Late Cretaceous chronology of large, rapid sea-level changes: Glacioeustasy during the greenhouse world

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ABSTRACT

We provide a record of global sea-level (eustatic) variations of the Late Cretaceous (99–65 Ma) greenhouse world. Ocean Drilling Program Leg 174AX provided a record of 11–14 Upper Cretaceous sequences in the New Jersey Coastal Plain that were dated by integrating Sr isotopic stratigraphy and biostratigraphy. Backstripping yielded a Late Cretaceous eustatic estimate for these sequences, taking into account sediment loading, compaction, paleowater depth, and basin subsidence. We show that Late Cretaceous sea-level changes were large (>25 m) and rapid ($\ll$1 m.y.), suggesting a glacioeustatic control. Three large $\delta^{18}O$ increases are linked to sequence boundaries (others lack sufficient $\delta^{18}O$ data), consistent with a glacioeustatic cause and with the development of small (<10^6 km^3) ephemeral ice sheets in Antarctica. Our sequence boundaries correlate with sea-level falls recorded by Exxon Production Research and sections from northwest Europe and Russia, indicating a global cause, although the Exxon record differs from backstripped estimates in amplitude and shape.

Keywords: eustasy, sequence stratigraphy, New Jersey Coastal Plain, Late Cretaceous, backstripping.

INTRODUCTION

Drilling by the Ocean Drilling Program (ODP) has established the number and timing of late Eocene–Miocene sequences boundaries and has demonstrated that these boundaries correlate with $\delta^{18}O$ increases. This links their formation with glacioeustatic falls and ice-volume increases (e.g., Miller et al., 1998a). Large (tens of meters), rapid (occurring in <1 m.y.) eustatic changes have also been reported for the Triassic to early Cenozoic (ca. 250–42 Ma; e.g., Haq et al., 1987; Hallam, 1992). This poses an enigma to geologists and climatologists. The growth and decay of continental-scale ice sheets is the only known mechanism for producing large, rapid eustatic changes (Pitman and Golovchenko, 1983), yet warm high latitudes have been well documented for the Mesozoic and early Cenozoic, and this interval is generally assumed to be ice free (e.g., Huber et al., 2002). Possible solutions to this apparent paradox include the following: (1) Triassic to early Eocene sequences were restricted to local basins and reflect regional or local signals rather than eustasy. (2) Eustatic falls during the Triassic to early Eocene were small. A 10 m eustatic change over 1 m.y. can be explained by several mechanisms (e.g., Pitman and Golovchenko, 1983). For example, Milankovitch-scale sea-level changes during the Late Triassic have been attributed to variations in storage of groundwater and lakes; this mechanism can explain 5–8 m of total change (Jacobs and Sahagian, 1993). (3) Intermittent ice sheets were present throughout much of the Triassic–early Eocene (Frakes and Francis, 1988; Stoll and Schrag, 1996; Miller et al., 1999a; Price, 1999). (4) Some unrecognized mechanism caused large, rapid eustatic changes during the Triassic–Eocene greenhouse world.

The New Jersey passive continental margin provides an excellent location for sea-level studies due to quiescent tectonics (Kominz et al., 1998), well-developed Late Cretaceous–Miocene sequences (unconformity-bounded units), and biostratigraphic and Sr isotopic age control (Miller et al., 1998a). ODP Leg 174AX drilling at Bass River and Ancora, New Jersey, identified 11 marine Upper Cretaceous sequences (Miller et al., 1998b, 1999b); we tentatively recognize three additional sequences (Navesink II, Merchantville I, and Merchantville II; Fig. 1). Sequence boundaries are recognized by physical stratigraphy and age breaks. Upper Cretaceous coastal plain sections generally follow a predictable transgressive-regressive pattern (e.g., Miller et al., 1998a) consisting of: (1) a basal unconformity; (2) a thin lower glauconite sand (transgressive systems tract); and (3) a coarsening-upward regressive succession of medial silts and upper quartz sands (highstand systems tract). Lowstand deposits are usually absent.

