Integrated sequence stratigraphy of Neogene deposits, New Jersey continental shelf and slope: Comparison with the Exxon model

STEPHEN M. GREENLEE
WILLIAM J. DEVLIN } *Exxon Production Research Company, P.O. Box 2189, Houston, Texas 77252-2189*
KENNETH G. MILLER *Department of Geological Sciences, Rutgers University, New Brunswick, New Jersey 08903* and *Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964*
GREGORY S. MOUNTAIN
PETER B. FLEMINGS } *Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964*

ABSTRACT

We have evaluated the Neogene stratigraphic succession beneath the continental shelf off New Jersey using high-quality seismic and well data to (1) construct geologic cross sections that relate seismic geometries to lithofacies in a prograding, tectonically quiescent setting; (2) apply a sequence-stratigraphic approach to subdivide the stratigraphic section and relate the characteristics of the depositional observed sequences to the published Exxon model; and (3) determine the resolution of the available biostratigraphy in the correlation of the offshore New Jersey depositional sequences to the published eustatic cycle chart. In the offshore New Jersey area, the well-developed progradational geometries in the Neogene section, the high-quality seismic data, and the relatively abundant lithologic information from wells allow us to use the results of this study to predict lithofacies distribution in similar, but less geologically constrained, settings.

Seismic sequence analysis and interpretation of stratal stacking patterns in well logs indicate that the observed depositional sequences can be subdivided into lowstand (lowstand fan and lowstand wedge) and highstand systems tracts. Lowstand fans of lowstand systems tracts are characterized by thick, aggradational sandstones that exhibit a "blocky" to fining-upward well-log signature. Lowstand wedges of lowstand systems tracts generally display upward-coarsening, but dominantly shale-prone, lithofacies. Transgressive systems tracts, if present, are very thin. Highstand systems tracts consist of strata that shoal from prodelta mudstone to thick, relatively homogeneous sandstone.

Sandstone beds occur in association with two distinct seismic facies. The first type compose the topset and toplapping beds of prograding depositional systems, typically highstand systems tracts. These sandstone beds thicken to as much as 150 m towards the depocenters of each sequence and thin along strike, away from the depocenters. The second type of sandstone is present at the toes of depositional slopes, where it onlaps against prograding deltaic wedges.

The observed geometry and lithofacies distribution of the Neogene depositional sequences are compared to the "standard" Exxon sequence stratigraphic model. Depositional sequences recognized in this study are characterized by similar overall stacking patterns within component systems tracts; however, the New Jersey sequences are different in several ways. These differences include the lack of type-2 unconformities, an absence of leveed channel deposits within lowstand wedges, very poorly developed transgressive systems tracts, and sandstone-rich, highly regressive highstand systems tracts. These differences are explained in terms of the limited Neogene accommodation on the New Jersey shelf that resulted from slow subsidence rates and a second-order Miocene eustatic fall.

Paleontologic data bracket the ages of the individual sequences but are not detailed enough at present to correlate precisely to the time scale and inferred global sea-level records. Based on the available biostratigraphy, however, Neogene depositional sequences from offshore New Jersey have a cyclicity consistent with interpreted third-order eustatic fluctuations on the global cycle chart.

INTRODUCTION

Previous industrial and academic studies have shown that thick Neogene deposits are present in the Baltimore Canyon Trough on the mid-Atlantic continental margin of the United States (for example, Schlee, 1981; Poag, 1985; Greenlee and others, 1988) (Fig. 1). The Neogene stratigraphy of this region is of significant interest from a sequence stratigraphic perspective for several reasons: (1) the stratal succession consists of a reasonably complete Neogene sedimentary section; (2) exploration seismic-reflection profiles indicate well-developed stratal geometry that can be directly related to sequence stratigraphic models; (3) the section occurs in a simple tectonic setting and is mostly unfaulted; (4) a relatively large number of wells have been drilled in the section; and (5) biostratigraphic data from the wells, together with outcrop and borehole information from the adjacent coastal plain, allow an estimation of geologic age of the depositional sequences that can then be related to proposed global sea-level changes.

The stratal geometry of prograding Neogene siliciclastic depositional sequences off New Jersey has been documented in detail using industry seismic profiles (Greenlee and others, 1988; Greenlee and Moore, 1988). The unconformities that bound the sequences are identified by erosional truncation, toplap, and basinward shifts in onlap as interpreted by using seismic sequence analysis techniques (Vail and others, 1977). These basinward shifts have been interpreted as a product of short-term (third-order)

Geological Society of America Bulletin, v. 104, p. 1403–1411, 6 figs., 1 table, November 1992.

