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1. INTRODUCTION[1]

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OCEAN DRILLING AND THE SEA-LEVEL ISSUE

The Second Conference on Scientific Ocean Drilling formulated major scientific issues to be addressed in the next decade of ocean drilling (Le Pichon, 1988). One of its major recommendations was that drilling programs must be developed to improve knowledge of the timing and magnitude of past global (eustatic) sea-level changes. To sharpen these recommendations further, JOI/USSAC sponsored a global sea-level workshop (Watkins and Mountain, 1990), and JOIDES established a sea-level working group (Sea Level Working Group, 1992) to identify the optimum site characteristics, survey data, and drilling strategies that are needed to advance the knowledge of global sea-level change. In addition to defining these criteria, these groups identified three intervals for which detailed study is especially critical: the Oligocene to Holocene "Icehouse World," when glacioeustatic changes were clearly operating; the middle Cretaceous "Greenhouse World," which lacked significant ice sheets; and the Paleocene-Eocene "Doubthouse World," a time for which debate continues over the existence of ice sheets.

COSOD II (Imbrie et al., 1988), JOI/USSAC workshop (Watkins and Mountain, 1990), and JOIDES sea-level working group reports recommended a threefold approach to sea-level studies that use data from passive continental margins, carbonate atolls, and deep-sea $\delta^{18}O$ records (see Chapter 2, this volume, for details). They recognized that the Ocean Drilling Program (ODP) and the *JOIDES Resolution* will play a key role in these studies, although supplementary offshore and onshore drilling would be needed. Leg 133 was the first ODP effort to address the sea-level issue by drilling carbonate sequences adjacent to a passive margin; Legs 143 and 144 drilled into atolls and carbonate platforms. The paleoceanographic objectives of other legs (particularly those from western equatorial locations such as Leg 130) continue to refine estimates of glacioeustatic history derived from measurements of $\delta^{18}O$. Building on the results of DSDP Legs 93 and 95 and the result of industry studies on the New Jersey margin, Leg 150 is the first ODP leg to address sea-level history recorded in siliciclastic sequences from a passive margin. The JOIDES panel structure selected the New Jersey margin for this first endeavor because of its excellent seismic resolution of "Icehouse" sequences and other criteria outlined in Chapter 2 (this volume).

LEG 150 AND THE NEW JERSEY MARGIN

The coastal plain, shelf, and slope of New Jersey have long been recognized as an excellent source of information on sea-level history. The onshore upper Cretaceous to Cenozoic section is discontinuous; nevertheless, it provides a record of transgressive-regressive sequences that can be correlated with other proxies of sea-level change (e.g., Owens and Gohn, 1985; Olsson et al., 1987; Miller et al., 1990; Sugarman et al., 1993). The thick sediment accumulations on the continental shelf and slope off New Jersey (the "Baltimore Canyon Trough," Fig. 1) drew the attention of oil companies in the 1970s. Seismic exploration and drilling on the continental shelf was led by the U.S. Geological Survey in the 1970s (e.g., Schlee, 1981), including several 300-m-deep boreholes drilled as part of the AMCOR project (Hathaway et al., 1976). Subsequently, oil companies collected thousands of kilometers of seismic data and drilled 28 outer shelf wells in this region, several of which obtained Cenozoic samples (Libby-French, 1984; Greenlee et al., 1992). Oil companies also drilled several discontinuously cored boreholes (the Atlantic Slope Project; Poag, 1978) and four exploration wells on the continental slope. The region proved to be economically unproductive for hydrocarbons and exploration stopped in 1983.