METHODS

We obtained a firm chronology by integrating biostratigraphic and Sr isotopic ages on age-depth plots (http://www.rci.rutgers.edu/~kgm/age-depth) using the Gradstein et al. (1994) time scale. Sr isotopic age estimates were obtained from mollusk and foraminifer shells. Sr-isotopic ages were assigned using two new linear regressions (http://www.rci.rutgers.edu/~kgm/Cretaceous_Sr-standard) developed for upper Coniacian through Maastrichtian sections, with an age error of ±1.0 m.y. (i.e., the external precision of ~0.000020 divided by the slopes of the regressions of ~0.000020/m.y.). Integration of Sr isotopic and biostratigraphic data sets provides age resolution of ~±0.5 m.y. for the middle Campanian to earliest Tertiary (ca. 80–64.5 Ma), although ages are estimated to one significant decimal place (Table 1) to maintain consistency. The chronology is less certain for the early Campanian. Diagenesis affects early Campanian and older Sr isotopic age estimates at Bass River. At both sites, the upper Turonian–Santonian nonmarine Magothy I and II sequences are dated primarily using pollen biostratigraphy. Moderate (±1 m.y.) resolution is provided by biostratigraphy for the Cenomanian–Turonian sections.

We provide a eustatic estimate (Fig. 1) based on one-dimensional backstripping of the Bass River and Ancora records (e.g., Kominz et al., 1998). Backstripping progressively removes the effects of sediment accumulation and loading, including the effects of compac-

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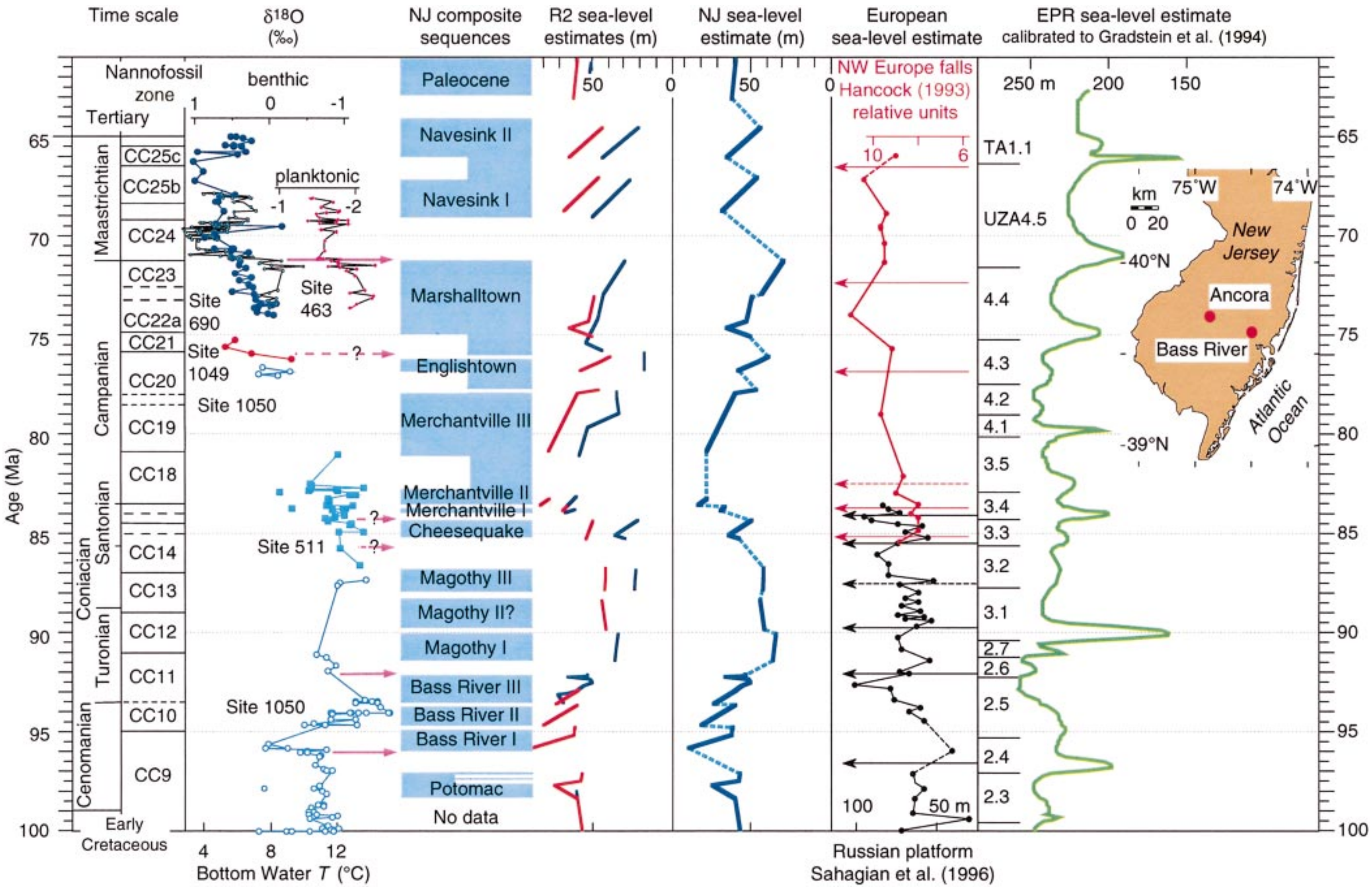

