Miller, K.G., Sugarman, P.J., Browning, J.V., et al.
Proceedings of the Ocean Drilling Program, Initial Reports Volume 174AX (Suppl.)

174AX LEG SUMMARY: SEQUENCES, SEA LEVEL, TECTONICS, AND AQUIFER RESOURCES: COASTAL PLAIN DRILLING[1]

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SUMMARY

This chapter provides the background, objectives, and major scientific accomplishments of Ocean Drilling Program (ODP) Leg 174AX/174AXS, during which four boreholes were drilled onshore in the New Jersey (NJ) and Delaware (DE) Coastal Plains. These boreholes not only targeted the onshore equivalents of Miocene sequences drilled offshore during Leg 174AX with holes at Ocean View, NJ, and Bethany Beach, DE, but also provided an unprecedented sampling of marine Upper Cretaceous–Paleogene onshore sequences with holes at Bass River and Ancora, NJ. Major scientific accomplishments of Leg 174AX include evaluating controls on sea level and sequences and global events in Earth history.

Sea Level

We established that eustasy is the dominant process that determines the template for potential sequences and their general architecture (stacking patterns and preservation of stratal surfaces) on the U.S. Mid-Atlantic margin. Leg 150X and 174AX onshore cores yielded a high-resolution (1-m.y. resolution) chronology of ~30 Cenozoic and 11–14 Late Cretaceous sequences by integrating Sr isotopic stratigraphy and biostratigraphy. Sequence boundaries (from 42 to 8 Ma) correlate with global $\delta^{18}O$ increases, linking them with glacioeustatic lowerings. One-

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[1] Examples of how to reference the whole or part of this volume.
[2] Shipboard Scientific Party addresses.

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and two-dimensional backstripping of mid-Cretaceous to Miocene sequences yields eustatic estimates for the interval from 100 to 8 Ma that are less than one-half of those published by Exxon Production Research (EPR). Oligocene sequences in NJ preserve a remarkably complete record of sea-level change derived from two-dimensional backstripping. Backstripping establishes that sea-level changes were large (>25 m) and rapid (<1 m.y.) even during the greenhouse world of the Late Cretaceous to middle Eocene. The rapidity and amplitude of these changes requires a glacioeustatic control of sea-level variations during the Late Cretaceous, or our understanding of sea-level mechanisms is fundamentally flawed. Comparisons between Late Cretaceous sequence stratigraphy and $\delta^{18}O$ records are consistent with the presence of small ice sheets in this alleged greenhouse world.

Comparisons between boreholes in NJ and DE allow evaluation of the effects of tectonics and sediment supply on sequence architecture. We discovered higher-order variability within lower Miocene sequences in NJ and DE embedded within the million-year-scale sequences previously defined onshore; these may be due to lobe switching or unusual preservation of high-frequency sea-level changes in areas with high sedimentation rates. Minor (~10-m scale) tectonic differences determine the preservation of sequences in different parts of the basin. Sediment supply determines paloeoenvironmental setting, regional and local facies, and the expression of stratal surfaces. Our studies show that Miocene facies in NJ are deltaic dominated, whereas those in DE are wave-dominated shorelines. Despite this difference, these areas share a similar Miocene sequence stratigraphic signature. Thin transgressive systems tracts (TSTs) are present at the base of most sequences. Highstand systems tracts (HSTs) can generally be divided into a lower fine-grained unit (silty clay in NJ and silts in DE) and an upper sandy unit. The general absence of lowstand systems tracts (LSTs) is due to bypassing. Understanding of sequence stratigraphic architecture allowed development of an improved hydrostratigraphic framework to be used in evaluating local and regional water resource potential.

Earth History

The record obtained at these sites allowed us to evaluate the causes and effects of several major global events in Earth history, including:

1. Demonstrating that the latest Cenomanian–Turonian (C/T) ocean anoxic event was unrelated to sea-level change on million-year or 100-k.y. scales.
2. Suggesting that a major cooling spanning the Campanian/Maastrichtian boundary was associated with a sea-level lowering and inferred ice volume increase.
3. Correlating a latest Maastrichtian global warming with Deccan trap volcanism.
4. Linking the marine mass extinctions at the end of the Cretaceous with ballistic ejecta. In addition, we showed that collapse of the vertical isotopic gradient (“Strangelove Oceans”) extended to neritic environments and that there was minimal change in sea level associated with the Cretaceous/Tertiary (K/T) boundary.
5. Establishing that low $\delta^{13}C$ and $\delta^{18}O$ and high kaolinite values were associated with the Paleocene/Eocene thermal maximum (PETM) in NJ neritic sections and that isotopic values remained low and kaolinite remained high throughout a thick section

above the carbon isotope excursion (CIE). This reflects either that warmer and wetter climate persisted for >300–400 k.y. in NJ (unlike deep-sea records that show an exponential return to pre-PETM conditions after ~200 k.y.) or that the extremely rapid deposition of this section occurred in response to a cometary impact.

6. Showing that a large (~60 m), earliest Oligocene drop in sea level was associated with development of an ice sheet equivalent in size to the modern East Antarctic ice sheet, though sea level again rose by nearly 50 m ~1 m.y. later, suggesting near collapse of the ice sheet. The ice sheet subsequently grew and decayed numerous times in the Oligocene–middle Miocene.

Future studies will integrate onshore and offshore drilling with seismic profiles and provide a full sampling of sequences across the margin.

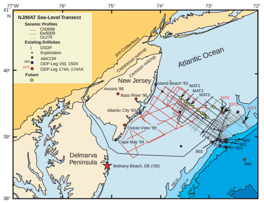
BACKGROUND

Passive continental margins such as those along the East and Gulf coasts of the U.S. contain thick sediment archives that record global sea level, depositional environments, regional/local tectonics, and global/regional climate changes in unconformity-bounded packages termed sequences (Mitchum et al., 1977; Christie-Blick and Driscoll, 1995). Deciphering these archives in a systematic manner has proven to be a challenge. Outcrops provided most of the information for early models of continental margin sedimentation, but these are often thin, weathered, poorly fossiliferous, and discontinuous on passive margins. Thicker sections are available in the subsurface downdip toward the submerged continental shelf, but subsurface sections have been mostly discontinuously sampled by oil or water wells. Continuous coring provides a direct means to sample the subsurface, although it is costly and complicated by unconsolidated nature of coastal plain strata. Advances in coring technology in the 1980's, particularly with extended bits (e.g., the Christensen bit and ODP's extended core barrel), has dramatically improved recovery rates and allowed recovery of undisturbed layers of strata to improve our information archives for passive margins.

In order to understand continental margin processes, passive continental margin studies require sampling from outcrops onshore to regions far offshore. Sampling onshore to offshore in transects (i.e., along dip profiles) or in arrays (i.e., transects with along-strike components) has proven programmatically challenging because it requires the interaction of organizations with distinctly different mandates (e.g., ODP and the International Continental Drilling Program [ICDP]). The Earth Science and Ocean Science Divisions of the National Science Foundation (NSF) recognized and met this challenge when they funded onshore drilling in the NJ Coastal Plain, which has been directly integrated with offshore efforts by ODP Legs 150 and 174A.

Coastal plain drilling by ODP began in 1993 with Leg 150X as part of the NJ/Mid-Atlantic Sea-Level Transect (Fig. F1) (Miller and Mountain, 1994). The primary goal of the transect was to document the response of passive continental margin sedimentation to glacioeustatic changes during the Oligocene to Holocene "icehouse world," a time when glacioeustasy was clearly operating (Miller and Mountain, 1994). During Leg 150 four sites were drilled on the NJ continental slope, providing a sequence chronology for the Oligocene–Miocene of the region (Moun-

F1. Location map for the NJ/MAT Sea-Level Transect, p. 23.



tain, Miller, Blum, et al., 1994). Concurrent with and subsequent to Leg 150, a complementary drilling program designated Leg 150X was undertaken to core coeval strata onshore in NJ. This drilling was designed not only to provide additional constraints on Oligocene–Holocene sequences but also to address an important goal not resolvable by shelf and slope drilling: to document the ages and nature of middle Eocene and older "greenhouse" sequences, a time when mechanisms for sea-level change are poorly understood (Miller et al., 1991). Sites were drilled at Island Beach (March–April, 1993), Atlantic City (June–August, 1993), and Cape May (March–April, 1994) (Miller et al., 1994, 1996a; Miller and Snyder, 1997) (Fig. F1). Together, Legs 150 and 150X were extremely successful in dating Eocene–Miocene sequences, correlating them to the $\delta^{18}O$ proxy for glacioeustasy, and causally relating sequence boundaries to glacioeustatic fall (Miller et al., 1996b, 1998a; Browning et al., 1996). Little information was garnered on Paleocene and older sequences during these legs, with only one lower Eocene–Maastrichtian section sampled at Island Beach.

ODP Leg 174A continued the Mid-Atlantic Transect by drilling between previous slope and onshore sites, targeting the NJ continental shelf (Austin, Christie-Blick, Malone, et al., 1998). The Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) planning committee endorsed a subsequent phase of onshore drilling as an ODP-related activity and designated the program ODP Leg 174AX. As part of this leg, sites were drilled at

1. Bass River, NJ (October–November, 1996; **Miller et al., 1998b**), targeting Upper Cretaceous to Paleocene strata (total depth [TD] = 1956.5 ft; recovery = 86%);
2. Ancora, NJ (July–August, 1998; **Chap. 1,** this volume), an updip, less deeply buried Cretaceous–Paleocene section complimentary to Bass River (TD = 1170 ft TD; recovery = 93%);
3. Ocean View, NJ (September–October, 1999; **Chap. 2,** this volume), targeting upper Miocene–middle Eocene sequences (TD = 1570 ft TD; recovery = 81%); and
4. Bethany Beach, DE (May–June 2000; **Chap. 3,** this volume) targeting Miocene sequences near where they reach their greatest thickness onshore (1470 ft TD; 80% recovery).

The U.S. Geological Survey (USGS) Eastern Earth Surface Processes Team drilled the Ancora, Ocean View, and Bethany Beach boreholes, whereas a commercial driller, Boart Longyear, drilled Bass River. Full suites of downhole geophysical logs were obtained at Ocean View and Bethany Beach by the DE Geological Survey (DGS) and gamma logs to TD were obtained at Bass River and Ancora by the NJ Geological Survey (NJGS). The excellent recovery overall (5409 ft recovered from 6172 ft drilled; recovery = 88%) is testimony to the skill of the drillers in coring the difficult to recover coastal plain strata.

Onshore drilling during Leg 174AX has provided new insights into greenhouse sequences and added a third-dimensional, along-strike view of Oligocene–Miocene sequences, allowing the evaluation of the effects of tectonics and sediment supply on sequence stratigraphic architecture. This paper summarizes the objectives and accomplishments of onshore drilling during Leg 174AX and provides a brief prospectus for the future of drilling integrated arrays of boreholes on passive continental margins.

This chapter differs from a typical *Initial Reports* summary chapter in that it is not only a companion to the four site chapters reproduced on CD-ROM, it also summarizes publications and papers. The Bass River Site Report was published in paper form in 1998 and bound with the Leg 174A *Initial Reports* as Leg 174AX (**Miller et al., 1998b**). The Ancora (**Chap. 1,** this volume), Ocean View (**Chap. 2,** this volume) and Bethany Beach (**Chap. 3,** this volume) Site Reports are published on the World Wide Web and in this volume on CD-ROM as Leg 174AXS. Because drilling of Leg 174AX spanned 5 yr (1996–2000, inclusive), we summarize the scientific results of a significant body of published, in press, and submitted works. Ongoing studies will be published in 2004 in a *Scientific Results* volume.

OBJECTIVES

Coastal plain drilling conducted as part of Leg 174AX had several major objectives:

1. Evaluate the variability of Oligocene–Miocene sequences and the influences of tectonics and sediment supply on sequence distribution and architecture. This is a direct outgrowth of studies conducted during ODP Leg 150 slope and 150X coastal plain drilling, which dated Oligocene–Miocene sequences and correlated them with global $\delta^{18}O$ records.
2. Provide material suitable for one- and two-dimensional backstripping of mid-Cretaceous to Miocene sections, providing a eustatic estimate for the interval from 100 to 8 Ma that can be compared with backstripped records from other areas. Backstripping is a proven method for extracting amplitudes of global sea level from passive margin records (e.g., Watts and Steckler, 1979). One-dimensional backstripping progressively removes the effects of sediment loading (including the effects of compaction), eustasy, and paleowater depth from basin subsidence to obtain tectonic subsidence. By modeling thermal subsidence on a passive margin, the tectonic portion of subsidence can be assessed and a eustatic estimate obtained (Kominz et al., 1998). Two-dimensional backstripping assumes projection of onshore Oligocene sections onto a single composite dip section of prograding clinoforms, integrating various data sets into a single, internally consistent interpretation of sea-level change (Kominz and Pekar, 2001).
3. Determine the ages and distribution of Cretaceous sequences not previously sampled during Legs 150X, 150, or 174A and provide additional samples of Paleocene–middle Eocene sequences that were only sparsely sampled previously. These sequences provide a window into understanding sea-level changes during the greenhouse world, a time considered to be ice free.
4. Evaluate major global events in Earth history in continental margin successions. Earth history has been punctuated by rapid events that have profoundly affected life. These events include the Cretaceous/Tertiary (C/T) extinction and ocean anoxic event (Arthur et al., 1985), the Campanian/Maastrichtian cooling (Barrera and Savin, 1999), the latest Maastrichtian warming (Barrera and Savin, 1999), the Cretaceous/Tertiary (K/T) impact event (Alvarez et al., 1980), the PETM and carbon isotopic excursion

(e.g., Kennett and Stott, 1990; Zachos et al., 1994), and the earliest Oligocene cooling and glaciation (Miller et al., 1987; Zachos et al., 2001). Whereas most reconstructions of global Late Cretaceous–Holocene events have focused on the deep-sea record because of its more continuous nature, passive continental margins potentially provide thick, continuous records of many of these events.

