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1. INTRODUCTION: OLIGOCENE TO PLEISTOCENE EUSTATIC CHANGE AT THE NEW JERSEY CONTINENTAL MARGIN—A TEST OF SEQUENCE STRATIGRAPHY[1]

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INTRODUCTION

The emergence of seismic/sequence stratigraphy since the late 1970s has led to a revolution in stratigraphy and a renewal of interest in the stratigraphic response to eustasy (global sea-level change; Vail et al., 1977, 1984, 1991; Vail and Hardenbol, 1979; Loutit and Kennett, 1981; Berg and Woolverton, 1985; Haq et al., 1987, 1988; Vail, 1987, 1992; Cross and Lessenger, 1988; Posamentier et al., 1988; Sloss, 1988; Eberli and Ginsburg, 1989; Fulthorpe and Carter, 1989; Christie-Blick et al., 1990; Van Wagoner et al., 1990; Haq, 1991; Mitchum and Van Wagoner, 1991; Loucks and Sarg, 1993; Posamentier and James, 1993; Weimer and Posamentier, 1993; Christie-Blick and Driscoll, 1995; Van Wagoner, 1995; Howell and Aitken, 1996; Fulthorpe and Austin, 1998; Miller et al., in press). Two arguments were advanced in support of the eustatic interpretation. One involved widespread seismic evidence for the existence of regional unconformities (sequence boundaries) characterized by apparently abrupt basinward shifts in onlap, which were interpreted to imply relatively rapid falls of sea level with amplitudes of up to several hundred meters. The second was based on the purported global synchroneity of these unconformities, which, if correct, would be difficult to explain by other than a eustatic mechanism.

These arguments were not universally accepted for several reasons (Watts, 1982; Thorne and Watts, 1984; Miall, 1986, 1991, 1992, 1994; Burton et al., 1987; Hubbard, 1988; Christie-Blick et al., 1990; Reynolds et al., 1991; Christie-Blick, 1991; Underhill, 1991; Christie-Blick and Driscoll, 1995).

1. Basinward shifts in onlap were shown not to require sea-level changes that were either rapid or of large amplitude; so there was no reason to assume a eustatic causal mechanism or to exclude possible local tectonic mechanisms for sequence-boundary development.
2. No mechanism was known that could produce rapid eustatic change during intervals such as the Mesozoic, for which there is little or no evidence for continental glaciation.
3. Limitations in the resolution with which sequence boundaries could be dated and correlated between basins cast doubt on the level to which global synchroneity had been established.
4. At least prior to 1987, the “sea-level curve” first published by Vail et al. (1977) was based primarily on proprietary data (see Haq et al., 1987). Thus, at the time of the Second Conference on Scientific Ocean Drilling (COSOD II, 1987), there was a great deal of interest in acquiring public domain data that could be used to establish a sea-level record independent of the Vail et al. (1977) synthesis.

Following COSOD II, the role of scientific ocean drilling in sea-level studies was advanced by means of a Joint Oceanographic Institutions, Inc. (JOI)/U.S. Scientific Advisory Committee (USSAC) Workshop (Watkins and Mountain, 1990) and a JOIDES working group (Sea Level Working Group Report, 1992). Sea-level studies were also prioritized in the JOIDES Sedimentary and Geochemical Processes Panel (SGPP) White Paper (1994), the JOIDES Long Range Plan (1996), and the Margins Initiative (Sawyer, 1996). These reports differ in detail and emphasis, but they endorse several broad objectives. These objectives include the following: (1) the dating of stratigraphic “events” and associated surfaces that might be related to sea-level change; (2) investigating how sedimentary architecture is related to sea-level variations (local or global); and (3) if a role for eustasy can be demonstrated, estimating the magnitudes and rates of eustatic change through time. All recognized that multiple drilling legs would be required to make comparisons among coeval successions at different locations, and that ODP would be able to sample only a small portion of Earth’s sea-level history. Therefore, three intervals were prioritized within the Mesozoic to Cenozoic span accessible to ocean drilling: (1) the late middle Eocene to Holocene (“Icehouse”) Earth, dominated by the waxing and waning of continental ice sheets; (2) the mid-Cretaceous (“Greenhouse” or “Hothouse”) Earth, when ice sheets were essentially absent; and (3) the intermediate interval from the latest Paleocene to the middle Eocene, when the degree of glaciation is unknown or uncertain, and for which the term “Doubthouse” Earth was suggested (Miller et al., 1987, 1991b; Watkins and Mountain, 1990; Barron et al., 1991; Frakes et al., 1992; Browning et al., 1996; Stoll and Schrag, 1996; Miller et al., in press).

The scientific ocean drilling community tacitly assumed that this approach would lead to insights about possible mechanisms of eustatic change, as well as to a broader understanding of the relationships between eustasy and various phenomena, including changes in continental ice volume (and hence global climate), nearshore ecosystems, particle and nutrient transfer to the deep sea, ocean circulation, biological evolution, and patterns of deposition, erosion, and hydrocarbon distribution in sedimentary basins. It is now clear that the main control on short-term eustasy is the continental ice budget and that during nonglacial times, sedimentary cyclicity is likely to have been influenced significantly by noneustatic mechanisms, including tectonics (Christie-Blick and Driscoll, 1995). There is no evidence to support the long-held assumption in sea-level studies that tectonic processes act only at long time scales (cf. Vail et al., 1991). New hypotheses have also been advanced concerning the stratigraphic response to eustatic change. Modeling studies suggest that this response may vary from one basin to another, because of variability of such factors as the local rate of subsidence and sediment supply, the relative abundance of siliciclastic vs. carbonate sediment, compaction history, and the physiography of the depositional surface. The locally determined timing of sea-level events is therefore expected to vary, even when the events are global (Jordan and Flemings, 1991; Reynolds et al., 1991; Christie-Blick, 1991; Steckler et al., 1993); strict stratigraphic synchroneity cannot be assumed as a criterion for judging the role of eustasy in the origin of observed sedimentary cy-

