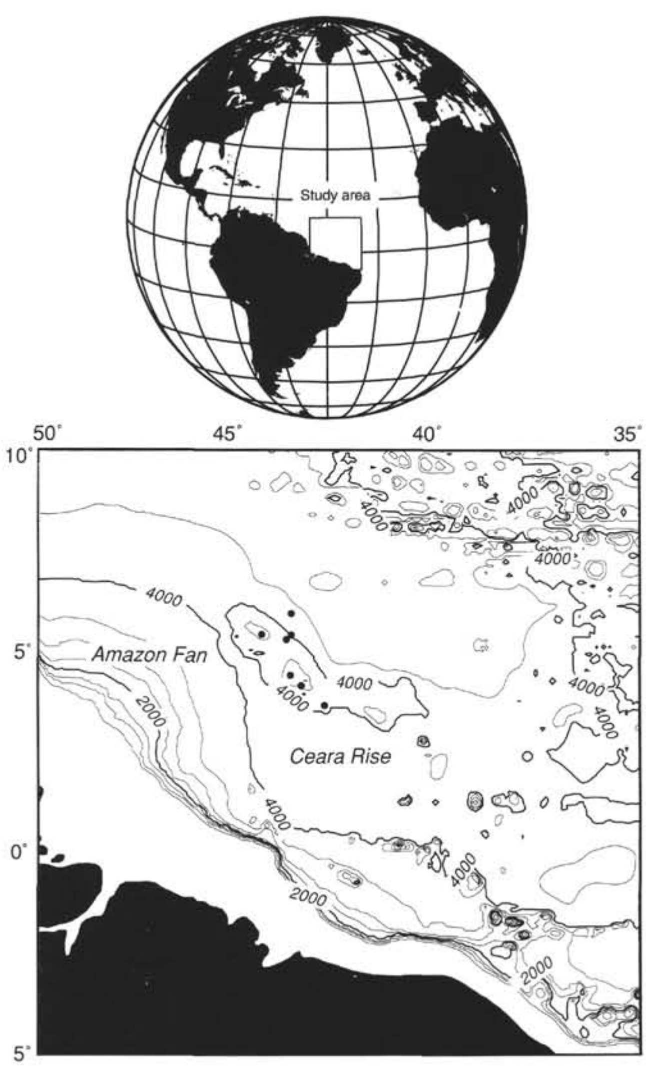

Figure 1. Location of Ocean Drilling Program (ODP) Leg 154 study area on the Ceara Rise in the Atlantic Ocean showing its position with respect to the South American coast and the Amazon Fan. The Amazon Fan is the study area for ODP Leg 155. Closed symbols locate the five primary and two alternate sites for Leg 154. Bathymetry in meters.

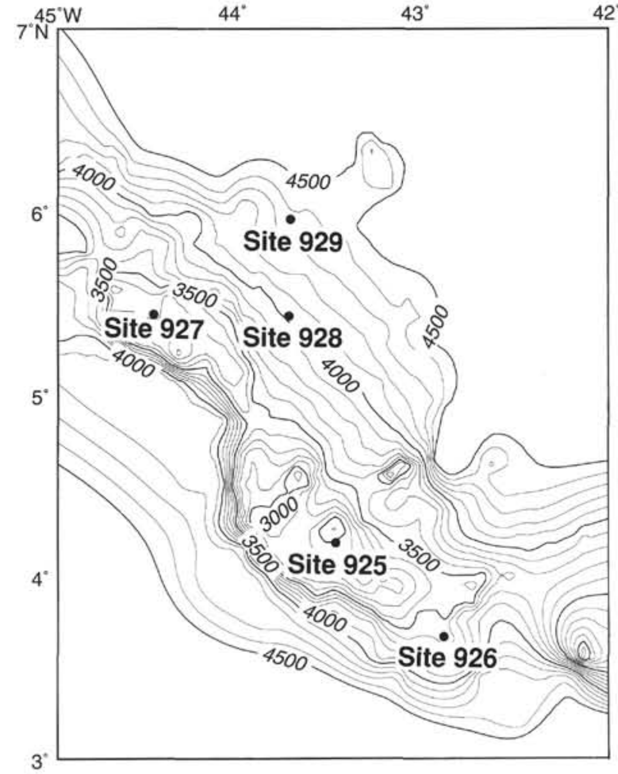

Figure 2. Location of the five coring and drilling sites on the Ceara Rise that constitute Leg 154. See Figure 1 for general location. Bathymetry in meters based on site survey results (Ew9209 Hydrosweep center beam).

east and east by the Ceara Abyssal Plain and on the north, west, and southwest by the Amazon Fan. The Amazon Fan deposits are flat-lying and lap onto the downfaulted base of the western side at about 4100 m water depth. Seismic reflection profiles in this area demonstrate that much of the rise on the southwest side is covered by fan deposits (see Mountain and Curry, this volume). The abyssal plain to the northeast is deeper (4500–4700 m) and exhibits topographic features and surface roughness that may be associated with strong bottom currents (Damuth, 1977).

