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Sea-Level Estimates for the Latest 100 Million Years: One-Dimensional Backstripping of Onshore New Jersey Boreholes

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Abstract

Backstripping analysis of the Bass River and Ancora boreholes from the New Jersey Coastal Plain (Ocean Drilling Project Leg 174AX) provided new Late Cretaceous sea-level estimates and tested previously published Cenozoic sea-level estimates. Amplitudes calculated from all New Jersey boreholes were based on new porosity-depth relationships estimated from New Jersey Coastal Plain electric logs. In most cases, amplitudes and duration of sea level were comparable when sequences were represented at multiple borehole sites, suggesting that the resultant curves were an approximation of regional sea level. Sea-level amplitudes as great as 50 m were required by third-order Cretaceous sequences. Most amplitudes were probably closer to 20 to 40 m. Third-order (0.5–3 m.y.) sea-level changes of Paleocene and younger sequences were generally less than 30 m and were superimposed on a long-term (= 100 m.y. duration) sea-level fall from a maximum early Eocene value of approximately 100 to 140 m.

Introduction

Stratigraphic sequences are the response of the geologic record to a combination of tectonic subsidence, sedimentation and sea-level change (e.g., Vail *et al.*, 1977; Posamentier *et al.*, 1988; Galloway, 1989; Christie-Blick and Driscoll, 1995; Steckler *et al.*, 1993). Early sequence stratigraphic analysis has been used to estimate past third order (half to three million year duration) sea-level change as the dominant factor in the formation of seismic-scale sequences (Vail and Mitchum, 1977). Sea-level change has also been estimated through backstripping (Watts and Ryan, 1976; Steckler and Watts, 1978). In backstripping, the effects of sedimentation are removed from a basin in which the form of tectonic subsidence is simple, allowing an estimate of sea-level change (*e.g.*, Watts and Steckler, 1979; Bond *et al.*, 1989). The sea-level estimates from backstripping can be instrumental in assessing the relative importance of eustasy, tectonics, and/or sedimentation in a sequence model. This is difficult to achieve in sequence modeling in that sediment compaction, sediment loading, and tectonic subsidence all vary laterally and are generally not taken into account.

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A recent Ocean Drilling Project in the Baltimore Canyon Trough region (Fig. 1) has focused on the study of sequence stratigraphy and its relationship to sea-level change. Drilling in poorly consolidated clastics has proven most successful on the coastal plain (Miller *et al.*, 1986a, 1986b, and 1994). Ocean Drilling Project leg 150 X and 174 AX have drilled successfully 6 cores on the coastal plain of New Jersey and Delaware (Miller *et al.*, 1994, 1986a, and 1986b; Miller and Snyder, 1997).

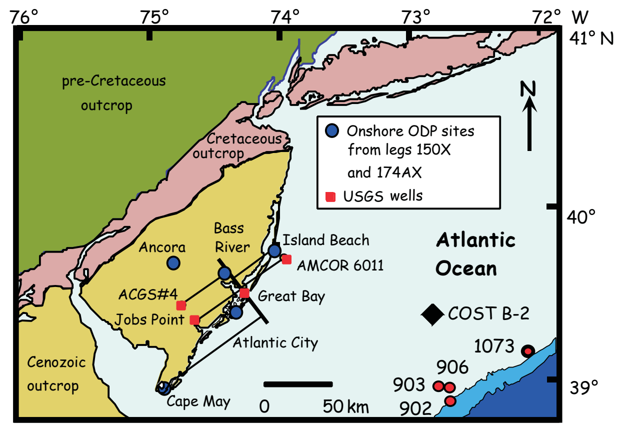

Figure 1. Location map of New Jersey Coastal Plain boreholes and wells used in this study. Boreholes include Leg 150X (Island Beach, Atlantic City, and Cape May) and Leg 174AX (Bass River and Ancora) sites. The USGS wells (Butler Place and Island Beach #33-01031), Island Beach borehole, and the offshore Cost B-2 well were used to estimate compaction of sand and mud.

Analyses of samples from five of those cores are sufficiently complete for quantitative analyses. The first three boreholes have penetrated sediments as old as Paleocene. Correlation of these sequences with each other and comparisons with global proxies has been reported by Miller *et al.* (1996b) and Miller *et al.* (1998), and the estimates of sea level from backstripping have been reported by Kominz *et al.* (1998). Kominz *et al.* (1998) have found that where sequences are present in more than one borehole, the magnitude of change is quite similar, suggesting little if any local tectonism has affected this simple thermal margin (Steckler *et al.*, 1988). They have found that both second-order (50 to 100 m.y.) and third-order sea-level changes are of lower magnitude than those estimated by Haq *et al.* (1987). Two new boreholes, Ancora and Bass River, have been drilled farther inland in order to penetrate the Cretaceous record (Miller *et al.*, 1998; Miller *et al.*, 2000; Miller *et al.*, 1999). This paper extends the work of Kominz *et al.* (1998) into the late Cretaceous. We estimate the magnitude of second and third-order sea-level change in the Late Cretaceous and test the Cenozoic estimates of Kominz *et al.* (1998).