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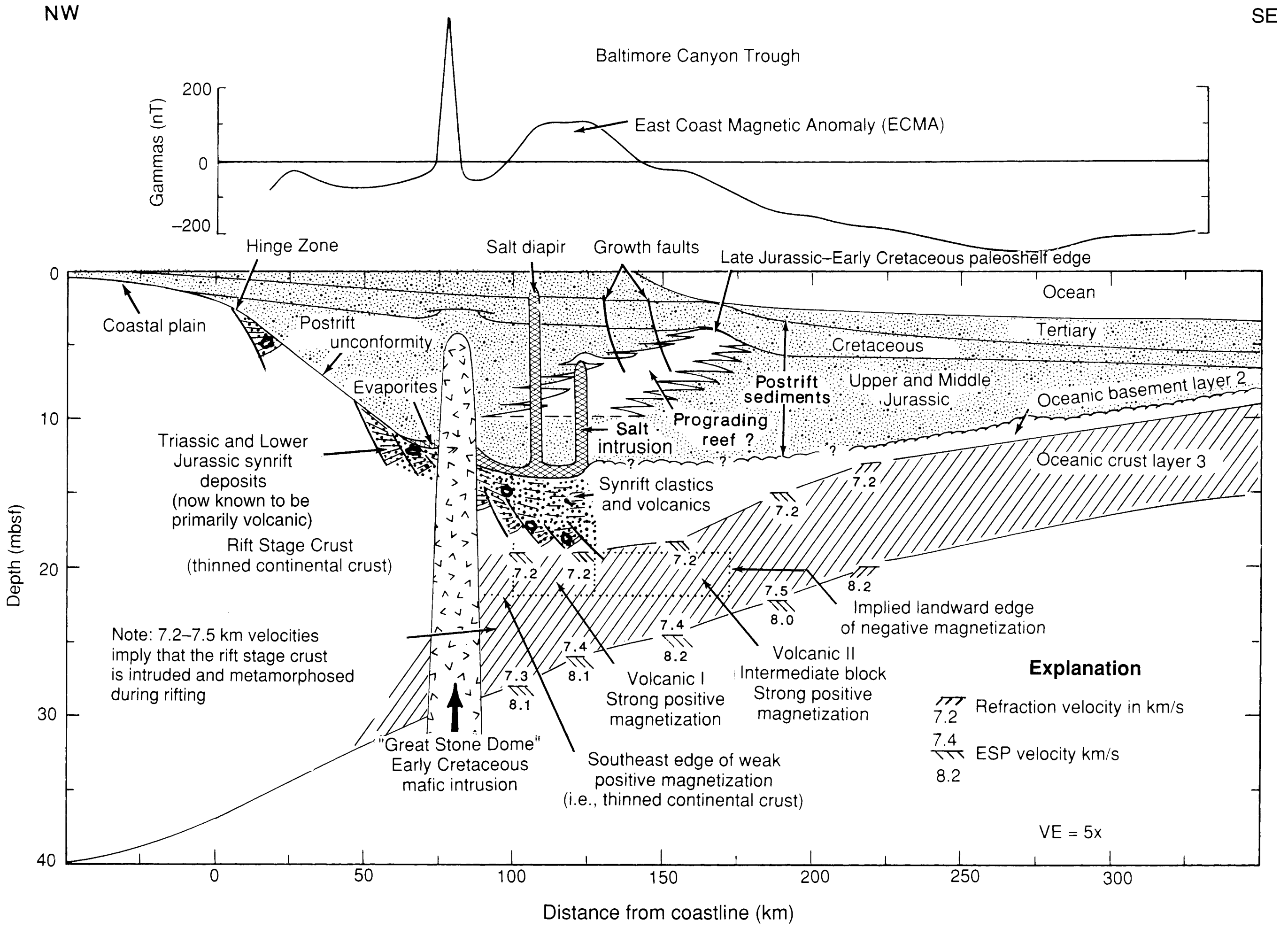

Figure 1. Schematic cross-section from the New Jersey Coastal Plain crossing the continental shelf, slope, and rise in the vicinity of Leg 174A (after Grow and Sheridan, 1988). The wedge labeled "synrift clastics and volcanics" is now known to be composed primarily of volcanic rocks (Sheridan et al., 1993).

clicity. Instead, precise dating of stratigraphic successions at a number of well-chosen locations may permit predicted leads and lags to be measured. Ocean drilling has been consistently envisioned as a primary tool for such an approach to studying the history of sea-level change.

The Sea Level Working Group (1992) endorsed a three-fold approach to sea-level studies, involving (1) passive continental margins (primarily siliciclastic); (2) carbonate atolls, guyots, and platforms, the so-called "dipstick" approach; and (3) the deep-sea oxygen isotopic record, a proxy for the growth and decay of continental ice sheets. This strategy has since been reaffirmed in the SGPP White Paper (1994) and in the JOIDES Long Range Plan (1996). ODP Legs 133 and 166 addressed "Icehouse" sea-level issues at the seaward margins of carbonate platforms off northeastern Australia and the western Great Bahama Bank, respectively. Legs 143 and 144 studied the "Greenhouse" drowning history of western Pacific guyots. Leg 174A is a continuation of the New Jersey Mid-Atlantic Sea-level Transect (MAT), the first concerted effort to evaluate the effects of "Icehouse" glacial-eustatic change at a passive continental margin characterized by predominantly siliciclastic sedimentation. Leg 174A follows successful sampling of the continental slope and rise during Leg 150 (Miller and Mountain, 1994; Miller et al., 1996c), and continuing studies of the adjacent New Jersey Coastal Plain (Legs 150X and 174AX; Miller et al., 1994, 1996a, 1998, in press; Miller and Sugarman, 1995; Pekar and Miller, 1996).

GEOLOGY OF THE NEW JERSEY CONTINENTAL MARGIN AND SUITABILITY FOR SEA-LEVEL STUDIES

The U.S. mid-Atlantic region, including parts of New Jersey, Delaware, and Maryland (Figs.1, 2), is a classic passive continental margin. Rifting began in the Late Triassic (Grow and Sheridan, 1988), and seafloor spreading commenced by the Middle Jurassic (~165 Ma; Sheridan, Gradstein, et al., 1983; Klitgord et al., 1988). Subsequent subsidence has been governed primarily by lithospheric cooling and by flexural loading and compaction of accumulating sediment (Watts and Steckler, 1979; Watts, 1988; Reynolds et al., 1991; Steckler et al., 1993; Pazzaglia and Gardner, 1994). In the vicinity of Leg 174A sites, the Jurassic section is composed of 8–12 km of shallow-water limestones and shales. A barrier reef complex fringed the margin until the mid-Cretaceous (Poag, 1985). Accumulation rates were generally low during latest Cretaceous to Paleogene, when the margin became relatively starved of sediment, and the shelf subsided to a depth of several hundred meters below sea level (Poag, 1985; M.S. Steckler, pers. comm., 1997). An abrupt increase in sediment supply in the Oligocene led to the deposition of a series of thick, unconformity-bounded sediment wedges that built seaward during Miocene time to produce a shelf with a terraced morphology. This physiography, which is quite different from that of the modern shelf, involves a shallow ramp and a deep ramp separated by an intervening slope of 4°–

