Evaluating the stratigraphic response to eustasy from Oligocene strata in New Jersey

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ABSTRACT

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

Keywords: New Jersey, Oligocene, eustasy, stratigraphic response, phase lag, sea level.

INTRODUCTION

The sequence stratigraphic literature includes numerous articles interpreting eustasy on the basis of physical stratigraphic and sedimentological data (e.g., Payton, 1977; Haq et al., 1987; Wilgus et al., 1988; de Graciansky et al., 1998). With the exception of the late Cenozoic, few independent constraints exist on either the timing or the amplitudes of eustatic change, and many stratigraphic studies lack the precise age control and quantitative rigor that are needed for an objective interpretation of eustasy (Kominz et al., 1998).

The New Jersey continental margin is well suited for tackling this issue. It is an old passive margin characterized by relatively uniform, slow subsidence. The Oligocene-Pleistocene section is relatively thick owing to pre-Oligocene sediment starvation (Steckler et al., 1999). Data suggest that since at least the late Eocene, the stratigraphic record was modulated strongly by eustasy (Browning et al., 1996; Miller et al., 1998).

Ocean Drilling Program (ODP) onshore Legs 150X and 174AX (see Miller et al., 1998) provide a remarkable record of Oligocene sedimentation beneath the onshore part of the margin, with excellent chronostratigraphy and constraints on paleodepth changes (Pekar, 1999; Pekar et al., 2000; Pekar and Kominz, 2001). These data have been used to determine both the timing and amplitudes of eustatic change for this interval with greater confidence than has hitherto been possible (Kominz and Pekar, 2001). Although comparable constraints also exist for Pleistocene sea-level change, from deep-marine oxygen isotope data (Kamp and Turner, 1990), the Oligocene is better suited for investigating the relationship between eustasy and patterns of sedimentation because amplitudes and rates of sea-level change were comparatively modest, and the stratigraphic record of those changes is more complete. In comparison, the Pleistocene record tends to be fragmentary (e.g., Carey et al., 1998).

This paper makes use of stratigraphic data and eustatic interpretations that are described more fully elsewhere (Kominz and Pekar, 2001) to tackle a simple question, but one with far-reaching implications for sedimentary geologists. What are the temporal relationships among eustatic change, the development of unconformity-bounded sequences, and the internal stratigraphic elements of sequences? It has long been assumed that sequence boundaries develop during times of most rapid eustatic fall (inflection points; e.g., Pitman, 1978; Haq et al., 1987; Posamentier et al., 1988; Vail et al., 1991). However, in settings such as the New Jersey margin during the Oligocene, when the rate of eustatic fall at times greatly exceeded the rate of tectonic subsidence, it might alternatively be expected either that lowstand sedimentation would begin early during a eustatic fall (a phase lead; Reynolds et al., 1991) or, in the absence of lowstand development, that renewed onlap against the sequence boundary would be delayed until sea level had fallen to close to its minimum level (a phase lag). This study for the first time documents systematic phase lags. Our records also show that stratigraphic condensation during times of maximum flooding significantly postdates times of most rapid eustatic rise.

SEQUENCE ARCHITECTURE, LITHOFACIES, AND AGE CONTROL

Detailed analysis of lithofacies, biofacies, and chronology from eight boreholes in the New Jersey Coastal Plain led to the identification of eight Oligocene sequences and interpretation of intrasequence facies variations (Pekar, 1999). The sequences are arranged laterally rather than stacked vertically, as a result of progradation across a starved carbonate ramp (Fig. 1; Pekar et al., 2000).

Sequence boundaries are recognized in boreholes according to criteria summarized in Pekar (1999): the presence of significant hiatuses, local evidence for abrupt base-level lowering, and offlap-onlap geometry implied by a comparison of high-resolution chronology in adjacent boreholes (Kominz and Pekar, 2001). Condensed sections are typically marked by at least one of the following: high concentrations of authigenic glauconite sand (an indicator of low terrigenous input; McRae, 1972); abundant benthic foraminifers, with peak species abundances of Uvigerinids; and a change from deepening- to shallowing-upward trends (Pekar, 1999; Pekar and Kominz, 2001). The absence of evidence for upward shoaling or coarsening above sequence boundaries at downdip locations suggests that lowstand units are not present in the boreholes studied.