Methods

Backstripping

Backstripping allows estimation of tectonic subsidence of a basin where sea level is known (e.g., Steckler and Watts, 1978) or sea-level change if the tectonic subsidence can be estimated (*e.g.*, Bond *et al.*, 1989). The borehole data from the New Jersey Coastal plain is ideal for backstripping, providing continuously cored, well-dated, records of sedimentation (Miller and Snyder, 1997; Miller *et al.*, 1994, 1996a, 1999; Browning *et al.*, 1996; Pekar *et al.*, 2000). An integral part of backstripping includes decompacting and unloading the sediment load through time. As such, the best possible porosity-depth curves should be used to estimate sediment compaction.

Sonic velocity logs from three coastal plain wells, the Island Beach borehole (ODP Leg 150X), the Island Beach well #33-01031, and Butler Place well (Fig. 1), were used to establish

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compaction trends for sand and shale. Both sands and shales showed much lower porosities beneath the coastal plain than beneath the outer shelf, as indicated by data from the Cost B-2 well (Fig. 2). The coastal plain wells only penetrated about a kilometer, to basement, thus, only the top kilometer of compaction is constrained. This allowed estimates of a range of compaction curves for both sand and shale (Fig. 2). The low end-member porosity-depth curves from the Cost B-2 wells were used by Kominz *et al*. (1998) to backstrip the Island Beach, Atlantic City and Cape May boreholes. The coastal-plain porosity data were more appropriate for these wells. These boreholes were also re-analyzed in this paper, to take advantage of more accurate compaction estimates.

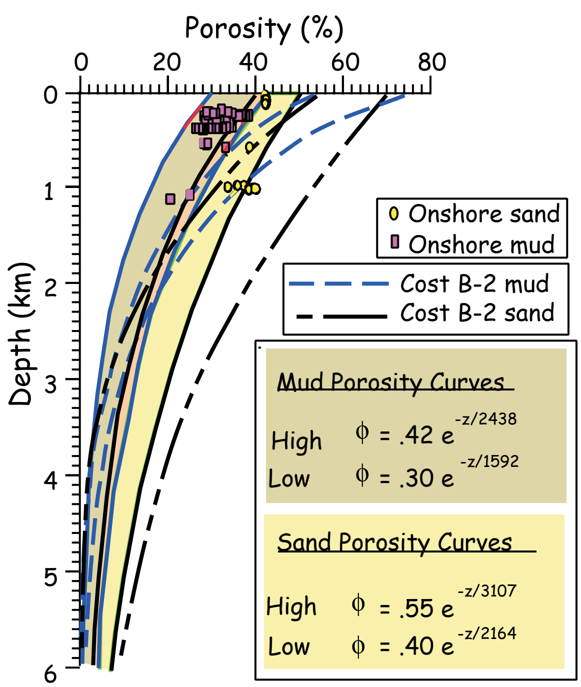

Figure 2. Cost B-2 sand and mud porosity and estimates from onshore sites (Island Beach borehole, Island Beach #33-01031, and Butler Place wells; Fig. 1). The solid black (sand) and red lines (mud) represent the new high and low, end-member porosity curves used in this study.

Sediments were decompacted, using the porosity-depth relations, in order to estimate the thickness (S*) and density ($\rho_{S}*$) of the sediment load with time. The first reduction (R1) of the backstripping method is an estimate of the water depth above the basement in the absence of sediment. This depth (R1) is the result of both tectonic subsidence (TS) and sea-level change (?SL). The water depth at the time of deposition (WD) is included in the R1 estimate because most preserved sediment are not deposited exactly at sea level.

$$R1 = TS + \Delta SL = S^*\left(\frac{\rho_a - \rho_{s*}}{\rho_a - \rho_w}\right) + WD \qquad (1)$$

Estimates of paleo-water depths (WD) were obtained from a combination of benthic biofacies, lithostratigraphy, and paleoslope modeling (Miller et al., 1998; Miller et al., 1999; and Pekar and Kominz, 2001).

Establishing á priori tectonic subsidence history (TS) for any basin is a non-trivial task. However, the thermal pattern of subsidence is well established for passive margins (McKenzie, 1978; Bond and Kominz, 1988). Combining McKenzie's (1978) model with the thermal parameters for lithosphere derived from ocean floor records (Stein and Stein, 1992) allows a theoretical thermal curve, fit to the R1 data, to be established as an estimate of tectonic subsidence (Bond *et al*., 1989). When this thermal curve is removed from R1 the amplitude of sea-

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level change, as viewed from the ocean floor, is obtained. An increase in the height of the water column depresses the oceanic lithosphere below it. Thus, the height of sea level as observed from the continent or from a fixed point in the center of the earth is calculated as follows:

$$R2_{SL} = (R1 - TS)\left(\frac{\rho_a - \rho_w}{\rho_a}\right) \qquad \text{.......(2)}$$

Any non-thermal tectonics will be included in $R2_{SL}$. If the $R2_{SL}$ results from the New Jersey Coastal Plain wells are consistent, there is a strong suggestion that local tectonism was minor if present at all, and that a record of regional sea-level change, in this 100 km x 125 km region, was obtained (*e.g.*, Kominz *et al*., 1998; Fig. 1).