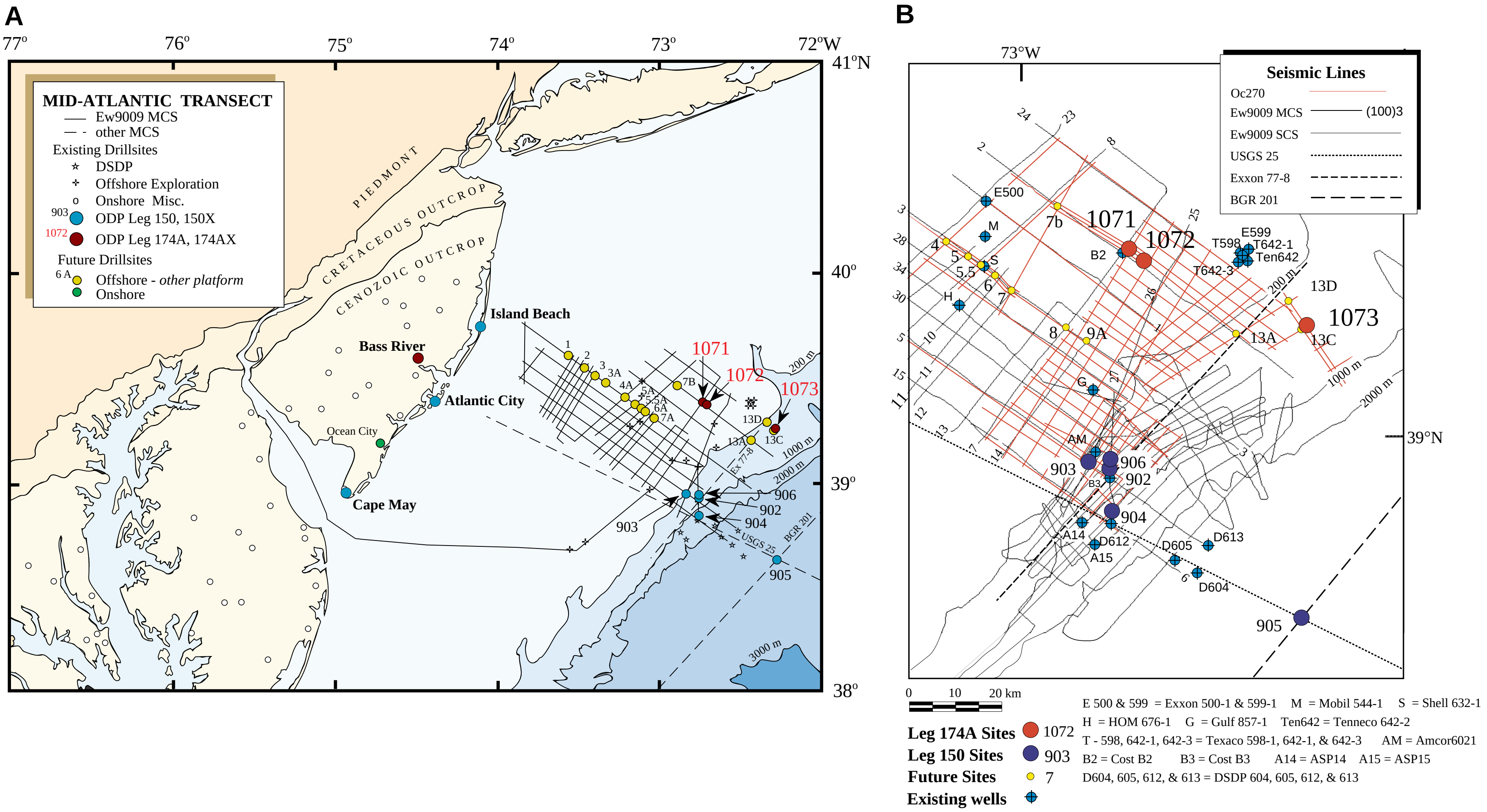

Figure 2. **A.** Locations of Leg 174A Sites 1071 and 1072 on the outer shelf and Site 1073 on the uppermost slope. Also shown are the locations of the Leg 174AX Bass River Site on the New Jersey Coastal Plain; Leg 150 Sites 902–906; Leg 150X Island Beach, Atlantic City, and Cape May Sites; and proposed MAT sites 1–13 (offshore), Ocean City (onshore). *Ewing* 9009 MCS lines are shown, along with the location of selected industry seismic profiles. **B.** *Oceanus* 270 high-resolution MCS coverage (bold lines), used to select all Leg 174A sites (except 13A, which was located at the intersection of Ew9009 and Exxon MCS profiles).

6° (Figs. 3, 4). The cause of the Oligocene increase in sediment supply is uncertain, but may reflect hinterland tectonic uplift and/or an increase in terrestrial weathering rates and associated soil erosion (Poag and Sevon, 1989; Poag and Ward, 1993; Sugarman et al., 1993; Pazzaglia and Brandon, 1996).

This part of the U.S. Atlantic margin is well suited for the study of sea-level changes during the Oligocene to Holocene "Icehouse" interval for several reasons.

1. Upper Oligocene to Miocene and Pleistocene records are relatively complete (the Pliocene record is uncertain), and high rates of sediment accumulation (tens to hundreds of meters per million years) make it possible to resolve stratal relationships in great detail on seismic data (Poag, 1977; Schlee, 1981; Greenlee et al., 1988, 1992).
2. The best possible biostratigraphic control is ensured by the mid-latitude setting (Poag, 1985; Olsson and Wise, 1987; Olsson et al., 1987; Poore and Bybell, 1988; Greenlee et al., 1992). Upper Eocene–Miocene sediments of this region have adequate carbonate to utilize strontium-isotope correlation techniques (Sugarman et al., 1993; Miller et al., 1991a, 1994, 1996b; Oslick et al., 1994; Miller and Sugarman, 1995). Pleistocene stratigraphic control afforded by integration of nannofossil and physical properties data is also excellent, particularly for deep-water sediments (better than 20-k.y. resolution; Mountain, Miller, Blum, et al., 1994).

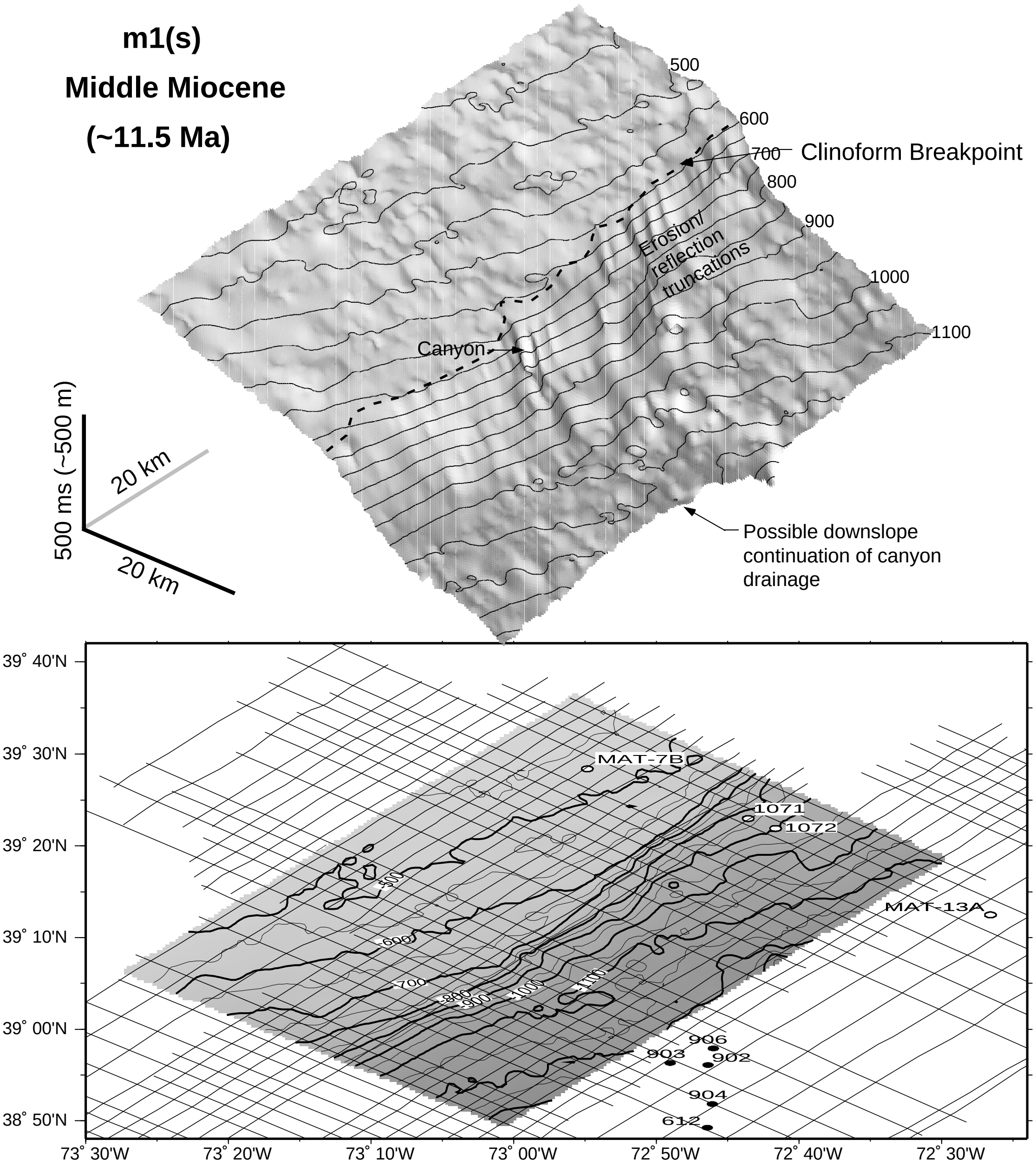

Figure 3. Example of a buried upper middle Miocene rollover or breakpoint and associated clinoform for sequence boundary m1(s) (~11.5 Ma), which was mapped using commercial seismic data available for the outer shelf and upper slope of the New Jersey margin (from Fulthorpe and Austin, 1998; Fig. 2). **Bottom:** Structure map showing seismic grid and drill sites for Leg 174A (1071, 1072), Leg 150 (902–904 and 906), and Leg 95 (612). Units are milliseconds two-way traveltime below present sea level. **Top:** 3-D perspective shaded image with traveltime contours (azimuth of artificial illumination = 220°). Both panels are viewed from an azimuth of 180° and an elevation of 30°.