Figure 1. Comparison of Late Cretaceous, deep-sea oxygen benthic foraminiferal $\delta^{18}O$ records (Sites 463 and 690, Barrera and Savin, 1999; Site 511, Huber et al., 1995; Sites 1049 and 1050, Huber et al., 2002), planktonic foraminiferal $\delta^{18}O$ records (Site 463, Barrera and Savin, 1999), New Jersey (NJ) composite sequences (derived from age-depth plots; Miller et al., 2003), backstripped R2 eustatic estimates for Bass River (blue discontinuous lines) and Ancora (red discontinuous lines), and our best estimate of eustatic changes derived from R2 curves (dark blue indicates portions of curve constrained by data, light blue indicates portions inferred), relative sea-level curve from northwestern Europe (red continuous line; Hancock, 1993) and backstripped record from Russian platform (black continuous line; Sahagian et al., 1996), and Exxon Production Research (EPR) eustatic estimate (green line; Haq et al., 1987). Pink arrows indicate positive $\delta^{18}O$ inflections (inferred cooling and/or ice-volume increases). For composite: blue boxes indicate time represented, white areas indicate hiatuses, and thin white lines indicate inferred hiatuses. Arrows are drawn through inflection points of European and Russian platform records. Thin, horizontal dashed lines are drawn at 5 m.y. increments. CC—nannofossil zones. Inset map shows location of boreholes.

tion and paleowater depth from basin subsidence. By modeling thermal subsidence on a passive margin, the tectonic portion of subsidence can be assessed and a eustatic estimate can be obtained (Kominz et al., 1998). The backstripped Late Cretaceous records (R2) from Bass River and Ancora are similar (Fig. 1), indicating that we have successfully removed any differential effects of thermal subsidence, loading, and water-depth variations.