Results and Discussion

R1 Results

The assumption of thermal subsidence and the effect of using various compaction curves were analyzed for the Ancora and Bass River boreholes (Fig. 3). The Bass River borehole penetrated 596 meters of sediment bottoming in the Turonian Bass River Formation (Miller *et al*., 1998). An additional 20 meters of Bass River Formation and a thickness of 409 m of underlying Potomac Group were estimated using a combination of well data and refraction data (Van Sickel, 2000). Minimum, best estimate, and maximum paleo-water depth values resulted in three sub-parallel R1 curves for both the assumption that porosities were relatively low (dark green, Fig. 3A) and that porosities were relatively high (light green, Fig. 3A). The Ancora borehole was drilled to 355 m, bottoming in the Potomac Group (Miller *et al*., 2000). An estimate of the depth to basement required an additional 333 m of Potomac Group sediments (Van Sickel, 2000). As in the case of the Bass River borehole, both low porosity curves (dark purple, Fig. 3A) and high porosity curves (light purple, Fig. 3B) were applied.

Both borehole R1 curves were readily fit to the thermal plate model of McKenzie (1978) modified for more recent ocean floor physical parameters (Stein and Stein, 1992). The R1 curves had a tighter curvature, suggesting a long-term sea-level rise in the Late Cretaceous and fall through most of the Cenozoic (Fig. 3A). The range of water depths indicated by the colored fill from high (greatest subsidence) to low were often quite large. The R1 subsidence predicted by the high end-member porosity vs. depth curves was considerably greater than that predicted by the low end-member porosity-depth curves.

To understand why this is the case, we will focus on the estimate of R1 for today (0 m.y.). The thickness of sediment is the same in both cases. It is today's observed sediment thickness and requires no decompaction at all. High porosity vs. depth curves requires that more of the section is interstitial water than low porosity vs. depth curves. This results in a relatively low density for ρ_{S*} in equation 1 and a higher R1 value. For earlier times, higher porosity vs. depth curves results in both thicker sections (larger S*) and lower density and, as such, higher R1 values. Notice that each R1 urve is fit independently to a thermal curve. This is because each R1 curve is an independent estimate of subsidence. Thus, the R2 curves are calculated by subtracting each R1 curve to its own best-fit thermal curve.

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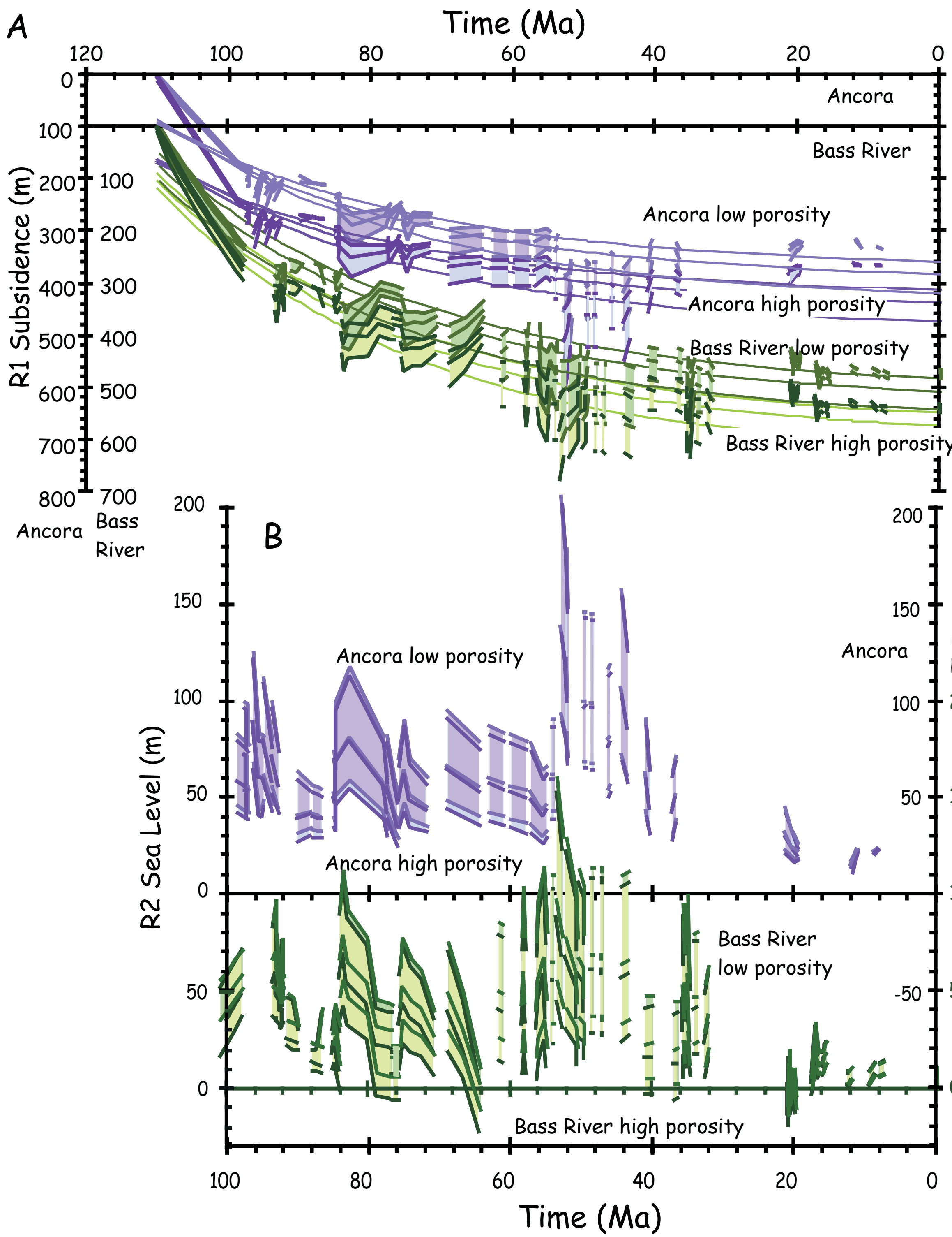