Oceanographic Setting: Deep Water

Because of westward intensification of deep-water circulation, the western basin of the Atlantic is the principal conduit for the flow of northern and southern sources of deep water. Today, these water masses meet and mix in a broad zone that extends from the South Atlantic to the equatorial region of the North Atlantic. The present mixing zone between northern-source deep water (NADW) and southern-source deep water (AABW) in the Ceara Rise region is between 4000 and 4500 m (Fig. 4). Today, this depth marks a steep gradient in deep-water chemistry that controls the dissolution of calcium carbonate in the western basin. The position of this mixing zone also affects the chemistry of deep water in the eastern Atlantic because it is deep water from the western basins that ventilates the eastern basins. Deep water in the eastern basins originates in the western basins and flows eastward through low-latitude fracture zones. Flow across two fracture zones provides most of the deep water to the eastern basins: the Romanche Fracture Zone at the equator (Metcalf et al., 1964) and the Vema Fracture Zone at about 10°N (McCartney et al., 1991; McCartney and Curry, 1993). The sill depths for these fracture zones are close to 4000 m (also the approximate depth of the mixing zone), so small changes in the relative intensity of northern- and southern-source deep waters can have a large effect on the initial chemical composition of deep water that enters the eastern basins and on the preservation of calcium carbonate in the eastern Atlantic.

The present mixing zone between NADW and AABW is mostly below the sill depth of the fracture zones, so the deep water entering and filling the eastern Atlantic below 3750 m is a mixture of 80% NADW and 20% AABW. Because it is dominated by NADW, the eastern deep water is warmer, saltier, and less corrosive to carbonate than deep water at the same depths in the western Atlantic (Fig. 4). Small changes in the depth of the mixing zone in the western basin, however, would produce large changes in the chemical and physical properties of the deep water in the eastern Atlantic. Mixing between NADW and AABW today also affects the initial chemical and physical composition of the deep water that enters the Indian and Pacific oceans. Studies have shown that the relative proportion of northern-source deep water decreased during the last glaciation, resulting in a lower $\delta^{13}C$ in Southern Ocean deep water (Oppo and Fairbanks, 1987; Curry et al., 1988; Charles and Fairbanks, 1992) and a greater proportion of southern-source water at the Ceara Rise. As a result, the $\delta^{13}C$ composition of the deep water that entered the fracture zones to the eastern Atlantic was lowered at that time. The Ceara Rise, located

