Long-term and short-term global Cenozoic sea-level estimates

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ABSTRACT

Backstripping analysis of three continuously cored, well-dated boreholes from the New Jersey Coastal Plain (Ocean Drilling Program [ODP] Leg 150X) indicates a long-term (10^8–10^7 yr) eustatic fall of ≈100 m since 55 Ma (early Eocene) and suggests short-term (0.5–3 m.y.) eustatic falls of less than ≈70 m. Eustatic estimates are calculated from residuals between the decompacted, unloaded, and paleodepth-corrected records and tectonic subsidence (assuming a cooling lithospheric plate). Because the residuals are similar among the three sites, we interpret them as an approximation of the eustatic signal.

INTRODUCTION

A key goal of the geologic community has been to evaluate the timing and amplitude of eustatic (global sea-level) change. Recent efforts on the New Jersey margin (ODP Legs 150 and 150X; Mountain et al., 1996; Miller and Snyder, 1997) have provided the timing of short-term sea-level changes over the past 55 m.y. (Miller et al., 1996; Browning et al., 1996). These studies have demonstrated a correlation among sequence boundaries, rapid glacioeustatic falls inferred from $\delta^{18}O$ records, and sea-level falls of Haq et al. (1987).

Studies of the New Jersey margin have not fully addressed the amplitude of sea-level changes. Relative water depth provides a proxy for sea-level change, but variable sedimentation rates and tectonics interfere with the eustatic signal (e.g., Steckler et al., 1988). Oxygen isotopes can be taken as a proxy for glacioeustatic change but are limited by their dependence on temperature and salinity and a lack of response to eustatic changes of non-glacial origin (e.g., Miller et al., 1991). This manuscript presents estimates of the amplitude of sea-level change using detailed data from the onshore New Jersey margin borehole sites, ODP Leg 150X, in a one-dimensional backstripping study.

DATA

Three Leg 150X boreholes drilled at Island Beach, Atlantic City, and Cape May penetrated upper Cretaceous, middle Eocene, and upper Eocene strata, respectively (Miller and Snyder, 1997; Fig. 1). Uppermost Miocene and younger strata are absent except for a thin Holocene cover.

Initial lithologic descriptions (Miller and Snyder, 1997) were supplemented by the relative percentages of the quartz sand, silt-clay, glauconite, and carbonate components. Unconformities (sequence boundaries) were indicated by erosional surfaces, gamma ray peaks, lithologic breaks, biofacies shifts, shell beds, indurated zones, and hiatuses determined by Sr isotopic stratigraphy and biostratigraphy (Miller and Snyder, 1997). Lowstand systems tracts (LST) are generally absent and sequences represent stacked transgressive (TST) and highstand (HST) systems tracts. Paleodepths were interpreted using benthic foraminiferal biofacies and sedimentary facies analyses (Miller and Snyder, 1997). Paleodepth ranges were obtained by allowing an uncertainty of –30% to +50% of best estimates (Table A).[1]

Sequences are tied to the Berggren et al. (1995) time scales using integrated magnetostratigraphy, Sr isotopic stratigraphy, and biostratigraphy (Miller and Snyder, 1997). Ages were assigned to the top and base of each sequence, and the ages of intermediate points were obtained via linear interpolation of decompacted sediment thicknesses (Table A1).[1] Although sedimentation rates were no doubt variable, a more detailed estimate of within sequence ages is beyond the accuracy of our age control (Miller and Snyder, 1997).

Backstripping requires stratigraphic information to the basement to account for accommodation due to compaction and to evaluate the amplitude of long-term eustatic change. Generalized Cretaceous lithologies and environments for the section beneath the Island Beach borehole were taken from the nearby Island Beach rotary borehole (Volkert et al., 1996). Direct evidence for the pre-middle Eocene section at Atlantic City is lacking. Cretaceous stratigraphy is assumed to be equivalent to that of the Island Beach rotary borehole with thicknesses scaled to that at the Atlantic City site. Stratigraphy beneath the Cape May site is based on the Anchor-Dickinson I well (Fig. 1; Olsson et al., 1988).