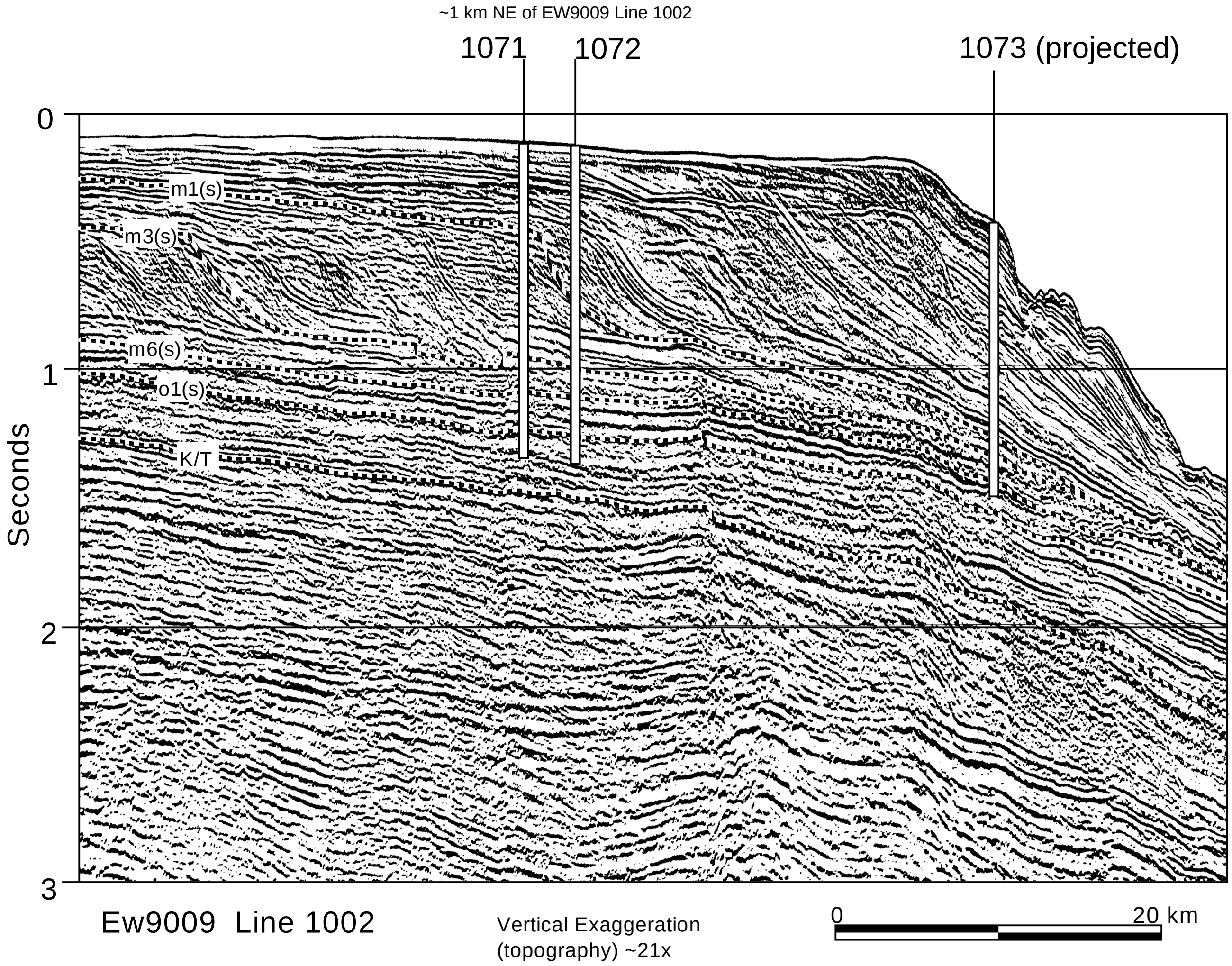

Figure 4. *Ewing* 9009 MCS Profile 1002, with projected locations of Leg 174A Sites 1071–1073. Prominent unconformity-bounded wedges of mid- to late Cenozoic age are the focus of Leg 174A and additional proposed drilling on the continental shelf. Selected surfaces are labeled. K/T = Cretaceous/Tertiary boundary.

3. Tectonic subsidence has been slow (<10 m/m.y.) and well-defined throughout the Cenozoic (Steckler and Watts, 1982), a situation that favors the preservation and identification of glacial-eustatic fluctuations in the stratigraphic record (Vail et al., 1977).
4. There is little seismic or outcrop evidence to suggest major faulting, tilting, or other large-scale disturbances of the Cenozoic section (Poag, 1985), although some differential subsidence may have occurred between New Jersey and the Delmarva Peninsula of Delaware, Maryland, and Virginia (Owens and Gohn, 1985).
5. A substantial body of useful data, including seismic profiles (at various frequencies) and data derived from boreholes, coastal exposures, and submarine outcrop, already exists for this margin (Fig. 1; Hathaway et al., 1976; Poag, 1978, 1980, 1985; Ryan and Miller, 1981; Kidwell, 1984, 1988, 1997; Olsson et al., 1987; Poag, Watts, et al., 1987; Greenlee et al., 1988, 1992; Pazzaglia, 1993; Mountain, Miller, Blum, et al., 1994; among others). This includes data from Deep Sea Drilling Project (DSDP) Legs 93 and 95, which represent an attempt to synthesize the overall stratigraphy and structure of the New Jersey margin (van Hinte, Wise, et al., 1987; Poag, Watts, et al., 1987). However, the shallowest site (Site 612; Fig. 1) was drilled at a water depth of 1400 m, and it proved to be poorly located for sampling Oligocene–Miocene strata (Miller et al., 1987). Nonetheless, these earlier drilling expeditions set the stage for more detailed studies, such as the Mid-Atlantic Transect, where the objectives have been to improve dating resolution of seismically imaged unconformity surfaces, and to do so at sites where paleobathymetry is shallow enough to be sensitive to eustatic variations.

PROGRESS ON THE MID-ATLANTIC TRANSECT

Before ODP could move to the adjacent New Jersey shelf, a grid of high-quality seismic data was needed to frame the objectives and locate optimal targets. Based on reinterpretation of Exxon Production Research Company multichannel seismic (MCS) data and well logs, Greenlee et al. (1992) published a refinement of previously identified Oligocene and Miocene depositional sequences and bounding surfaces (Greenlee and Moore, 1988; Greenlee et al., 1988). An MCS seismic program performed aboard the *Maurice Ewing* in November 1990 (Ew9009) collected 3700 km of single-channel seismic (SCS) and MCS profiles (Fig. 2). The Ew9009 MCS profiles roughly doubled the number of prograding late Paleogene–Neogene wedges that could be resolved using older seismic data (Fig. 4). Furthermore, this grid included dip lines that extended from the inner shelf to a position seaward of the shelf break. For the first time, “Icehouse” sequence boundaries could be mapped across the shelf to the slope. In 1995, the

Ewing profiles were augmented by higher resolution MCS profiles, including detailed hazards grids, collected aboard the *Oceanus* (Oc270; Figs. 2, 5). Locations of all but one site (MAT-13A; Fig. 2) proposed for drilling during Leg 174A were chosen on the basis of analysis and continuing interpretation of the newer *Oceanus* data.