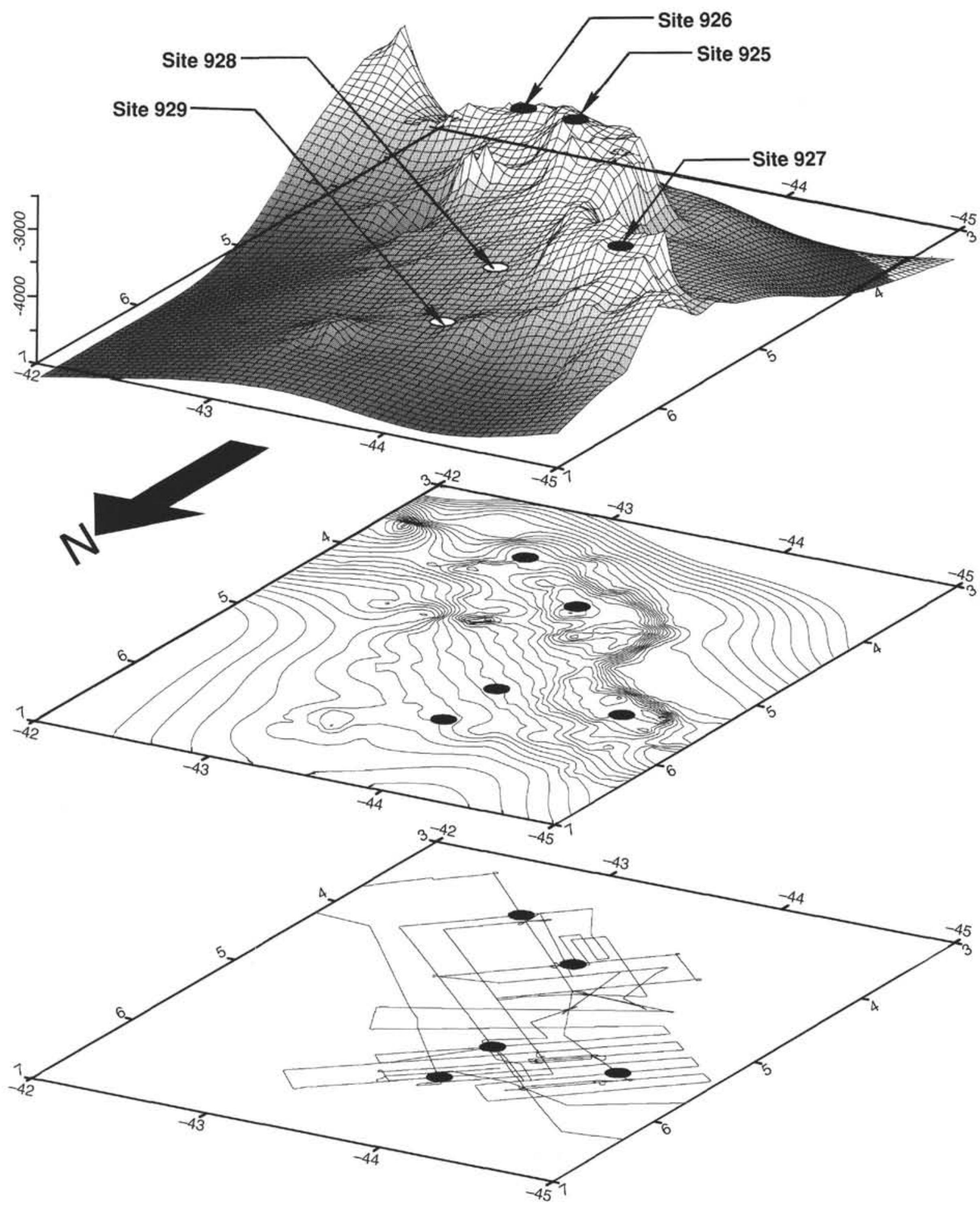

Figure 3. Perspective view of the Ceara Rise from the northwest pointing out the steep slopes on the southwest margin and gentle slopes on the northeast flank. The prominent platform tops of the rise are usually shallower than 3200 m. Several of these platforms were selected for shallow coring sites (Sites 925, 926, and 927). The deeper coring sites of the bathymetric transect (Sites 928 and 929) fall on the gently sloping northeast flank. Beneath the perspective view of the rise are the bathymetric contours (100-m interval) produced by the Ew9209 Hydrosweep swath-mapping system and the track lines for the site survey cruise.