Figure 3. R1 and R2SL results for Bass River and Ancora boreholes using both high and low end-member porosity-depth curves. (A) R1 results are plotted with thermal fits (solid lines). R1 curves older than 98 m.y. represent estimated stratigraphic data beneath the borehole (see text). Bass River results are offset by 100 m from Ancora for clarity. (B) R2SL results plotted in reference to sea level today (R2SL = 0). R2SL curves younger than 90 m.y. are not plotted since it does not represent borehole data.

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The R2 results are a bit surprising in two ways. First, there is very little difference between the R2 curves that are calculated by the different porosity vs. depth relations. The difference in R1 values resulting from the two porosity assumptions is about 100 meters. The difference in R2 values resulting from the same assumptions is a maximum of 5 meters and generally less than 2 meters. The reason for this is the fact that each R1 is individually fit to a thermal curve. The other surprising result is the fact that compaction calculated using the low porosity vs. depth curves results in slightly higher R2 estimates than application of the high porosity vs. depth curves. This may be due to the fact that the R2 values are highest when there is a larger difference in the curvature of the thermal curves and that of the R1 curves. Because the R1 values are lower for the low porosity vs. depth assumption, the thermal curves that are fit to them have a lower curvature.

With very little difference between the R2 curves generated using high vs. low porosity vs. depth curves, we follow the lead of Kominz *et al*. (1998) and only utilize the low end-member porosity vs. depth curves in the following results. We apply the coastal plain porosity vs. depth curves to all boreholes, improving on the earlier results of Kominz *et al*. (1998).

New Jersey Coastal Plain R2 Results

The R2 results for all 5 boreholes (NJR2 curves) suggested a relatively consistent long-term sea-level history (Fig. 4). Sea level was generally about 40 to 100 meters higher than today from the beginning of the Late Cretaceous until about 55 Ma (the early Eocene). At that time, there was an abrupt rise in sea level, the sea-level maximum continued for approximately 10 Ma. A long-term fall began in the late-middle Eocene and persisted into the early Oligocene. Subsequent sea levels fluctuated near present sea level.

The third-order sea-level story is more complex (Fig. 4). Gaps in the record represent hiatuses in the coastal plain record, and correspond to sequence boundaries. Lowstand deposits are generally absent in this part of the section because of its proximal location. That is, the lowest portion of most third-order cycles can not be obtained from this data set. The vertical range in sea-level estimates at each well is a representation of the uncertainty in paleo-water depth at each borehole site. Overlap suggests that we are looking at a regional sea-level signal. A lack of overlap (e.g., ~65 Ma Ancora vs. Bass River) suggests that local tectonism may be operative or there is an error in our modeling assumptions. For example, the paleo-environment at Ancora might have been shallower than the outer shelf water depths assumed.