DSDP first ventured into this region on Leg 11 (Hollister, Ewing, et al., 1972), drilling Sites 105 and 106 (5251 and 4500 m water depth, respectively) on the lower continental rise, Site 107 on the upper rise (2571 m water depth), and Site 108 on the lower continental slope (1845 m) in an outcrop belt of Eocene sediments. These sites were discontinuously cored and only provided a glimpse of slope and rise stratigraphy. Ocean drilling has subsequently moved into progressively shallower water on the New Jersey margin. DSDP Legs 93 and 95 were specifically designed as the beginning of a marginwide transect to address sea-level changes on the New Jersey margin (van Hinte, Wise, et al., 1987; Poag, Watts, et al., 1987) with continuously cored and logged boreholes. One hole was drilled on the lower rise (Site 603), three holes were drilled on the upper rise (Sites 604, 605, and 613, in water depths of 2364, 2197, and 2323 m, respectively), and one site was drilled on the lower continental slope (Site 612, 1400 m water depth). Legs 93 and 95 did not continue onto the upper slope because of time constraints. Although these water depths are well below the direct influence of sea-level change, Legs 93 and 95 determined that several important disconformities correlate with other proxies for sea-level change (van Hinte, Wise, et al., 1987; Poag, Watts, et al., 1987).

ODP Leg 150 was first designed to continue this transect of the upper slope and continental shelf off New Jersey, exploring the region most sensitive to sea-level changes. The data and rationale for the transect are discussed in Chapter 2 (this volume). Nine boreholes were proposed on the continental shelf (MAT1–9) along with three on the continental slope (MAT10–12; Sites 902–904; Fig. 2). Unfortunately, concerns over the hazards of drilling led to disapproval of all sites in less than 200 m water depth. Consequently, one additional slope site (MAT13) and one rise site (MAT14, Site 905) were proposed. All of the Leg 150 sites drilled by the *JOIDES Resolution* are on the continental slope and rise, and they represent only part of the transect of holes deemed necessary by COSOD II, the Sea Level Workshop, and the Sea Level Working Group. Onshore drilling began in concert with Leg 150. The result is five sites on Leg 150 and three onshore sites (at Island Beach, Atlantic City, and Cape May, New Jersey; see Chapter 2, this volume) that together constitute the end-points of a marginwide transect. When safety and survey shortfalls are met in the future, we expect that the remaining critical shelf holes will be drilled. Completing the New Jersey Sea-level Transect will be only the first step in ocean drilling investigations of sea level. Margins in other settings, including those with carbonate platforms (e.g., the Bahamas) or car-