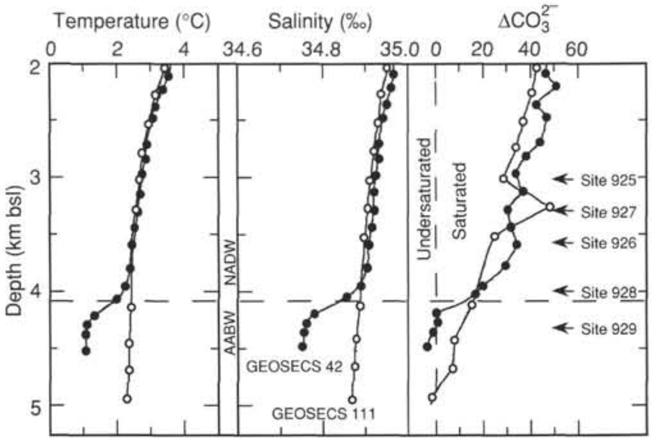

Figure 4. Depth distribution of temperature, salinity, and ΔCO_3^{2-} (Broecker and Takahashi, 1978) in GEOSECS stations from the western and eastern equatorial Atlantic. Closed symbols are from GEOSECS 42 from the western basin, and open symbols are from GEOSECS 111 from the eastern basin. The corresponding water depth for each site is plotted in the right-hand panel. Note that the rapid decrease in temperature that marks the presence of southern-source deep water (AABW) occurs today below the sill depth (4000 m) separating the western and eastern Atlantic. The horizontal dashed line denotes the transition between NADW and AABW. Today, the deep water below the sill depth in the eastern Atlantic is warmer and less corrosive to carbonate than water at comparable depths in the western Atlantic. The chemical and physical composition of the deep water that enters the eastern Atlantic is very sensitive to changes in water-mass geometry in the western basin. Past changes in the chemistry of eastern Atlantic deep water have occurred that are related to vertical migrations of the mixing zone between northern and southern sources of deep water (Oppo and Fairbanks, 1987; Curry et al., 1988).

near the western entrances of the fracture zones, provides an excellent monitor of the initial chemical composition of deep water entering the eastern Atlantic.

Oceanographic Setting: Surface Water

The rise is located in the western equatorial Atlantic beneath a surface-water pool that exhibits a small annual range in temperature. Surface-water temperatures generally exceed 27°C and nutrient concentrations are kept low because surface-water productivity exceeds upwelling of nutrients to the mixed layer. On glacial-interglacial time scales, CLIMAP Project Members (1976) have suggested that surface-water cooling in this region was small (<2°C). Because this pool of warm surface water is located on the western side of the Atlantic, it is less affected by annual or glacial-interglacial variations in upwelling; therefore, the nutrient concentration of the surface-water mixed layer is always low (Curry and Crowley, 1987). Thus, a surface-water $\delta^{13}C$ record from this location will be an ideal representation of the Cenozoic history of nutrient-depleted $\delta^{13}C$ and $\Delta\delta^{13}C$ (e.g., Shackleton and Pisias, 1985; Curry and Crowley, 1987). Because of the low variability in surface-water temperature, this location will also be ideal for reconstructing the history of late Cenozoic surface-water temperature caused by global, rather than local, changes in climate.

SHIPBOARD CORING AND SAMPLING STRATEGY

Leg 154 followed a drilling strategy that resulted in a depth transect of APC, XCB, and rotary core barrel (RCB) cores for the sedimentary sequences deposited during the Cenozoic at the Ceara Rise. Five sites were chosen at approximately 300-m depth intervals down the gentle slopes of the northeast face of the rise (Fig. 3). Sites 925 through 929 were located at about 3041, 3598, 3315, 4012, and 4356 mbsl, respectively; all five sites obtained APC/XCB cores into the Miocene section. Deeper penetration was planned at three of the sites (925, 926, and 929) to provide a depth transect that would span the period since the lower Oligocene. Drilling near to basement (0.9 to 1.3 s below the seafloor) was planned at Sites 925 and 929. Slow rates of penetration limited recovery, so the oldest sections date to the middle Eocene at Site 925; on the other hand, the importance of the Oligocene section encouraged us to extend a fourth site into the Oligocene (Site 928); Site 929 extended into the Paleocene.

The goal of drilling during Leg 154 was to obtain the most complete sections possible for the drilled intervals; thus, all five sites included triple, overlapping APC coring to refusal. Below APC depths, the choice of XCB or RCB drilling bits depended on the recovery observed. The work on board ODP Leg 138 had shown that it was possible to plan drilling and shipboard work that would enable documentation of truly complete recovery of the stratigraphic section at each site before proceeding to the next, at least for the part of the section that can be cored with the APC. With high-resolution downhole logs and continuous data on cores (magnetic susceptibility, GRAPE density, color, natural gamma), Leg 154 attempted to extend this capability through the Paleogene. Because the sites cored on Leg 154 were all from a small geographical area, we also expected to be able to demonstrate high-resolution correlations between the sites using high-resolution biostratigraphy and magnetostratigraphy as well as core and downhole log data. Composite depth sections for the Leg 154 sites extend continuous records back to at least the late Miocene (~7 Ma), with confident site-to-site correlations of orbital scale variability throughout, despite the fact that we were unable to obtain magnetostratigraphy (see "Synthesis" chapter, this volume).