BACKSTRIPPING METHOD AND ASSUMPTIONS

The backstripping method used is one dimensional and assumes an Airy isostatic response to loads (Bond et al., 1989). Thus, the actual amplitude of tectonic and R1 subsidence ($TS = R1 - \Delta SL[\rho_a/(\rho_a - \rho_w)]$; $R1 = S^*[\rho_a - \rho_s^*]/[\rho_a - \rho_w] + WD$; where TS = tectonic subsidence, ΔSL = eustasy, $R1$ = accommodation, S^* = decompacted sediment thickness, WD = paleodepth, ρ = density, a = asthenosphere, and w = water) is generally incorrect, although the form of subsidence is accurate (e.g., Bond and Kominz, 1984).

Decompacted sediment thickness is calculated using low end-member porosity-depth curves. Fitting the data independently to thermal subsidence curves minimizes the impact of using low rather than high porosity-depth curves on interpretation of R2 (second reduction; $R2 = [R1 - TS][(\rho_a - \rho_w)/\rho_a]$, Bond et al., 1989). Porosities from the COST-B2 well were used for sandstone and shale (Rhodehamel, 1977). Glauconite is assumed to compact like sandstone. Carbonates and siltstones are decompacted using the generalized curves of Bond and Kominz (1984). Four R1 curves are calculated for each borehole: no paleodepth corrections, best-estimate, minimum, and maximum paleodepth estimates (Fig. 1).

R2 curves are estimates of eustasy if the input data, tectonic subsidence assumptions, and backstripping assumptions are correct. Because most or all of the subsidence observed on the coastal plain is due to loading by sediment offshore (Steckler et al., 1988), the form of subsidence is

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[1]GSA Data Repository item 9834 (input data used in backstripping analysis, New Jersey Coastal Plain Boreholes, ODP Leg 150X) is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Data Repository item 9834 contains additional material related to this article.