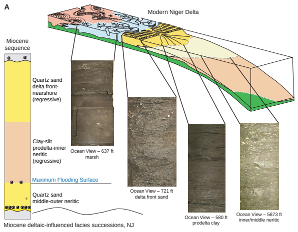
5. Evaluate stratigraphic continuity and hydrogeological potential of aquifers and confining units. The NJGS and DGS provided funds for drilling to address hydrogeological objectives that directly affect groundwater resources in the rapidly growing areas of southern NJ and DE. Sequence stratigraphy has the potential to increase our understanding of the stratigraphic architecture of aquifers in the same way it has improved our understanding of reservoir architecture in the oil industry.

ACCOMPLISHMENTS

Evaluated Sequence Variability

We confirmed the conclusions of Legs 150 and 150X (see summary in Miller et al., 1997) that eustasy is the dominant process that determines the template of potential sequences and their general architecture (stacking patterns and preservation of stratal surfaces). We attribute some of the differential preservation of sequences in boreholes from DE through NJ to minor (~10-m scale) tectonic differences caused by minor movement on basement blocks (e.g., the rolling basins concept of Owens et al., 1997). Sediment supply can also locally affect the preservation of sequences, with preferential preservation of sequences near depocenters resulting from excess accommodation by loading and preferential removal in regions of sediment starvation. Sediment supply also determines the paloeoenvironmental setting (e.g., wave vs. deltaic dominated) (Fig. F2), the facies expressed regionally and locally, and the local expression of stratal surfaces.

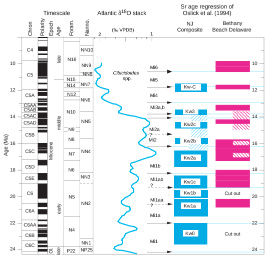
F2. Facies models, p. 24.



Sequence Correlation with Global Records

We identified, dated, and correlated sequences among sites in NJ and DE with other global records (Fig. F3) (e.g., $\delta^{18}O$), confirming the link between sequence boundaries and $\delta^{18}O$ determined by Miller et al. (1996b) based on Leg 150 and 150X studies. Sequence boundaries are unconformities that are recognized on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, gamma ray peaks, and paraconformities inferred from age breaks. Sr isotopic stratigraphy provided the primary age control on Oligocene–Miocene sections supplemented by calcareous nannofossil, planktonic foraminiferal, and dinocyst biostratigraphy. During Leg 174AX, thick Miocene sequences at Ocean View and Bethany Beach were sampled, identified, and dated. It extended our record of sequences dated onshore from ~10 Ma (Leg 150X) to 8 Ma, complementing Leg 174A drilling.

F3. Comparison of Bethany Beach borehole with NJ sequence ages, p. 27.



Facies Models

We developed facies models for deltaic-dominated (NJ) (Fig. F2A) and wave-dominated (DE) (Fig. F2B) successions. The deltaically influenced Miocene sections in NJ fit a facies model similar to the Niger Delta (Fig. F2A) (Allen, 1970). Facies include marsh deposits, nearshore to delta front sands, prodelta silty clays, and shelfal sands (glauconitic in Paleogene and older sections and primarily quartz in the Miocene) (Fig. F2A) (Allen, 1970). The facies are arranged as basal transgressive sands, medial prodelta silty clays, and upper quartz sands. The DE Miocene and younger sequences sampled at Bethany Beach consist of silts and sands deposited in fluvial to upper estuarine, lower estuarine, upper shoreface/foreshore, distal upper shoreface, lower shoreface, and inner and middle neritic environments (Fig. F2B).

Intrasequence Architecture

We evaluated intrasequence architecture. Despite fundamentally different sedimentary regimes (wave-dominated shorelines in DE vs. deltaic systems in NJ), both regions share a similar sequence stratigraphic signature for the Miocene. LSTs are largely absent, and thus transgressive surfaces are usually merged with sequence boundaries; the exceptions include lowstand deposits identified for the first time in the Miocene Kirkwood Formation at Ocean View in the Kw2a and Kw1a sequences. TSTs are present at the bases of some sequences but are thin. In general, HSTs are divided into a lower fine-grained unit (silty clay in NJ and generally silts in DE) and an upper sandy unit. The upper HST sands comprise important aquifers in both regions that are generally confined by the overlying lower HST. Aside from these similarities, there are important sequence stratigraphic differences between regions. Maximum flooding surfaces (MFSs) identified in the Bethany Beach borehole show much greater evidence of erosion than MFSs in NJ, whereas sequence boundaries are often more subtle in DE because of the juxtaposition of similar facies.

Higher-Order Variability

We discovered higher-order (400?-k.y. scale) variability within lower Miocene sequences at Ocean View and Bethany Beach embedded within the million-year-scale sequences defined onshore during Leg 150X drilling. The Kw2a and Kw1a sequences are each provisionally subdivided into three higher-order sequences (Kw2a1, Kw2a2, and Kw2a3 and Kw1a1, Kw1a2, and Kw1a3, respectively). The preservation of higher-order lower–middle Miocene sequences may be the result of higher sediment supply and accommodation space because they are only recognizable in sections with high (~100 m/m.y.) sedimentation rates. Alternatively, the great thickness of the section is consistent with an autocyclical cause (lobe switching) for these apparent sequences. Analyses of nearshore seismic profiles recently collected near Ocean View (Fig. F1) should reveal if the higher-order cyclicity is due to base level lowering and, hence, if these are eustatically controlled sequences.

Comparison of NJ and DE Sequences

Comparison of NJ and DE (Bethany Beach) Miocene sequences highlights regional differences in sedimentation and possible tectonic controls. Equivalents of the Kw3, Kw2c, Kw2b, Kw1c, and Kw1a NJ sequences are represented at Bethany Beach (Fig. F3), although the sequences are generally thicker and sedimentation rates are higher in DE. Nevertheless, thickness does not equate to stratigraphic continuity: the NJ record is much more complete in the early part of the early Miocene (19–23.8 Ma), with the Kw1b and Kw0 sequence apparently missing in DE. The DE section is more complete in the late part of the early Miocene (~19–16.2 Ma), with one sequence (18.0–18.4 Ma) not represented in NJ. The upper part of the Oligocene (~27–23.8 Ma; sequences O6 and O5 of Pekar et al., 2000) is also absent at Bethany Beach because of truncation. These minor differences in preservation may be due to (1) minor tectonic movements (tens of meters) of basement blocks (Owens et al., 1997) or (2) differential preservation resulting from local sediment loading.

Oligocene Strata Geometry Reconstruction

The geometry of Oligocene strata in NJ was reconstructed using two-dimensional flexural backstripping (Pekar et al., 2000; Kominz and Pekar, 2001), and water depths were estimated for the margin using two-dimensional paleoslope modeling of the benthic foraminiferal biofacies (Pekar and Kominz, 2001; Pekar et al., in press b). These results allowed quantitative evaluation of factors controlling sedimentation on passive margins and comparison with other stratigraphic models (Fig. F2C) (Pekar et al., in press b). NJ Oligocene sequences are highstand dominated, TSTs are thin, and LSTs are absent. Pekar et al. (in press b) suggested that the absence of LSTs was due to bypassing because of efficient transfer of sediment across the shallow shelf, combined with the absence of major river systems in the area of study. They concluded that well-developed offlap at each sequence boundary is due primarily to marine bypassing and degradation, rather than to "forced regression" (Pekar et al., in press b).

Stratigraphic Response to Eustatic Change

Stratigraphic architecture observed at the NJ continental margin was also compared with Oligocene eustatic records to evaluate the stratigraphic response to eustatic change (Pekar et al., 2001). Early to "mid"-Oligocene sequence boundaries (33.8–28.0 Ma) were associated with relatively long hiatuses (0.3–0.6 m.y.), in which sedimentation in many places terminated during eustatic falls and resumed early during eustatic rises. Late Oligocene sequence boundaries were associated with relatively short hiatuses (<0.3 m.y.); they provide the best constraints on phase relations between sea-level forcing and margin response. The interval represented by each late Oligocene sequence varies in dip profile. At updip locations landward of the clinoform rollover in the underlying sequence boundary, sedimentation commenced after the eustatic low and terminated before the eustatic high (with partial erosion of any younger record) (Fig. F2C). At downdip locations, sedimentation within each sequence was progressively delayed in a seaward direction, beginning during the eustatic rise and terminating near the eustatic low (Fig. F2C). Combining data from all available boreholes, Pekar et al. (2001) showed that the ages of sequence boundaries (correlative surfaces) correspond closely to the timing of eustatic lows, and ages of condensed sections (intervals of sediment starvation) to eustatic highs (Fig. F2C).

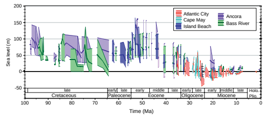
Core–Log Integration

Core log-downhole log integration provided a means of further evaluating sequences and variability within sequences. Lanci et al. (2002) integrated core-log magnetic susceptibility (MS) and natural gamma ray (NGR) measurements from Ancora with lithology and the downhole NGR log. They used a simple linear model to explain MS and NGR values by lithologic variation. Spectral NGR shows that high gamma values are due to the ^{40}K radioisotope associated with glauconite and clay, sediment components that also tend to give high MS values. The major deviation from their model was at an anomalous level with high NGR but low MS values; this level was attributed to high uranium concentration in phosphorite. With only few exceptions, sequence boundaries identified at Ancora are expressed in the NGR and/or MS logs.

Backstripping and Eustatic Estimates

Leg 174AX provided material suitable for one- and two-dimensional backstripping of mid-Cretaceous to Miocene sections, providing a eustatic estimate for the interval from 100 to 8 Ma. Backstripping analysis of the Bass River and Ancora boreholes (Fig. F4) (Van Sickel et al., unpubl. data) provides complete Late Cretaceous sea-level estimates and tests previously published Cenozoic sea-level estimates based on Leg 150X drilling (Fig. F4) (Kominz et al., 1998). Van Sickel et al. (unpubl. data) used electric logs to provide a new porosity-depth calibration for decompacting sediments, showing considerably lower porosity than those previously calculated at the offshore Cost B-2 well. Amplitudes and duration of sea-level changes were comparable when sequences were represented at multiple borehole sites, suggesting that the resultant curves are an approximation of regional sea level (Fig. F4). Sea-level amplitudes as great as 50 m are associated with Cretaceous sequences, whereas most Late Cenozoic amplitudes were closer to 20 to 40 m (Fig. F4) (Van Sickel et al., unpubl. data).

F4. Backstripped R2 eustatic estimates, p. 28.

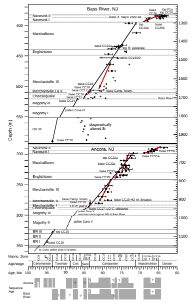


Two-dimensional backstripping of prograding Oligocene sequences reconstructed by Pekar et al. (2000) provided a detailed and precise eustatic estimate (Kominz and Pekar, 2001). Ten latest Eocene to earliest Miocene sequences provided the basis for estimates of ~20- to 60-m eustatic lowerings (Kominz and Pekar, 2001). The slightly higher eustatic estimates obtained by Kominz and Pekar (2001) vs. Van Sickel et al. (unpubl. data), particularly for earliest Oligocene rises and fall (see below) are attributed to the greater precision provided by two-dimensional backstripping that more nearly captured the full amplitude of eustatic change (Pekar and Kominz, 2001). Both one- and two-dimensional backstripping yielded Oligocene eustatic estimates that are lower than those published by the EPR group (e.g., Haq et al., 1987) by a factor of two or more (Kominz and Pekar, 2001; Van Sickel et al., unpubl. data). Oligocene eustatic lowerings were linked to global $\delta^{18}O$ increases (Pekar et al., 2001) and used to provide a sea level/$\delta^{18}O$ calibration for the Oligocene (Pekar et al., in press a).

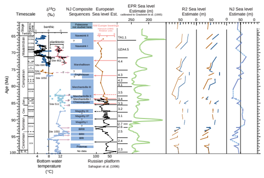
Greenhouse Sequences

The Bass River and Ancora Cretaceous sections provided the means to estimate global sea-level (eustatic) variations of the Late Cretaceous (99–65 Ma) greenhouse world (Miller et al., unpubl. data). These two sites recorded 11–14 Upper Cretaceous sequences that were dated by integrating Sr isotopic stratigraphy and biostratigraphy (Fig. F5). The ages of sequence boundaries not only correlate regionally between sites (Fig. F5), they also correlate with the sea-level lowerings of EPR (Haq et al., 1987), northwest European (Hancock, 1993) and Russian sections (Fig. F6) (Sahagian et al., 1996), indicating a global cause. Backstripping yielded a Late Cretaceous eustatic estimate for these sequences, taking into account sediment loading, compaction, paleowater depth, and basin subsidence (Fig. F6). Sea-level changes were large (>25 m) and rapid (<1 m.y.), strongly suggesting glacioeustatic control of sea-level variations during the Late Cretaceous. Though the timing of EPR eustatic lowerings may be more or less correct, the EPR curve cannot be used as a valid Late Cretaceous eustatic record. Eustatic estimates from NJ and the Russian platform clearly show that the amplitudes of the major EPR eustatic lowerings were too high by a factor of at least two (Fig. F6). In addition, the EPR record differs in shape from the backstripped eustatic estimates. For example, the extremely large mid-Turonian and mid-Maastrichtian events reported by EPR are much lower in amplitude in the backstripped records, whereas the major flooding events at 69, 76, and 84 Ma in the NJ record are less important in the EPR record (Fig. F6).

F5. Age-depth plots for Bass River and Ancora, p. 29.



F6. Estimate of eustatic changes, p. 30.



Oxygen isotopic comparisons with Late Cretaceous sequence boundaries have not attained the resolution needed to unequivocally link the two as has been done for the past 42 m.y. (Miller et al., 1998a). Nevertheless, comparisons between Late Cretaceous sequence stratigraphy and $\delta^{18}O$ records are intriguing (Fig. F6) (Miller et al., unpubl. data), further suggesting small ice sheets in this alleged greenhouse world: (1) a major mid-Cenomanian sequence boundary (see also Gale et al., 2002) between the Potomac and Bass River I-sequences (hiatus = ~96–97 Ma) correlates with a major (>1‰) $\delta^{18}O$ increase; (2) two minor $\delta^{18}O$ increases spanning the Cenomanian/Turonian boundary may correlate with sequence boundaries at the base of Bass River II and Bass River III; and (3) a mid-Turonian sea-level lowering associated with the Bass River III/Magothy contact (91.5–92 Ma) may correlate with a major increase in benthic foraminiferal $\delta^{18}O$ values (~1.0‰), though additional data are needed to determine the precise timing of the increase (Fig. F6). Several other Coniacian–Campanian $\delta^{18}O$ increases (dashed arrows in Fig. F6) may be related to sequence boundaries, but the data are too sparse to provide a firm correlation. Miller et al. (unpubl. data) note that $\delta^{18}O$ data are consistent with a glacioeustatic cause for Late Cretaceous sequence boundaries. The data shown on Fig. F6 require that either large, rapid sea-level variations occurred during the Late Cretaceous greenhouse world or our understanding of causal mechanisms for global sea-level change is fundamentally flawed.