Leg 150 (June–July, 1993; Mountain, Miller, Blum, et al., 1994) capitalized on the *Ewing* shelf-to-slope imaging and drilled four locations (Sites 902–904 and 906) at water depths of between 445 and 1134 m (Fig. 2). These sites document the age and facies of sediments associated with a total of 22 lower Eocene to mid-Pleistocene reflecting surfaces tentatively interpreted as, or jump-correlated landward with, sequence boundaries (Fig. 6). Integrated biostratigraphic, magnetostratigraphic, and strontium isotopic stratigraphy yield temporal resolution approaching several hundred thousand years (Miller et al., 1996c, in press). In most cases, interpreted sequence boundaries are associated with little or no temporal hiatus; many are expressed by a slight coarsening of sediment transported to the slope, it was presumed, during low stands of sea level.

To complement the Leg 150 results, MAT proponents launched a land-based drilling program with support from ODP, the National Science Foundation (NSF), and the U.S. and State of New Jersey geological surveys (Miller et al., 1994). Primary objectives of these onshore boreholes (Leg 150X and related; Fig. 2) have been to date Late Cretaceous to Cenozoic sequences, including the Paleocene–Eocene "Doubthouse" section, and to evaluate facies architecture in an updip setting. Thus far, four holes have been cored and logged, all at sites close to the modern shoreline (Fig. 2), and more are planned (Miller et al., 1994, 1996a, 1998, in press). Late middle Eocene to middle Miocene sequence boundaries in both onshore and Leg 150 boreholes appear to correlate, at available resolution, with prominent δ^{18}O increases, consistent with the hypothesis that these surfaces developed during global lowstands of sea level (Mountain, Miller, Blum, et al., 1994; Miller et al., 1996a, 1996c, 1998, in press). The ages of these sequence boundaries compare well with timing of the Haq et al. (1987) "global" boundaries (Miller et al., 1996a, 1996c, in press). Recently completed drilling at Bass River, New Jersey (ODP Leg 174AX; Fig. 2), has also recovered a complete Cretaceous/Tertiary boundary section (Olsson et al., 1997; Miller et al., 1998).

Facies successions on shore are generally well developed for the Paleocene through middle Miocene, with a transgressive shell bed or glauconite sand at the base of each sequence and quartz sand at the top (upper part of the highstand facies tract; Sugarman et al., 1993; Miller et al., 1994). Onshore drilling has provided important data for regional profiles, but all of the boreholes are landward of the Oligocene–Miocene clinoforms imaged in seismic reflection data beneath the shelf (Figs. 2–4). The shelf sites, tackled during Leg 174A, are the ones most critical for estimating amplitudes of sea-level change during the "Icehouse" interval.

AVAILABLE DATA

The New Jersey margin is one of two study areas recently selected by the U.S. Office of Naval Research (ONR) for a multiyear initiative that it has termed "Strata Formation on Margins" (STRATAFORM). Together with studies of a contrasting margin off northern California, the goal is to investigate the range of factors affecting the deposition and preservation of shelf and slope stratigraphy (Nittrouer and Kravitz, 1995). Off New Jersey, the missions of STRATAFORM and the MAT coincide.

As a result, ONR and JOI/USSAC supported a consortium of investigators from the University of Texas Institute for Geophysics (UTIG), Lamont-Doherty Earth Observatory (LDEO), and Rutgers University to collect, analyze, and interpret high-resolution MCS data on the New Jersey shelf and upper slope in support of proposed drilling during the summer of 1995 (Fig. 2). These data, collected during cruise Oc270, included a series of detailed "hazards" seismic grids mandated by ODP (Fig. 5), augmenting a substantial set of regional geophysical and geological data that includes the following: (1) the 60-fold Ew9009 MCS profiles collected from the inner shelf to the rise (Fig. 4); (2) 2-D and 3-D SCS seismic grids (using a Huntec deep-towed system) and associated vibracores collected by UTIG in 1989 and 1993; (3) commercial MCS profiles collected during the 1970s in a dense grid (~2.5-km line spacing) across the outer shelf and upper slope (Fulthorpe and Austin, 1998; Fig. 2); and (4) multibeam bathymetry/backscatter coverage of the entire area using a commercial Simrad EM-1000 system (Goff et al., 1996).

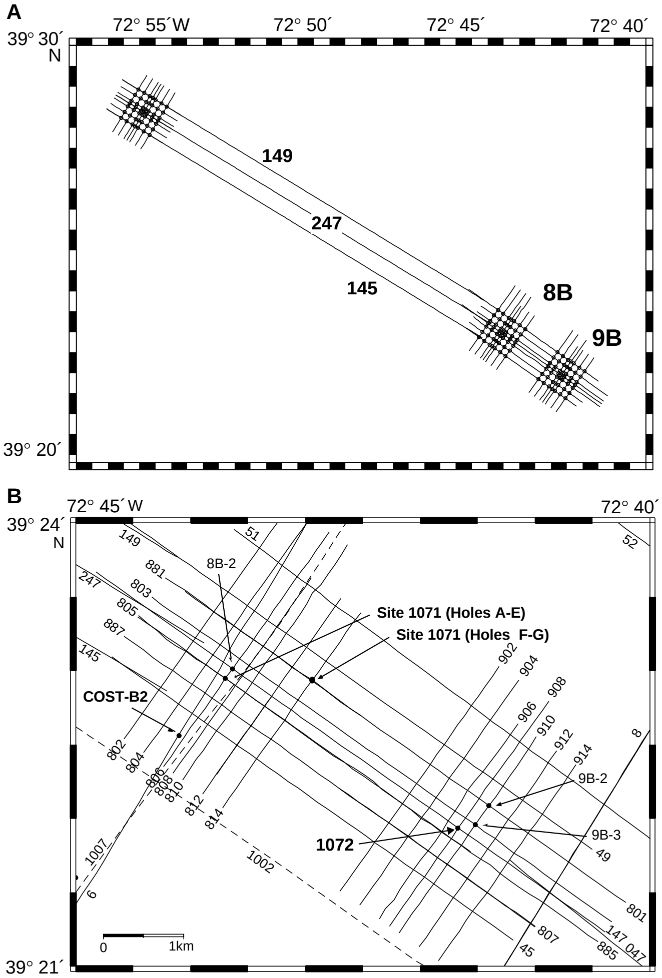

Figure 5. **A.** "Hazards-type" MCS surveys completed in 1995 at locations proposed and approved for Leg 174A drilling on the New Jersey shelf: MAT-8B (Site 1071) and MAT-9B (Site 1072; see Fig. 2). Individual profiles are spaced at 150/300 m; the total area of each grid is ~2 km × 2 km. Also included are connecting regional profiles 145, 149, and 247. **B.** Locations of Sites 1071 and 1072 within the 8B and 9B grids. Oc270 profiles (solid lines) and Ew9009 profiles (dashed lines) are shown, as is the Continental Offshore Stratigraphic Test (COST) B2 well (see "Site 1071" chapter, this volume).