Gross lithologic variations within each sequence can be summarized with reference to the location of the clinoform rollover in bounding unconformities (Fig. 2). The rollover is the point in a profile at which the shallow shelf portion of a surface steepens into a clinoform. (1) Transgressive sediments are

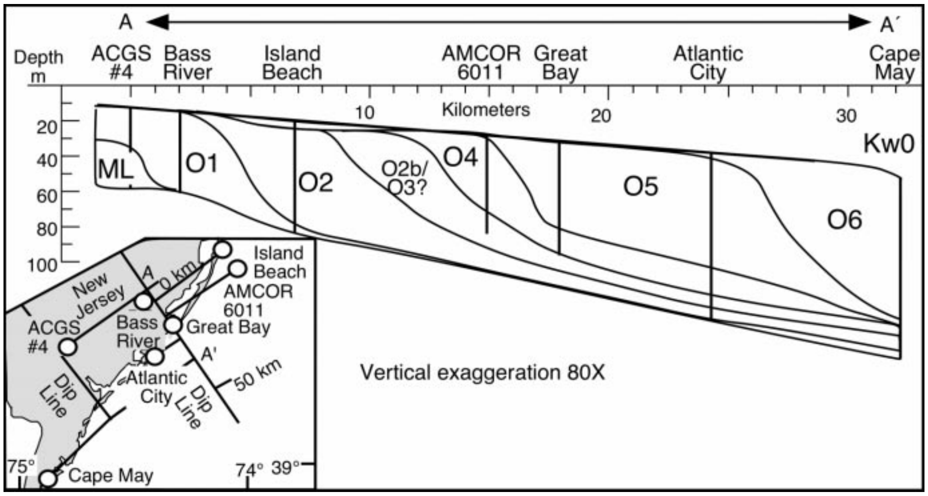

Figure 1. Distribution of New Jersey Oligocene sequences projected onto dip line A-A′, based on reconstructions of stratal geometry from two-dimensional backstripping results (Kominz and Pekar, 2001). Inset map shows locations of boreholes: Leg 150X (Island Beach, Atlantic City, and Cape May); Leg 174AX (Bass River); and U.S. Geological Survey boreholes (AMCOR 6011, ACGS#4, and Great Bay). Dip lines are perpendicular to Cretaceous outcrop, and strike lines are projected from boreholes onto dip profile.

preserved landward of the rollover in the underlying sequence boundary only in the case of the uppermost Oligocene sequence O6, where a basal shell lag is overlain by as much as 6 m of in situ glauconite sand (Pekar et al., 2000). (2) The section deposited seaward of rollover within the underlying sequence boundary is relatively thick (40–70 m), and includes both transgressive and regressive sediments. The transgressive part ($<$10 m thick) consists of a basal shelly glauconite sand that in some cases fines upward into a clayey glauconite sand. The regressive portion of each sequence is composed of silt overlain by glauconitic fine to coarse quartzose sand. (3) Farther seaward, beyond the rollovers in both underlying and overlying boundaries, each sequence thins to $<$10 m and consists of interstratified clayey glauconite sand, glauconitic clay and silt, and minor glauconitic fine quartzose sand.

Age control for New Jersey strata was obtained by an integrated approach using Sr isotope chemostratigraphy, planktonic foraminiferal biostratigraphy, nannofossil biostratigraphy, and limited magnetostratigraphy (Pekar et al., 2000). This approach results in absolute uncertainties of $\pm$0.3 to $\pm$0.7 m.y. for individual age estimates. However, the combination of this chronology with sequence stratigraphy provides age estimates with a relative precision of $\sim\pm$0.1 m.y (Pekar et al., 2000; Kominz and Pekar, 2001). This high precision was achieved by correlating sequence boundaries and condensed sections interpreted at the eight sites and by estimating sedimentation rates for lithologies above and below these surfaces on the basis of rates determined from correlation of five parasequences in the Cape May borehole to five 400 k.y. cycles from isotopic records from ODP Site 929 (Pekar, 1999). The Berggren et al. (1995) time scale is used throughout.