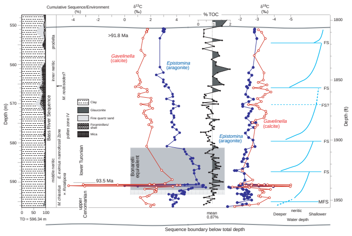
Global Events in Earth History

Cenomanian/Turonian Boundary Events

Uppermost Cenomanian to lower Turonian strata are characterized by worldwide organic carbon–rich deposits (Ocean Anoxic Event 2 [OAE2]) (Arthur et al., 1985, 1987) reflected in a pronounced positive excursion of $\delta^{13}C$ (e.g., Schlanger et al., 1987; Jenkyns et al., 1994). The Bass River borehole recovered a thick (61 m) record of the latest Cenomanian to early Turonian that is continuous as measured by biostratigraphy (Sugarman et al., 1999) and cyclostratigraphy (Cramer in Wright et al., unpubl. data). Benthic foraminiferal $\delta^{13}C$ records show a large (>2‰) increase immediately below the C/T boundary (Fig. F7) (Sugarman et al., 1999). Above the sharp $\delta^{13}C$ increase, elevated $\delta^{13}C$ and sedimentary organic carbon (>0.9%) values continue into the lower Turonian, culminating in a sharp $\delta^{13}C$ decrease (Fig. F7) (Sugarman et al., 1999). High $\delta^{13}C$ values in the uppermost Cenomanian–lower Turonian at Bass River correlate with the OAE2, a global carbon burial event recorded in Europe and the U.S. western interior (Sugarman et al., 1999); we estimate that the duration of this event at Bass River is 850 k.y. based on cyclostratigraphy (Cramer in Wright et al., unpubl. data).

The OAE2 event occurred during long-term eustatic rise (10-m.y. scale), yet it occurs within a 1- to 2-m.y.-long sequence at Bass River and is not associated with maximum flooding. Thus, there is no relationship between OAE2 and sea-level lowering on the million-year scale (Fig. F7) (Sugarman et al., 1999). Within the sequence spanning the carbon event, there are at least four shallowing-upward parasequences (durations = ~350–460 k.y.) indicated by changes in abundance and type of *Epistomina* species, $\delta^{18}O$ variations, and minor lithologic variations (Fig. F7). There is no clear association between parasequence boundaries (Fig. F7) and OAE2, indicating that there is no relationship of the event and sea-level change on the 100-k.y. scale (Fig. F7) (Sugarman et al., 1999). Thus, Sugarman et al. (1999) concluded that whereas the organic carbon burial event was associated with a general long-term (10-m.y. scale) eustatic rise, the initiation and termination of the peak organic burial event itself were unrelated to sea-level change (Fig. F7).

F7. Cenomanian–Turonian section at Bass River, NJ, p. 31.



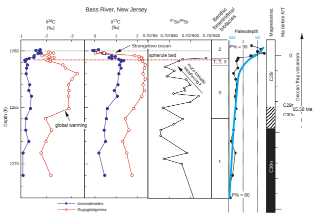
Campanian/Maastrichtian Boundary Events

A ~71-Ma sequence boundary separating the base of the Maastrichtian Navesink Formation from the underlying Campanian Mount Laurel Formation (Fig. F5) is one of the most dramatic of the ~30 Cenozoic and 11–14 Late Cretaceous sequence boundaries identified in the NJ Coastal Plain (Miller et al., 1998a; Miller et al., 1999). This unconformity is found throughout the eastern U.S. (Owens and Gohn, 1985). The amount of eustatic lowering associated with this event is uncertain because of a hiatus, but ~30 m of eustatic rise is recorded at Ancora and Bass River, providing a minimum range of sea-level change (Fig. F6). The event has been linked to a $\delta^{18}O$ increase that occurred in both deep-sea benthic and low-latitude planktonic foraminifers (Fig. F6) (Miller et al., 1999). Based on this correspondence, Miller et al. (1999) argued that this event resulted from the growth of a transient ice cap (equivalent to ~40% the volume of the present-day east Antarctic ice cap) that caused a ~25- to 30-m glacioeustatic lowering at 71 Ma. The ~71-Ma Campanian/Maastrichtian boundary sea-level lowering was associated with a major reorganization in deepwater circulation as cool water from a high-latitude source influenced intermediate depths in the tropical Pacific (Barrera et al., 1997). A global $\delta^{13}C$ decrease is also correlated with the sea-level lowering, perhaps because of increased weathering of organic-rich sediments exposed on continental shelves (Barrera et al., 1997).

Latest Maastrichtian Events

Global $\delta^{18}O$ records show general cooling conditions in deep waters and high latitudes from the late Campanian to latest Maastrichtian (~73–66 Ma) (Fig. F6) (Barrera and Savin, 1999), punctuated by the ~71-Ma ice volume and sharp cooling event (Miller et al., 1999). During the latest Maastrichtian, planktonic foraminiferal distributions (particularly the thermophilic taxon *Pseudotextularia elegans*) and global $\delta^{18}O$ records (Figs. **F6, F8**) (Barrera and Savin, 1999) show a warming of sea-surface temperatures of ~5°C (Fig. **F8**) (Olsson et al., 2001). Planktonic foraminiferal $\delta^{18}O$ records from Bass River display this warming as a very large decrease that began at ~500 k.y. and ended about 22 k.y. before the K/T boundary (Fig. **F8**) (Olsson et al., 2001). Neritic benthic foraminiferal $\delta^{18}O$ records from Bass River show only a 0.2‰–0.5‰ coeval decrease (a 1°–2°C warming), indicating a strengthening in the thermocline at this time (Olsson et al., 2001). The latest Maastrichtian warming event may have been caused by a greenhouse effect resulting from the main outpouring of the Deccan Traps in India beginning at ~65.6 Ma (Courtillot et al., 1986). Sr isotopic data from Bass River (Fig. **F8**) (Olsson et al., 2002) and other sections (Vonhof and Smit, 1997) that show a distinct decrease from ~65.5 to 65 Ma are consistent with increased basaltic weathering. This warming may have contributed to the decline in dinosaur diversity (Sloan et al., 1986), though it was the impact at the K/T boundary that is unequivocally linked to the mass extinction of marine and presumably terrestrial taxa.

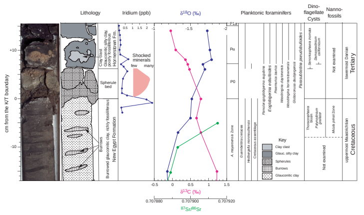
F8. Maastrichtian events at Bass River, NJ, p. 32.



K/T Boundary Impact and Tsunami

The Bass River borehole provides a continuous depositional record across the K/T event (Olsson et al., 1997), which has been attributed to a bolide impact (Alvarez et al., 1980) near Chicxulub, Mexico (Hildebrand et al., 1991). K/T boundary sections in the Gulf Coast show thick ejecta, including glass spherules and tsunamites (Smit et al., 1992). Nonetheless, the relationship between ejecta and the marine mass extinction has been controversial (e.g., Keller et al., 1994), in part because the extensive mixing by a megatsunami in the Gulf Coast. In contrast, the U.S. East Coast was sheltered from the megatsunami's direct effects. The Bass River borehole directly ties impact ejecta to the highest occurrence of planktonic foraminifers and calcareous nannofossils (Fig. **F9**), providing the first unequivocal link between bolide impact and marine mass extinctions that mark the end of the Cretaceous (Olsson et al., 1997). Similar results were noted during ODP Leg 171B on the Blake Nose (Norris et al., 1999), with the ejecta present at the level of the marine mass extinction. A tsunami immediately followed the fallout of tektites from the Chicxulub ejecta vapor cloud in the Gulf of Mexico (Smit et al., 1992); a clast unit present above the K/T ejecta at Bass River (Fig. **F9**) (Olsson et al., 1997) and on the Blake Nose (Norris et al., 1999) also appears to be related to a tsunami. Although direct effects of the impact can explain tsunamites in the Gulf of Mexico, it has been difficult to explain the cause of tsunamites outside this region because the Florida platform would have attenuated the waves. Massive slumping on the Atlantic slope, including NJ, may have triggered a tsunami on the Atlantic margin as exemplified by a clast layer found at Bass River (Fig. **F9**) (Olsson et al., 1997, 2002), Ancora, and outcrop sections in the NJ Coastal Plain.

F9. Cretaceous/Tertiary (K/T) boundary at Bass River, NJ, p. 33.



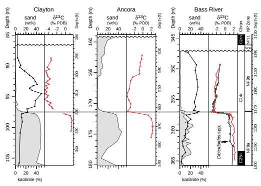
Though sea-level change has long been associated with the K/T boundary, the records from Bass River and Ancora clearly show that the impact event occurred within a sequence that spans the K/T boundary (the Navesink sequence; ~69–64.5 Ma) (Fig. **F6**) (Olsson et al., 2002). The sequence shallows upsection, particularly in the last 0.5 m.y. of the Cretaceous, culminating in a sharp shallowing in the last 100 k.y. of the Cretaceous (Fig. **F8**). However, there is no sequence boundary associated with the K/T boundary; a major sequence boundary is present in Biochron P1b, with a hiatus from ~64 to 63 Ma (Figs. F5, F6). Thus, Olsson et al. (2002) concluded that there was a minimal change in sea level associated with the K/T boundary.

Zachos and Arthur (1986) showed that the vertical carbon isotopic difference in the oceans (viz. between surface-dwelling planktonic and deep-sea [particularly Pacific] benthic foraminifers) disappeared at the K/T boundary. This "Strangelove" ocean was one with minimal export productivity (D'Hondt et al., 1998). Planktonic (*Rugoglobigerina*) and benthic (*Anomalinoides*) δ^{13}C records from Bass River (Fig. F8) (Olsson et al., 2002) demonstrate that the collapse of the vertical gradient also occurred in neritic sections. Sedimentation in the earliest Paleocene in the Mid-Atlantic shelf was dominated by slow glauconitic sedimentation, as both siliciclastic and pelagic input were low.

P/E Boundary Event

First recognized by Kennett and Stott (1990), the PETM is associated with a large (2.5‰–4‰), rapid (<20 k.y.) transient global carbon isotopic excursion (the CIE of Zachos et al., 1993), a negative excursion (1‰–3‰) in oxygen isotopes (e.g., Kennett and Stott, 1991), a deep-sea benthic foraminiferal extinction event (e.g., Tjalsma and Lohmann, 1983), a terrestrial mammalian turnover (e.g., Gingerich, 1989), and a kaolinite spike (Robert and Kennett, 1994). The CIE has been attributed to methane release from gas hydrate reservoirs (e.g., Dickens et al., 1995; Katz et al., 1999). Gibson et al. (1993, 2000) and Cramer (2002) studied this event in a borehole from Clayton, NJ, providing clay mineralogic and isotopic data (Fig. F10). Drilling at Bass River and Ancora preserves an exceptional record of the PETM with a chronology provided by integrated nannofossil, planktonic foraminiferal, and magnetostratigraphy; these neritic sections rival the best deep-sea sections in providing a complete record of these global climatic events (Cramer et al., 1999, 2000; Cramer, 2002). Isotopic analyses at all three boreholes show a rapid (<10 k.y.) negative shift in δ^{13}C and δ^{18}O values (~4‰ in carbon and ~2‰ in oxygen), and clay mineralogical analyses for Bass River and Clayton show a sharp increase in kaolinite coincident with the isotopic shift (Fig. F10) (Cramer et al., 1999; Cramer, 2002). Stable isotopic values remain low and kaolinite content remains high throughout a thick section above the CIE in these neritic sections. Cramer et al. (1999) interpreted these data as indicative of an abrupt shift at the time of the CIE to a warmer and wetter climate that persisted for >300–400 k.y. along the North American Mid-Atlantic coast, unlike deep-sea records that show an exponential return to pre-CIE conditions after ~200 k.y. (Katz et al., 1999, Rohl et al., 2000). The thick interval of low isotopic values at Bass River, Ancora, and Clayton coincides with an interval magnetically dominated by <100-nm-diameter magnetite grains. The magnetically anomalous material has been interpreted as derived from a compact impact plume condensate, leading to speculation that the P/E boundary event may have been triggered by a major impact event and reinterpretation of the thickness of this interval on the NJ coastal plain as due to rapid redeposition of impact ejecta over <20 k.y. rather than persistent warm conditions following the PETM (Kent et al., 2001; Cramer, 2002; Kent et al., unpubl. data).

F10. Paleocene/Eocene boundary from Bass River, NJ, p. 34.



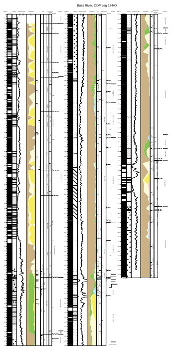
Earliest Oligocene Event

Kominz and Pekar (2001) provided a backstripped estimate of 54 ± 10 m of eustatic lowering that can be correlated (Pekar et al., 2001) with the well-known earliest Oligocene global $\delta^{18}O$ increase (e.g., Miller et al., 1987). This implies development of an ice sheet that was as large, if not slightly larger, than the modern East Antarctica ice sheet, consistent with the results of Miller et al. (1987) and Zachos et al. (1994). Nevertheless, the large size of the earliest Oligocene (~33.8 Ma) ice sheet is surprising, especially considering its near disappearance about a million years later: Kominz and Pekar's (2001) eustatic estimate shows a 46 ± 15-m eustatic rise at 32.7 Ma, and records from Antarctica show the return of alpine *Nothofagus* trees at about this time to the Ross Sea, Antarctica (Cantrill, 2001). Transient ice sheets returned numerous times during the Oligocene–middle Miocene (e.g., Barrett, 1999), and eustatic estimates show numerous large rises and falls (Pekar et al., 2001; Miller et al., 1998a), testifying to a very dynamic ice sheet between ~33 and 14 Ma. By the middle Miocene, the East Antarctic ice sheet had become a permanent feature (e.g., Barrett, 1999) and ice volume changes were primarily controlled by small changes in Antarctica and the nascent growth of Northern Hemisphere ice sheets (Wright, 1998).