The Oc270 MCS survey consists of two interwoven track plans with complementary missions. One element of the survey involved acquisition of hazards-type grids at eight proposed shelf sites to meet MAT goals set by the JOIDES Pollution Prevention and Safety Panel. Multiple locations within individual site grids 8B and 9B (Fig. 5) were approved for drilling by both JOIDES and ODP-TAMU safety panels in September 1996. The second Oc270 element is a regional grid (Fig. 2) across the outer shelf and upper slope, to achieve both STRATAFORM objectives and MAT goals by attempting to tie Leg 150 sites to the shelf stratigraphy. In conjunction with the earlier seismic data (Fig. 2), Oc270 profiles allow us to determine the configuration of buried stratal surfaces and their accompanying acoustic

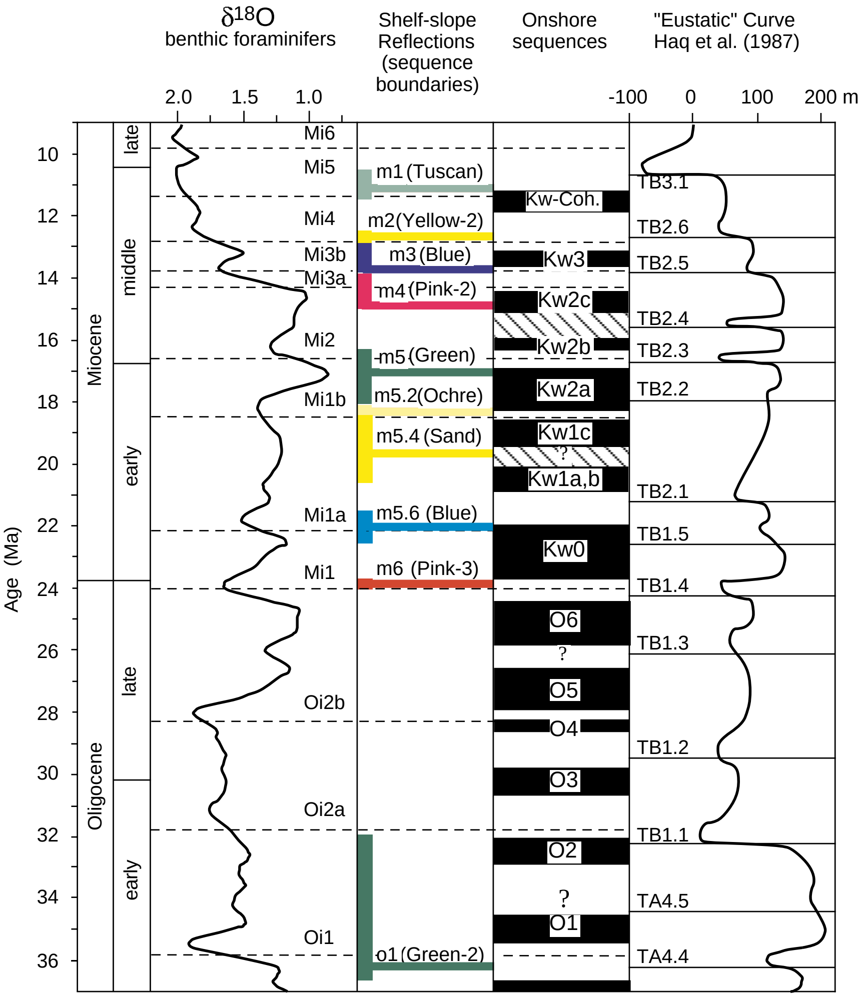

Figure 6. Comparison of the timing of Oligocene to middle Miocene reflections on the New Jersey slope with a benthic foraminiferal $\delta^{18}O$ record, a summary of onshore sequences, and the inferred eustatic record of Haq et al. (1987; after Miller et al., 1996c). The $\delta^{18}O$ record is a stacked composite of *Cibicidoides* ssp. from several sites that has been smoothed to remove all periods >1 m.y. Oi1 through Mi6 are $\delta^{18}O$ maxima, and dashed lines indicate inflections in the $\delta^{18}O$ records immediately predating the maxima. Reflections o1 through m1 are dated on the New Jersey slope (Leg 150) and are shown with best age estimates (indicated with thin lines) and error bars (indicated with boxes). Onshore sequences = dark boxes; white areas = hiatuses. Drilling on the New Jersey Coastal Plain is continuing (see Fig. 1). Sequences O1 through O6 are Oligocene, and Kw0 through Kw-Coh (Cohansey) are Miocene onshore New Jersey sequences. Cross-hatched areas = uncertain ages. Sequences TA4.4 through TB3.1 are from Haq et al. (1987). Note that this illustration provides no information about the ages of sequence boundaries < 10 Ma, a primary focus of shelf drilling as part of Leg 174A. Revision of the age of m1 (= m1[s]; see Fig. 3) is mainly due to revision of the Miocene time scale (Berggren et al., 1995).

characteristics across the wide range of depositional environments expected for the "Icehouse" section beneath the New Jersey shelf and adjacent upper slope; to establish links among the various elements of the STRATAFORM initiative; and to tie well-dated Leg 150 slope sequences to coeval shelf/uppermost slope (Leg 174A) and onshore (Legs 150X/174AX and related) sections.

SEISMIC STRATIGRAPHY

Seismic-reflection data acquired aboard the *Maurice Ewing* in 1990 and *Oceanus* in 1995 have been interpreted using standard sequence-stratigraphic principles (Vail et al., 1977; Vail, 1987; Christie-Blick et al., 1992; Mountain et al., 1996). The Miocene through Pleistocene succession of the shelf portion of the MAT is divisible into at least 18 unconformity-bounded sequences (Fig. 6). In dip sections, these typically thin in both landward (northwest) and seaward (southeast) directions and are thickest immediately seaward of the rollover at the top of the underlying sequence (Fig. 4). The term rollover is used here for the position at which the sequence boundary steepens abruptly basinward into a clinoform (not in the sense of the structural feature commonly associated with growth faults). Fulthorpe and Austin (1998) have used the term "clinoform breakpoint" (see Fig. 3) in reference to this same geometric feature. Sequence boundaries are defined at the New Jersey margin in the vicinity of the rollover/breakpoint by offlap of underlying strata and by onlap of overlying strata. Offlap and onlap refer to the progressive updip termination of seismic reflections (and strata) against overlying and underlying surfaces, respectively (Mitchum, 1977; Christie-Blick, 1991). For many of the New Jersey margin sequences, offlap is subtle and not necessarily apparent on every seismic profile, even where these are appropriately oriented relative to regional depositional strike and dip (Fulthorpe and Austin, 1998). Such offlap is nevertheless important as an indication that depositional base level was lowered during development of the surface, a key element needed to demonstrate the existence of a sequence boundary. Onlap is particularly well developed at sequence boundary clinoforms (Fig. 4); onlap is present also where there is erosional relief. Such relief is observed locally both inboard of the rollover/breakpoint and, in some cases, on the deep part of the paleoshelf, presumably as a result of mass wasting in the vicinity of the paleoshelf edge (Fig. 3). Landward of the rollover/breakpoint and any associated offlap, seismic reflections beneath a sequence boundary are approximately parallel to the boundary, producing a sigmoid geometry (Mitchum, 1977). Seaward of clinoform toes, sequence boundaries are characterized by downlap of overlying sediments and, in some cases, by subtle mound-shaped units with internal imbrication or bidirectional downlap (so-called basin-floor fans; Greenlee et al., 1992).

Within some sequences, it has been possible to map one or more additional "downlap surfaces" (Mitchum, 1977; Vail, 1987). These differ from sequence boundaries in several respects. They tend to be approximately planar (rather than sigmoid), of lower gradient, and, in most cases, there is no evidence for offlap updip. The presence of such downlap surfaces is important for delineating a systematic pattern of alternate forestepping (overall progradational) and backstepping (overall transgressive) parasequences that are expected within each unconformity-bounded sequence. In some sequences, it is also possible to use such downlap surfaces to discriminate tentatively between lowstand-transgressive and highstand facies tracts. However, flooding surfaces cannot generally be used to separate lowstand and transgressive units, because they are not necessarily associated with distinctive reflection geometry.