RELATIONSHIP BETWEEN SEQUENCE DEVELOPMENT AND EUSTASY

Lower to mid-Oligocene sequence boundaries (33.8–28.0 Ma) are associated with comparatively long hiatuses (0.3–0.6 m.y.). This limits the resolution with which boundary ages can be compared with eustatic timing (Fig. 3). In contrast, the best constraints on phase relationships are provided by three upper Oligocene sequences (28.0–23.8 Ma). These are bounded by surfaces associated with hiatuses of $<$0.3 m.y.

The age range of preserved sediments in sequences O4 to the base of Kw0 (upper Oligocene to lowermost Miocene) varies in dip profile. Landward of the rollover in the underlying sequence boundary, sedimentation appears to have resumed after the eustatic low and to have ceased close to the eustatic high (sequence O6 at Atlantic City and Island Beach; Fig. 3). This finding is similar to what is observed in lower Miocene sequences at onshore sites in both New Jersey and Maryland (Kidwell, 1997; Miller et al., 1997), where preserved sediments are also predominantly transgressive. Seaward of the rollover of the underlying sequence boundary, sequences are considerably more complete, representing as much as 80% of the eustatic cycle (e.g., sequence O6 at Cape May; Fig. 3). Typically, sedimentation resumed progressively later in a downdip direction (downlap in Fig. 2), and continued later in the same direction beneath the overlying sequence boundary (offlap in Fig. 2). For example, at Great Bay, which is located immediately seaward of the rollover in the sequence boundary beneath sequence O5, sedimentation resumed near the eustatic low and continued until approximately midway through the next eustatic fall (26.4 Ma). In comparison, at Atlantic City, sequence O5

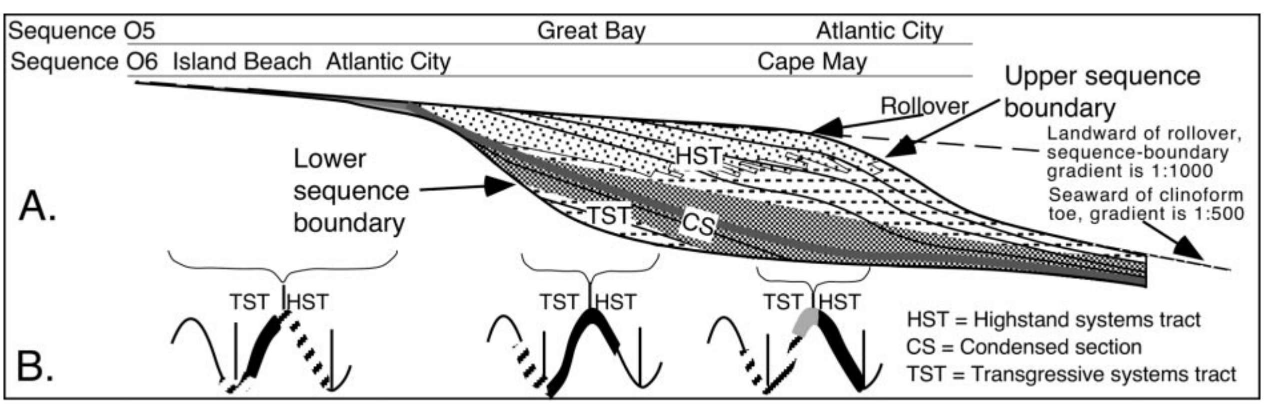

Figure 2. A: Conceptual architecture of New Jersey Oligocene depositional sequence, with borehole locations appropriate for sequences O5 and O6. B: Stratigraphic interval preserved at various locations along dip profile within sequence, as compared with eustasy. Black segments represent preserved sediment; gray segment represents uncertainty in time of resumption of sedimentation between Cape May and Atlantic City; striped segments represent nondeposition and/or erosion (sequence-boundary development).