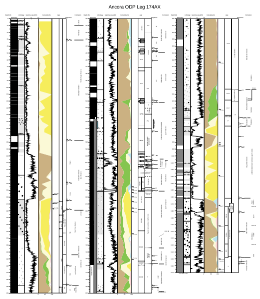
Aquifer Resources

Drilling as part of Leg 174AX (Figs. **F11, F12, F13, F14**) was very successful in addressing local water resource issues. The Bass River and Ancora boreholes targeted Cretaceous aquifers in the Mount Laurel, Englishtown, and Potomac-Raritan-Magothy (PRM) Formations (see Zapecza, 1989, for discussion of these aquifers). Ocean View targeted Miocene aquifers (e.g., the Atlantic City 800-ft sand aquifer of Zapecza, 1989) and confining units between Cape May and Atlantic City. Bethany Beach targeted the hydrogeology of the locally important Pocomoke, Ocean City, and Manokin aquifers, especially in delineating the distribution of freshwater and saline-water zones deeper in the subsurface (see Andres, 1986, for discussion of these aquifers). Continuous coring has shown that aquifer-confining unit couplets are sequences, bounded by unconformities (e.g., Sugarman and Miller, 1997). The upper HST sands comprise important aquifers in both regions that are generally confined by the overlying TST or lower HST. Thus, sequence stratigraphy provides a means to predict the continuity and regional distribution of aquifer-confining bed units (Sugarman and Miller, 1997). Coring has helped resolve issues with the updip-downdip and along-strike relationships of aquifer-confining bed units. For example, the Atlantic City 800-ft sand near Atlantic City is comprised of two sand bodies that make up the HSTs of the Kw1a and Kw1b sequences (Sugarman and Miller, 1997). However, at Cape May, there are two to three sand bodies that could be mapped as the Atlantic City 800-ft sand, with the highest of these associated with the Kw1c sequence (Miller et al., 1996a). Drilling at Ocean View shows that the Kw1c sequence pinches out between Cape May and Ocean View and thus the upper sand at Cape May is not equivalent to the upper sands at Ocean View, Atlantic City, and points north. The drilling also makes clear the control of depositional facies on aquifer architecture. In DE, aquifer sand units developed in HST shoreface deposits are areally extensive and can be correlated tens of kilometers from the Bethany Beach borehole. These include the middle and lower Miocene aquifer units en-

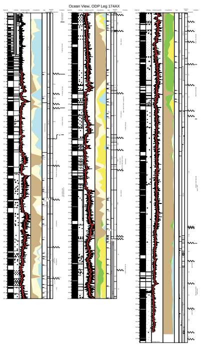
F11. Summary for Bass River, NJ, p. 35.



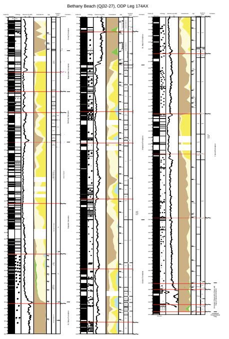
F12. Summary for Ancora, NJ, p. 36.



F13. Summary for Ocean View, NJ, p. 37.



F14. Summary for Bethany Beach, DE, p. 38.



countered at Bethany Beach: the Milford aquifer, which appears to represent the upper HST of Kw2a based on current interpretation of the Sr age control; and the Cheswold aquifer, which is interpreted as the upper HST of the Kw1a. Both can be correlated on geophysical logs through most of southern and central DE. In contrast, aquifer units developed in estuarine-barrier facies, such as the upper? Miocene Pocomoke and Ocean City aquifers at Bethany Beach, are laterally discontinuous, reflecting the high degree of facies change in these environments. The amount of sand present in these estuarine-barrier intervals varies even on the kilometer scale, making detailed local correlation difficult.

Pore water geochemical studies of onshore sites provide important constraints on the role of confining units (see Leg 150X studies by Szabo et al., 1997; Pucci et al., 1997). Pore waters of the lower Miocene confining units at Bass River were geochemically typed and compared with adjacent aquifers (Reilly, 2001). Pore water in the confining units are geochemically distinct from adjacent aquifers and correlative confining units at Atlantic City, 15 km to the south.

FUTURE PROSPECTS

Deep Sea Drilling Project (DSDP) and ODP coring has provided an unparalleled database from the oceans, recovering strata and hard rocks that were not accessible to geologists with hammer and Brunton. The sediments and rocks obtained by DSDP and ODP led to a revolution in how we view tectonics and the evolution of the planet. ODP has provided centralized core libraries and databases and coordinated publications and represents one of the finest examples of international cooperation in science. In comparison, continental drilling is still in its infancy. Outcrops and subsurface samples are more accessible to geologists onshore, and their study has not generally required large international programs like ODP. However, outcrop sections or discontinuously sampled oil or water wells are poor substitutes for continuous cores. Both national (NSF Continental Dynamics Program) and international (ICDP) efforts are now drilling the continents in an integrated fashion, providing the continuous cores and logs that scientists need to address major scientific themes.

In this context, drilling during Legs 150X and 174AX has provided cutting-edge integration of ODP and onshore drilling efforts, coordinated on the themes of global sea-level change and sequence architecture (Miller and Mountain, 1994; Christie-Blick and Austin, 2002). In this contribution, we have shown that onshore drilling can rival the best of ODP drilling in the ocean for continuous records of major global events. For example, during Leg 171B the Blake Nose was drilled in search of continuous Cretaceous to Paleogene records and spectacular records of the C/T, K/T, and PETM events were obtained (Norris, Kroon, Klaus, et al., 1998). We show here that drilling at Bass River and Ancora has provided equally spectacular records of these events. It must be noted that drilling the oceans and continents are complementary: the deep-sea record is generally superior for long, continuous time series and contains a better record of global reservoirs of carbon, whereas the onshore records reflect the direct effects of sea-level change and continental climates.

Future drilling efforts must continue to integrate the strengths of deep ocean drilling (such as planned for the Integrated Ocean Drilling

Program [IODP]) and coordinated onshore efforts. Several major onshore ICDP drilling projects have potential ties to IODP, including the Hawaii Drilling Project (Hawaii Scientific Drilling Project, 2001), the Gulf of Corinth (**www.icdp-online.de/html/sites/corinth/news/news.html**), and Chicxulub (**www.icdp-online.de/html/sites/chicxulub/news/20011203-Chicxulub_en.html**). In addition, various ICDP lake drilling efforts (Titicaca, Malawi, Bosumptwi, and El'gygytgyn; **www.icdp-online.de**) have direct ties to global change studies of the global paleoceanographic array being constructed by ODP and future IODP drilling.

Future drilling in NJ is also being planned as a joint ICDP/IODP effort on the inner continental shelf of NJ (Sites MAT1–MAT3 in Fig. F1) to evaluate the response of passive continental margin stratigraphic architecture to changes in global sea level, sediment supply, and regional tectonics. This drilling project will be the culmination of the NJ/Mid-Atlantic Sea-Level Transect strategy developed and endorsed by several advisory and review bodies over the last decade. Integration of borehole records (lithofacies, biofacies, and logs) with seismic profiles will provide the temporal and spatial control needed to evaluate the response and to perform two-dimensional backstripping, yielding eustatic estimates that can be compared with other eustatic proxies. Prior MAT drilling has focused on the NJ slope (ODP Legs 150 and 174A), outer shelf (ODP Leg 174A), and onshore (ODP Legs 150X and 174AX). Collectively, these efforts have provided ages of sequence boundaries and have tied each to the oxygen isotopic proxy of glacioeustasy, yet have fallen short of the ultimate objectives because facies that register the most sensitive record of sea-level change, the paleoinner shelf, have not been continuously sampled. Funds will be partially provided ICDP, and this project will be the first to unite ICDP and ODP in a cooperative international effort, forging new alliances for future drilling.

ACKNOWLEDGMENTS

We thank the Members of the Coastal Plain Drilling Project for helping to fulfill the promise of onshore drilling and G. Mountain, N. Christie-Blick, and J. Austin for collaboration in planning the NJ sea-level transect. We thank the numerous scientists involved in the Coastal Plain Drilling Project who are not listed here, especially those who supplied critical data sets for Sr isotopes (M. Feigenson, J. Hernandez, and D. Monteverde), nannofossils (M.-P. Aubry, D. Bukry, and L. de Romero), pollen (G. Brenner), and nearshore seismics (G. Mountain and D. Monteverde). The NJ Geological Survey (H. Kasabach, State Geologist [retired] and R. Dalton, Chief Geologist) supplied materials, personnel, and logging support, funded all drilling costs for Bass River, and provided partial support for drilling costs at Ancora and Ocean View. The Delaware Geological Survey (R. Jordan, State Geologist and J. Talley, Associate Director) provided logging for Ocean View and Bethany Beach, materials, personnel, and partial support for drilling costs at Bethany Beach. The USGS Eastern Region Mapping Team (ERMT; J. Quick, Team Leader) provided partial support for Bethany Beach drilling. We thank the ERMT drillers for their exemplary efforts (G. Cobbs, G. Cobbs III, and D. Queen), their drilling coordinators (W. Newell and J. Self-Trail), and Boart Longyear and its drillers (T. McDonald, head driller). Rutgers University provided space for core storage and core analyses, field vehicles, and materials. The National Science Foundation

Continental Dynamics Program (L. Johnson, Program Director) funded the onshore boreholes (Leg 174AX) and, along with PCOM (JOIDES Planning Committee) and ODP, are to be commended for their flexibility and vision in authorizing Leg 174AX as an ODP activity. The publications staff at ODP was supportive throughout production of this and other Leg 174AX volumes; Ann Klaus was particularly helpful in providing insights into publishing this unusual leg. Discussions with and reviews by M. Katz are greatly appreciated. This research is supported by NSF grants EAR94-17108, EAR97-08644, and EAR99-09179 (Miller) and EAR98-14025 (Kominz).

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Figure F1. Location map showing existing ODP boreholes analyzed as a part of the New Jersey/Mid Atlantic (MAT) Sea-Level Transect. Also shown are multichannel seismic data (MCS) from *Ewing* Cruise 9009 (Ew9009), *Oceanus* Cruise (Oc270), and *Cape Hatteras* cruise (Ch0698). NJGS = New Jersey Geological Survey, USGS = U.S. Geological Survey, AMCOR = Atlantic Margin Coring Project.

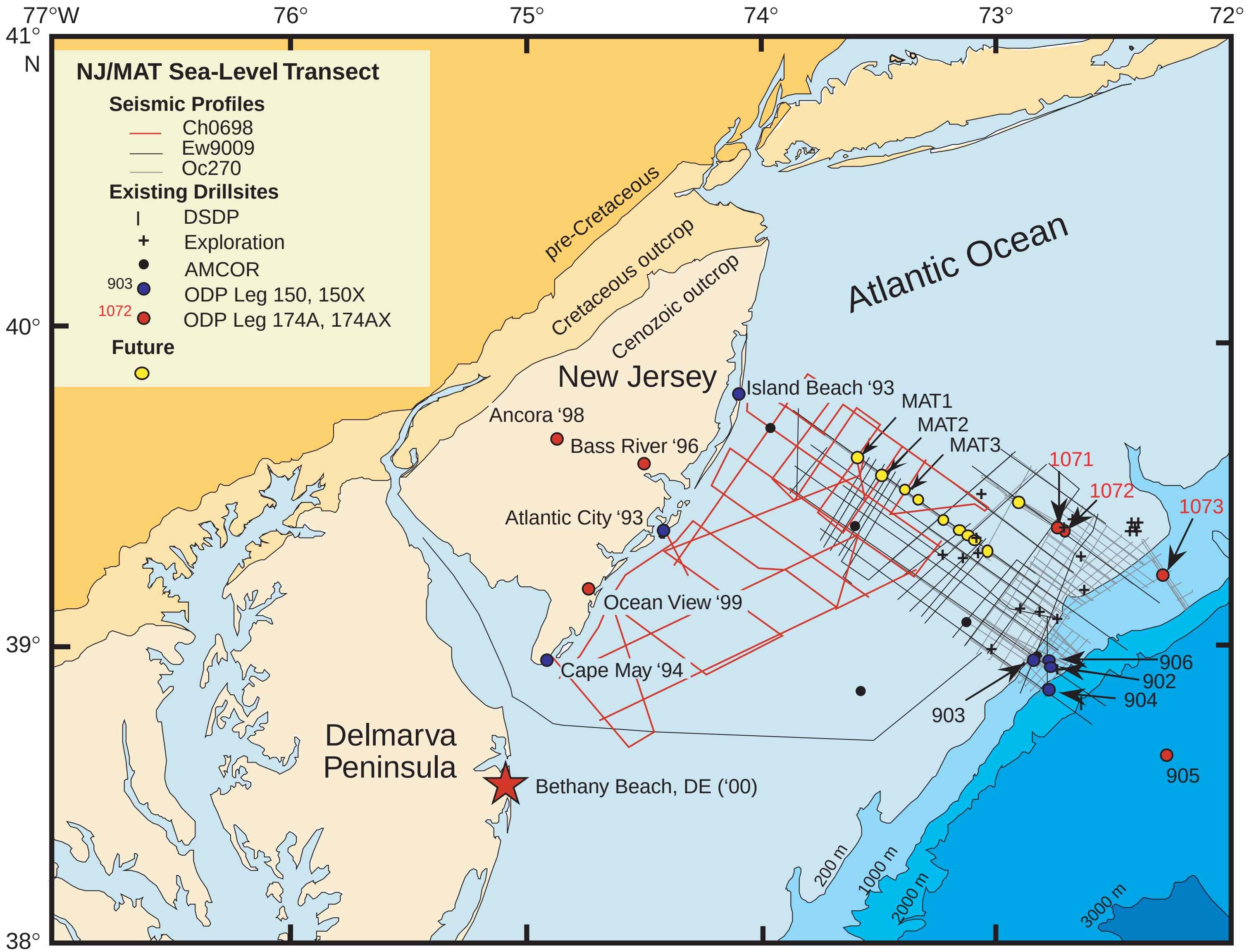


Figure F2. A. Facies model for deltaic-dominated facies showing core photographs from the Miocene section at Ocean View. Modern environments from the Niger Delta (Allen, 1970) are illustrated at the top. On left is a summary of facies successions within a Miocene onshore sequence (modified after Sugarman et al., 1993). (Continued on next two pages.)