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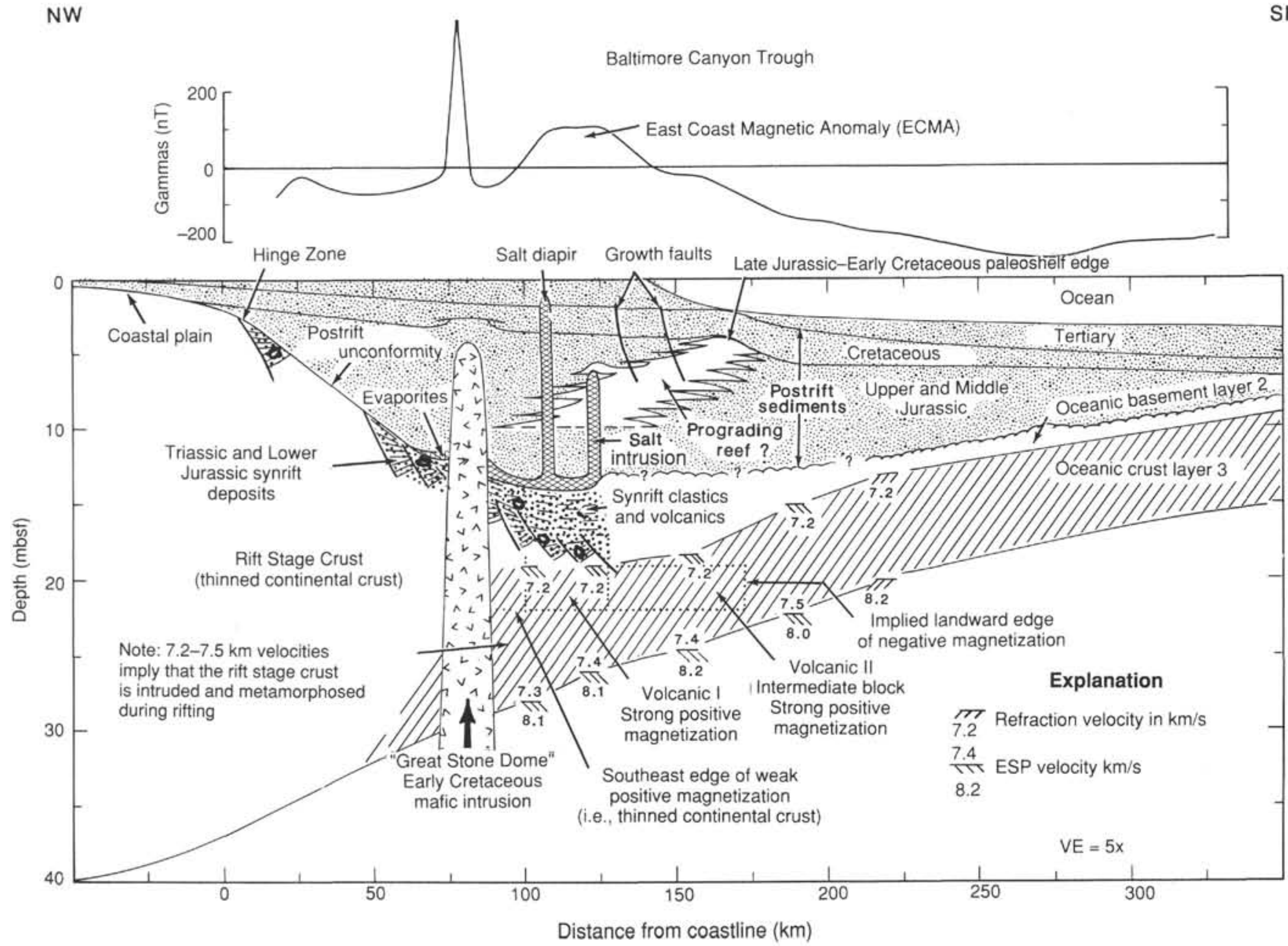

Figure 1. Cross-section running from the New Jersey coastal plain through Island Beach, New Jersey, across the continental shelf and onto the slope and rise in the vicinity of Leg 150 (after Grow and Sheridan, 1988). VE = vertical exaggeration.

bonate ramps (e.g., west Florida) and different tectonic histories (e.g., Canterbury Basin, New Zealand), must be studied to investigate and understand fully the global record of eustatic change.

SETTING OF LEG 150

Physiography

During Leg 150, Sites 902 through 906 were drilled on the continental slope and rise offshore of New Jersey. These physiographic provinces were defined by Heezen et al. (1959) on the basis of seafloor gradient: the shelf dips seaward with a gradient of less than 1:100 (<0.6°), the continental slope with a gradient greater than 1:40 (>1.6°) slope, and the continental rise with a gradient of about 1:100 (~0.6°). The continental shelf is wide (>80 nmi, >147 km) in this region and the water depth at the shelf/slope break averages about 135 m (Heezen et al., 1959). The slope is incised by numerous submarine canyons, the largest of which indent the shelf/slope break.

Hydrography

Surface waters in the vicinity of slope sites drilled by Leg 150 are dominated by three water masses: (1) relatively fresh Shelf Water (salinities = <35‰); (2) more saline Slope Water (35‰–36‰); and (3) the warm (>18°C), salty (>36‰) Gulf Stream (Beardsley and Boicourt, 1981). Slope Waters dominate in this region, although the front between Shelf and Slope Waters is not rigidly fixed to the shelf/slope break. In addition, Gulf Stream eddies (warm core rings) advect warm, salty water to the region; several were noted during drilling at Sites 902–904. The source of Slope Water has been attributed to the Labrador Current, although it is probably locally derived through winter cooling (Beardsley and Boicourt, 1981). A cyclonic gyre of northeast-flowing Slope Water and southwest-flowing Shelf Water is geostrophically balanced by regional wind forcing, although the processes controlling the position and movement of the boundary between Shelf and Slope Waters are poorly understood (Beardsley and Boicourt, 1981). The main thermocline and oxygen minimum zone in this region are shallow and seasonably stable (<400 m) (Miller and Lohmann, 1982). Oxygen in the water column remains high, even in the O_2 minimum zone (>3 mL/L). The continental rise falls within the influence of the Western Boundary Undercurrent (WBUC), a strong southwest-flowing bottom current composed primarily of North Atlantic Deep Water with an admixture of Antarctic Bottom Water (Heezen et al., 1966; Amos et al., 1971; McCave and Tucholke, 1986). The strongest flow of this deep geostrophic current is between water depths of 3000 and 4900 m on the continental rise; however, sedimentation at continental rise Site 905 (2761 m; see Fig. 2) has probably been influenced, at least periodically, by this strong contour-current flow.