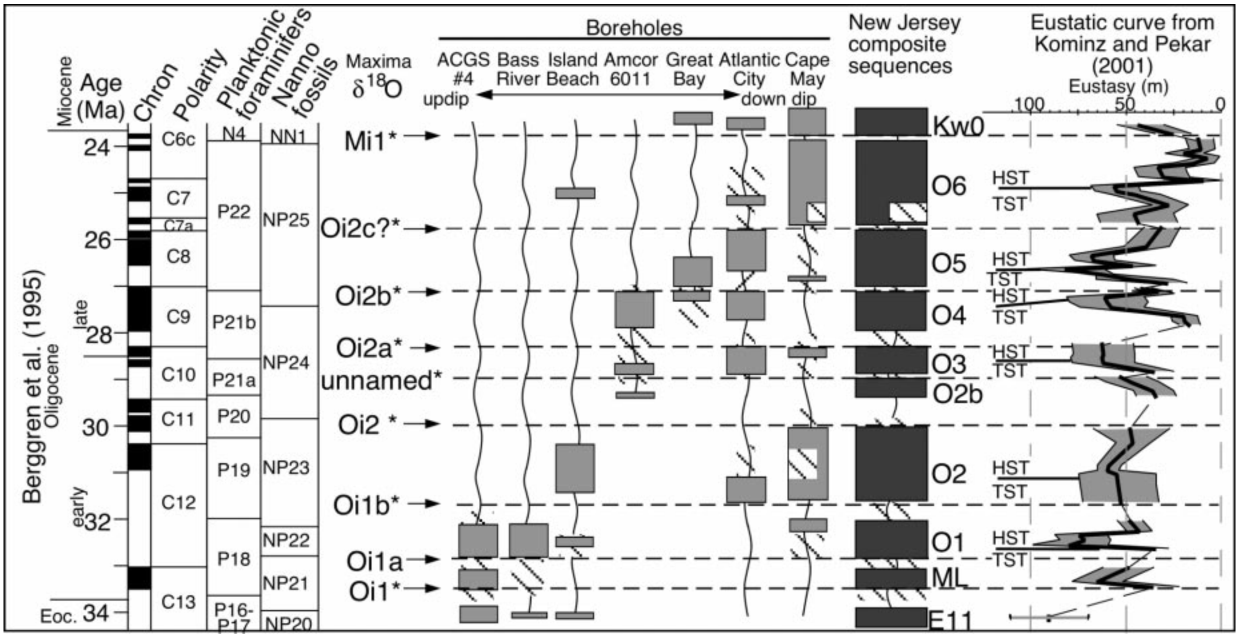

Figure 3. Oligocene stratigraphic record as function of time for individual boreholes, and as composite, compared with interpreted eustatic changes (Kominz and Pekar, 2001) and oxygen isotope events (inferred glacio-eustatic lowerings; Miller et al., 1991; Pekar and Miller, 1996). Isotope events with asterisk were also recognized by Abreu and Anderson (1998). Filled boxes indicate preserved sediment; white areas indicate hiatuses; diagonal ruling indicates age uncertainty. Abbreviations for sequences: E11, oldest Eocene (Browning et al., 1996); ML and O1–O6, Oligocene; Kw0, oldest Miocene (Miller et al., 1997). Other abbreviations as in Figure 2. In eustatic interpretation, bold line represents best estimate and gray shaded area represents spatial resolution (Kominz and Pekar, 2001). Eustatic estimates are relative and not tied to present-day sea level.

sedimentation began more than one-quarter of a cycle later, commencing late in the eustatic rise, and continued to the eustatic minimum (25.8 Ma). At Cape May in sequence O6, a brief interval of initially slow sedimentation (~0.8 m.y; 1.4 m/m.y.) recorded by an extremely thin basal unit (<1 m) was followed during the eustatic rise by more rapid sedimentation (>5 m/m.y). Taken together, these data imply that upper Oligocene sequence boundaries developed close to eustatic lows, a lag of about one-quarter of a cycle compared with times of most rapid eustatic fall (inflection points). Condensed sections are similarly offset from times of most rapid eustatic rise, to near eustatic highs (Figs. 3 and 4).

A different pattern of sedimentation is observed in lower Oligocene sequence O2; sedimentation commenced initially at downdip locations (e.g., at Atlantic City and Cape May; Fig. 3). It is not known whether the sediments are lowstand or transgressive deposits owing to uncertainties in water depth (and in trends in water-depth change) in deep-shelf facies.