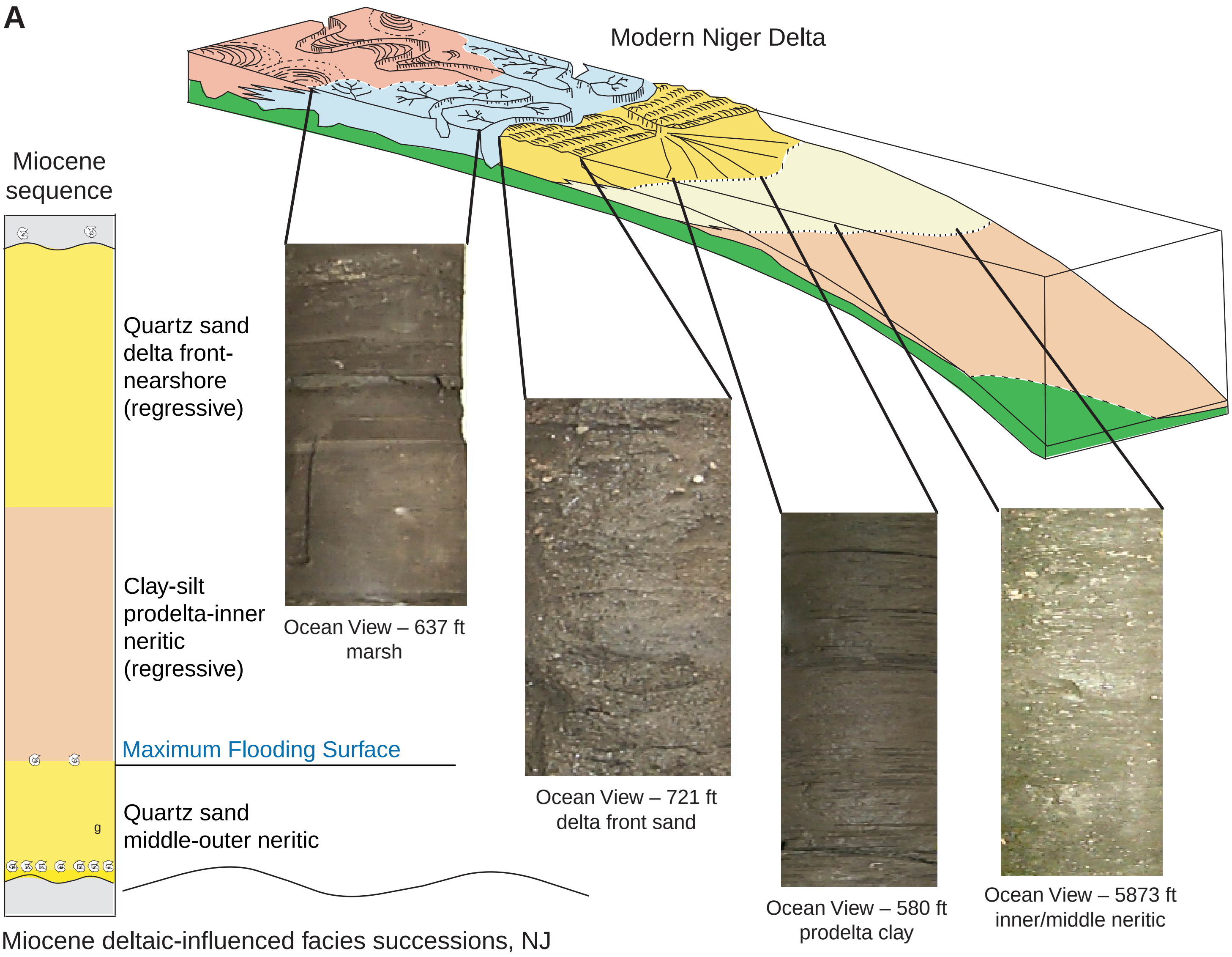
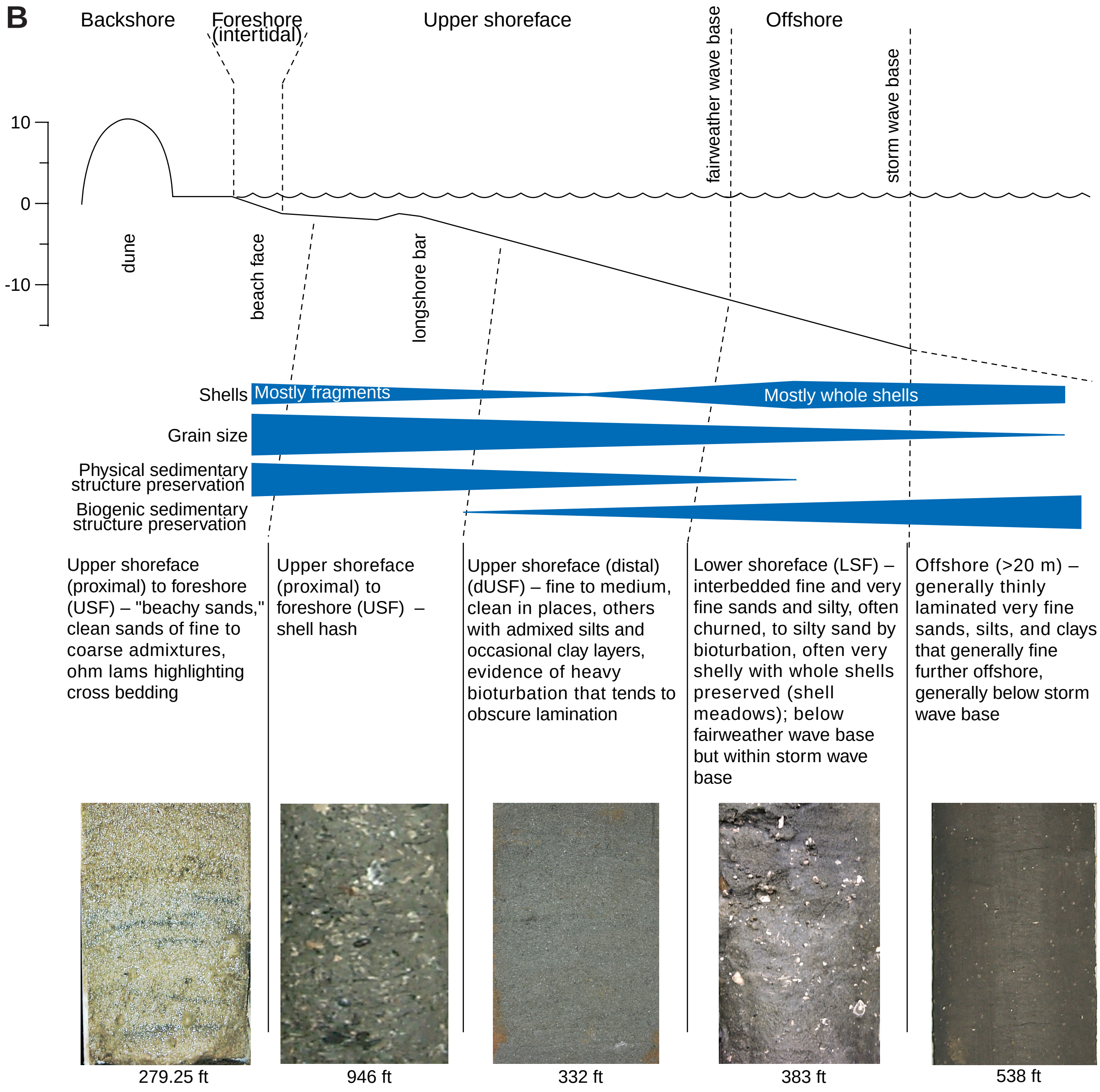


Figure F2 (continued). B. Facies model for wave-dominated nearshore sedimentation, Miocene of Delaware. Trends in textural characteristics shown by bars of varying widths are generalized; see text for explanation. Photographs are examples of each facies in core from given levels in the Bethany Beach borehole.



Upper shoreface (proximal) to foreshore (USF) – "beachy sands," clean sands of fine to coarse admixtures, ohm lams highlighting cross bedding

Upper shoreface (proximal) to foreshore (USF) – shell hash

Upper shoreface (distal) (dUSF) – fine to medium, clean in places, others with admixed silts and occasional clay layers, evidence of heavy bioturbation that tends to obscure lamination

Lower shoreface (LSF) – interbedded fine and very fine sands and silty, often churned, to silty sand by bioturbation, often very shelly with whole shells preserved (shell meadows); below fairweather wave base but within storm wave base

Offshore (>20 m) – generally thinly laminated very fine sands, silts, and clays that generally fine further offshore, generally below storm wave base

Figure F2 (continued). C. Conceptual architecture of an upper Oligocene sequence in New Jersey with borehole locations appropriate for sequences O5 and O6. Stratigraphic intervals preserved for each location are indicated in blue on the sea-level representations, striped intervals = nondeposition or erosion, gray = uncertainty. TST = transgressive systems tract, HST = highstand systems tract (after Pekar et al., in press b).

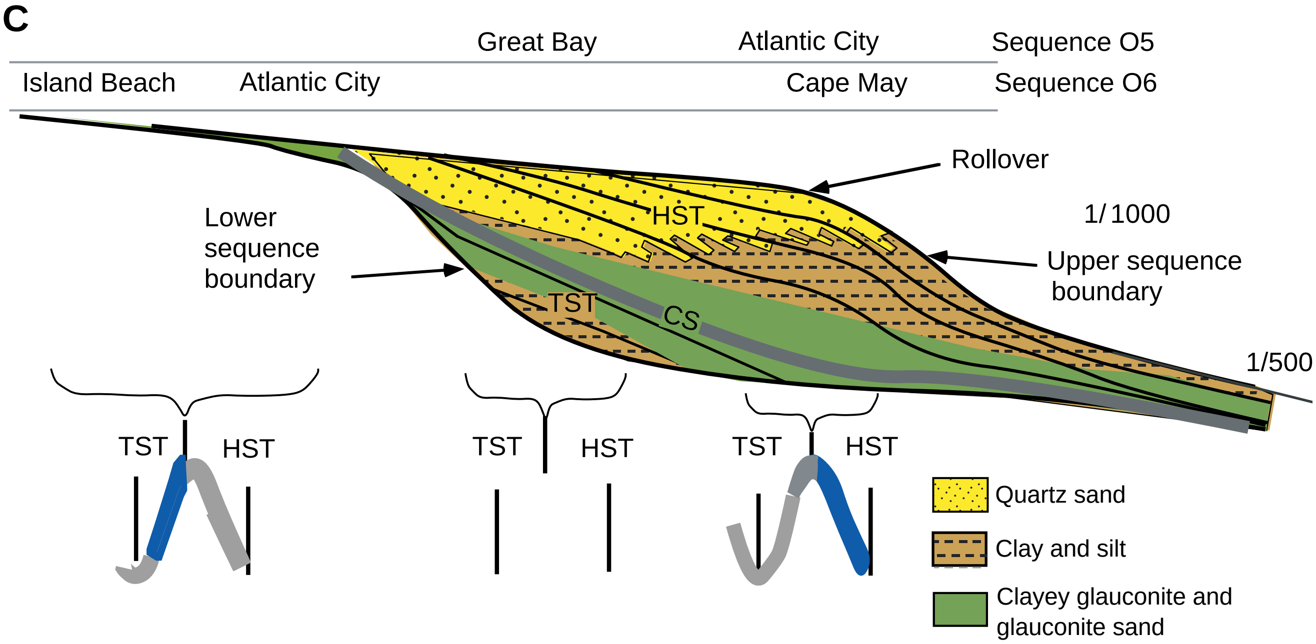


Figure F3. Comparison of the ages of the Miocene sequence from the Bethany Beach borehole with the ages of sequences identified in New Jersey. Cross hatched = uncertain ages. Also shown is the benthic foraminifer oxygen isotopic record for Atlantic deep-sea sites (modified after Miller et al., 1997). Mi events are major isotopic increases that are inferred to correlate with ice growth events on Antarctica; arrows are placed at inflection points. Timescale is after Berggren et al. (1995).