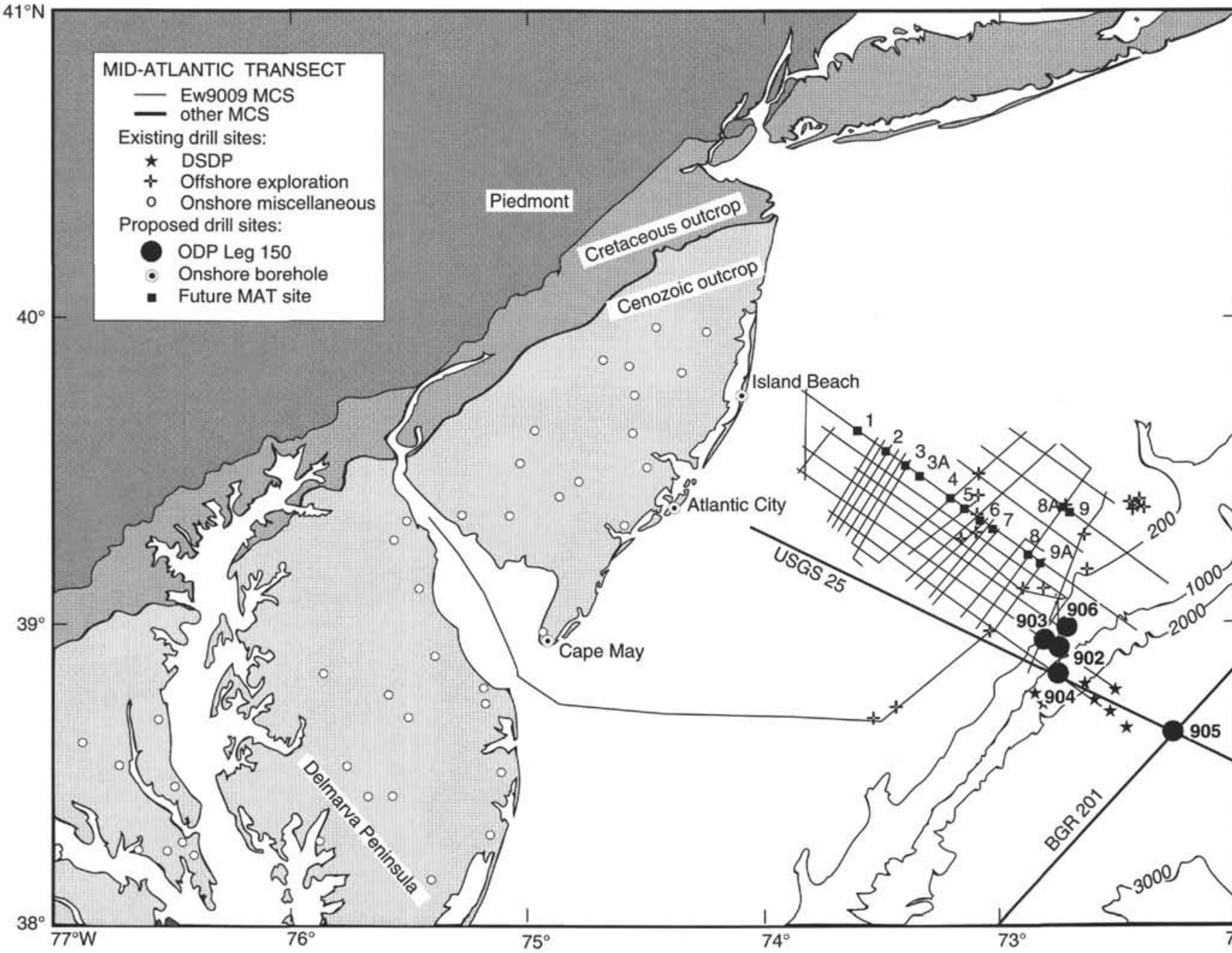

Figure 2. Generalized bathymetric location map showing proposed Sites MAT1–9, the three onshore sites (Island Beach, Atlantic City, and Cape May), and ODP Leg 150 Sites 902 through 906.

Geological Setting

The U.S. middle Atlantic margin (New Jersey–Delaware–Maryland; Figs. 1–2) is a classic passive margin. Rifting began in the Late Triassic (Grow and Sheridan, 1988) and seafloor spreading began by the Callovian (~165 Ma, Middle Jurassic; Sheridan, Gradstein, et al., 1983). The subsequent tectonic history has been dominated by simple thermal subsidence, sediment loading, and flexure (Watts and Steckler, 1979; Reynolds et al., 1991). In the region of the Baltimore Canyon Trough, the Jurassic section is composed of thick (typically 8–12 km), shallow-water limestones and shales (Fig. 1). A barrier reef complex fringed the margin until the mid-Cretaceous (Poag, 1985). Accumulation rates were generally low (typically 20 m/m.y.) during Upper Cretaceous to Paleogene siliciclastic and carbonate deposition (Poag, 1985). Upper Cretaceous to Cenozoic strata buried beneath the shelf can be traced updip to outcrops in the onshore coastal plain (Fig. 2). Sedimentation rates increased dramatically in the Oligocene to Miocene (to greater than 200 m/m.y.) when siliciclastic sedimentation dominated (Poag, 1985). Sediments prograded progressively seaward during this interval, producing thick sets of clinoforms now observed on seismic profiles (e.g., Greenlee