RESULTS

Comparison of the ages of sequences and hiatuses shows (Fig. 1; Table 1) the following: (1) Deposition was continuous across the Cretaceous-Tertiary (K-T) boundary (Olsson et al., 2002); sequence boundaries are associated with an early Danian hiatus (biochron P1b; 63–64.5 Ma) and a major hiatus (~2.2 m.y.; 69–71.2 Ma) separating the Maastrichtian Navesink I sequence from the late Campanian Marshalltown sequence. (2) A nearly complete Santonian–Campanian section contains six sequences separated by brief hiatuses $\ll$1 m.y. long. The Santonian Cheesequake sequence is separated from the Magothy III sequence by a 1.5 m.y. hiatus (85.2–86.7 Ma). (3) The upper Turonian–Coniacian Magothy Formation may represent two or three sequences; differentiation of the Magothy II (pollen zone V) at Ancora from the Magothy I (zone IV) at Bass River is based on pollen data. (4) A major middle Turonian sequence boundary separates the Magothy I from the Bass River III sequence. (5) Two middle-late Cenomanian (Bass River I and II) sequences occur only at Ancora; Bass River did not penetrate these strata; a major middle Campanian sequence boundary separates the Bass River sequences from the Potomac Group. (6) Lowermost Cenomanian and older Potomac Group strata are not discussed due to poor age control.

The sequence boundaries at the base of the Navesink, Marshalltown, upper Englishtown, Merchantville I, Cheesequake, Magothy III, Magothy I, and Bass River I sequences are regional in extent, occurring not only in both boreholes (Fig. 1), but throughout the Atlantic Coastal Plain (e.g., Owens and Gohn, 1985). The significance of other potential sequence boundaries (Navesink II, Merchantville II, Merchantville III, Magothy II, Bass River I, and Bass River II) requires verification.

We provide the first fully backstripped sea-level estimates for the entire Late Cretaceous (Fig. 1). Our backstripping of Late Cretaceous onshore New Jersey sequences yields sea-level amplitude changes of >25 m in <1 m.y. (Fig. 1). We do not capture the full eustatic amplitude across major hiatuses (light blue lines, Fig. 1); therefore, the actual lowstands are

TABLE 1. AGES OF SEQUENCES AT BASS RIVER AND ANCORA COMPARED TO EXXON PRODUCTION RESEARCH AND EUROPEAN ESTIMATES

NJ Sequence	Bass River age (Ma)	Ancora age (Ma)	Hiatus age (Ma)	EPR Sequence	EPR old/new age	Northwestern Europe	Russian platform	Matthews and Frohlich (2002)
Paleocene			63.0–64.5					
Navesink II?	64.5–66	64.5–66	66–67	TA1.1	68/67	66–67	NR	67.45
Navesink I	67.1–69	67–68.7	69–71.2	UZA4.5	71/70.5	71.2–74	NR	70.69
Nav I-II (alt.)	64.5–69	64.5–68.7	69–71.2					
Marshalltown	71.2–75.7	73–75	75–76	UZA4.4	75/75	75.5–79	NR	75.54
Marshalltown		71.8–76	76					
Englishtown	75.8–76.7	76–76.7	76.7–77.8	UZA4.3	77.5/78.5	NR	NR	77.15
Englishtown (alt.)		76–77.8	77.8					
Merchantville II	77.8–81	77.8–80.8	81.0–83.1	UZA4.1	79/80	NR	NR	79.98
Merchantville II	83.1–83.7	83.2–83.5	83.5	UZA3.5	80/82.5	NR	NR	82
Merchantville I	83.7–83.9	83.5–83.8	84–84.3	UZA3.4	85/84	82–83	84	84.83
Merch I-III (alt.)	76.9–83.9	77.8–83.8	83.9–84.3					
Cheesequake	84.3–85.2	84.3–85.2	85.2–86.7	UZA3.3	87.5/85.5	85–85.5	85.5	86.85
Magothy III	86.7–87.8	86.7–87.8	87.8–88.3	UZA3.2	88.5/87.5	NR	87.5	88.87
Magothy II	NR	88.3–89.8	89.8–90	UZA3.1	90/90.5	NR	89.8	
Magothy I	90–91.4	NR	91.4–92.1	UZA2.7	90.5/91	NR	92	91.7
Bass River III	92.1–93.5	92.8–93.5	93.5	UZA2.6	91/92	NR	NR	93.72
Bass River II	NR	93.5–94.6	94.6	UZA2.5	93/95	NR	NR	
Bass River I	NR	94.6–95.8	95.8–97	UZA2.4	94/97	NR	96.6	95.74
Potomac	NR	97–98.3	>98.3	UZA2.3	95.5/99.5	NR	99.7	