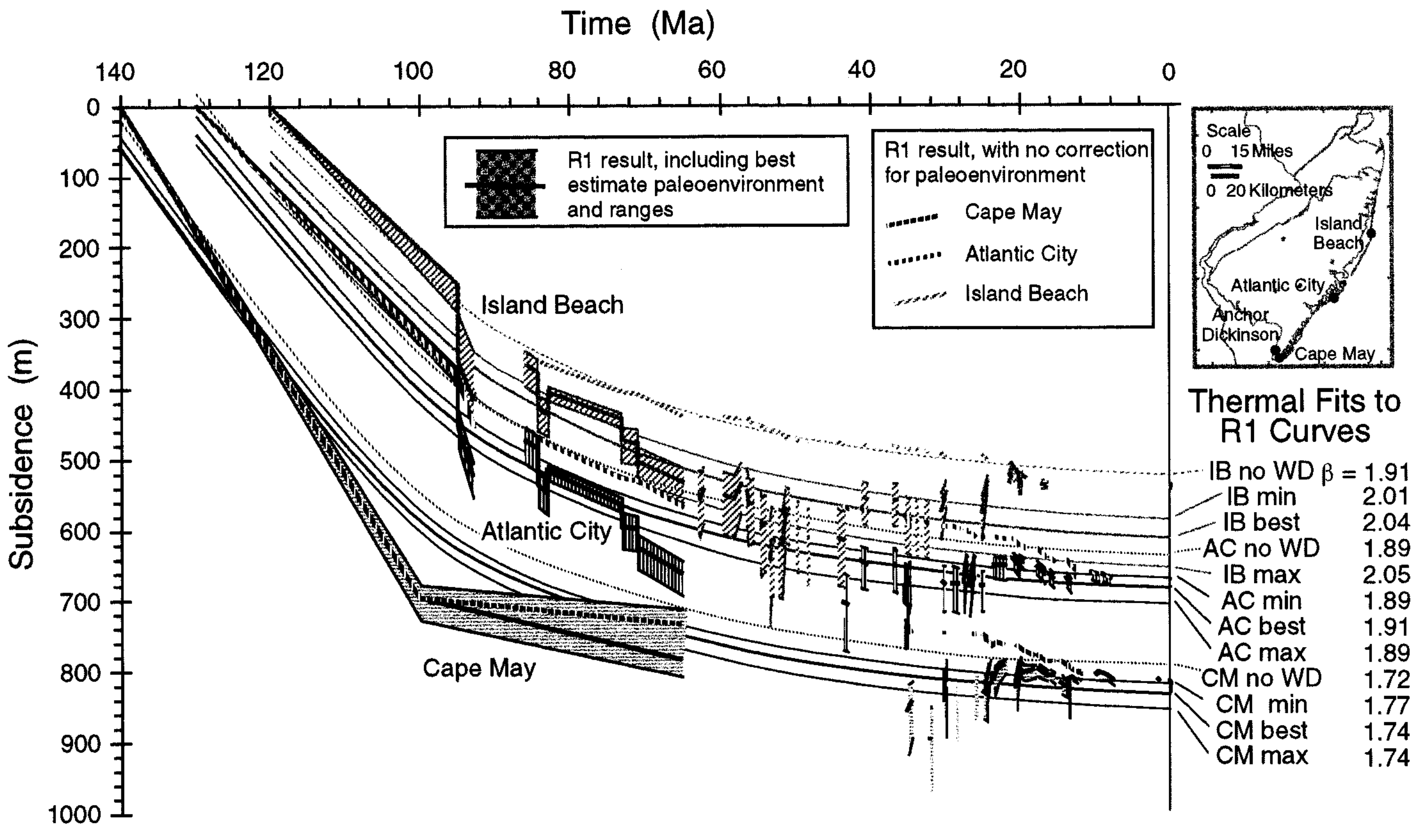

Figure 1. R1 (first reduction) curves. Curves are plotted where sediment is present, gaps represent hiatuses. Best-estimate paleodepth curves are plotted as thick line; minimum and maximum estimates are filled patterns. Also plotted are R1 curves with no paleodepth estimates (WD = 0). Best-fit thermal plate curves are plotted for each R1 curve and labeled, with stretching factors, β (ratio of stretched to pre-stretched lithosphere thickness) to right of graph (IB = Island Beach; AC = Atlantic City; CM = Cape May). Map in upper right gives locations of boreholes.

that of a thermally subsiding basin, and theoretical subsidence is assumed to be that of a cooling plate (McKenzie, 1978). Thermal subsidence is calibrated to an ocean floor with a thermal decay constant of 36 m.y. and an equilibrium plate thickness of 95 km (Stein and Stein, 1992). Best-fit thermal subsidence is calculated by first fitting an exponential curve with a decay constant of 36 m.y. by linear regression. The best-fit value of the exponential fit at 0 m.y. is used to constrain a best-fit stretching factor (McKenzie, 1978). Coastal plain subsidence began after the formation of the passive margin (Steckler et al., 1988; Olsson et al., 1988). The time of initial thermal subsidence is taken as 150 Ma. The curves are plotted using present sea level as the zero datum.

RESULTS

The subsidence recorded in these boreholes is illustrated by the R1 curves (Fig. 1). A break in the character of the curves at the Cretaceous-Tertiary boundary (65 Ma) reflects a change in the nature of the data. The thermal curve is fit primarily to the older portion of the R1 curve. The misfit in the Cenozoic is only minimally affected by the curvature, which is quite low by this time. In general, Island Beach shows the least amount of subsidence and Cape May shows the most subsidence. However, Island Beach has the greatest stretching factor (Fig. 1) because the Island Beach R1 curve has the tightest curvature, requiring a steeper Cretaceous curve. For each borehole, apparent stretching tends to increase from the R1 curve without paleodepth corrections to the R1 curve with maximum assumed paleodepths. The low stretching amplitudes are indicative of the flexural response to offshore loading.

The detailed subsidence patterns are best observed and compared in the R2 curves (Fig. 2). We limit our discussion to the Cenozoic portion of the record, which has well-defined input data. Because lowstand deposits were absent, it is appropriate to imagine the R2 curve dipping downward in the gaps between the observed sequences. Comparison of results with and without paleodepth estimates show that they are critical in the derivation of R2 curves for this margin.