et al., 1992). The cause of this large increase in sediment supply is unknown, although it may reflect tectonics in the hinterland (Poag and Sevon, 1989; Sugarman et al., 1993). Slope outcrops of Oligocene to Pleistocene siliciclastic strata occur in the upper to middle slope canyons, whereas middle and lower Eocene carbonates are exposed in lower slope canyons and in a 10- to 15-km-wide section that extends from 38° to 42°N on the middle slope.

Sedimentation on the Slope and Rise

Surficial sediments on the continental slope consist of silts on the upper slope that grade down to clays on the lower slope (Ericson et al., 1961; Hollister, 1967, 1973). Because of the Holocene high sea-level stand, most modern riverine sediment input is trapped in the Hudson and Delaware river estuaries and relatively little, if any, terrigenous sediment reaches the outer shelf or slope. Thus, modern sedimentation on the slope is primarily hemipelagic and sediments are derived from muds carried as suspended material from river discharge or from resuspended shelf sediments carried off the shelf (Doyle et al., 1979). Surficial slope sediments are rich in organic matter (>1%), although organic carbon values are highly variable on the slope (Miller and Lohmann, 1982). In general, the surficial slope sediments are carbonate poor (<20%), although carbonate content increases with depth as a result of increased input of pelagic carbonates (Miller and Lohmann, 1982) and decreased input of terrigenous material.