Note: NR = not resolved/recovered; alt. = alternate (conservative) age model; where only one number is given for hiatus age, there is no discernable time gap and this is the best age. NJ is New Jersey; EPR is Exxon Production Research.

probably lower than our estimates (Fig. 1). The most prominent features of our eustatic estimate are three major rises ca. 69, 76, and 84 Ma; these represent major flooding events expressed in the development of widespread glauconite deposition on this and other passive margins. The Campanian-Maastrichtian boundary sea-level fall and subsequent rise at 69 Ma has been documented as the most obvious event in the >100 m.y. record of the U.S. Atlantic Coastal Plain (Miller et al., 1999a) although our record indicates that the middle Santonian event ca. 84 Ma (basal Merchantville I) appears to be just as large.

The ages of New Jersey sequences are remarkably similar to the global compilation of Exxon Production Research data (Haq et al., 1987) and Late Cretaceous events in northwest Europe (Hancock, 1993) and Russia (Fig. 1; Sahagian et al., 1996). Of 16 Late Cretaceous to earliest Paleocene eustatic falls reported by Exxon Production Research (Haq et al., 1987), 15 show correlative events (within ±0.5 m.y.) in New Jersey (Fig. 1; Table 1). In northwest Europe (Hancock, 1993), five to six Late Cretaceous sequences younger than ca. 85 Ma appear to correlate with sequences in New Jersey (Fig. 1); age control and the lack of northwestern Europe backstripping preclude closer comparison. A backstripped early Late Cretaceous eustatic estimate from the Russian platform (Sahagian et al., 1996) provides an excellent comparison, with six events correlating with New Jersey; two minor New Jersey events are not discernible in the Russian platform record. Correlation with the U.S. Western Interior Seaway is complicated by compressional tectonics in that region. The timing of eustatic falls in New Jersey compares remarkably well with those theoretically predicted from Milankovitch forcing by Matthews and Frohlich (2002) (Table 1). The correspondence among records indicates that large, rapid eustatic changes occurred during the supposedly ice-free Late Cretaceous.

Although the ages of Exxon eustatic falls are approximately correct (Table 1), eustatic estimates from New Jersey and the Russian platform suggest that Exxon amplitudes are too high by a factor of two. While we do not capture the full amplitude of falls, other studies have also shown that the Exxon amplitudes are about two times too high (Isern et al., 2001; Kominz and Pekar, 2001). The Exxon record also differs in shape from backstripped eustatic estimates. For example, the extremely large middle Turonian and middle Maastrichtian events reported by Exxon are in the backstripped record, while the major flooding events at 69, 76, and 84 Ma in the New Jersey record are less important in the Exxon Production Research record (Fig. 1).

COMPARISON WITH $\delta^{18}O$ RECORDS

In the Oligocene–Holocene icehouse world, ice volume, sea level, and $\delta^{18}O$ variations occurred in lockstep. In the greenhouse world, the warm deep-water temperatures and relatively small ice volumes preclude any definitive statement about ice volume based solely on the $\delta^{18}O$ record. However, the rapidity and magnitude of sea-level changes calculated from the New Jersey margin record imply glacioeustatic variations that require $\delta^{18}O$ changes. Our approach here is to test these predictions.

The sequence boundary spanning the Campanian-Maastrichtian boundary (Fig. 1) can be linked to $\delta^{18}O$ increases that occurred in deep-sea benthic and low-latitude planktonic foraminifera (Fig. 1; Barrera and Savin, 1999). Miller et al. (1999a) argued that this event resulted from the growth of a transient ice cap (equivalent to ~40% the volume of the present-day East Antarctic ice cap) that caused ~25 m glacioeustatic falls at 71.2 Ma.