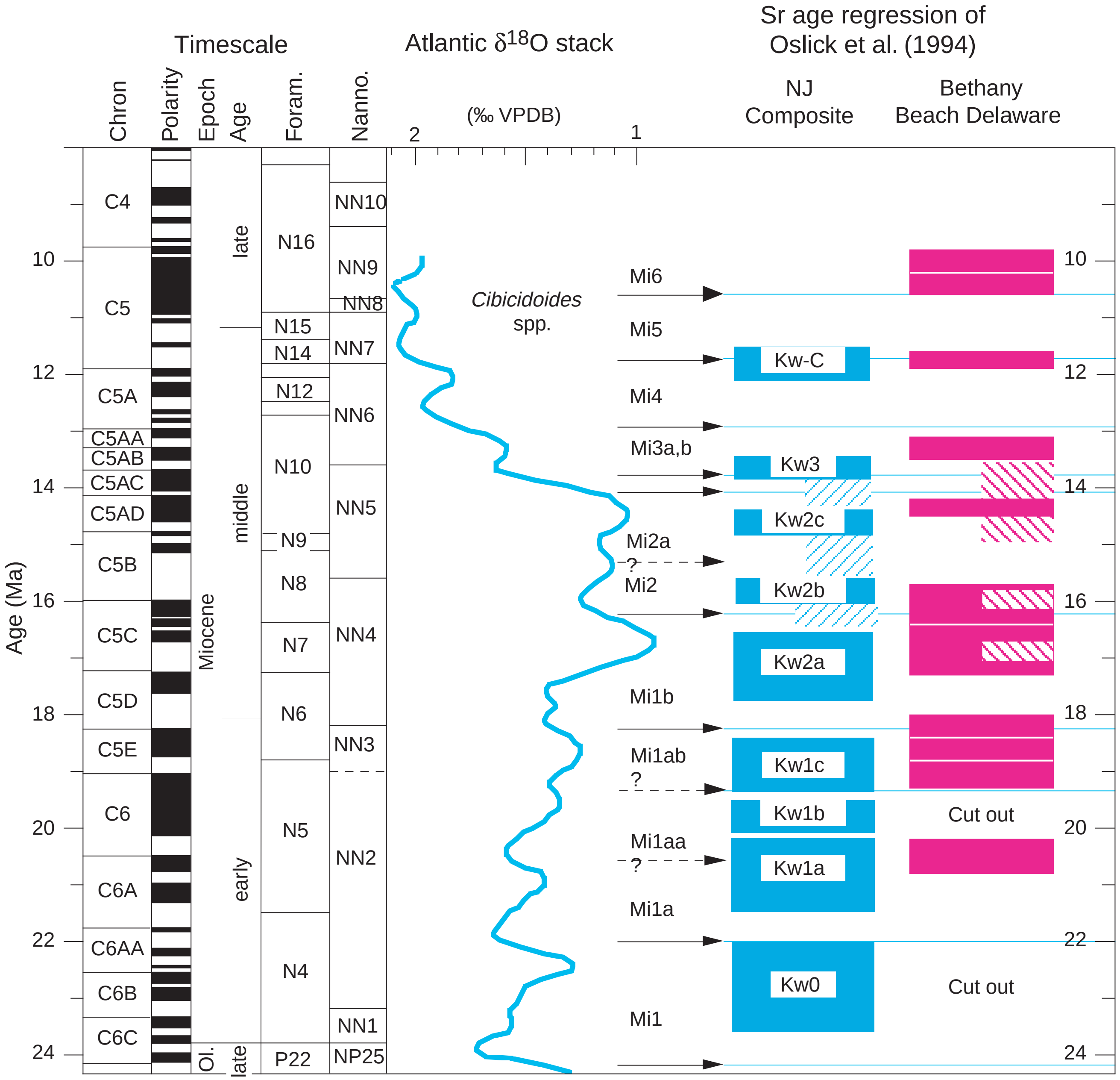


Figure F4. Backstripped R2 eustatic estimates (Van Sickle et al., unpubl. data) for five coastal plain boreholes. Backstripping studies of Ocean View and Bethany Beach are ongoing. Heavy lines = best estimates, light lines outlining color shared areas = error bars. R2 is the second reduction of Bond and Kominz (1984) that provides a eustatic estimate (see Kominz et al., 1998, for discussion).

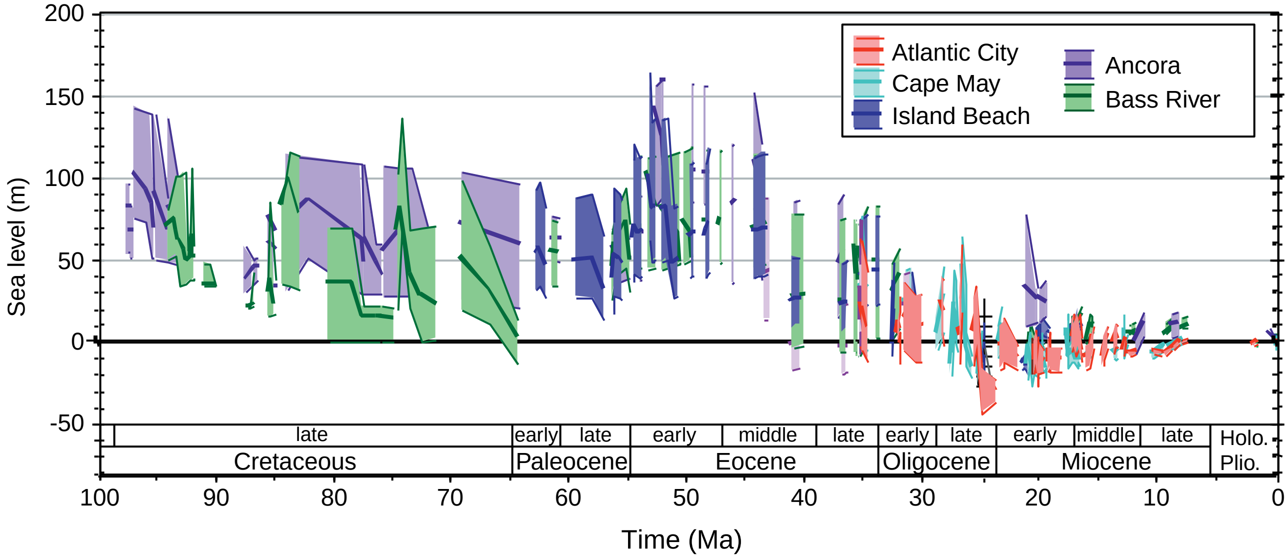


Figure F5. Late Cretaceous age-depth plots for sequences at Bass River (top) and Ancora (bottom). Solid black circles = Sr isotopic ages computed using the regressions (Age = 39104.339163 – $^{87}Sr/^{86}Sr$ × 55154.82511), applicable from 73.5 to 86.0 Ma and (Age = 31908.531372 – $^{87}Sr/^{86}Sr$ × 44984.801888), applicable from 65 to 73.5 Ma with ±1-m.y. error bars, blue circles = diagenetically altered samples, red = conservative age models, green = alternate age models. Horizontal olive-green lines indicate sequence boundaries. Blue triangles = CC nannofossil zones, × = planktonic foraminiferal age estimates. Blue blocks at bottom = time represented in each borehole (after Miller et al., unpubl. data).

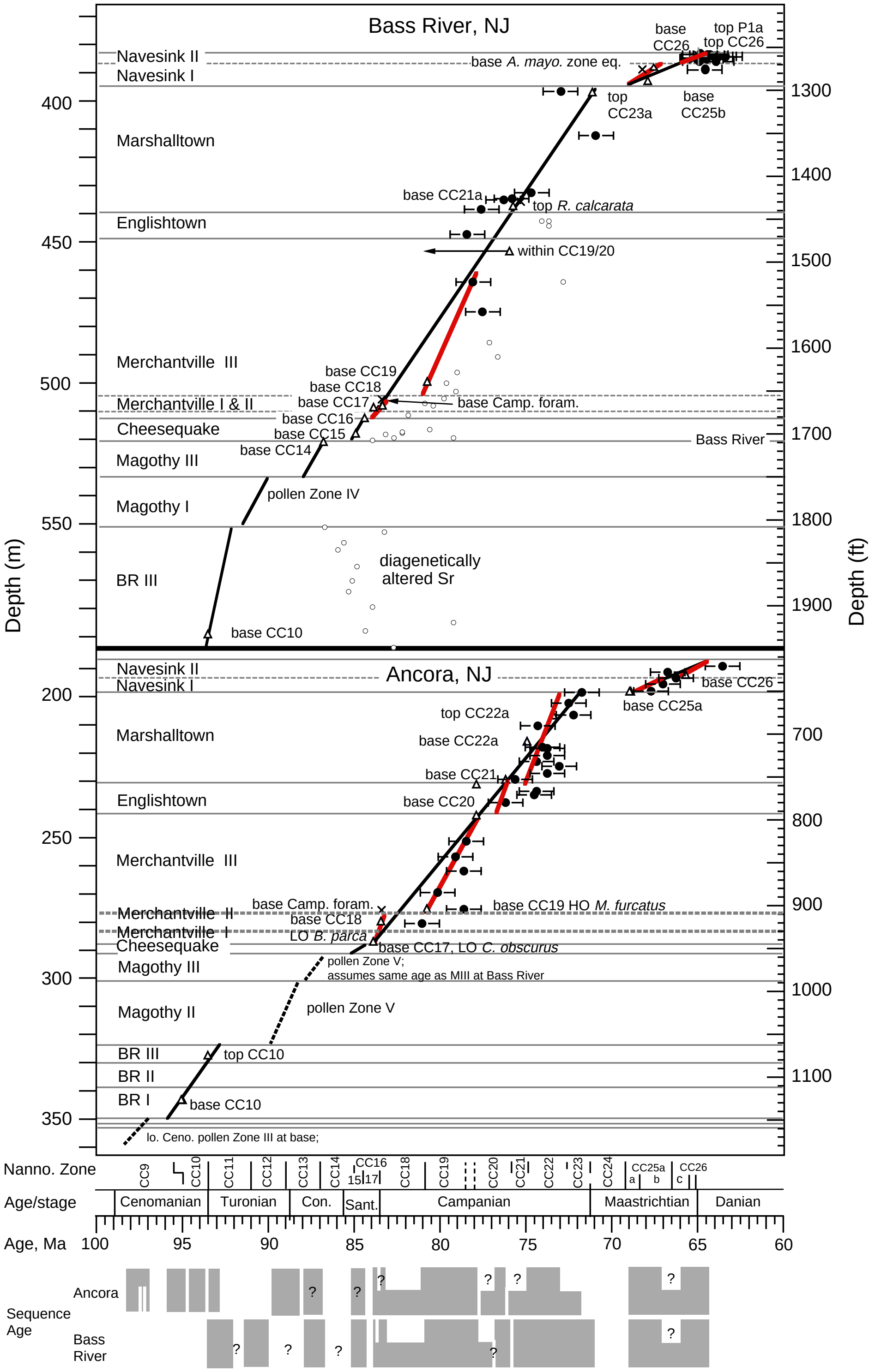


Figure F6. Comparison of Late Cretaceous deep-sea oxygen benthic foraminiferal $\delta^{18}O$ records (Site 463, Barrera and Savin, 1999; Site 690, Barrera and Savin, 1999; Site 511, Fassel and Bralower, 1999; Sites 1049 and 1050, Huber et al., 2002), planktonic foraminiferal $\delta^{18}O$ records (Site 463, Barrera and Savin, 1999), New Jersey composite sequences (derived from Fig. F5, p. 29), the relative sea-level curve from northwest Europe (red continuous line; Hancock, 1993) and the backstripped record from the Russian platform (black continuous line; Sahagian et al., 1996), the EPR eustatic estimate (green line, Haq et al., 1987), backstripped R2 eustatic estimates for Bass River (pink discontinuous lines) and Ancora (red discontinuous lines), and our best estimate of eustatic changes derived from the R2 curves (dark blue indicates portions of the curve constrained by data, light blue indicate portions inferred). Pink arrows indicate positive $\delta^{18}O$ inflections (inferred cooling and/or ice volume increases). For the composite: blue boxes = time represented, white areas = hiatus, thin white lines = inferred hiatuses. Arrows are drawn through the inflection points of the European records. E.K. = Early Cretaceous (after Miller et al., unpubl. data).

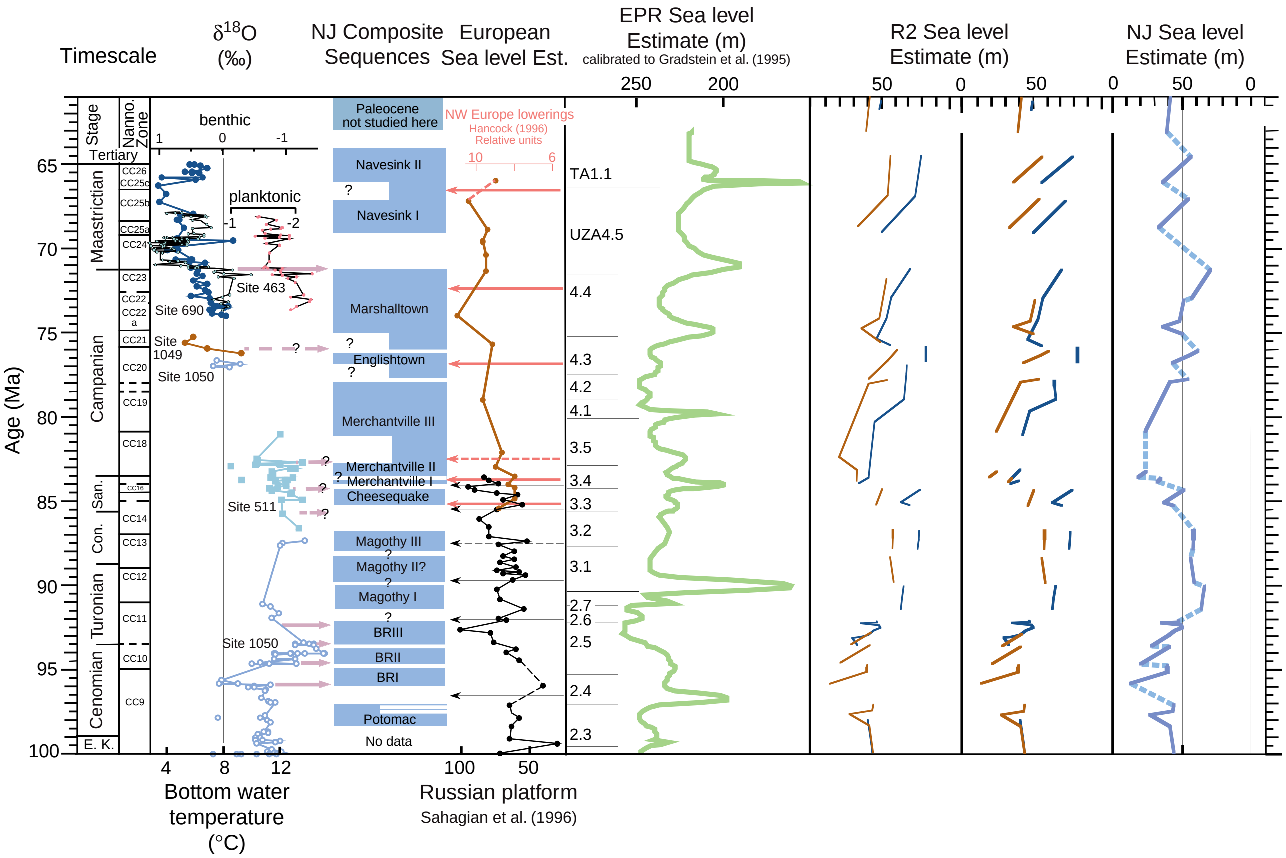


Figure F7. Cenomanian–Turonian section at Bass River, New Jersey, showing lithology, environment of deposition, nannofossil and pollen biostratigraphy, benthic foraminiferal carbon isotopic data, percent organic carbon in the sediments, benthic foraminiferal oxygen isotopic data, and water depth changes inferred from benthic foraminiferal biofacies. FS = flooding surface, MFS = maximum flooding surface, TD = total depth (modified after Sugarman et al., 1999, using data from Wright et al., unpubl. data).

