SEA LEVEL CHANGE, LAST 250 MILLION YEARS

Introduction

One of the most fundamental geological observations has been that the seas once inundated large areas of the Earth's surface that are now exposed on land. Early observers attributed these marine incursions to one or multiple "Noachian" floods, but empirical science prevailed as uniformitarian concepts were applied to the stratigraphic record. Charles Lyell (1830) recognized that changes in sea level due to volcanic activity were responsible for the submergence and subsequent emergence of the temple at Serapis near Naples, Italy (see discussion by Gould, 1999). Observing cycles of shallow-water sedimentation across Europe, Lyell reasoned that apparent rises in sea level could explain the flooding of the continents (geologists call these "transgressions") and the subsequent retreat of the seas (called "regressions"). For over a century after Lyell's work, geologists mapped these advances and retreats of the sea, noting that during intervals such as the middle Cretaceous (ca. 80 MyBP), much of the continents were inundated, whereas at other times, such as today, sea level was much lower. Geologists have equated these transgressions and regressions with global sea level (or "eustatic") changes.

Transgressions and regressions may be related to eustatic sea level changes, but they also are caused by processes of subsidence or uplift, and changes in sediment supply. These processes are revealed by 20th century tide gauge data that indicate a global sea-level rise of $\sim$1.5–2 mm yr^{-1} (Church et al., 2001), due to the effects of ocean warming and melting of glaciers. However, tide gauge data for the mid-Atlantic United States uniformly show a rise of greater than 3 mm yr^{-1}, in part due to regional subsidence (Psuty and Collins, 1986). Although sea level is rising globally, *relative sea level* (in this region a term encompassing both the effects of subsidence/ uplift and eustatic change) is rising much faster. High sediment supply can cause regression even during a relative sea level rise. For example, relative sea level is rising rapidly in the Mississippi Delta region due to the effects of global sea-level rise and rapid regional subsidence. Consequently, this region is generally experiencing a rapid transgression. However, near the mouth of the Mississippi, the high supply of sediments results in regression as the delta builds upward and into the Gulf. These modern examples illustrate the differences between a eustatic rise, a relative rise in sea level, and a marine transgression.

Global sea level has risen and fallen many times in response to growth and decay of the Northern Hemisphere Ice Sheets that have dominated the last 2.5 Myr ("the Ice Ages"). Drilling of submerged reef terrace records off Barbados (Figure S3) and Tahiti provided Rosetta Stone, which showed a 120 m lower sea level than present during the Last Glacial Maximum (Fairbanks, 1989; Bard et al., 1996). Uplifted reef terrace records (corrected for long-term uplift) have extended global sea-level estimates back to 130,000 years ago (Fairbanks and Matthews, 1978; Chappell et al., 1996); however, it has proven difficult to firmly extend reef terrace records further back in time due to dating problems.

Pre-Quaternary sea level change

Oxygen isotope ratios (δ^{18}O) provide a potential means for reconstructing sea-level change over the past 100 Myr. δ^{18}O

values reflect the effects of temperature and ice-volume (hence sea level) changes in the shells of single-celled organisms called foraminifera. By calibrating foraminiferal $\delta^{18}O$ variations to the reef terrace record, geologists can make an estimate of global sea-level changes (Figure S3). However, it is difficult to extend oxygen isotopic sea-level estimates beyond the past million years because the temperature history of the planet prior to this is less well known. In addition, diagenetic alteration potentially overprints Late Cretaceous to early Tertiary $\delta^{18}O$ values (ca. 100–25 MyBP), whereas records older than 100 Myr are typically altered.

Our primary information on sea-level change prior to the Quaternary (>2 MyBP) is derived from stratigraphic records of continental inundation. Transgressions have flooded the continents on roughly 100-Myr timescales (e.g., Sloss, 1963), reflecting changes in the rates of ocean crust production. Finer-scale cycles (1–10 Myr) have been attributed either to sea-level change (Suess, 1885) or to tectonic controls (Sloss, 1963; Stille, 1924; Grabau, 1936). These cycles are observed in the sediment and rock record with deeper water environments representing transgressions and shallower water environments representing regressions.