We compare overall R2 trends to the long-term (10^8–10^7 yr) sea-level curve of Kominz (1984), derived from estimates of changes in mid-ocean-ridge volumes since 80 Ma, and to the long-term sea-level curve of Haq et al. (1987), derived from global correlations of sequences (Fig. 2). Because the R1 curves begin at about 130 Ma (Fig. 1), the maximum long-term sea-level change that can be obtained from this analysis, the misfit to thermal subsidence, must return to zero sea-level change at about 130 Ma. The long-term Haq et al. (1987) curve is 120 m at 132 Ma. This was set to zero and the entire curve reduced accordingly for both long-term sea-level estimates (Fig. 2). Using our best-estimate paleodepth results, the long-term eustatic change is about one-half to two-thirds of that predicted by Haq et al. (1987) for Paleocene and middle Eocene, and it is much lower (100–150 m) through the Miocene. However, the predicted amplitudes agree very well with the long-term sea-level change predicted by Kominz (1984).

Comparison of the R2 results reveals that the amplitudes of the R2 curves are similar when sequences are represented in all three boreholes (Fig. 2). This suggests that we have isolated a eustatic signal. The greatest misfit in amplitude is in the Eocene overlap of the Island Beach and Atlantic City boreholes. Here, the Atlantic City R2 curve is 20 m lower than the Island Beach curve (Fig. 2). Considering the assumptions, the agreement (i.e., ±10 m) among sites is remarkable.

The R2 curves reveal part of the short-term (ca. 0.5–3 m.y.) eustatic changes and longer term trends (Fig. 2). The Paleocene through early-middle Eocene eustatic curves show considerable variability (as much as 35 m assuming best-estimate paleodepths) both within and between sequences. Assuming that the observed record captures at least half of the eustatic signal