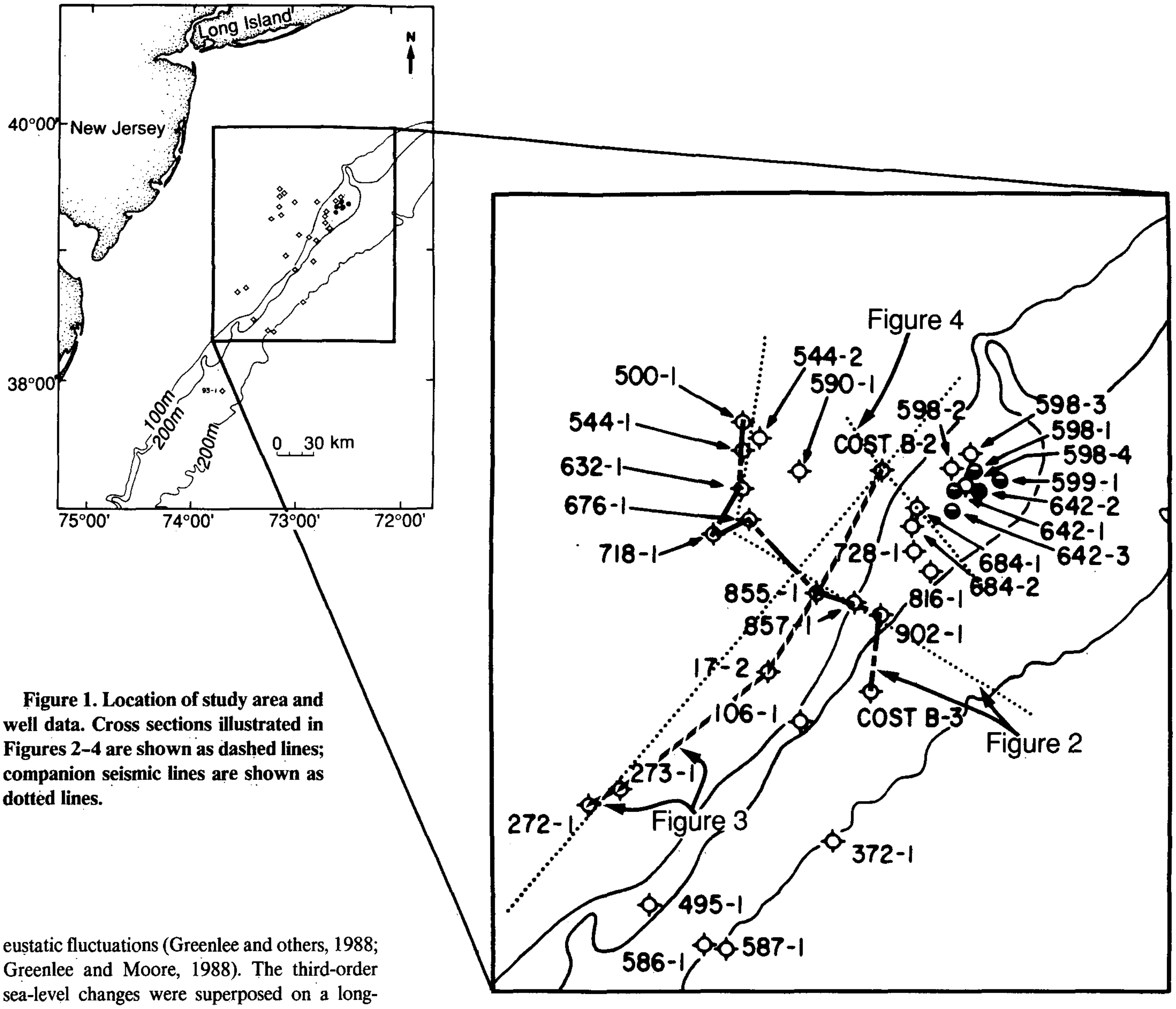

Figure 1. Location of study area and well data. Cross sections illustrated in Figures 2-4 are shown as dashed lines; companion seismic lines are shown as dotted lines.

eustatic fluctuations (Greenlee and others, 1988; Greenlee and Moore, 1988). The third-order sea-level changes were superposed on a long-term (second-order) Neogene eustatic fall and occurred on a mature, slowly subsiding margin. In this paper, we illustrate the lithofacies associated with these depositional sequences and their stratal geometry using well logs tied to the seismic data and document the ages of the interpreted sequences using the available biostratigraphy. The data base used for this analysis consists of (1) seismic profiles from the shelf and slope and (2) industry wells from the middle to outer shelf and the upper slope that provide both wire-line logs and paleontological samples (Fig. 1). The results are compared with the "standard" Exxon stratigraphic model for siliclastic lithofacies distribution (Vail, 1987; Posamentier and others, 1988). We also compare the ages of the interpreted sequences with ages predicted from coastal onlap curves (Haq and others, 1987).

NEOGENE SEQUENCE AND LITHOSTRATIGRAPHY

Stratal geometry observed on the seismic data was used to correlate surfaces on the well-log sections (Figs. 2, 3, and 4). Dip-oriented sections (Figs. 2 and 4) show all of the middle Miocene sequences and were assembled by projecting some of the wells along depositional strike, which is oblique to the present continental shelf edge. The sequences consist of lobate deltaic sediments that thin along strike; this is illustrated in Figure 3. The well logs were tied to the seismic data using synthetic seismograms where sonic logs were available, or velocity surveys where they were not. Sequence and systems tract boundaries were identified using seismic geometry (Vail and others, 1977) and log-based stratigraphic concepts (Van Wagonner and others, 1990). Six middle Miocene and three upper Miocene-Pliocene sequence boundaries were correlated throughout the seismic grid (Fig. 2). From oldest to youngest, these surfaces were identified as Green, Red-2, Pink-2, Blue, Yellow-2, Tuscan, Red-1, Yellow-1, and Pink-1. Component systems tracts contained within each sequence were identified by their position within the depositional sequence, reflection terminations recognized on the seismic data, and the stacking patterns of parasequences in the wells. The stacking, or vertical succession of parasequences within systems tracts, results in a characteristic arrangement of lithofacies as was described in Posamentier and others (1988) and