SCIENTIFIC RATIONALE

Several questions of paleoceanographic significance can be addressed by the depth transect recovered at the Ceara Rise:

1. What was the history of deep-water flow in the Atlantic during the Cenozoic? What has been the relationship between deep-water circulation and chemistry and the Earth's climate?
2. What was the history of carbonate production and dissolution in the equatorial Atlantic during the Cenozoic? How have changes in carbonate production and dissolution been affected by changes in deep circulation and in the Earth's climate?
3. What has been the Cenozoic history of surface water and climate in the tropics? How have the $\delta^{13}C$ of nutrient-depleted surface water and oceanic $\Delta\delta^{13}C$ varied throughout the Cenozoic? How have the flora and fauna evolved in response to changes in surface-water hydrography?

Because of the continuity of sedimentation at the Ceara Rise, these scientific questions can be answered for several important intervals of the Earth's history where questions about deep-water circulation remain unresolved: the Pliocene–Pleistocene, the middle Miocene, and the Eocene/Oligocene.

Pliocene–Pleistocene

Deep-water circulation during the latest Quaternary is linked to and provides an important amplification of climate change. During glacial maxima, transfer of the ocean's dissolved carbon and nutrients from intermediate depths to the deep ocean provides a mechanism for reducing the pCO_2 of the surface ocean and atmosphere (Boyle, 1988). These changes in ocean chemistry are linked to changes in the production rate and depth distribution of deep water in the North Atlantic (Boyle and Keigwin, 1987) and to changes in the intensity and distribution of carbonate dissolution in the oceans (Boyle, 1988). Although the history of deep-water circulation is well-known for the last glacial-interglacial cycle, for older sediments the spatial coverage of data is limited. The sites cored on the Ceara Rise will provide significant new information about the Pliocene–Pleistocene history of deep-water circulation because of its strategic location in the present mixing zone of NADW and AABW.

The depth profile we have established will quantify the extent to which depth redistribution of nutrients and carbon is common to glaciations earlier in the Pleistocene or the Pliocene and the extent to which deep circulation responds to or amplifies glacial-interglacial climate change. At all five Leg 154 sites, we recovered complete Pliocene–Pleistocene sections with sedimentation rates of 25 to 50 m/m.y.

Miocene

The presence of a large hiatus in the middle and late Miocene throughout much of the Atlantic (and possibly at Site 354 on the Ceara Rise) has made reconstructing deep-water circulation and chemistry very difficult for this period of time. Given the important climatological changes occurring then, large changes in deep-water circulation and chemistry were probably also occurring. Several competing hypotheses (summarized by Wright et al., 1992) about Miocene deep-water circulation generally agree that deep water was produced in the northern Atlantic by the late middle Miocene, but these hypotheses differ regarding the timing of the initiation of northern component water mass. Miller and Fairbanks (1985) placed the initiation within the Oligocene; Blanc et al. (1980), Schnitker (1980), and Woodruff and Savin (1989) placed the initiation in the middle Miocene. Schnitker (1980) proposed that the flux of heat to the Southern Ocean by northern component deep water triggered an increase in the moisture flux to Antarctica and subsequently an increase in ice growth. Woodruff and Savin (1989) suggested that the closing of the Tethys resulted in a heat loss to Antarctica that triggered the glaciation. They concluded that early Miocene deep-water circulation was dominated by water masses of southern and Tethyan origin and that there was little evidence for deep-water production in the North Atlantic before 12 Ma.

Leg 154 offers an opportunity to assess these competing hypotheses because it is located today in the mixing zone between southern and northern deep-water masses. The drilling strategy of Leg 154 focused on increasing the likelihood of coring a quality upper and middle Miocene section in this region. At all five sites, we recovered sediments dating to the middle Miocene. The composite sections developed for this interval document many sections that are completely recovered and correlatable between sites. Unexpectedly we encountered no hiatuses at the shallowest site, although there is evidence for increased dissolution and thinning of the section down the slopes of the Ceara Rise (see "Synthesis" chapter, this volume). Below 4 km (present water depth), nearly pure clays dating to the middle Miocene attest to the severity of dissolution at this time. We now know that the severe dissolution during much of this period has contributed to the incompleteness of previous records. Large changes in deep-water chemistry, perhaps associated with the reorganization of deep-water circulation patterns, occurred during the middle Miocene.