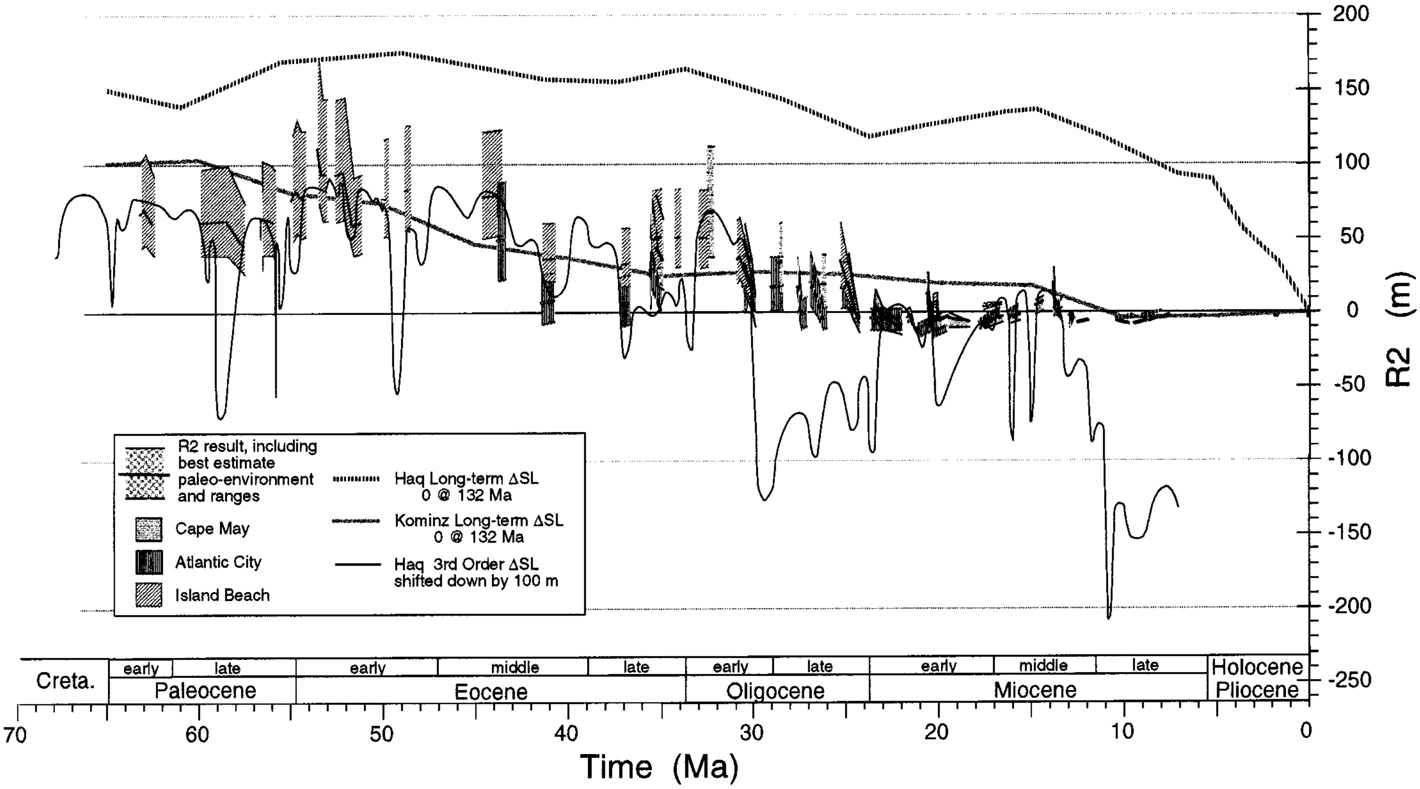

Figure 2. Cenozoic portion of R2 (second reduction) curves. R2 curves are constrained to zero at present. Range in R2 values for each borehole is less than those for R1 (first reduction) due to removal of water loading and fitting each R1 curve to thermal curve. Also plotted are long-term sea-level curves of Haq et al. (1987) and Kominz (1984) and detailed Haq et al. (1987) record shifted down 100 m. Long-term sea-level curves are also plotted adjusted for maximum long-term sea-level change that can be observed at boreholes (see discussion in text).

in the TST and HST, the maximum amplitude of short-term sea-level change was ≈70 m. The maximum short-term variations in R2 of late-middle Eocene through Oligocene sequences, assuming best-estimate paleodepths, is as much as 40 m, but is generally less than 20 m. During the Miocene, eustatic variations are as great as 30 m, but are generally less than 5 m. The minor variations between cycles suggest that short-term sea-level changes may not have been as large as in earlier times or that less of the cycles are represented. The decrease in uncertainty toward the younger portion of the record results from more accurate paleodepth estimates in the nearshore. Although the full short-term eustatic amplitudes are not recorded in the coastal plain, amplitudes are 20–30 m in the most complete sequences, at about 20 and 14 Ma (Fig. 3). These are two intervals in which the hiatuses are shorter than our detection limit and we suggest that the observed R2 amplitudes may approximate eustatic change.

Overlapping variations in R2 curves are readily explained (Fig. 3). The inconsistencies in sequence E10 can be resolved if Cape May lacks the TST and early HST, and the Island Beach section only records the HST. Sequences O2 (ca. 30 Ma) and O6 (ca. 25 Ma) show similar patterns and amplitude of sea-level rise and fall (Fig. 3). Although the Kw1 sequence (ca. 22–20.2 Ma, Fig. 3) shows similar patterns among boreholes, the timing and amplitudes are not identical. A rapid R2 fall ca. 21.7–21.3 Ma is unique to Island Beach; similarly, a fall ca. 20.8–20.3 Ma is unique to Cape May. Poor age control on the Island Beach Miocene section allows the possibility that these rapid drops in R2 are the same event. Alternatively, rapid loading out of the plane of the section could have caused a subsidence event at Island Beach to record an earlier eustatic event. The latter interpretation is consistent with a dramatic shift to rapid deltaic sedimentation in the New Jersey coastal plain at about 22 Ma (Miller and Snyder, 1997). Truncation of sequence Kw0 at Atlantic City and limitations on our ability to resolve time (±0.5 m.y.) may explain the different records in Cape May and Atlantic City (Fig. 3).

In many cases, the sequences present in one borehole are absent in one or both of the other two boreholes. This is most readily attributed to the vagaries of patterns of sedimentation on the coastal plain of a passive margin, and cannot be used to infer uncertainties in regional or global sea level. However, the magnitude of sea level is poorly constrained in the absence of corroborative evidence from multiple boreholes.