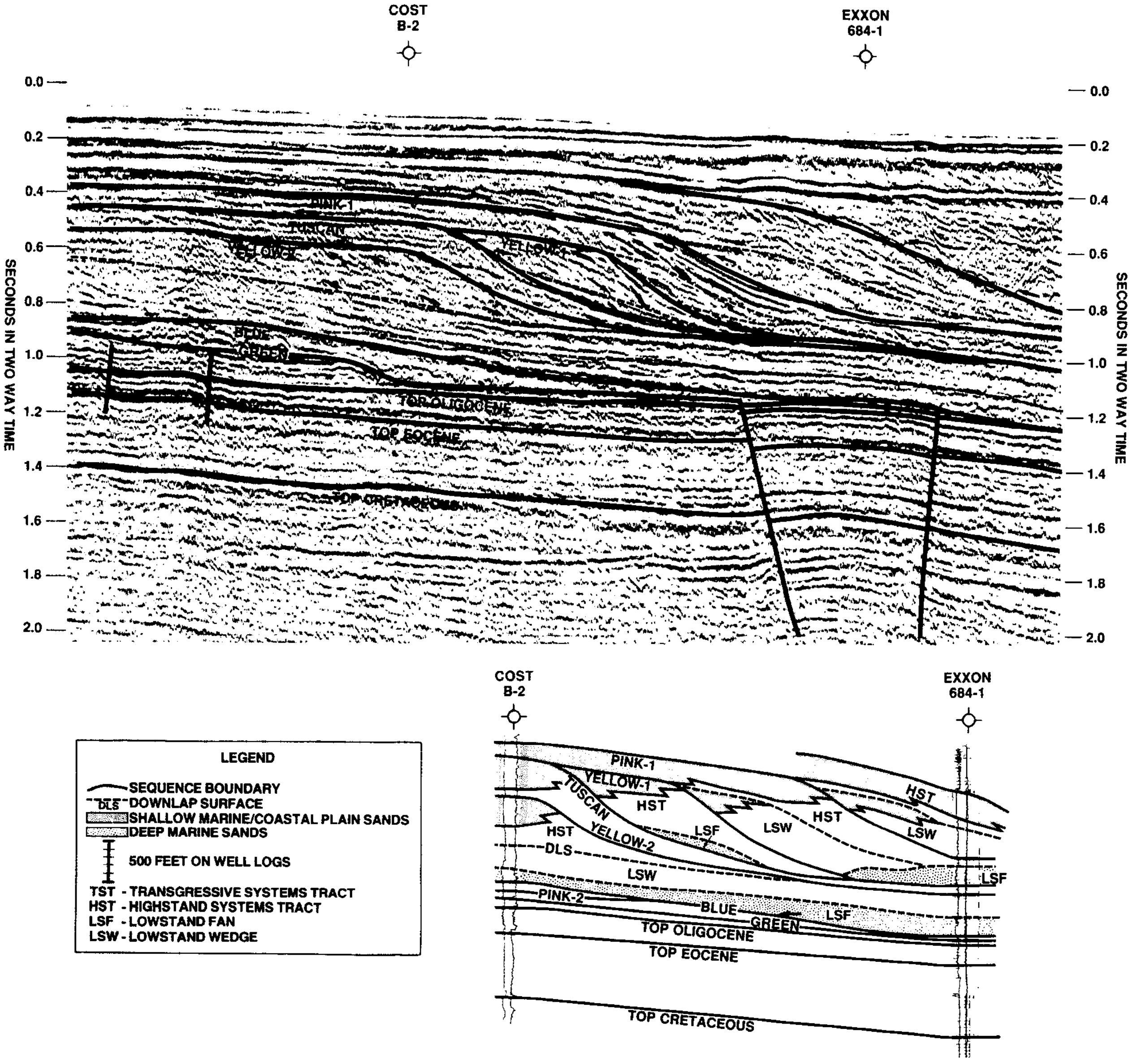

Figure 4. Seismic line and well-log cross section passing through COST B-2 well and Exxon 684-1.

Van Wagonner and others (1990). Consequently, the identification of systems tracts within the sequences was a process that involved the integration of both seismic sequence analysis and interpretation of well-log patterns. Two systems tracts were identified in most sequences: the lowstand systems tract (consisting of a basin floor fan and lowstand wedge) and the highstand systems tract.

Lowstand Systems Tract—Lowstand Fan

Several lowstand fans were recognized in the seismic and well data. Each fan directly overlies a sequence boundary and is overlain by the downlapping toes of overlying lowstand wedge or highstand deposits. The fans are in localized areas near the clinoform toes of the previous highstand offlap break[1] and onlap the highstand clinoforms. The lowstand fan deposits are characterized by a uniform, aggradational ("blocky") to fining-upward log character, which consists of relatively thick (15–75 m) sandstones encased in basinal and slope mudstone. Biostratigraphic and paleobathymetric analysis of these sandstones by Exxon Company, U.S.A. (unpub. reports) indicates a mixture of shallow- and deep-water benthic foraminifera. Lowstand fans are present in the Exxon 500-1, HOM 855-1, Gulf 857-1, Exxon 902-1, COST B-2, and Exxon 684-1 wells (Figs. 2, 3, and 4). The fans are expressed on the seismic data as one or two mostly parallel seismic cycles that onlap the underlying clinoforms. Seismic mounding and internal bidirectional downlap, as described by Mitchum (1985), are present locally (see fan on Yellow-1 sequence boundary, Fig. 4). The coarse spacing of the seismic grid did not permit

---

[1] The offlap break refers to the break in slope between the relatively flat topset beds and more steeply dipping foreset beds of the actively prograding depositional systems. The long-term, structurally controlled shelf-slope break, a remnant of the Late Jurassic reef margin, was located farther seaward during most of the Tertiary. In the Neogene of the New Jersey shelf, the offlap break is the depositional shoreline break of Posamentier and Vail (1988).

mapping of individual feeder canyons or fan lobes.

Lowstand Systems Tract—Lowstand Wedge

In the wells examined, prograding lowstand wedge strata are composed mostly of fine-grained rocks, with sandstone only locally present at the tops of the progradational wedges. In contrast to the uniform lithologic character of the lowstand fans, the lowstand wedge sandstone exhibits serrated log signatures that display overall coarsening-upward patterns (for example the HOM 855-1; Fig. 2). Such a coarsening-upward parasequence stacking is interpreted to represent shallowing-upward lithofacies (Van Wagonner and others, 1990). This distribution of lithofacies is consistent with the idealized sequence stratigraphic model of Vail (1987) and Posamentier and others (1988). In this model, coarse sand is found only in areas proximal to feeder canyons and within updip incised valleys. None of the wells in this study penetrated a wedge in such an updip position to document this coarse-grained valley fill; however, erosional valleys have been recognized on seismic lines in areas landward of the depositional shelf edge (Greenlee and others, 1988, their Fig. 2).

Transgressive Systems Tract

We have not recognized deposits typical of the transgressive systems tract on either seismic or well data. In most cases, the sandstone of the highstand systems tract is directly overlain by mudstone. The mudstone is either the downdip stratigraphic equivalent of landward-stepping shoreline deposits, representing a condensed transgressive systems tract deposit, or the toes of the overlying prograding highstands. Upward-deepening sets of parasequences common to transgressive systems tracts (Van Wagonner and others, 1990) are typically not present in this section.

Highstand Systems Tract

Neogene highstand systems tracts from the offshore New Jersey section consist of thick, prograding wedges that coarsen upward from slope mudstone into homogeneous sandstone. The sandstone is interpreted as a delta-plain and delta-front deposit. The thickness of the sandstone exceeds 150 m in the depocenters of the individual delta lobes, such as in the sequence beneath the Pink-2 surface in the Exxon 500-1 well in Figure 2, or the sequence beneath the Yellow-2 surface in the Cost B-2 well (Figs. 3 and 4). The highstand sandstone thins both along strike and downdip away from the depocenters. Significant truncation of some highstand sandstone by the overlying sequence boundaries is indicated on the seismic sections, suggesting that the sandstone may be a major source of re-worked coarse-grained sediment for the lowstand fans.

COMPARISON WITH THE EXXON SEQUENCE STRATIGRAPHIC MODEL

The geometric and lithostratigraphic expression of Neogene depositional sequences of the New Jersey middle shelf and upper slope is different from the idealized sequence stratigraphic models of Vail (1987) and Posamentier and others (1988) (Fig. 5). The general geometry, parasequence stacking, and lithofacies distribution within systems tracts of the idealized model and the offshore New Jersey sequences are similar. Both the model and the data exhibit (1) stratal surfaces that subdivide individual systems tracts (for example, sequence boundaries and downlap surfaces); (2) sand-prone basin-floor fans; (3) onlapping, mud-prone lowstand wedge deposits; and (4) thick, regressive highstand systems tracts. The major differences between the two models are that (1) leveed channel deposits have not been recognized within the lowstand wedge in our study area; (2) thick, transgressive deposits are not present in our data as they are in the idealized model; (3) highstand systems tracts are more sand-rich and regressive in the New Jersey data; and (4) all of the sequences that were recognized from offshore New Jersey have either submarine fans and/or extensive erosion of the shelf, indicative of type-1 unconformities (that is, no type-2 unconformities are recognized).