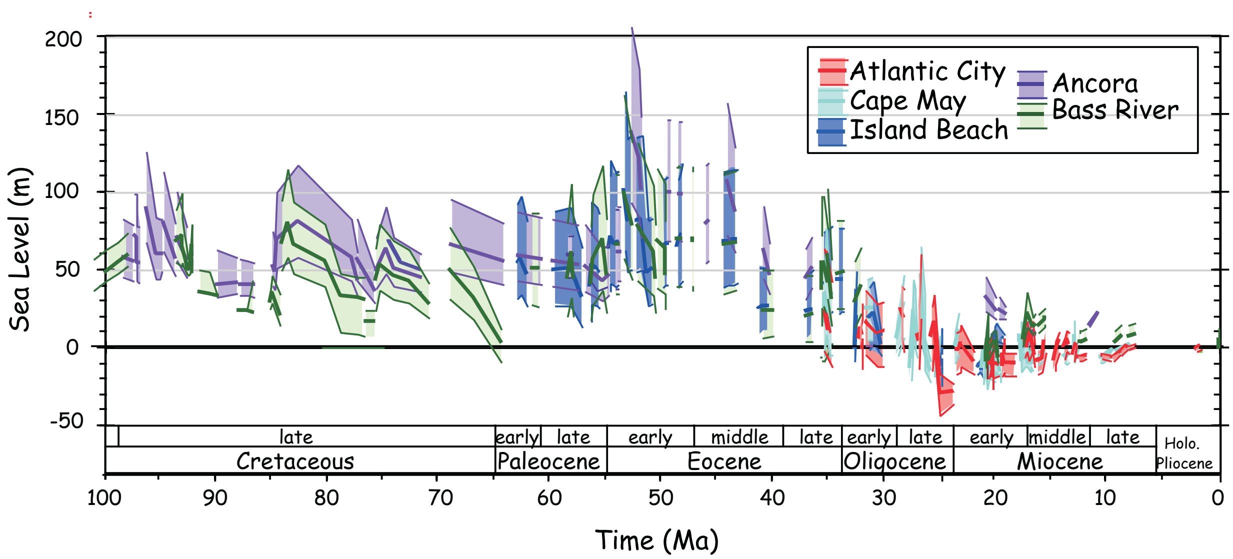

Figure 4. R2SL results for the five New Jersey coastal plain boreholes.

Porosity curves used for decompaction assume that there is no overpressuring. If overpressuring occurs at Ancora prior to deposition of these latest Cretaceous sediments, but is removed at this time, additional space would be available for deposition, resulting in a local, apparent sea-level rise. Another possible error arises from the one-dimensional approach. While a basin that responds elastically to loads subsides with a thermal form (*e.g.*, Bond *et al.*, 1988), response to nearby local sediment loading may result in variations in subsidence that could account for some discrepancies between NJR2 results at different wells. In these cases, a two- or three-dimensional approach is required to determine if the difference is due to modeling errors or local tectonism.

While fairly large uncertainty ranges allow for possible sea-level change in most sequences, third-order sea level change was only required where variations in R2 were greater than the uncertainty resulting from water-depth estimates (*e.g.*, 80 Ma or 25 Ma). Additionally, where the change in R2 between sequences is greater than the uncertainty, an additional sea-level change is required (*e.g.*, across the Oligocene - Miocene boundary). These minimum sea-level changes generally range between about 5 and 20 meters. If the best-estimate paleo-water depths are used, however, variations in sea level up to 50 meters, but generally less than 10 meters, are suggested by the NJR2 results. The lack of lowstand facies in our sections requires an additional sea-level fall. These magnitudes are entirely unconstrained by our data but might be conservatively estimated to also range between 5 and 50 meters based on the fairly short time intervals of the missing sections.

New Jersey Coastal Plain R2 Results Compared to Sea-Level Estimates from other Proxies and Other Regions

First and Second Order Sea-Level Change

The long-term sea-level curve derived from the New Jersey boreholes (NJR2 curve) was quite different from previous long-term estimates (Fig. 5). The long-term sea-level curve derived from ridge volume changes (RVSL) by Kominz (1984) was somewhat similar to the NJR2 curve from early Eocene to the present. The overall magnitudes of the two curves were quite consistent for that time period. From 80 Ma to 50 Ma, the ridge volume curve suggested about 100 m of sea-level fall; however, the R2NJ curve suggested that sea-level was relatively constant but rising from about 55 to 50 Ma. Inclusion of the Ancora and Bass River boreholes results in the R2NJ curves means that a possible error arising from fitting a thermal curve to a data set which did not include the rise in sea-level as well as the fall (Kominz *et al.*, 1998) is reduced greatly. In fact, the similarity in the long-term trends of the Island Beach borehole (incomplete record) with the Bass River and Ancora R2 results suggest that this has never been a significant problem. The RVSL curve discussed to this point is only the best-estimate curve (Kominz, 1984) of sea-level change resulting from spreading rates. However, error ranges due to uncertainties in spreading rates (range of blue dashed lines, Fig. 5), and uncertainties in time scales (purple curves, Fig. 5), also are presented by Kominz (1984). The first-order (~ 100 Ma) sea-level trend in the NJR2 result is within the uncertainty introduced by these factors. However, second-order (10 - 40 Ma) variability is not well matched by the ocean ridge data. In particular, the Eocene sea-level maximum is missing from the ridge volume record. This suggests that this particular change is not a result of variations in sea-floor spreading rates. This climatic optimum could have been a time of minimum land-ice and maximum ocean water temperatures. There might also have been rapid submarine volcanism (*e.g.*, the generation of the Norway/Greenland passive margin, Talwani and Eldholm, 1977). Cooling of ocean water, increase in small glaciers, and continent-continent collision of India and Asia might have been factors that influenced the subsequent sea-level fall.