Considerable speculation has centered on whether Holocene sedimentation on the slope is dominated by downslope transport or by in situ pelagic sedimentation. Examination of grab samples and piston and gravity core tops obtained on the lower slope in the Lindenkohl-Carteret Canyon region shows a pattern of largely in situ benthic biofacies (Miller and Lohmann, 1982; Christensen and Miller, 1991). Submersible observations of the lower slope in the immediate region of Leg 150 (Lindenkohl, Carteret, upper Carteret, and Hendrickson canyons) using the *Alvin* show that the bottom is draped by Holocene pelagic sediments; outcrops are rare and restricted to occasional near-vertical walls (W.B.F. Ryan and K.G. Miller, unpubl. observ., 1989). Visual and core evidence for large- and small-scale transport is largely limited to blocks found at the foot of the slope (2200 m in the immediate region of Leg 150) and sporadic turbidity-current activity in some canyon thalwegs (McHugh et al., 1993).

Sedimentation during the Pleistocene was different than in the Holocene. During glacial intervals, lowering of sea level exposed much of the continental shelf and rivers debauched sediments into a narrow zone along the outermost shelf and directly into the heads of submarine canyons. Deltas prograded over the shelf edge or into submarine canyon heads. Evidence exists for widespread downslope transport in Pleistocene sections on the continental slope between the Lindenkohl and Hendrickson canyons (Christensen and Miller, 1991; see Chapters 6–8 in this volume; see also Pilkey and Cleary, 1986; Laine et al., 1986). Point sources for these sands and muds include the Hudson River, Delaware River, and possibly input from a point south of Atlantic City (Swift et al., 1980); reworking of the riverine input in the narrow neritic zone provided material along the entire region. In general, Pleistocene-Holocene sedimentation rates on the slopes are high (~30 cm/k.y.; Emery and Uchupi, 1972; Doyle et al., 1979); these rates are consistent with those estimated at Site 902 (Chapter 6, this volume). The submarine canyons funneled large quantities of terrigenous sediments to the lower continental slope, rise, and Hatteras Abyssal Plain by means of turbidity currents and related gravity-controlled flows (Ericson et al., 1961; Pilkey and Cleary, 1986, and references therein). These flows spread laterally outward and downslope from the lower ends of the canyons and built fanlike features across the continental rise (e.g., Hatteras Fan, Wilmington Fan) and eventually coalesced to build part of the rise. Large-scale mass wasting of the continental slope also produced large volumes of sediment that moved downslope to the rise by means of slumps, slides, debris flows, and related mass movements (Embley and Jacobi, 1986; Laine et al., 1986). The timing of transport is not well known, and Site 905 was designed, in part, to determine the nature and time of emplacement of downslope transported sediments (see Chapter 2, this volume).

Although the bulk of sediments that form the continental rise are introduced by these downslope, gravity-controlled processes, parallel-to-slope processes (i.e., contour currents) are also extremely important in constructing and shaping the continental rise (Heezen et al., 1966; Hollister, 1967; Mountain and Tucholke, 1985; McCave and Tucholke, 1986; Laine et al., 1986). The Western Boundary Undercurrent (WBUC) is a strong contour-following geostrophic current that flows southwest along the continental rise between about 3000 and 4900 m (Heezen et al., 1966; Amos et al., 1971; McCave and Tucholke, 1986). This strong contour current entrains sediment from downslope turbidity flows, erodes and transports sediments from the seafloor, and redistributes and redeposits vast quantities of sediment as large- to small-scale drift deposits and features along the continental rise (Heezen et al., 1966; Tucholke and Laine, 1982; McCave and Tucholke, 1986; Laine et al., 1986). The relative role of along-slope vs. downslope sedimentation processes is still uncertain (see Chapter 2, this volume).

GOALS OF LEG 150

Leg 150 sailed from Lisbon, Portugal, on 28 May 1993, conducted 40 days of on-site drilling on the New Jersey slope and rise, and arrived in St. Johns, Newfoundland, on 24 July 1993, having completed drilling in five boreholes. Concurrent with Leg 150, two boreholes were drilled at Island Beach and Atlantic City, New Jersey, as part of the overall New Jersey Sea-level Transect. As outlined in Chapter 2 (this volume), the primary goals of Legs 150 and 150X are to (1) date major Oligocene to Holocene unconformities on the New Jersey margin, and (2) determine possible correlations of these hiatuses with the marine $\delta^{18}O$ record. These are requisite first steps in assessing the causes and effects of sea-level change. Two other objectives—equally important—require drilling on the adjacent shelf at some future date. They are to (1) estimate the amplitudes and rates of sea-level changes that are detected and (2) evaluate marginwide unconformities as sequence boundaries and fully document the stratigraphic response to glacioeustatic and tectonic forcing.