The differences between the idealized model and the Neogene sequences arise from the very small amount of additional space made available for sediment deposition (accommodation) created on the New Jersey margin during the Tertiary epoch. This is in contrast to the relatively higher accommodation that is assumed in the generation of the Vail (1987) and Posamentier and others (1988) models. Accommodation is a function of subsidence, eustasy, and sediment supply (Jervey and Posamentier, 1988). The low accommodation in the offshore New Jersey area was due to slow subsidence on a mature passive margin (Steckler and Watts, 1976), during a slow Neogene second-order eustatic fall (Haq and others, 1987). Both of these factors reduce the potential space available for sediments to accumulate, especially on continental shelves. Low accommodation potential results in limited aggradation of shelf strata, and pronounced progradation of highstand shelf margins (Schroeder and Greenlee, 1989). The relatively thick Neogene section is a result of these deltaic sediments prograding into water of several hundred meters depth and not from thermal subsidence of the margin. In addition, low subsidence-related accommodation on a margin is likely to lead to a type-1 sequence boundary formation during short-term eustatic falls, because of the low rates of subsidence at the highstand offlap break relative to the rate of eustatic fall. Low subsidence rates at the highstand offlap break means that only moderate rates of eustatic fall are needed to drop sea level below the offlap break and cause widespread subaerial exposure of the shelf, which is a type-1 sequence boundary. Transgressive systems tracts may be poorly represented in the offshore New Jersey Neogene section because of the paleogeographic setting of our seismic and well data. Transgressive sandstone may be landward of our study area. Alternatively, the lack of a well-developed transgressive systems tract may be related to the low subsidence rates and long-term sea-level fall.

BIOSTRATIGRAPHY OF NEOGENE DEPOSITIONAL SEQUENCES

We have biostratigraphically estimated the ages of the Neogene sequence boundaries on the New Jersey shelf and slope. Ages were previously assigned to these sequences (Greenlee and others, 1988; Greenlee and Moore, 1988) by bracketing the ages using published and Exxon U.S.A. biostratigraphy (Fig. 3 in Greenlee and Moore, 1988) and then by correlation to the global cycles depicted on the chart of Haq and others (1987). We re-evaluted these age determinations because (1) two additional Miocene sequences were recognized and correlated through the grid (Pink-2, Yellow-2), (2) additional biostratigraphic data and range information of certain key foraminifera have become available (Table 1 caption), and (3) we needed to evaluate the potential of this region for biostratigraphic correlations for future drilling by Ocean Drilling Program Leg 150 (May–July, 1993).

Precise age estimates with greater than 1–2 m.y. resolution are not possible with the existing data for several reasons. First, many industry wells were only sampled below the Neogene because hydrocarbon targets were located in the Mesozoic section. Second, many of the diagnostic species are found in deep-water mudstone where the sequences thin by distal starvation and erosion; the surfaces are difficult to place precisely and the ranges of these taxa may be environmentally restricted (Loutit and others,

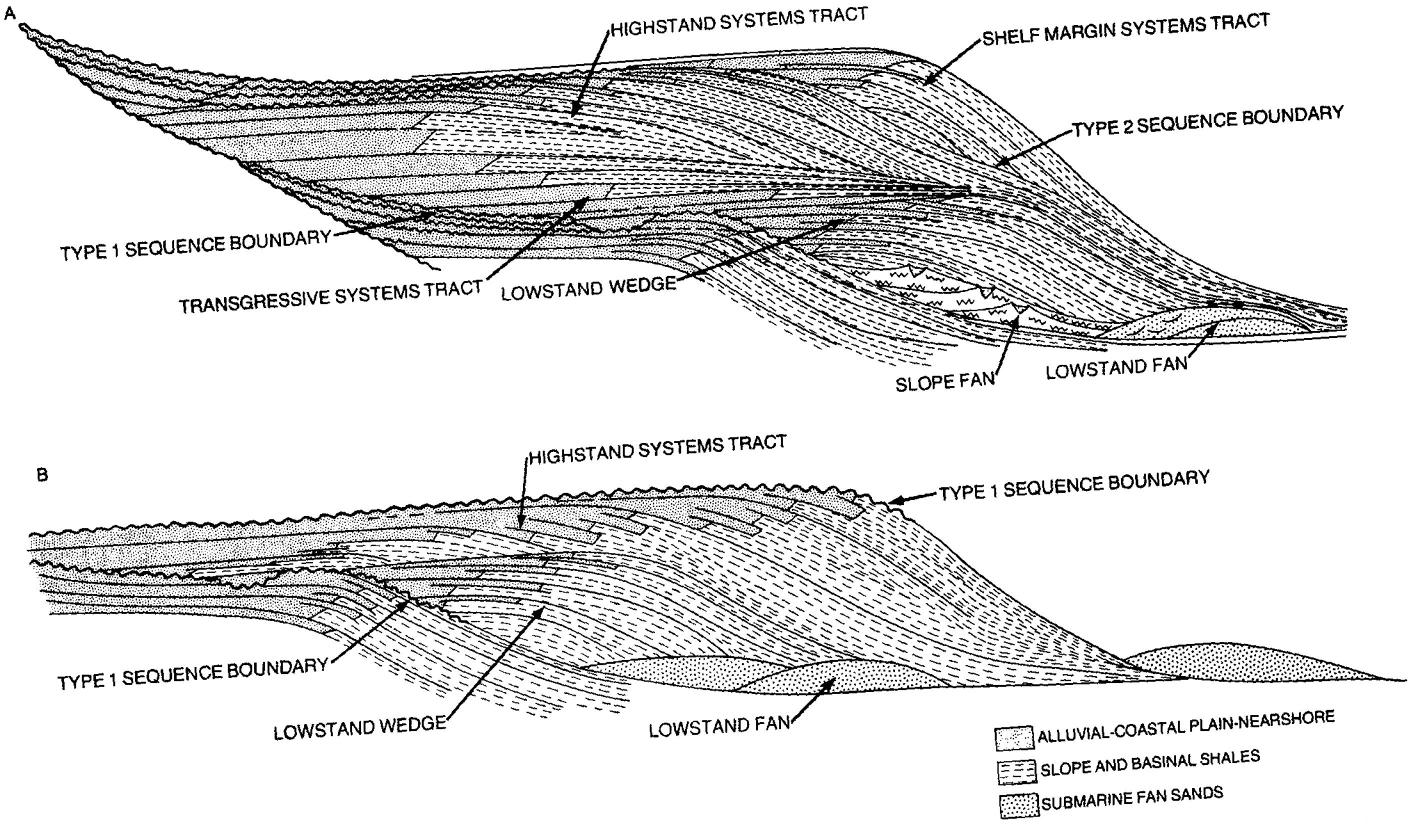

Figure 5. Comparison of the sequence stratigraphic model for siliciclastic lithofacies of Vail and others (1987) (top) with the observed sequence architecture and lithofacies from the offshore New Jersey Neogene (bottom). Significant differences observed in the Neogene section from the Vail and others (1987) model include (1) the lack of recognizable leveed channel deposits within lowstand wedges in the Neogene strata, (2) the lack of a thick transgressive systems tract, (3) more sandstone-rich and better-developed highstand systems tracts, and (4) no type-2 sequence. See text for discussion.