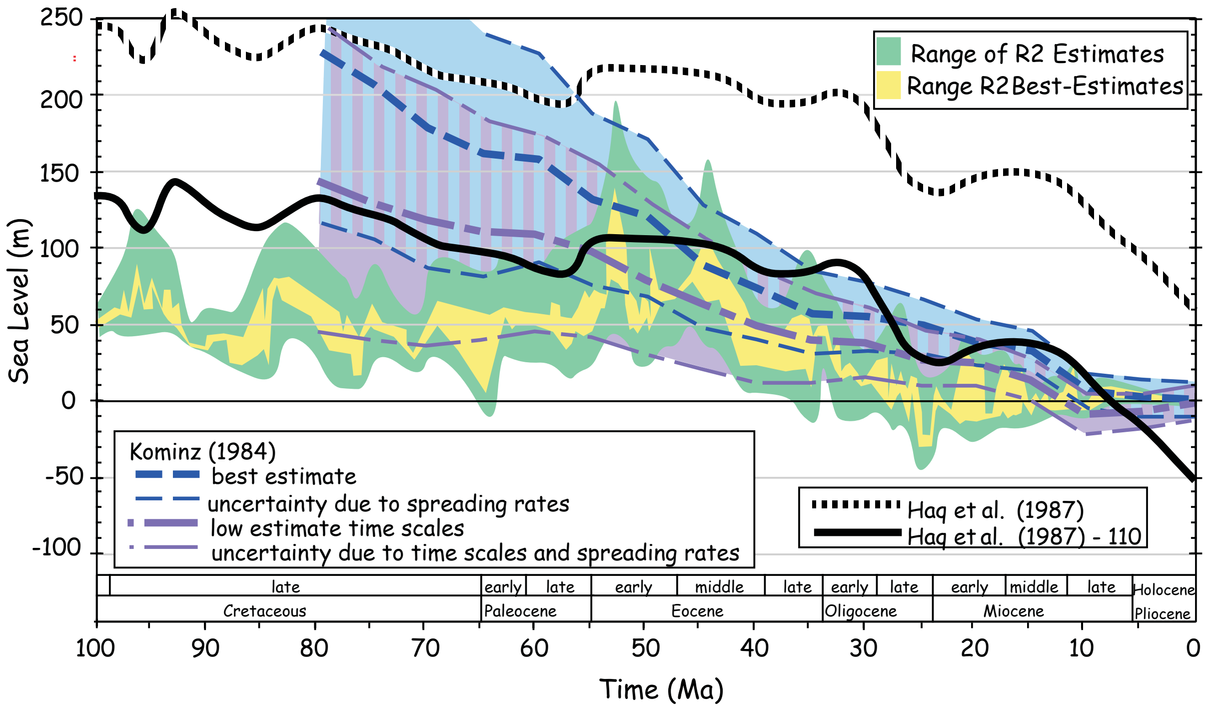

Figure 5. Smoothed sea level (R2SL) from the five boreholes. The green indicates a smoothed range of results, while the yellow indicates the range of best-fit estimates. The R2 results are compared to the Haq et al. (1987) long-term sea-level curve (corrected to the Gradstein et al. (1995) and the Berggren et al. (1995), time scales. Comparison has been made with the Kominz (1984) long-term sea-level curve; uncertainty ranges are due to spreading rates and time scales.

The Haq *et al.* (1987) record was recalibrated to the Gradstein *et al.* (1995) and Berggren *et al.* (1995) revised biostratigraphic time scales. The NJR2 curves clearly lacked the major sea-level fall indicated by the Haq *et al.* (1987) record from the middle Miocene to the present (Fig. 5). The discrepancy was reduced by shifting the long-term Haq *et al.* (1987) sea-level curve 110 m, as shown in Figure 5. This difference was most likely tied to the uncertainties in ridge volume as discussed above. The long-term sea-level estimate of Haq *et al.* (1987) was derived from backstripping a well from the west-African passive margin by Hardenbol *et al.* (1981), coupled with a Turonian estimate based on ocean volume changes as estimated by Harrison (1990). The Harrison (1990) estimate was dominated by ridge volume changes, which were estimated using the best-estimate curve of Kominz (1984). Thus, if the lower range of RVSL curves are more appropriate, as discussed above, the Haq *et al.* (1987) long-term magnitudes were also too high by the same amount.

From the late Paleocene to the Middle Miocene, there is some consistency between the shifted curve (HSL-110 curve) and the NJR2 results. Both records are relatively flat in the Paleocene. They both rise in the early Eocene to a new plateau. The NJR2 curve shows two subsequent 5 to 10 Ma sea-level falls, one in the middle Eocene, and one in the early Oligocene. The HSL-110 curve shows a slight falling trend throughout the Eocene but the major fall begins in the early Oligocene and concludes at the end of the Oligocene. Both the NJR2 and HSL-110 curves show little change in the Cretaceous; however the variations suggested are quite different in timing (Fig. 5).