Although reasonable coverage has been available for the late Campanian to early Maastrichtian (Barrera and Savin, 1999), scarce $\delta^{18}O$ data limit detailed evaluation of links between other Late Cretaceous global $\delta^{18}O$ records and sequences. Huber et al. (2002) began to rectify this problem by providing improved benthic foraminiferal $\delta^{18}O$ coverage from the Cenomanian–Turonian and the first data available for the middle Campanian (Fig. 1), although there are large $\delta^{18}O$ data gaps in the early-middle Campanian and late Turonian to Coniacian.

Within these limitations, comparisons between Late Cretaceous sequences and $\delta^{18}O$ records are intriguing (Fig. 1), further suggesting small ice sheets in this greenhouse world. A major middle Cenomanian sequence boundary (see also Gale et al., 2002) between the Potomac and Bass River I sequences correlates with a large benthic foraminiferal $\delta^{18}O$ increase (>1.0‰); a middle Turonian sea-level fall (Bass River III–Magothy sequence boundary) may correlate with an ~1.0‰ $\delta^{18}O$ increase, although additional data are needed to determine the precise timing of the increase (Fig. 1). Other Late Cretaceous sequence boundaries lack sufficient $\delta^{18}O$ data to test a link. The $\delta^{18}O$ record is consistent with ice-volume variations, but alone it provides insufficient evidence for sea-level variations driven by the waxing and waning of ice sheets. Nevertheless, based on the rapidity and amplitude of sea-level changes observed in New Jersey and their links to the $\delta^{18}O$ record, we suggest that the glacial history of Antarctica must be reevaluated.

RECONCILIATION OF GLACIOEUSTASY AND WARM POLES

We reconcile the records of apparent warm high latitudes during the Late Cretaceous with glacioeustasy by proposing that ice sheets were restricted in area in Antarctica, ephemeral, and paced by Milankovitch forcing. Modeling evidence (DeConto and Pollard, 2003) indicates that a 5–10 $\times$ 10^6 km^3 ice sheet could have developed when atmospheric CO_2 fell below a threshold that was three times that for middle Cenozoic configurations. This ice sheet would not have reached the Antarctic coast, hence explaining relative warmth in coastal Antarctica, but it would have significantly influenced sea level by as much as ~25 m and global δ^{18}O to 0.25‰ (see Fig. 3B of DeConto and Pollard, 2003, for a 10 $\times$ 10^6 km^3 ice-sheet scenario). The ~1‰ δ^{18}O increases ca. 71.2, 92–93, and 96 Ma cannot be entirely attributed to ice-volume changes because this would require ice sheets larger than those of modern times. The modeling results of DeConto and Pollard (2003) suggest that a maximum of 25% of the δ^{18}O signal may be attributed to ice (~25 m of eustatic lowering), with ~75% attributed to deep-water cooling of 3–4 °C (which by itself would cause only 3–4 m of eustatic lowering). Unlike the Oligocene and younger icehouse world, these ice sheets probably only existed during short intervals of peak Milankovitch forcing, and the continent was ice free during much of the greenhouse Late Cretaceous to middle Eocene. Modeling studies of Matthews and Frohlich (2002) predicted glacioeustatic falls from Milankovitch orbital solutions that are remarkably similar to those we obtained from the New Jersey margin (Table 1). The alternative to invoking Late Cretaceous ice sheets is that global sea-level changes were paced by as yet undefined mechanisms, because none of the other hypothesized mechanisms—temperature effects, storage in lakes, deep-water changes, groundwater, or sea ice—can explain the observed 20–30 m changes in $<$1 m.y.

Thus, because our data require that large, rapid sea-level variations occurred in the Late Cretaceous greenhouse world, we must conclude that either moderate-sized ice sheets (5–10 $\times$ 10^6 km^3) paced sea-level changes during this time, or that our understanding of causal mechanisms for global sea-level change is fundamentally flawed.

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