1988). Third, the data are primarily from cutting samples. Interpretation of cutting samples is complicated by downhole caving and reworking, and reworking is not usually recognizable. Only stratigraphic last occurrences (LO or "tops") can be obtained for biostratigraphic correlations using these data.

The last occurrences of key foraminiferal taxa derived from five wells on the shelf and slope are compared with the major sequences delineated here and the ages obtained by previous correlation with the Haq and others (1987) global cycle chart (Table 1). The ages of most[2] biostratigraphic last occurrences were estimated using the Berggren and others (1985) time scale (Table 1, Fig. 6).[3] The age estimates for the seismic sequence boundaries were based on the interpolation or extrapolation of sedimentation rates between the biostratigraphic last occurrences (Fig. 6). Sedimentation rates may have varied dramatically in any given interval; however, resulting age differences are relatively minor because of the short time intervals (generally 1–2 m.y.) between interpolation points, although there are several important exceptions (for example, Blue at COST B-2; see below). Nevertheless, our age estimates are coarse (±1.0 m.y. in the best cases) because of problems with cutting samples, varying taxonomic concepts, environmental restriction of marker taxa, and uncertainties in well-seismic correlations. This is illustrated by the occurrences of biostratigraphic markers above, below, and coincident with seismic sequence boundaries (Table 1, Fig. 6).

The age of the youngest interpreted sequence boundary, Pink-1, is uncertain; it may be either late Miocene or Pliocene. At COST B-2, Pink-1 is within the range of *Globorotalia plesiotumida* (N17, upper Miocene). At Exxon 902-1, this sequence boundary lies 80 ft (24 m) above the LO of *Sphaeroidinella semulina* (N21, ~3 Ma), whereas at Shell 273-1, it is 1,010 ft (307 m) above the LO of *G. margaritae* (3.4 Ma) (Table 1). A reliable age determination for the underlying Yellow-1 and Red sequence boundaries was not possible (Table 1). These uncertainties underscore problems in upper Neogene biostratigraphic correlations in this region.

More biostratigraphic information is available to estimate the ages of middle Miocene sequence boundaries than those of the overlying upper Miocene-Pliocene. The Tuscan surface is asso-

---

[2] The ages of a few biostratigraphic last occurrences that were not considered by Berggren and others (1985) were estimated using the biostratigraphy (Miller and others, 1985) and revised magnetostratigraphy (Miller and others, 1991) of site 563.

[3] The Berggren and others (1985) time scale differs from the Haq and others (1987) time scale, particularly near the middle/late Miocene boundary (Gradstein and others, 1988). We use the former because of its tabulation of magnetobiostratigraphic calibrations, which are used here.

TABLE 1. MIOCENE BIOSTRATIGRAPHY AND AGE ESTIMATES FOR FIVE WELLS, NEW JERSEY CONTINENTAL SHELF AND SLOPE

Sequence Boundaries & Ages		COST B-2 298' (91 m) 98' kb	SHELL 273-1 292' (89 m) 84' kb	EXXON 684-1 399' (122m) 38' kb	EXXON 902-1 433' (132 m) 72' kb	COST B-3 2686' (819 m) 42' kb	Interpreted Age	
PINK-1	"5.5"	*Gt. plesiotumida* 810^1 *B. elongata* 880^4 1345	1210	*B. elongata* 1964^4 2365	*B. elongata* 2810^4 2910	N.D.	?3 Ma ? 9-3 Ma	Pliocene?
YELLOW-1	"6.3"	ONLAPPED OUT N.D.	1660	N.D.	*S. seminulina* 2990^4 (N21; ~3 Ma) 3110	N.D.	?	
RED-1	"8.2"	ONLAPPED OUT N.D.	*Gt. margaritae* 2220^4 (3.4 Ma) *B. elongata* 2220^4 2430	N.D.	N.D.	N.D.	?	upper Miocene
TUSCAN	"10.5"	1500	*Gt. mayeri* 2640^4 (10.4 Ma) 2860	2810	3475	Reflector M1 of Miller et al, 1987 ~3700?	10 Ma ~11-9 Ma	
YELLOW -2	"DLS"	*Gt. mayeri* 1510^1 (10.4 Ma) 2000	*Gt. fohsi lobata* 3030^4 (11.6 Ma) 3050	*Gt. mayeri* 2940^4 (10.4 Ma) 3230	*Gt. mayeri* 3590 (10.4 Ma) *Gt. fohsi robusta* 3650^5 (11.5 Ma) 3800	*Gt. fohsi lobata* 3800^6 (11.6 Ma) *Gt. mayeri* 3800^{4,7} *Gt. fohsi fohsi* 3990^4 (~12.3 Ma) ~4100	11.7 Ma 12.2-11.2 Ma	
BLUE	"12.5"	*Gt. fohsi fohsi* 2800^3 (~12.3 Ma) *Gt. peripheroronda* 2860^1 (~N10; 14.6 Ma?) 3270	*Gt. fohsi fohsi* 3120^4 (~12.3 Ma) 3260	3610	4030	4335	13.5 Ma (?16) 14.9-12.8 Ma	middle Miocene
PINK-2/RED-2	"13.8"	N.D.	*Gt. peripheroronda* 3420^4 (~14.6 Ma?) 3470?	3610	4170	*G'lla insueta* 4430^6 (~15 Ma) 4480	14.5 Ma 15.3-13.5 Ma	
GREEN	"15.5"	3535	3950	*Gt. peripheroronda* 3630^4 (~14.5 Ma?) 3650	*G'lla insueta* 4250^4 (~lower N9; ~15 Ma) 4270	*C. unicavus* 4490^6 (17.6 Ma) 4650	16 Ma? ~19-14.8 Ma	
		C. stainforthi 3580^4 (~mid N7; ~17 Ma) *Gt. kugleri* 3610^{1,2} (21.7 Ma) *P. opima opima* 3850^5 (28.2 Ma)	*G. ciperoensis* 3990^4 (~23 Ma) *P. opima opima* 4230^4 (28.2 Ma)	*P. opima* cf. *opima* 3690^4 (?28.2 Ma)	*Gt. peripheroronda* 4406^4 (~14.6 Ma) (premature LO ?) *P. opima opima* 4422^4 (28.2 Ma)	*Gt. kugeri* 4670^6 (21.7 Ma) *P. opima opima* 4760^8 (28.2 Ma)		? up. Ol.- lo. Mio. ?