The quality of MCS data collected for the MAT is substantially better than for those acquired previously by industry (e.g., Greenlee et al., 1992), particularly for the shallow section (<~1 s two-way traveltime). However, separation of shelf profiles is sufficiently great (~3 to >10 km for the *Ewing* data and 0.15 to ~4 km for the *Oceanus* data) that mis-ties arose frequently, particularly where sequence boundaries are characterized by erosional relief and/or where water-bottom and peg-leg multiples of both dipping and near-horizontal reflections introduce uncertainties in tracing locations of clinoform segments. Mis-ties were resolved by systematic regional mapping using both the *Ewing* and *Oceanus* seismic grids. Although some profile sections proved to be more useful than others in this regard, no section can be regarded as definitive; strike sections are just as important as dip sections for regional sequence-stratigraphic interpretation. In fact, few of the high-resolution MCS sections available are strictly parallel or transverse to depositional strike at any stratigraphic level. Confidence in interpretation drops off both landward of rollovers/breakpoints and seaward of clinoform toes, where sequence boundaries become closely spaced and either merge at seismic resolution (~5 m vertically for the Oc270 profiles) or pass into zones of poorer reflection continuity and/or multiple interference.

Each interpreted sequence boundary targeted for drilling beneath the shelf was tentatively correlated with seismic reflections identified beneath the continental slope during Leg 150 (m1, m2, m3, etc.; Mountain, Miller, Blum, et al., 1994). However, because of unavoidable uncertainties in physical stratigraphic correlation, surfaces that are defined on the shelf are indicated with the suffix “s” (e.g., m1[s]), indicating a stratigraphic level close to the presumed coeval horizon on the slope (e.g., m1), but not necessarily precisely coincident. The best pre-Leg 174A drilling estimates of ages for these surfaces are given in Figure 6, from Greenlee et al. (1992), Miller and Mountain (1994), and Miller et al. (1996c).

Clinoforms in all sequences indicate overall progradation from northwest to southeast, a pattern already established from interpretation of lower frequency industry MCS profiles (Greenlee and Moore, 1988; Fulthorpe and Austin, 1998). However, individual rollovers/breakpoints are characterized by locally prominent excursions in map view (e.g., m4[s] and m5.6[s]). Maximum thicknesses within individual sequences also vary markedly from one dip section to another. Sequence thickness and paleobathymetric relief from rollover/breakpoint to clinoform toe increase from lower Miocene wedges to middle Miocene and younger wedges because of increasing accommodation for sediment in a seaward direction (Fig. 4). Rollovers/breakpoints form two distinct clusters, with especially strong progradation between m5(s) in the lower Miocene and m4(s) in the middle Miocene. The degree of offlap at sequence boundaries also increases significantly from the lower and middle Miocene wedges to those of Pliocene–Pleistocene age. The increase in degree of offlap is presumably related to increasing exposure of the shallow shelf during sequence-boundary development as a result of increasing amplitudes of associated glacial-eustatic change.

OBJECTIVES OF LEG 174A, STRATEGY FOR SITE SELECTION, AND EXPECTED OPERATIONS

Scientific Objectives

The primary goals of Leg 174A are the following:

1. To date as precisely as possible sequence boundaries of Oligocene–Pleistocene age, and to compare this stratigraphic record with the timing of glacial-eustatic changes inferred from deep-sea δ^{18}O variations;
2. To place constraints on the amplitudes and rates of sea-level change that may have been responsible for unconformity development;
3. To assess the relationships between depositional facies and sequence architecture; and
4. To provide a baseline for future scientific ocean drilling that will address the effects and timing of sea-level changes on this and other passive continental margins.

An additional goal for Leg 174A is technical. The leg represents the first attempt by scientific ocean drilling in almost 30 years to sample a thickly sedimented continental margin in water depths <150 m. Two sites (Sites 1071 and 1072) are located on the outer part of the continental shelf in water depths of 88–90 and 98–100 m, respectively. An additional site (Site 1073) is located on the uppermost continental slope, part of the Hudson Apron, in a water depth of 639 m.

Transect Strategy

Precise dating of sequence boundaries and estimating amplitudes of sea-level change at the New Jersey margin require a transect of holes across the shelf. An idealized representation of the transect strategy as envisioned for Leg 174A is illustrated in Figure 7. Optimal drilling locations identified for each sequence boundary are indicated by thick vertical lines. Planned Leg 174A sites on the shelf (Sites 1071 and 1072) are generally equivalent to the landward and center locations shown, to sample for the upper middle Miocene sequence boundary m1(s).

Biostratigraphic resolution is best achieved in deep-water settings of the continental slope and rise, where open-ocean marine faunas are most abundant in pelagic sediments (i.e., seaward of the segment of the hypothetical profile shown; Fig. 7). Leg 150 drilling concentrated on this setting, as does Site 1073. However, geometric evidence for the existence of a sequence boundary (offlap and onlap) is best preserved near its rollover/breakpoint; for Oligocene–Pleistocene sequences of the New Jersey margin, these features are located beneath the modern shelf (Fig. 4). Thinning and condensation of sequences in a seaward direction, as well as locally marked erosion on the continental slope (Mountain, Miller, Blum, et al., 1994), lead to uncertainties in tracing sequence boundaries across the modern shelf break to the slope (Fulthorpe et al., 1996). This, in turn, leads to uncertainties in the dating of those surfaces, independent of any other inherent limitations in biostratigraphic resolution.

For this reason, the Leg 174A strategy includes drilling at or near the clinoform toes of Miocene sequence boundaries beneath the shelf (i.e., central location in Fig. 7). At this location (Site 1072), the section is expanded, yet sufficiently close to the rollover/breakpoint for the location of the sequence boundary to be geometrically well established. Reflection geometry at clinoform toes suggests that the associated hiatus is minimized. As a practical matter, such a location might also be chosen inboard of any suspected “lowstand” sands above the sequence boundary (Greenlee et al., 1992), because these sediments are expected to include displaced faunas, as well as prove difficult to penetrate and recover using the *JOIDES Resolution* drill string.

Estimating amplitudes of sea-level change is best undertaken by “backstripping” a cross section across the shelf (Steckler and Watts, 1982; Steckler et al., 1993). This requires information from multiple sites about stratigraphic thickness, age, composition (to account for the effects of flexural loading and compaction), and paleobathymetry (from the interpretation of lithofacies and paleoecology). As the amplitude of the sea-level signal is typically small in comparison with the thickness of the strata in which it is recorded, the potential errors are large. Estimates of sea-level change are especially sensitive to errors in paleobathymetry. Therefore, key drilling locations for amplitude estimates are best located close to the sequence boundary rollover/breakpoint (i.e., left-hand location in Fig. 7; Site 1071 for surface m1[s]) and in the vicinity of the clinoform toe (i.e., center location in