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Third Order Sea-Level Change)

The NJR2 third-order sea-level estimates show both similarities and differences as compared to other sea-level estimates (Fig. 6). Overall, sequences in the Late Cretaceous are somewhat less frequent but at least as great in magnitude as those seen in the Cenozoic. This trend is rather consistent with that obtained from global sequence stratigraphic data (Haq *et al*., 1987). A decrease in period of sea -level variations as indicated by the averaged $\delta^{18}O$ curve of Abreau and Anderson (1998) from around 2 Ma in the Paleocene and Eocene to about a million years from late Oligocene through the Miocene is also reflected in the NJR2 data set. The NJR2 data set does not record the high frequency Pliocene and Pleistocene sea level resulting from the most recent ice age. Only the Holocene cover and occasionally Pliocene sediments are observed above late Miocene strata.

Focusing on the Late Cretaceous record, which was the new contribution of this data set, the magnitudes of the NJR2 results did not compare well with the sea-level curve of Haq *et al*. (1987). There was no indication of 100+ meter sea level lowering, as indicated in the latest Turonian or in the late Maastrichtian Haq *et al*. (1987) curve. In fact the latter sequence boundary fell within a sequence that was observed at both the Ancora and the Bass River boreholes. Similarly, the very minor hiatus in latest Turonian left little room for a major sea-level fall. Thus, we suggested that the timing and/or the magnitude of these events need revision. Our best-estimate magnitudes of sea-level change between most cycles are at least 10 to 20 meters in the Late Cretaceous. Adding an additional 10 to 20 meters for the missing lowstand would bring these magnitudes into line with those indicated in the Haq *et al*. (1987) data set for Late Cretaceous sequence boundaries at about 97, 83.5, 79, and 70 Ma. The timing of sequence boundaries were not, however, particularly well correlated with those of the New Jersey Coastal Plain. Thus, either one or both of these data sets needs revision in age dating or is not a record of eustasy.

Sahagian *et al*. (1996) calculate the magnitude of sea-level change in late Cenomanian through earliest Campanian time by R2 analysis of the Russian platform (Fig. 6A). Their estimates of sea-level change show less variation in amplitude compared to the NJR2 curves. The sea-level lowstands are represented by hiatuses on the Russian platform so that this portion of the curve has been obtained by splicing in estimates from nearby, subsiding regions (Sahagian *et al*., 1996). As such, the magnitude of variation between low and high sea-level estimates is somewhat problematic and it may not be unreasonable to increase that range. By increasing the difference between the maximum and minimum sea-level estimates of Sahagian *et al*. (1996) by a factor of two and keeping their highest values fixed (Fig 6A), the overall form of sea-level change is quite similar to that indicated by the NJR2 results. The Bass River borehole seems to record the lowest events seen on the Russian Platform. Minor variations in timing of highs and lows in sea-level estimates may be due to uncertainties in correlation of age between these distant data sets. The remarkable similarity of these two results from different geological settings and different continents suggests that these records may be indicative of eustasy.

As was the case in the upper Cretaceous, the Paleocene through Oligocene NJR2 data showed no evidence of sea-level falls in excess of 100 m indicated by Haq *et al*. (1987; Fig. 6B). Of the three events (59, 56 and 49.5 Ma), only the early Eocene (49.5 Ma) event corresponded in time with a hiatus in the New Jersey sequences. Many of the sequences observed on the New Jersey Coastal Plain corresponded to sequence boundaries of the global sea-level curve (Haq *et al*., 1987). Examples include Pa 2, Pa3, E3, E5, E6, and E9. In other cases there was no consistent relationship between the timing of the R2 events and the third-order Haq *et al*. (1987) curve. Similarly, there was no consistent relationship with the averaged $\delta^{18}O$ curve. However, the number of events was about the same (as mentioned above).