Note: see Figure 1 for well locations. All depths are in feet below kelly bushing (kb); water depths are given below each well designation. The depths to sequence boundaries, indicated above each surface, were derived from seismic–well-log ties using synthetic seismograms and velocity surveys, except for the Tuscan sequence boundary at COST B-3, which is after Miller and others (1987). All biostratigraphic events are last occurrences ("tops"). N.D. = not discerned. Sequence boundary ages shown in quotes (for example, "5.5") are ages from Greenlee and others (1988) and Greenlee and Moore (1988). Biostratigraphic data from (1) R. K. Olsson (1990, personal commun.), (2) Poag (1977), (3) W. Poag (1990, personal commun.), (4) Exxon Company U.S.A. paleontological data published in Greenlee and Moore (1988), (5) Olsson and others (1980), (6) Melillo (1985), (7) Poag (1980), and (8) Miller and others (1990, personal commun.).

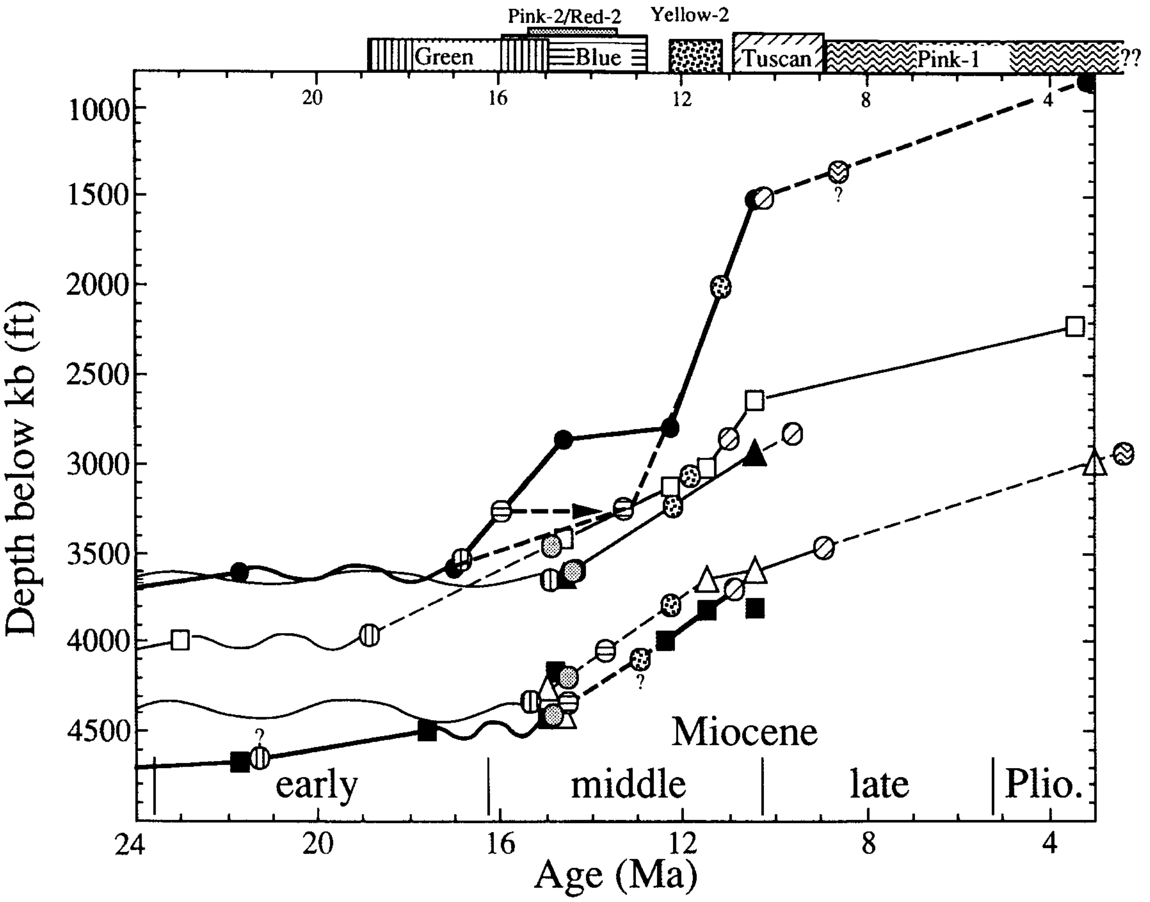

Figure 6. Age-depth diagram for five wells, New Jersey continental shelf and slope. Wavy lines represent hiatuses. The age-depth lines were constructed using the depths and ages of planktonic foraminiferal LO shown in Table 1; the depths of the seismic reflectors corresponding to the six sequence boundaries were plotted in these lines, and the ages of the sequences were estimated. These age estimates are presented on the top margin. The anomalously old age estimate for Blue at COST B-2 may be explained by the extrapolation of sedimentation rates (dashed line), which is consistent with the section in the depocenter of the Blue–Yellow-2 sequence.

ciated with the LO of *Paragloborotalia mayeri* (10.4 Ma). Age estimates based on interpolations of sedimentation rates range from 9 to 11 Ma (Fig. 6). The presence of this taxon above Tuscan at Shell 273-1 suggests that the surface is older than 10.4 Ma, consistent with the Greenlee and others (1988) correlation of Tuscan with the 10.5 Ma sequence boundary of Haq and others (1987); however, this age estimate assumes no uncertainty in the seismic-well correlation at Shell 273-1 and no stratigraphic reworking. Because of these and other uncertainties listed above, we have made a conservative age assignment of Tuscan to 11–9 Ma (Table 1).

We identified a sequence boundary, Yellow-2, below Tuscan, which had not been previously correlated throughout the area. At COST B-2, the Yellow-2 sequence boundary is 800 ft above the LO of *Globorotalia fohsi fohsi* (Table 1); here it has an age estimate of 11.2 Ma based on interpolation of sedimentation rates (Fig. 6). At Shell 273-1, Yellow-2 lies between the LO of *G. fohsi lobata* (11.5 Ma) and *G. fohsi fohsi* (12.3 Ma) with an age estimate of 11.8 Ma (Fig. 6). At Exxon 684-1, Yellow-2 has an age estimate of 12.2 Ma based on a long interpolation from the LO of *P. mayeri* (10.4 Ma) to the LO of *G. perifereroronda* (14.6 Ma). The same age estimate (12.2) is obtained at the Exxon 902-1 based on a similar long interpolation (Fig. 6). The age estimate at COST B-3 is slightly older (13.0 Ma); however, the seismic correlation to this is ambiguous as these sequences thin into this well. Based on the firm correlations at the other four wells, we estimate the age of Yellow-2 as 12.2–11.2 Ma (Table 1, Fig. 6).