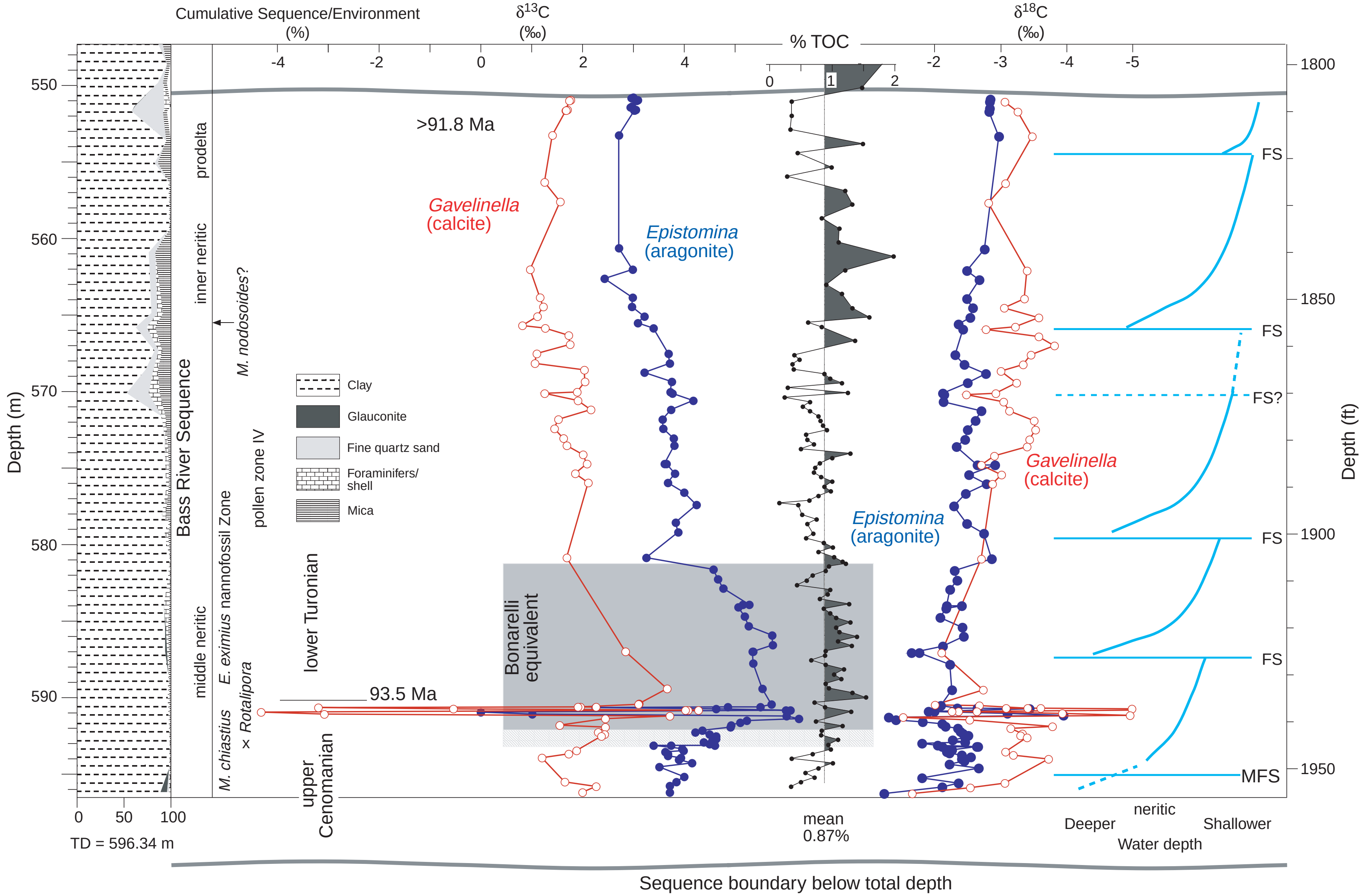


Figure F8. Maastrichtian events at Bass River, New Jersey, showing oxygen and carbon isotopic data for benthic (solid circles, *Anomalinoides*) and planktonic (closed circles, *Rugoglobigerina*) foraminifers, Sr isotopic data generated on foraminiferal tests, benthic foraminiferal biofacies (1 = middle neritic *Anomalinoides midwayensis–Gyrodinoides imitata*; 2 = middle neritic *A. midwayensis–Anomalinoides acuta*; 3 = inner–middle neritic *Anomalinoides* cf. *welleri*), P% = percent planktonic foraminifers (solid circles). Interpreted paleodepth curve (light line), magnetic polarity interpretation for Bass River, and a line indicating the correlation of the Deccan Traps (modified after Olsson et al., 2002).

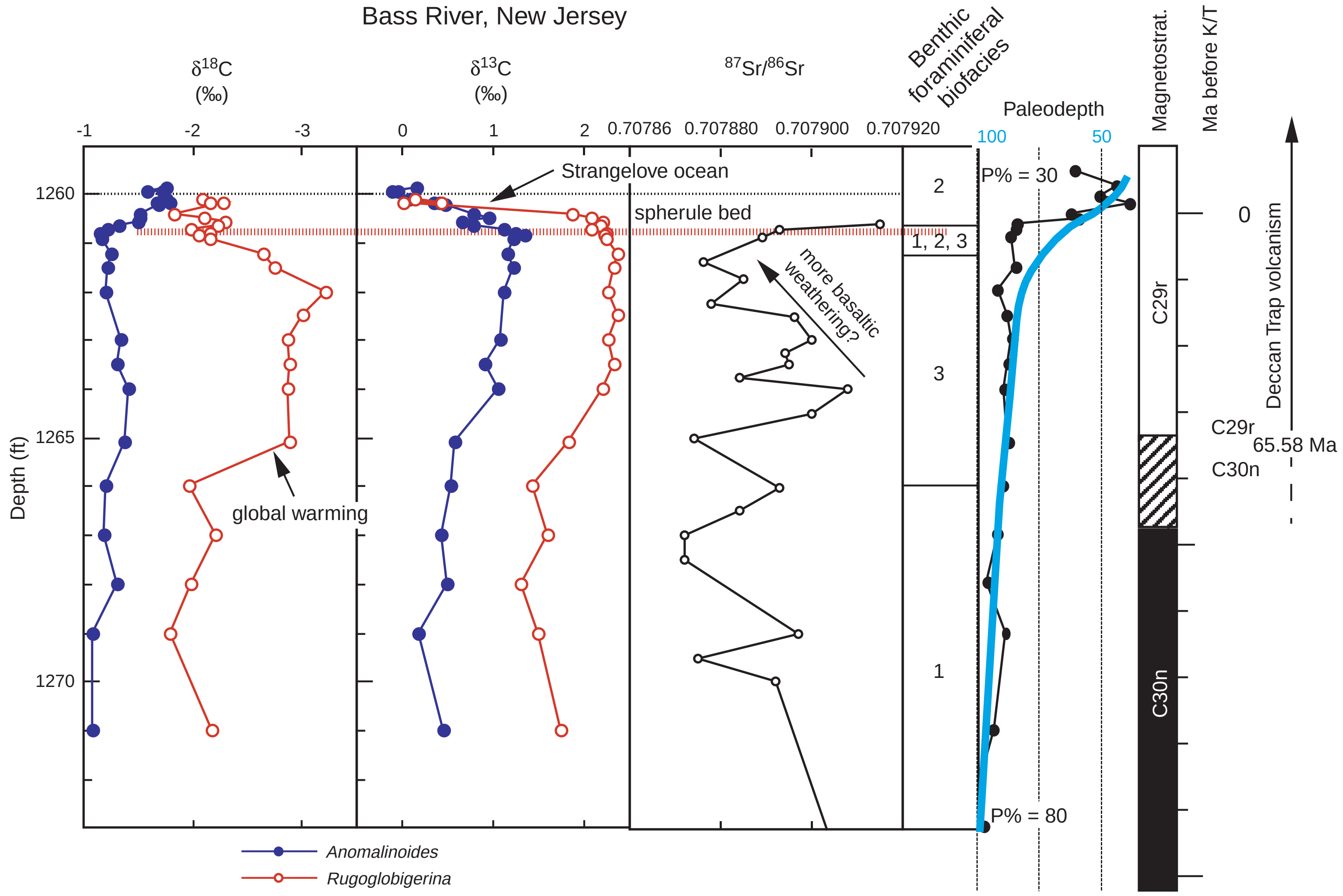


Figure F9. Cretaceous/Tertiary (K/T) boundary at Bass River, New Jersey, showing core photograph and lithology of spherule bed, Ir and shocked mineral concentration, and biostratigraphic data (planktonic foraminifers, dinocysts, and nannofossils). Clay clasts are interpreted as being emplaced by a tsunami (modified after Olsson et al., 1997, 2002).

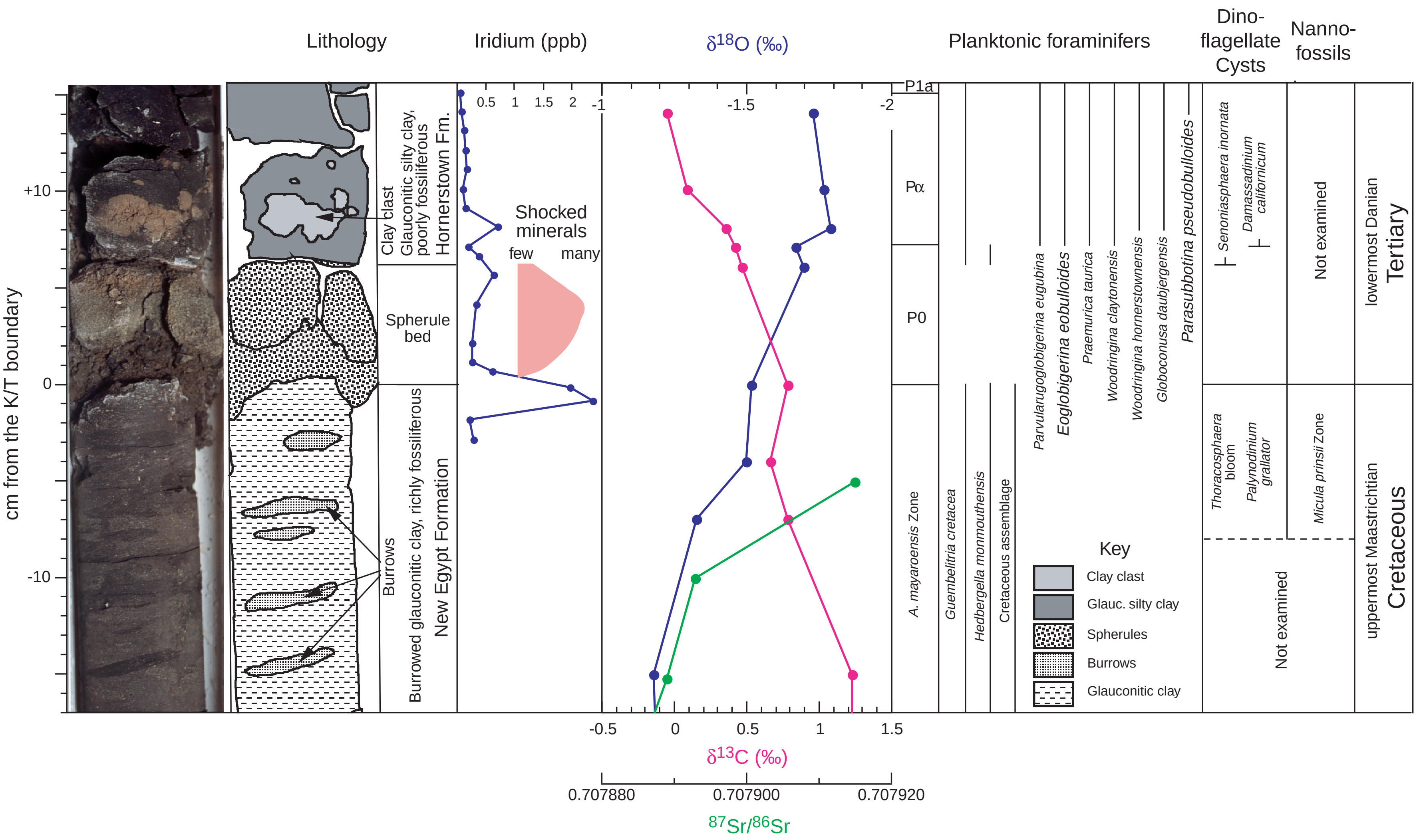


Figure F10. Paleocene/Eocene boundary from Bass River, New Jersey, showing magnetostratigraphic interpretation of nannofossil biostratigraphy, percent kaolinite of total clay fraction, stable isotopic data, and grain-size data. Grain-size data and nannofossil biostratigraphy are shown for Ancora, New Jersey (modified after Cramer et al., 1999, 2000).