DISCUSSION

Our R2 estimates are substantially lower than the long-term Cenozoic sea-level estimates of Haq et al. (1987). The long-term pattern as recorded in HSTs is similar to that observed in the Haq et al. (1987) curve if it is shifted from an adjusted Maastrichtian high of about 150 m to about 50 m (Fig. 2). R2 values for best-fit paleodepths from the Island Beach core correspond very well to the shifted Haq et al. (1987) highstands, including a maximum in the early Eocene with a falling trend through the middle and late Eocene. A slight sea-level rise in earliest Oligocene followed by a fall is observed in both curves (Fig. 2). However, the eustatic falls as estimated by Haq et al. (1987) are much greater than that seen in the R2 curves. By the early Miocene, the downward-adjusted Haq et al. (1987) highstands are similar to the R2 curves at 0–20 m above present sea level (Fig. 2). However, the sea-level drop that begins in middle Miocene (about 13 Ma) on the Haq et al. (1987) curve is not observed in the coastal plain subsidence data.

The short-term amplitudes of the R2 curves cannot be directly compared with Haq et al. (1987) because they do not record the full cycle. However, short-term R2 amplitudes appear to be significantly lower. For example, the highstand of sequence O3 (ca. 28 Ma) is about 20 m below that of O2 (ca. 30 Ma); in contrast, the same drop is assigned a magnitude of ≈140 m by Haq et al. (1987). Where the onshore sequences are most complete, the R2 falls are much lower than the

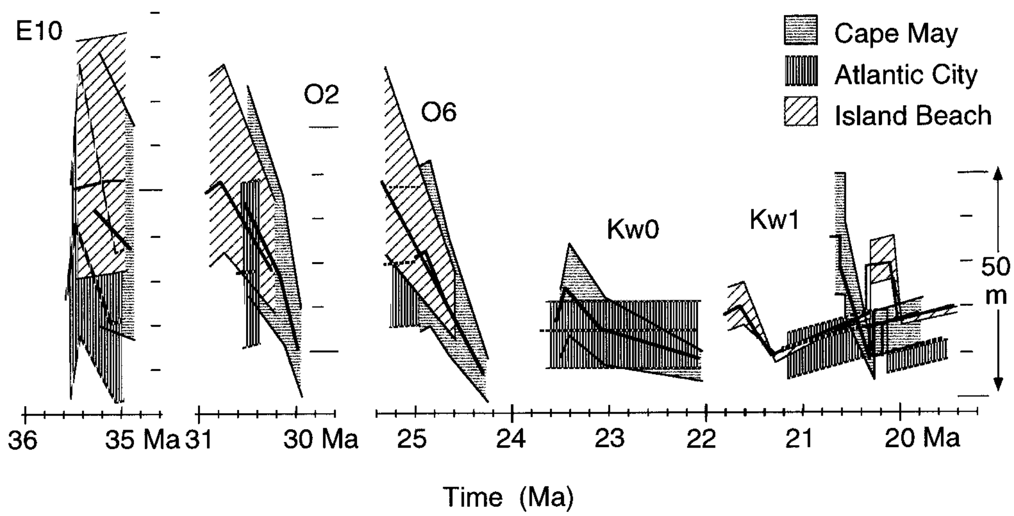

Figure 3. R2 (second reduction) results for selected sequences plotted at increased scale. Vertical scale is same for all sequences but is not hung on an absolute R2 scale.

correlative fall of Haq et al. (1987; e.g., 20–30 m vs. 60 m for the ca. 20 Ma fall; Figs. 2 and 3).

CONCLUSIONS

Eustatic estimates obtained from R2 curves from ODP Leg 150X boreholes yield consistent magnitudes of transgressive and highstand short-term eustatic cycles. Magnitudes are similar to Kominz's (1984) long-term sea-level estimates and are considerably lower than those of Haq et al. (1987). General trends in sea-level change from the R2 curves are consistent with estimates of Haq et al. (1987), although details vary. In particular, the largest fall predicted by Haq et al. (1987) at the end of the early Oligocene is not observed nor is the general falling sea-level from late Miocene to the Holocene. Magnitudes of short-term eustasy are difficult to estimate in the absence of lowstand deposits in these sites. However, where hiatuses are extremely short, the R2 results suggest a magnitude of sea-level change of about one-half that predicted by Haq et al. (1987).