Biostratigraphy indicates that the Blue sequence boundary is middle Miocene in age (Table 1, Fig. 6). Blue clearly predates the LO of *G. fohsi fohsi* (~12.3 Ma) at COST B-2, Shell 273-1, and COST B-3. At Exxon 684 and Shell 273-1, the Blue sequence boundary clearly postdates the LO of *G. peripheroronda* (~14.6 Ma). The last occurrences of *G. fohsi fohsi* and *G. periferoronda* are not well calibrated to the Neogene time scale (their ages were not provided by Berggren and others [1985]; they were obtained from correlations at site 563), and additional studies are needed to verify the global ranges. At COST B-2, Blue appears to underlie the LO of *G. periferoronda* and has a much older estimated age than at the other wells (16 Ma compared with 12.8–14.9 Ma; Fig. 6). This suggests that the LO of *G. periferoronda* is either reworked or misidentified at this well and illustrates a potential hazard in dating sequence boundaries based on sedimentation rate interpolation. The section between Blue and Yellow-2 at COST B-2 is within the depocenter of this sequence and includes thick lowstand fan and progradational deltaic deposits of the lowstand wedge and highstand systems tracts (Figs. 3 and 4). This interval, as would be expected, had high sedimentation rates between the LO of *P. mayeri* and LO of *G. fohsi fohsi* (Fig. 6). Extrapolation of these sedimentation rates downward yields a consistent age estimate for Blue (dashed line, Fig. 6), but interpolations using the LO of *G. peripheroronda* yield an anomalously old age.

The Pink-2 and Red-2 sequences are recognized on seismic and well-log data; however, the sequence boundaries merge updip of the wells with biostratigraphic control (Fig. 2). Only the rocks between Red-2 and Green are preserved downdip. The Pink-2/Red-2 sequence boundary is closely associated with the LO of *Globigerinatella insueta* (lower Zone N9, ~15 Ma) at Exxon 902-1 and COST B-3. A younger age estimate of Red-2 is derived from the broad interpolation at Exxon 684. The interpreted age of the Pink-2/Red-2 sequence boundary (13.5–15.3 Ma; Table 1, Fig. 6) is reasonable, but may be in error by at least 1 m.y.

The age of the Green sequence boundary is difficult to estimate using the available biostratigraphic data. This unconformity is associated with distinct early middle Miocene hiatuses at Exxon 684 and Exxon 902-1 (Table 1). Age estimates of 15.3 to 15.0 Ma were obtained for the Green surface at these wells (Fig. 6) but should be considered minimum ages because of the hiatuses. The Green sequence boundary is 45 ft (14 m) above the LO of *Catapsydrax stainforthi* (~N7, 17 Ma) at COST B-2, providing the least equivocal age of 16 Ma. Age estimates on Green are unreliable at Shell 273-1, where the sequence boundary is 530 ft (161 m) below the LO of *G. peripheroronda*, with an age estimate older than 18 Ma. This anomalously old age reflects the extrapolation of sedimentation rates needed to estimate the age of this surface (Fig. 6). At COST B-3, this surface has been correlated with the sections older than the LO of *Catapsydrax unicavus* (17.6 Ma), although this was based on one specimen that could have been reworked.

This biostratigraphic analysis documents six middle Miocene sequence boundaries between 10 and 16 Ma on the shelf and upper slope of New Jersey (the Tuscan to Green surfaces; Table 1). Biostratigraphic resolution is too coarse at present to correlate these sequences unambiguously with other basins, with the global coastal onlap chart (Haq and others, 1987) or with other proxy records for sea-level change (for example, Miller and others, 1991). Within a 1 m.y. range of age uncertainty, our biostratigraphic age estimates are consistent with the correlation of Tuscan, Yellow-2, Blue, Red-2, and Green with the 10.5, 12.5, 13.8, 15.5, and 16.5 Ma sequences of the Haq and others (1987) chart (making Pink-2 an additional sequence not recognized on the global chart). It would be equally plausible to correlate the Blue with the 14.5, and to change the correlation of those below accordingly. Although the exact correlation of several of the individual events is ambiguous, the frequency of sequence boundaries (six middle Miocene sequence boundaries between approximately 10 and 16 Ma) suggests that they are in response to third-order sea-level changes at a frequency of approximately 1 m.y. This periodicity compares well with that represented on the global cycle chart of Haq and others (1987) and the oxygen isotopic record (Miller and others, 1991). Further biostratigraphic calibration from more-carefully sampled wells within the physical stratigraphic framework provided by the seismic and well-log data could make this area an ideal reference for future studies of global sea-level change.

CONCLUSIONS

The Neogene stratigraphy beneath the continental shelf off New Jersey provides an ideal section for comparison with seismic and sequence stratigraphic models. Seismic and sequence stratigraphic techniques used in this study demonstrate a predictable relationship between seismic geometry and the location of lithofacies within a depositional sequence. Thick sandstone beds are present in both highstand and lowstand systems tracts. In the former, they are at the topset and toplapping parts of progradational clinoforms; in the latter, they are at the toe of the clinoform slope immediately above the underlying sequence boundaries. Whereas thinner sandstone than that of the highstands is present in the topset beds of progradational lowstand wedges, we predict that thicker sandstone than that shown on our cross sections should be present near the point sources of the prograding wedges. These observations provide criteria that could be useful in the predrill prediction of reservoir and seal facies for oil and gas exploration in similar, highly progradational, depositional settings.

The distribution of lithofacies in the Neogene sequences is significantly different from that represented in the conceptual block diagrams depicted in the Exxon model (Vail, 1987; Posamentier and Vail, 1988; Van Wagonner and others, 1991). The sequence stratigraphic model described in this paper may be regarded as an end-member example of the most progradational, accommodation-limited case. This is in contrast to the aggradational, higher-accommodation case illustrated by Van Wagonner and others (1990). In particular, the thickest and highest-quality reservoir sandstone beds in the Miocene sequences presented here occur in the highstand systems tracts. This contrasts with the cross sections illustrated in Van Wagonner and others (1990; their Figs. 22, 26, 31, and 33) where the thickest sandstone on the shelf lies within the incised valley-fill deposits of the lowstand systems tract. The model presented here is closer to that of the diagrams illustrated in Posamentier and Vail (1988), which depicted somewhat thinner sandstone bodies within the highstand systems tract but also showed a sand-prone transgressive systems tract overlying the sequence boundary. All of the sequence representations predict thick sandstone in the lowstand fan and similar parasequence stacking patterns within the systems tracts.