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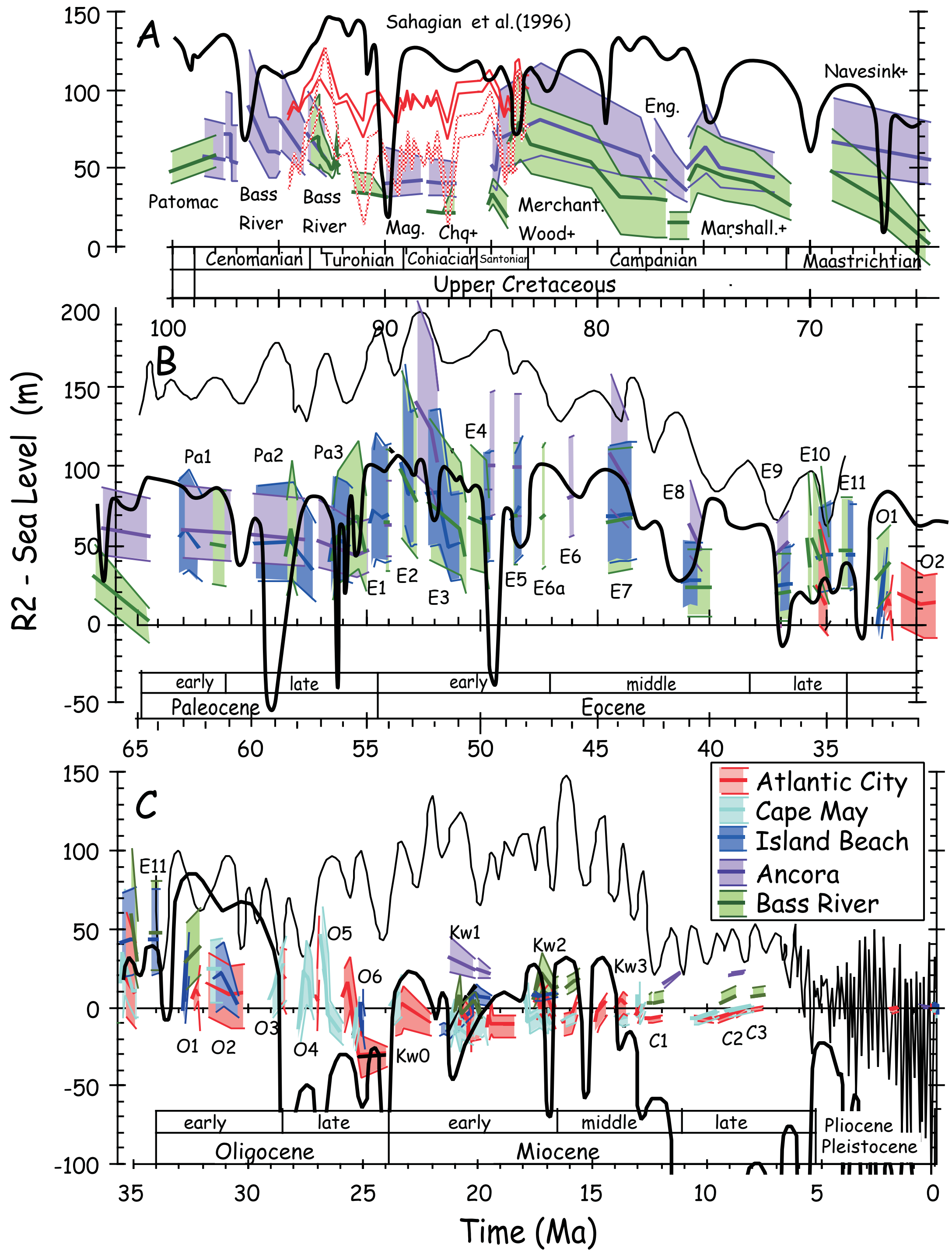

Figure 6. R2SL results for the five New Jersey coastal plain boreholes expanded and compared to other third-order sea-level estimates. The thick black line is the Haq et al. (1987) sea-level curve re-calibrated for biostratigraphic time scales and shifted down by 110 meters. The light line is Abreau and Anderson's (1998) sea-level estimate from $\delta^{18}O$. The red Upper Cretaceous curve is from Sahagian et al. (1996). The light-red curve is this same curve modified as discussed in text.

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In the Oligocene and the Miocene, NJR2 results (Fig. 6C) again did not indicate the large sea-level lowerings of the Haq *et al.* (1987) curve. The 100 + meter fall at about 29 Ma corresponded to sequence O3 rather than to a sequence boundary. The fairly large fall at about 24 Ma did correspond to the Oligocene-Miocene boundary sequence event. However, a fall at about 21.5 Ma occurred within sequences Kw2. The fall at about 15.1 Ma corresponded to a sequence boundary between several Kw2 sub-sequences. Very little variation in sea level was required by the Miocene NJR2 results. Larger variations, as large as 60 meters, were required by the R2NJ data in the late Oligocene. Approximately 30 m of sea-level change was suggested for sequence O1 if the three boreholes could be tied together with the degree of certainty shown in Figure 6C. This result could be confirmed by comparison to the two-dimensional analyses of Kominz and Pekar (2001).

Conclusions

Borehole data from the Late Cretaceous through Miocene age New Jersey Coastal plain were quantitatively analyzed for magnitudes of sea-level change (R2). In most cases, all boreholes that sampled the same sequences revealed R2 (sea level) estimates of similar magnitudes, suggesting that at least regional sea level was obtained. The long-term trends did not show the large fall since Late Cretaceous suggested by many earlier workers. Instead, an early Eocene sea-level maximum was indicated. This suggested that ridge volume curves were closer to minimum than to mean values as calculated from ocean floor ages (Kominz, 1984). The duration of third order events decreased with time as suggested by the Haq *et al.* (1987) global sea-level analysis and by synthesis of oxygen isotopes (Abreau and Anderson, 1998). The exact timing of these events, however, did not correlate directly to either of these proxy records. In general, the third order R2 magnitudes did not support large (˜ 100 meter) sea-level falls invoked by Haq *et al.* (1987). The data set most consistent with the NJR2 curves was the Shahagian *et al.* (1996) Late Cretaceous sea-level estimates derived from the Russian platform.

Acknowledgments

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