Additional coring and detailed analyses from early Cenozoic sections are necessary to corroborate results from the Island Beach borehole. Estimates of the magnitude of long-term sea-level change requires detailed coring and analyses of the Cretaceous portion of the record. These data would also yield important information on older short-term eustatic signals. Two additional types of study are needed to constrain short-term eustatic amplitudes: (1) sampling of sections underlying the modern shelf that record the full amplitude of eustatic change; and (2) two-dimensional subsidence analyses.

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REFERENCES CITED

Berggren, W. A., Kent, D. V., Aubry, M. P., and Hardenbol, J., eds., 1995, Geochronology, time scales and global stratigraphic correlation: SEPM (Society for Sedimentary Geology) Special Publication 54, 386 p.

Bond, G. C., and Kominz, M. A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173.

Bond, G. C., Kominz, M. A., Steckler, M. S., and Grotzinger, J. P., 1989, Role of thermal subsidence, flexure and eustasy in the evolution of early Paleozoic passive-margin carbonate platforms, *in* Crevello, P. D., Wilson, J. L., Sarg, J. F., and Read, J. F., eds., Controls on carbonate platform and basin development: SEPM (Society for Sedimentary Geology) Special Publication 44, p. 39–61.

Browning, J. V., Miller, K. G., and Pak, D. K., 1996, Global implications of Eocene Greenhouse and Doubthouse sequences on the New Jersey Coastal Plain—The icehouse cometh: Geology, v. 24, p. 639–642.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): Science, v. 235, p. 1156–1167.

Kominz, M. A., 1984, Oceanic ridge volumes and sea level change—An error analysis, *in* Schlee, J., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 109–127.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

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

Miller, K. G., and Snyder, S. W., editors, 1997, Proceedings of the Ocean Drilling Program, Scientific Results, Leg 150X: College Station, Texas, Ocean Drilling Program, 151 p.

Miller, K. G., Mountain, G. S., the Leg 150 Shipboard Party, and Members of the New Jersey Coastal Plain Drilling Project, 1996, Drilling and dating New Jersey Oligocene-Miocene sequences: Ice volume, global sea level, and Exxon records: Science, v. 271, p. 1092–1094.

Mountain, G. S., Miller, K. G., Blum, P., Poag, C. W., and Twichell, D. C., editors, 1996, Proceedings of the Ocean Drilling Program, Scientific Results, v. 150: College Station, Texas, Ocean Drilling Program, 493 p.

Olsson, R. K., Gibson, T. G., Hansen, H. J., and Owens, J. P., 1988, Geology of the northern Atlantic coastal plain: Long Island to Virginia, *in* Sheridan, R. E., and Grow, J. A., eds., The Atlantic Continental Margin, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. I-2, p. 87–105.

Rhodehamel, E. C., 1977, Sandstone porosities, *in* Scholle, P. A., ed., Geological studies on the COST No. B-2 well, U.S. mid-Atlantic outer continental shelf area: U.S. Geological Survey Circular 750, p. 23–31.

Steckler, M. S., Watts, A. B., and Thorne, J. A., 1988, Subsidence and basin modeling at the U.S. Atlantic passive margin, *in* Sheridan, R. E., and Grow, J. A., eds., The Atlantic Continental Margin, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. I-2, 399–416.

Stein, C. A., and Stein, S., 1992, A model for the global variation in oceanic depth and heat flow with lithospheric age: Nature, v. 359, p. 123–129.

Volkert, R. A., Drake, A. A., Jr., and Sugarman, P. J., 1996, Geology, geochemistry, and tectonostratigraphic relations of the crystalline basement beneath the coastal plain of New Jersey and contiguous areas: U.S. Geological Survey Professional Paper 1565-B, 48 p.

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