DISCUSSION

Offlap at Oligocene sequence boundaries in New Jersey is thought to be due primarily to bypassing during progradation, and not to short-lived truncation of initially sigmoidal clinoforms (see also Christie-Blick, 1991; Christie-Blick and Driscoll, 1995; cf. Posamentier et al., 1988). This interpretation is supported in this case by the absence of evidence for lowstand sedimentation and by the compositional contrast between relatively thick (30–50 m) quartzose highstand sediments and thinner (<10 m), more glauconitic, silty and clayey transgressive sediments (Fig. 2), a contrast that precludes significant erosion during transgression. Although it is possible that incised valleys were simply not intersected in available boreholes through upper Oligocene sequences, it is unlikely that significant thicknesses of lowstand sediments are present nearby, but not yet sampled. This is because high-resolution age control shows that at specific sequence boundaries, the oldest transgressive sediments above are only slightly younger than the youngest highstand sediments below (as little as ~100 k.y.).

Available evidence suggests that bypassing of the shallow shelf inboard of the clinoform rollover was controlled mainly by marine processes, specifically wave action, and was not the result of subaerial exposure (see also Nummedal et al., 1993; Steckler et al., 1999). With the possible exception of the earliest Oligocene eustatic fall at 33.5–32.6 Ma (the largest of the late Paleogene), there is no evidence that rollovers were exposed. Apparently, the critical conditions needed for the reorganization of sedimentation patterns and onset of lowstand deposition (particularly the development of point sources) did not arise.

The lag in the development of condensed sections is thought to be related to low sediment input (Steckler et al., 1999). We infer that during times of eustatic rise, sediments would have become trapped in estuaries and

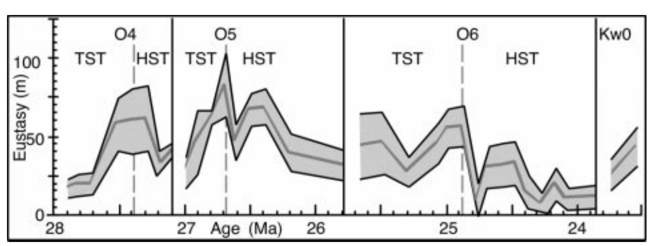

Figure 4. Eustatic curve for late Oligocene through earliest Miocene (from Kominz and Pekar, 2001). For each sequence, deposition continued through most of sea-level fall; sequence boundaries at 27.1 Ma, 25.8 Ma, and 23.8 Ma developed near eustatic lows. These results indicate phase lag of as much as one-quarter of cycle with respect to time of most rapid eustatic fall. Bold line represents best estimate and gray shaded area represents spatial resolution. Vertical lines indicate ages of sequence boundaries (black) and condensed sections (gray dashed). Abbreviations as in Figure 2.

barrier islands, and regression of the shoreline would have begun only when the sediment supply was sufficient to fill available nearshore accommodation. We speculate that the deep shelf and parts of the shallow shelf remained sediment starved for some additional span of time that is not well determined, but was probably not more than a few hundred thousand years (Fig. 4).

Neither type 1 nor type 2 terminology is applicable to the Oligocene sequences of New Jersey (e.g., Posamentier et al., 1988). These sequences differ from the supposed end members in terms of overall architecture and both mechanisms and timing of sequence boundary development.

CONCLUSIONS

Oligocene sequences at the New Jersey margin are arranged laterally rather than stacked vertically, and sediment accumulation is primarily seaward of the clinoform rollover in each underlying sequence boundary. In spite of well-developed offlap and rates of eustatic fall that at times greatly exceeded the rate of subsidence, lowstand deposits are poorly developed or absent. The sequence boundaries for which the best age control is available (<0.3 m.y.), those of late Oligocene age, developed close to eustatic lows, a phase lag of about one-quarter of a cycle compared with times of most rapid eustatic fall (inflection points). Condensed sections are similarly offset from times of most rapid eustatic rise, to near eustatic highs. Offlap in the sequences studied is thought to be due primarily to bypassing during progradation, and controlled by wave action and other marine processes rather than by subaerial exposure. In the region of study, the critical conditions needed for the deposition of lowstand units, including the development of point sources, did not arise. This and the lag in the development of condensation during sea-level rises are thought to be related to low sediment input. Our results do not imply that comparable lags characterize all sequences, but they do call into question the widely held assumption that sequence architecture is related in a simple way to eustatic change.

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