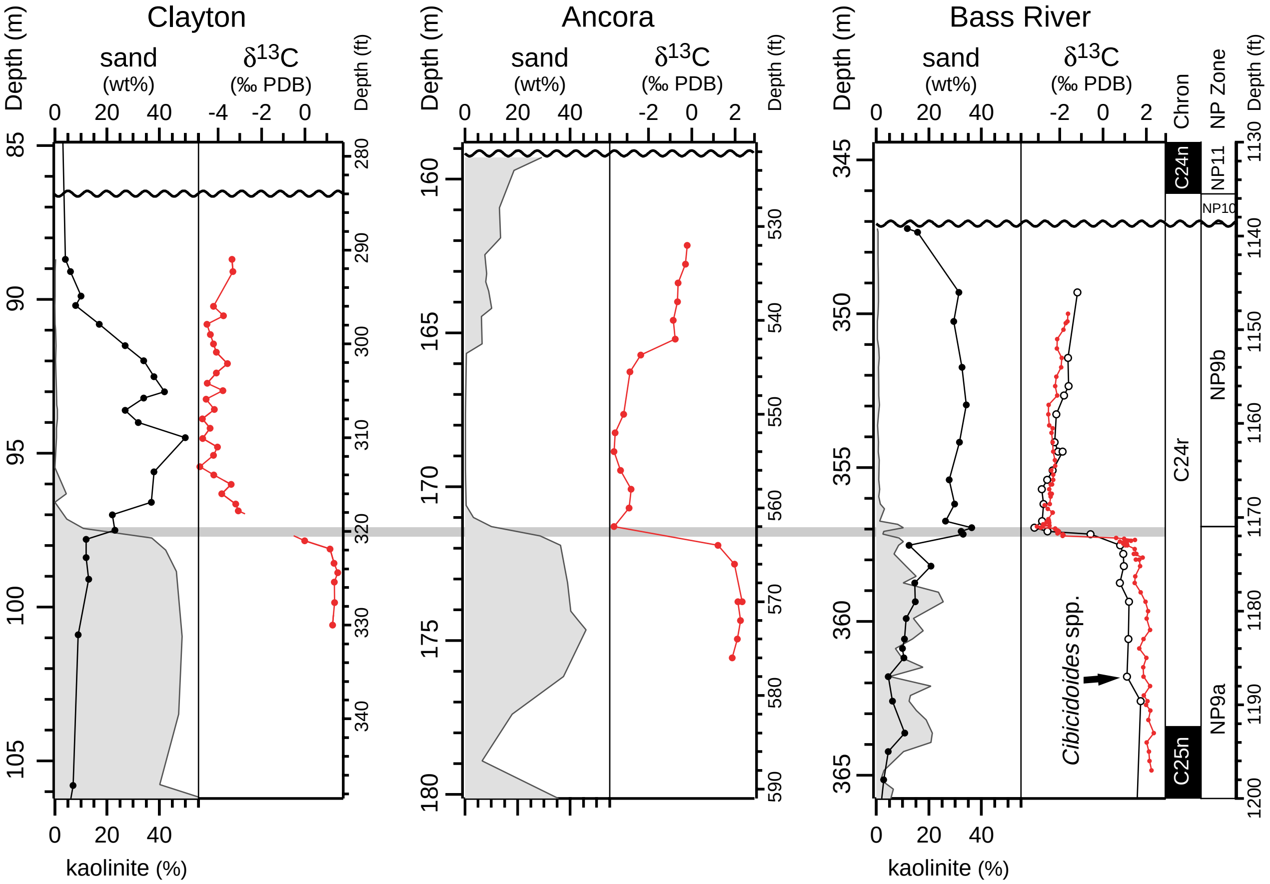


Figure F11. Summary for Bass River, New Jersey. (This figure is available in an oversized format.)

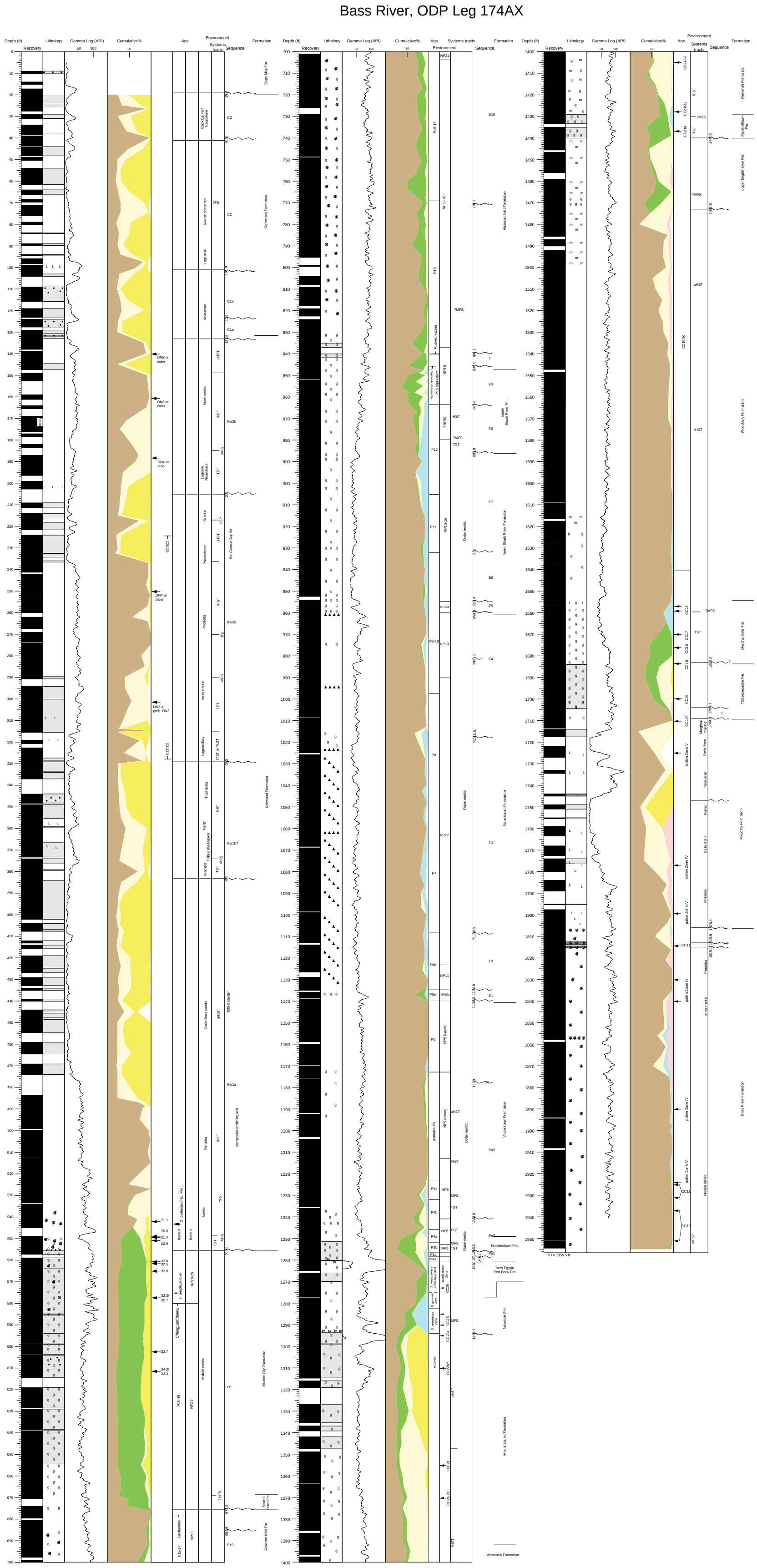


Figure F12. Summary for Ancora, New Jersey. (This figure is available in an oversized format.)

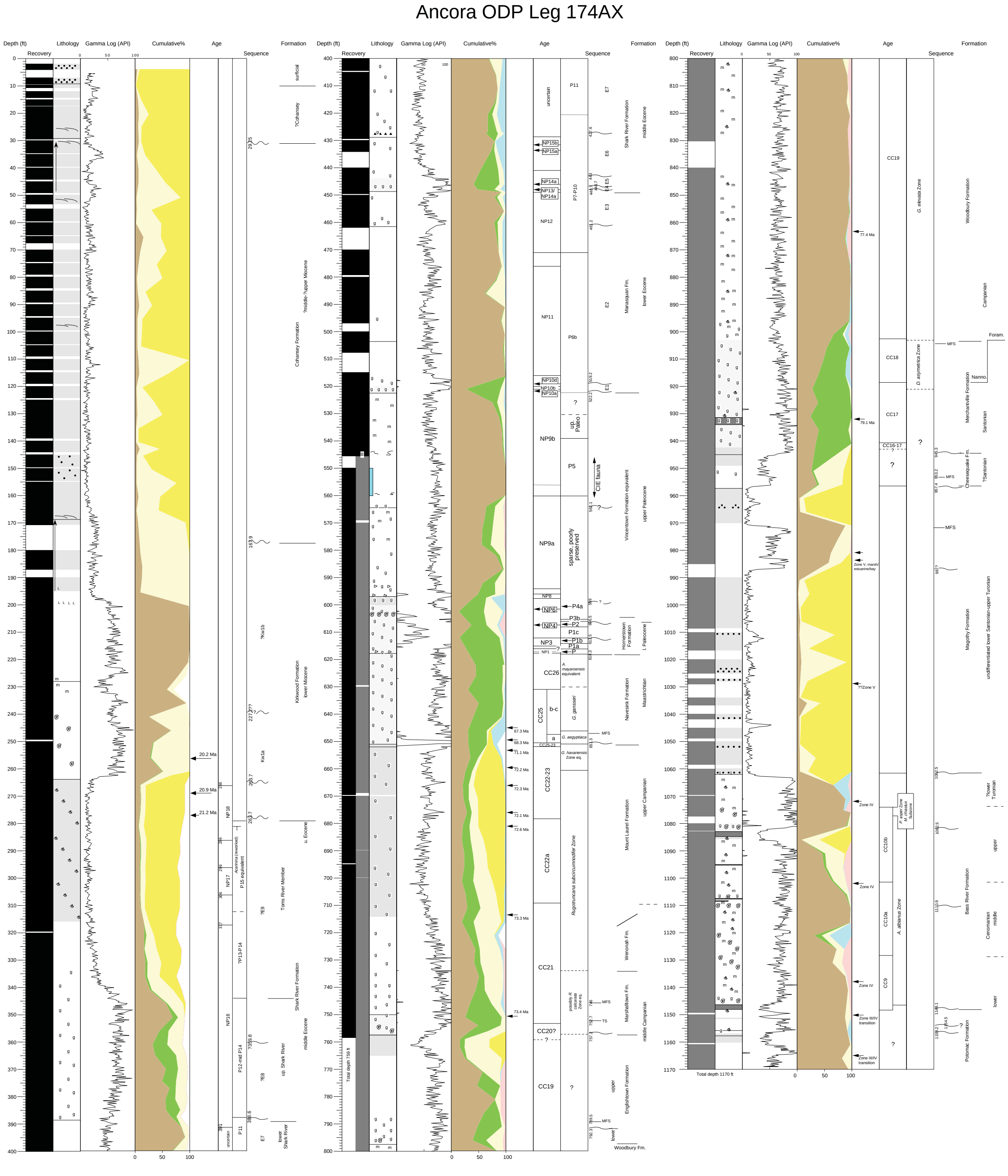


Figure F13. Summary for Ocean View, New Jersey. (This figure is available in an oversized format.)

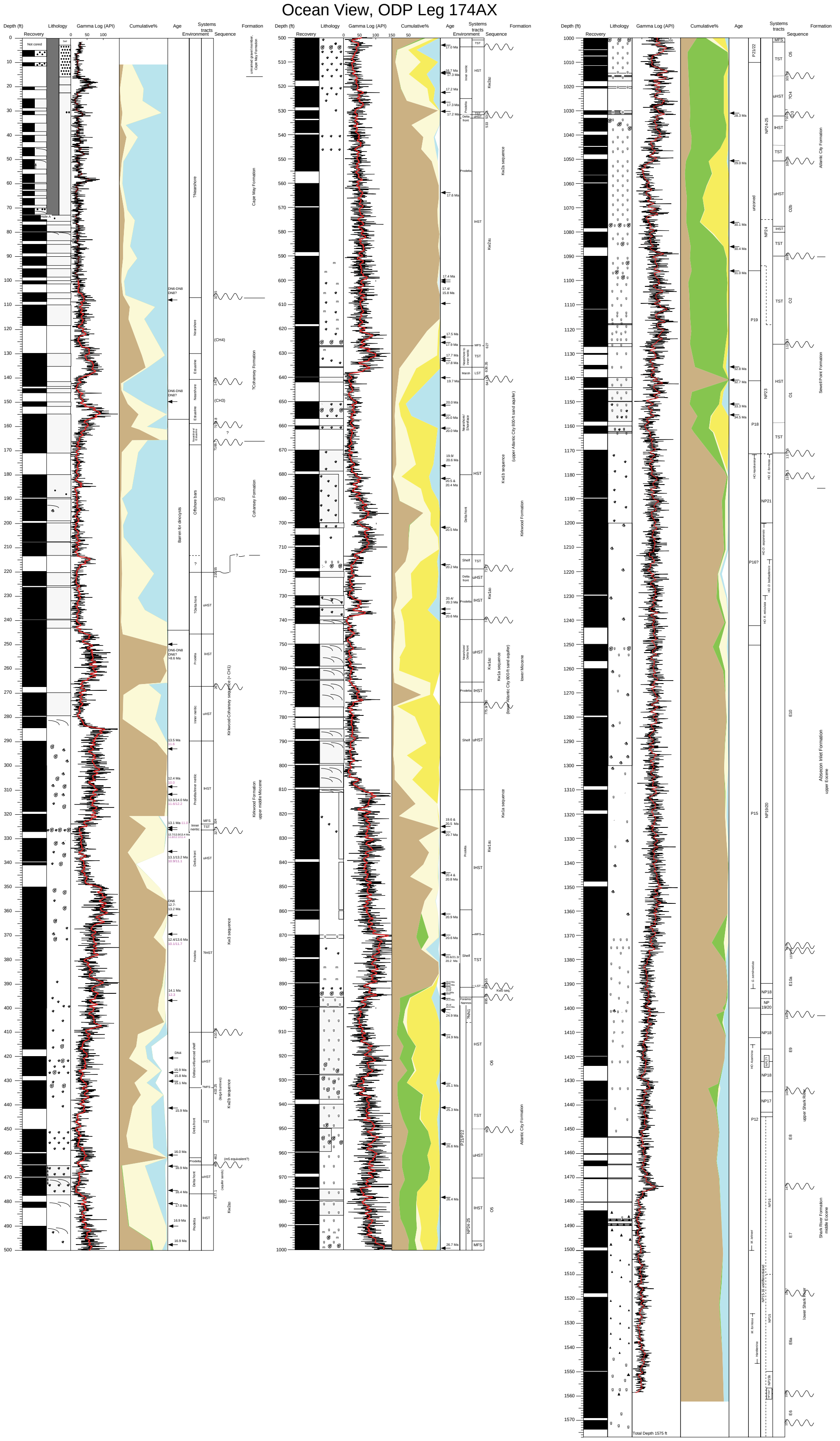


Figure F14. Summary for Bethany Beach, Delaware. (This figure is available in an oversized format.)