An important secondary goal of the transect (including Leg 150) is to determine ages of major Eocene "Doubthouse" unconformities. As noted in Chapter 2 (this volume), Eocene and older sequences are well represented in this region (Poag, Watts, et al., 1987; Olsson and Wise, 1987; Miller et al., 1990; Aubry, 1991); however, they lack the well-developed seismic geometries observed in the Oligocene to Holocene section. Thus, facies geometry and amplitudes of Eocene relative sea-level changes will not be fully addressed by the transect, although it will be possible to determine the ages of Eocene sequences.

One major scientific goal is unique to Leg 150 relative to onshore and shelf drilling: to evaluate the relative importance of along-slope vs. downslope sediment transport processes and establish their links to eustatic variations (see Chapter 2, this volume, for discussion).

The scientific party engaged in a wide range of methods and measurements to further the primary goals mentioned above. Each discipline had specific objectives, described as follows.

The major objectives of the lithostratigraphic studies are to evaluate the sources, transport, and depositional processes of sediment deposition within slope and rise depositional environments and to understand the relationships of the various lithologies and processes to changes in sea-level and climatic fluctuations. These objectives include investigation of the nature of lithologic, diagenetic, and mineralogic changes across unconformities and sequence boundaries, which are observed in the boreholes and on seismic reflection profiles. These studies will include characterization of the depositional facies of various "systems tracts" (lowstand, highstand, transgressive) within the deep-water portions of depositional sequences on a passive margin. Another objective is to study the rhythmicity of signals (sea-level, climatic, and other fluctuations) using time-series and coherence analyses. Integration of lithologic, biostratigraphic, paleomagnetic, and geochemical data are critical to this approach because jointly these can yield a reliable set of datum levels that can be used for transformation from the layer thickness to the time domain.

Micropaleontological studies will serve to date sequences, determine the ages of sequence boundaries, and determine the nature of biofacies and thanatofacies changes in a sequence stratigraphic framework. Paleomagnetic investigations will evaluate the fidelity of the slope paleomagnetic record in correlating sedimentary sequences to the Geomagnetic Polarity Time Scales and use the rock magnetic record to determine environmental and diagenetic effects on Fe-oxides and sulfides.

Organic chemistry will provide information on the sources, supply, and diagenetic history of organic carbon and use biomarkers as potential paleoceanographic tools. Inorganic chemistry will determine the sources and migration of fluids and the diagenetic history of the sediments in relation to sea-level and paleoceanographic changes.

Shipboard measurements of physical properties from cores and from wireline logging will aid in the characterization of lithologic units and help correlate core lithology, downhole geophysical logs, and seismic data. Core-log correlation will be attempted using laboratory and downhole log bulk density and natural gamma measurements. Physical properties data from known lithologies will be fitted to downhole log responses. The logs may then serve as a proxy for these data through intervals of poor core recovery. Cyclicity, present at various scales in physical properties data sets, will be integrated with seismic and lithologic data to define deep-sea depositional sequences. Physical properties data will be used to calibrate the seismic sequence stratigraphic interpretation by generating reflection coefficient series and synthetic seismograms. Synthetic seismogram modeling will focus on the correlation of physical properties data and the lithology with seismic sequence surfaces and boundaries as well as on an investigation of the physical causes of seismic reflections. A further research focus will be on physical and chemical (e.g., diagenetic) processes responsible for downhole trends.

This volume presents preliminary results from five boreholes (Sites 902–906) drilled during Leg 150. The attached Leg 150X volume contains results from two boreholes (Island Beach and Atlantic City) drilled onshore. Our studies to date show that Leg 150 and related drilling has recovered the critical sections needed to address the goals that we have outlined.

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