Eocene–Oligocene

The Eocene/Oligocene boundary is of particular interest because there is good evidence for a deep-water cooling of several degrees associated with some significant accumulation of ice on Antarctica. The evidence further suggests that this climate change caused a major reorganization of deep- and intermediate-water circulation; without a depth transect, however, it is difficult to evaluate the nature of this change. Indeed, a high-quality, low-latitude planktonic isotope record will also be of great value for testing competing interpretations of the isotope record derived from benthic species. The drastic Eocene/Oligocene boundary event was followed by several brief Oligocene episodes of continental ice sheet formation on Antarctica (events Oi-1 and Oi-2: Miller et al., 1991; Wright et al. 1992; Zachos et al., 1993). The forcing mechanisms behind the Eocene/Oligocene events are largely unknown. This event and the subsequent Oligocene pulses of climate variability are presently thought to mark the beginning of the transition into the Cenozoic "icehouse world." Instabilities in the ice-ocean-atmosphere system at this time may have resulted in short-term extremes in ice growth (Zachos et al., 1993).

A chief component in any attempt to understand the nature of this transition will be to distinguish high-latitude ice growth from temperature change in the isotopic records, which requires access to high-quality, low-latitude oxygen isotopes derived from both planktonic and benthic foraminifers. Such isotope data will also be of immense value for understanding the possible ice-volume connection of the sea-level coastal onlap and offlap record during the later Paleogene. Moreover, low-latitude isotope records will be crucial for characterizing the higher frequency variability of Paleogene climate in the Milankovitch band, which is essential for understanding the feedback mechanisms of Paleogene insolation cycles as well as for satisfying the strong need for improved Paleogene chronologic resolution.

The sections recovered during Leg 154 will provide an excellent opportunity to determine the changes in deep-water circulation and carbon chemistry associated with the Oligocene ice-growth events. Sites 925, 926, 928, and 929 recovered sediments coeval with the middle Oligocene increase in $\delta^{18}O$ (Oi-2; Wright et al., 1992; Zachos et al., 1993); Sites 925 and 929 recovered sediments coeval with the early Oligocene increase in $\delta^{18}O$ (Oi-1).

The carbonate chemistry and fertility of the ocean underwent enormous change during the Paleogene, as indicated, for example, by the single largest Cenozoic deepening of the carbonate compensation depth (CCD) close to the Eocene/Oligocene boundary (van Andel, 1975; Thunell and Corliss, 1986; Peterson and Backman, 1990). Variations in the CCD are intimately linked to the global carbon cycle and the exchange of carbon dioxide between four major reservoirs: the atmosphere, the ocean, the carbonate-bearing deep-sea sediments, and the mantle. The rationale for drilling depth transects at locations such as the Ceara Rise is strongly rooted in the perception that quantitative sediment budgets as a function of water depth and time are necessary to establish realistic models of the interaction of the ocean-climate-sediment system. Pelagic seafloor carbonate constitutes well over 50% of all oceanic sediments, and the interplay between biogenic carbonate production and flux, on the one hand, and carbonate dissolution at the seafloor, on the other, is of critical importance for the global carbon cycle. Meaningful reconstructions of depth- and time-dependent carbonate budget variations can be addressed only through drilling depth transects in small geographic areas to ensure a similar pelagic input along the transect and to capture the depth-dependent dissolution at any given time. Except for an early campaign in the southeastern Atlantic (DSDP Leg 74), no ocean drilling has focused on Paleogene depth transects.

The sediments recovered during Leg 154 provide an excellent opportunity to calculate sediment budgets for the Paleogene at least as early as 42 Ma, as Sites 925 and 929 each contain continuously cored intervals down to the middle Eocene. Although both sites are moderately lithified, they each contain rich calcareous nannofossil assemblages and both have excellent biostratigraphic age control. They are separated by more than 1300 m in water depth. The sites were at abyssal water depths in the Eocene, so a valid two-point depth comparison can be developed for Eocene deep-water chemistry and temperature gradients. Thus, these sites may help sort out the extent to which warm saline bottom waters were common in the Paleogene as well as identify the source regions for deep-water masses (e.g., Kennett and Stott, 1991). In addition, the long records in Sites 925 and 929 are dominated by cyclical changes in sediment lithology, which will help to constrain the rates and timing of major changes in surface-water hydrography and microfossil evolution.

SUMMARY

The sediments recovered during Leg 154 span the last 55 m.y. and are suitable for depth-transect reconstructions for a variety of temporal resolutions. When compared with similar depth transects in the Indian and Pacific oceans, the Ceara Rise depth transect will help to constrain the Cenozoic history of deep-water circulation and chemistry. The sites will undoubtedly prove to be an extremely valuable resource for paleoceanographic studies for many years to come.

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*Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

Ms 154IR-101