This difference in the accommodation potential of a basin has important implications for the prediction of hydrocarbon reservoirs and seals. In the low-accommodation setting, such as that of the Neogene of the New Jersey shelf, highstand sandstone overlain by transgressive or highstand mudstone on structure would provide the optimal trap configuration. Hydrocarbons within incised valley deposits in this setting would leak into the surrounding sandstone-rich highstand strata. In a high-accommodation setting, such as those depicted in the sections of Van Wagonner and others (1990), fine-grained sedimentary rocks of the highstand systems tract would provide an excellent lateral seal for the sandstones within incised valleys.

More biostratigraphic data are needed to refine the age model for the offshore New Jersey section and establish a reliable chronostratigraphic framework. In addition to a better chronostratigraphic framework, more detailed biostratigraphy should enable better correlations into wells where the sequences are condensed. Because of the well-developed geometric and lithostratigraphic criteria for sequence recognition in this area, enhanced biostratigraphic resolution would provide a meaningful comparison of sequence timing to the global eustatic cycle chart and isotopic records.

ACKNOWLEDGMENTS

This paper resulted from a joint Exxon Production Research Company/Rutgers/Lamont-Doherty Geological Observatory (L-DGO) workshop held in March 1990 in New Brunswick, New Jersey. Our primary objectives were to evaluate existing industry seismic and well data and to plan the acquisition of high-resolution seismic data. In addition to the authors, other participants included N. Christie-Blick and M. Steckler of L-DGO and R. Sheridan of Rutgers University. We thank R. K. Olsson and C. W. Poag for providing unpublished biostratigraphic data from the COST-B2 well. We are especially grateful to Exxon Company, U.S.A., for the release of seismic, well, and biostratigraphic data. Reviews by W. Poag, B. Haq, and W. Berggren significantly improved the manuscript. Discussion with P. McLaughlin and L. de Verteuil improved the manuscript. This work was partially supported by National Science Foundation Grant OCE89-11810 (Mountain, Miller, Christie-Blick).

REFERENCES CITED

Berggren, W. B., Kent, D. V., Flynn, J. T., and Van Couvering, J. A., 1985, Cenozoic geochronology: Geological Society of America Bulletin, v. 96, p. 1407–1418.

Gradstein, F. M., and 12 others, 1988, Sea level history, technical comment: Science, v. 241, p. 599–601.

Greenlee, S. M., and Moore, T. D., 1988, Recognition and interpretation of depositional sequences and calculation of sea level changes from stratigraphic data—Offshore New Jersey and Alabama Tertiary, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G., Posamentier, H. W., Ross, C. A., and Van Wagonner, J. C., eds., Sea level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication No. 42, p. 329–353.

Greenlee, S. M., Schroeder, F. W., and Vail, P. R., 1988, Seismic stratigraphic and geohistory analysis of Tertiary strata from the continental shelf off New Jersey; Calculation of eustatic fluctuations from stratigraphic data, *in* Sheridan, R. E., and Grow, J. A., eds., The geology of North America, Volume I-2: The Atlanic continental margin: U.S. Boulder, Colorado, Geological Society of America, p. 437–444.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, The chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Jervey, M. T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expressions, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G., Posamentier, H. W., Ross, C. A., and Van Wagonner, J. C., eds., Sea level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication No. 42, p. 47–69.

Loutit, T. S., Hardenbol, J., Vail, P. R., and Baum, G. R., 1988, Condensed sections: The key to age determinations and correlation of continental margin sequences, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G., Posamentier, H. W., Ross, C. A., and Van Wagonner, J. C., eds., Sea level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication No. 42, p. 183–213.

Miller, K. G., Melillo, A. J., Mountain, G. S., and Farre, J. A., 1987, Middle to late Miocene canyon cutting on the New Jersey continental slope: Biostratigraphic and seismic stratigraphic evidence: Geology, v. 15, p. 509–512.

Miller, K. G., Wright, J. D., and Fairbanks, R. G., 1991, Unlocking the ice house: Oligocene-Miocene oxygen isotopes, eustasy, and margin erosion: Journal of Geophysical Research, v. 96, p. 6829–6848.

Mitchum, R. M., 1985, Seismic stratigraphic expression of submarine fans, *in* Berg, O. R., and Woolverton, D. G., eds., Seismic stratigraphy II—An integrated approach: American Association of Petroleum Geologists Memoir 39, p. 117–136.

Olsson, R. K., Miller, K. G., and Ungrady, T. E., 1980, Late Oligocene transgression of middle Atlantic coastal plain: Geology, v. 8, p. 549–554.

Poag, C. W., 1980, Foraminiferal stratigraphy, paleoenvironments, and depositional cycles in the outer Baltimore Canyon Trough, *in* Scholle, P. A., ed., Geological studies of the COST No. B-3 well, United States Mid-Atlantic continental slope area: U.S. Geological Survey Circular 833, p. 44–65.

Poag, C. W., 1985, Cenozoic and Upper Cretaceous sedimentary facies and depositional systems of the New Jersey slope and rise, *in* Poag, C. W., ed., Geological evolution of the United States Atlantic Margin: New York, Van Nostrand and Reinhold, p. 217–264.

Posamentier, H. W., and Vail, P. R., 1988, Eustatic controls on clastic deposition II—Sequence and systems tract models, *in* Wilgus, C. K., Hastings, B. S., Kendall, C. G., Posamentier, H. W., Ross, C. A., and Van Wagonner, J. C., eds., Sea level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication No. 42, p. 125–154.

Schlee, J. S., 1981, Seismic stratigraphy of Baltimore Canyon Trough: American Association of Petroleum Geologists Bulletin, v. 65, p. 26–53.

Schroeder, F. W., and Greenlee, S. M., 1989, Modeling the effects of subsidence and eustatic changes on depositional sequences—An example from the Baltimore Canyon, offshore New Jersey, *in* Franseen, E. K., and Watney, W. L., eds., Sedimentary modeling: Computer simulation of depositional sequences, Kansas geology series no. 12: Lawrence, Kansas, Kansas Geological Survey, p. 25–26.

Steckler, M. S., and Watts, A. B., 1978, Subsidence of the Atlantic-type continental margin off New York: Earth and Planetary Science Letters, v. 42, p. 1–13.

Van Wagonner, J. C., Mitchum, R. M., Campion, K. M., and Rahmanian, V. D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Studies in Geology No. 27, p. 1–10.

MANUSCRIPT RECEIVED BY THE SOCIETY MAY 31, 1991
REVISED MANUSCRIPT RECEIVED MARCH 3, 1992
MANUSCRIPT ACCEPTED MARCH 6, 1992
LAMONT-DOHERTY GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 4961.

Printed in U.S.A.