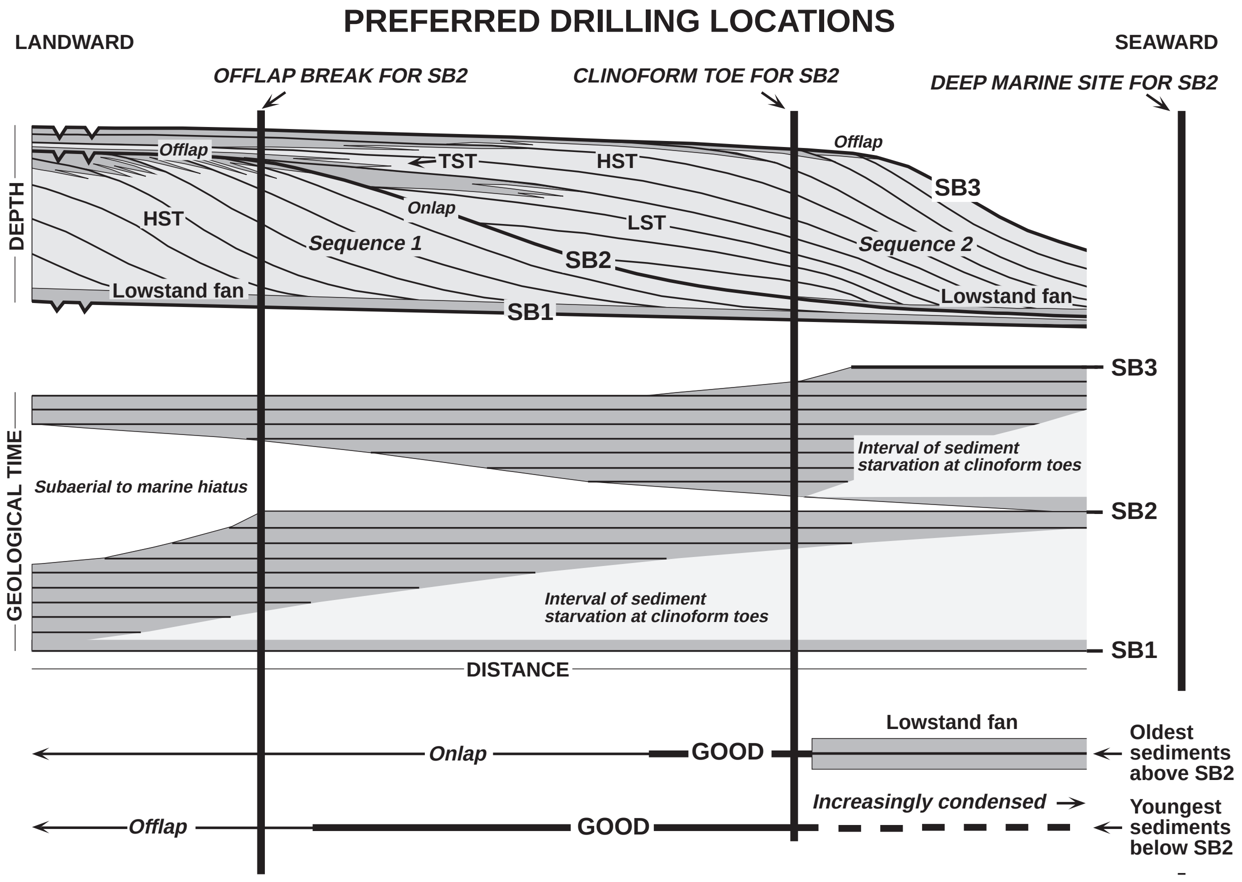

Figure 7. Diagrams of depth and geological time vs. distance for idealized sequences and the optimal strategy for drilling them. The most seaward drill location is most likely to recover a complete record across sequence boundary SB2, which is targeted to be m1(s) for Leg 174A, and contains biostratigraphic markers known from the deep-sea record. This was the strategy used during Leg 150 and continued on Leg 174A at (backup) upper slope proposed site 13B (Site 1073; Fig. 2). The other two locations shown are designed to recover shallow-water facies across boundary SB2/m1(s), below the surface in the vicinity of the rollover/breakpoint (Site 1071) and above the surface in the vicinity of the clinoform toe (Site 1072). Such site pairing is the optimal way of obtaining information about both age and amplitude of sea-level change, as well as about the relationship between stratal geometry and sedimentary facies. Note that this figure assumes the conceptual stratigraphic model of Greenlee et al. (1992) for the distribution of facies tracts within sequences, including a well-developed lowstand prograding wedge and a relatively thin transgressive facies tract landward of the rollover/breakpoint of the underlying sequence boundary.

Fig. 7; Site 1072 for m1[s]). Together, these locations are expected to provide the most complete record of paleobathymetric change both above and below the targeted sequence boundary.

Although Leg 174A sites were approved for drilling to depths of >1 km, equivalent to deep-shelf deposits of Oligocene age, the precruise operational strategy focused on the upper middle Miocene sequence boundary m1(s). That boundary was chosen because it is well developed geometrically (Fig. 3) and accessible at intermediate drilling depths (~300–550 mbsf) in an area of the outer shelf where present-day water depths exceed 75 m. That water depth was determined to be the shallowest in which the *JOIDES Resolution* might operate safely under optimal weather conditions. The m1(s) surface is also representative of the development of underlying middle Miocene surfaces; in comparison, late Miocene–Pleistocene sequence boundaries are characterized by increasing amounts of offlap, perhaps indicative of increasing amplitudes of glacial-eustatic change through this interval. Finally, the m1(s) rollover/breakpoint is located close to the COST-B2 well (Scholle, 1977). Location of Site 1071 close to COST-B2, which was drilled safely, figured strongly in JOIDES safety considerations for Leg 174A with respect to the possibility of encountering shallow biogenic gas beneath this site.

Given the strategy and sequence-stratigraphic considerations described above, primary drilling locations were chosen as follows: (1) within the MAT-8B grid (Site 1071; Fig. 5), close to the m1(s) rollover/breakpoint (left-hand location in Fig. 7), to provide the most complete record of paleobathymetric change in the underlying sequence; (2) within the MAT-9B grid (Site 1072; Fig. 5), in the vicinity of the corresponding clinoform toe (center location in Fig. 7), for the most complete record of the overlying sequence; and (3) in deep-water settings beneath the modern slope and rise (Site 1073 and Leg 150; right-hand location in Fig. 7).

The MAT ultimately requires drilling into the slope, shelf, and coastal plain (Fig. 2); all are under way. Slope drilling by Leg 150 has provided the "deep-water" age control (right hand location in Fig. 7). Onshore drilling (Legs 150X/174AX and related) has supplied updip facies control at multiple locations (Miller et al., 1994, 1996a, 1998, in press; Miller and Sugarman, 1995) and is continuing. Drilling on the intervening shelf, the primary focus of Leg 174A, is critical both to the calibration of sequence boundaries at geometrically favorable sites and to the estimation of amplitudes of eustatic change.

Expected Operations

As described above, Sites 1071 and 1072 are located within the MAT-8B and 9B "hazards" grids to optimize sampling in the vicinity of the rollover/breakpoint and clinoform toe of upper middle Miocene sequence boundary m1(s). These sites are also intended to sample the updip and somewhat condensed shallow-water portions of overlying upper Miocene to Pliocene–Pleistocene sequences, and the deeper water portions of underlying Oligocene to middle Miocene sequences, time and hole conditions permitting. However, from the outset, achieving stratigraphic precision was viewed as more important than reaching some preapproved target depth. Of vital importance is the objective of tying seismic and various types of core and log data as completely as possible without resorting to arguments about seismic vs. sedimentary facies. This is necessary to test existing sequence-stratigraphic models (e.g., Greenlee et al., 1988, 1992) for the New Jersey margin, rather than simply to interpret new data in the context of those models. In addition to optimizing core recovery in multiple holes, therefore, the operational plan includes acquisition of wireline logs (including Formation MicroScanner [FMS] data), logging while drilling (LWD), and a checkshot survey/vertical seismic profile (VSP) at each site.

Site 1073 (MAT-13B) is one of four sites (MAT-13A through 13D) designated as alternates on the uppermost slope (the so-called Hudson Apron) adjacent to the outer New Jersey shelf. These alternate sites were chosen in case of safety problems (e.g., inability to maintain dynamic positioning within stated limits), weather conditions too inclement for shallow-water operations, and/or other intractable operating conditions in the shelf environment. These sites are designed to date Miocene to Pleistocene sequence boundaries, particularly an expanded section of Pleistocene age (Fig. 4), and to help develop a sequence interpretation for the Pleistocene in a setting characterized by mass wasting and other marine processes that may be independent of base-level changes on the shelf. The operational plan for these sites includes wireline logs, LWD, and a VSP.

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