Studies at Exxon Production Research Company (EPR) revolutionized our view of the stratigraphic record of sea-level change. Sea level falls and tectonic changes both produce erosion surfaces termed "unconformities"; packages of sediments on continental margins bracketed by unconformities are called "sequences." Researchers at EPR made a revolutionary breakthrough in using seismic reflection profiles to identify sequences and then using these sequences to estimate the ages and magnitudes of past sea level changes (Figure S4; Haq et al., 1987; Vail et al., 1977). These estimates proved highly controversial, in part because of the proprietary nature of the data used to construct them and in part because of flaws in the method used to estimate the amplitudes of sea-level change. Nevertheless, more than a decade of studies, described below, have been carried out, validating the general number and timing of eustatic events published by EPR – a landmark achievement. However, estimation of eustatic amplitudes remains one of the thorniest problems in geology.

A large mid-Oligocene (ca. 30–32 MyBP) sea level lowering illustrates problems with estimating amplitudes. Vail et al. (1977) initially concluded that this event comprised over 400 m of global sea level lowering, a remarkably large drop. Geophysical studies showed that the methodology employed in these estimates did not properly account for the effects of basin subsidence and water depth and thus grossly overestimated the amplitudes (see summary in Christie-Blick et al., 1990). A further decade of study by EPR scientists provided an estimate of ∼160 m of lowering for this mid-Oligocene event (Figure S5), an amplitude that still strained credulity. Stable isotopic studies have long suggested amplitudes closer to 30–60 m for this event (e.g., Miller et al., 1985, 1998). Rigorous studies of borehole transects on the New Jersey margin yield an estimate for this event of 50 m (Kominz and Pekar, 2001) using a method called backstripping (see below for definition), and this estimate is probably correct within ±10 m. Despite these recent studies, the amplitude of sea-level change remains one of the poorest constrained boundary conditions of the Earth.

Recognizing that it had the unique ability to provide a global dataset, the international Ocean Drilling Program (ODP), operator of the drillship *JOIDES Resolution*, entered into sea-level research in the 1990s. ODP identified four major goals in sea-level research: (a) test the synchrony of sea-level events in widely separated locations; (b) estimate the amplitude of sea-level changes; (c) evaluate various models that seek to explain the stratigraphic response to sea-level oscillations; and (d) determine the mechanisms that control sea level. To accomplish these goals, a strategy of drilling transects of boreholes on passive margins was adopted.

The New Jersey sea level transect

The New Jersey margin was selected by ODP as an ideal location to begin the investigation of the Late Cretaceous to Cenozoic history of sea-level change because of its rapid sedimentation, tectonic stability, good chronostratigraphic control, and abundant seismic well log and borehole data (Miller and Mountain, 1994). To evaluate sequences and sea-level changes, the "New Jersey Sea-Level Transect" was designed as a series of boreholes from the onshore New Jersey Coastal Plain across the continental shelf to the slope and rise (Figure S5). The transect initially focused on the past 34 Myr (Oligocene-Recent; Miller and Mountain, 1996), a time when large ice sheets waxed and waned, potentially changing sea level by up to 100 m. More recent studies
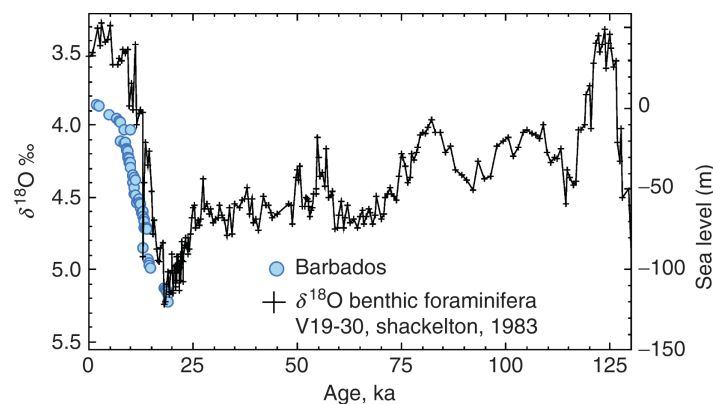
Figure S3 Comparison of the global estimate for sea-level derived from Barbados terraces (Fairbanks, 1989) with deep-sea benthic foraminiferal $\delta^{18}O$ values from Pacific core V19-30 scaled to sea-level assuming 0.11‰/10 m of sea-level change (Fairbanks and Matthews, 1978) (Wright, Miller, Sheridan, unpublished).

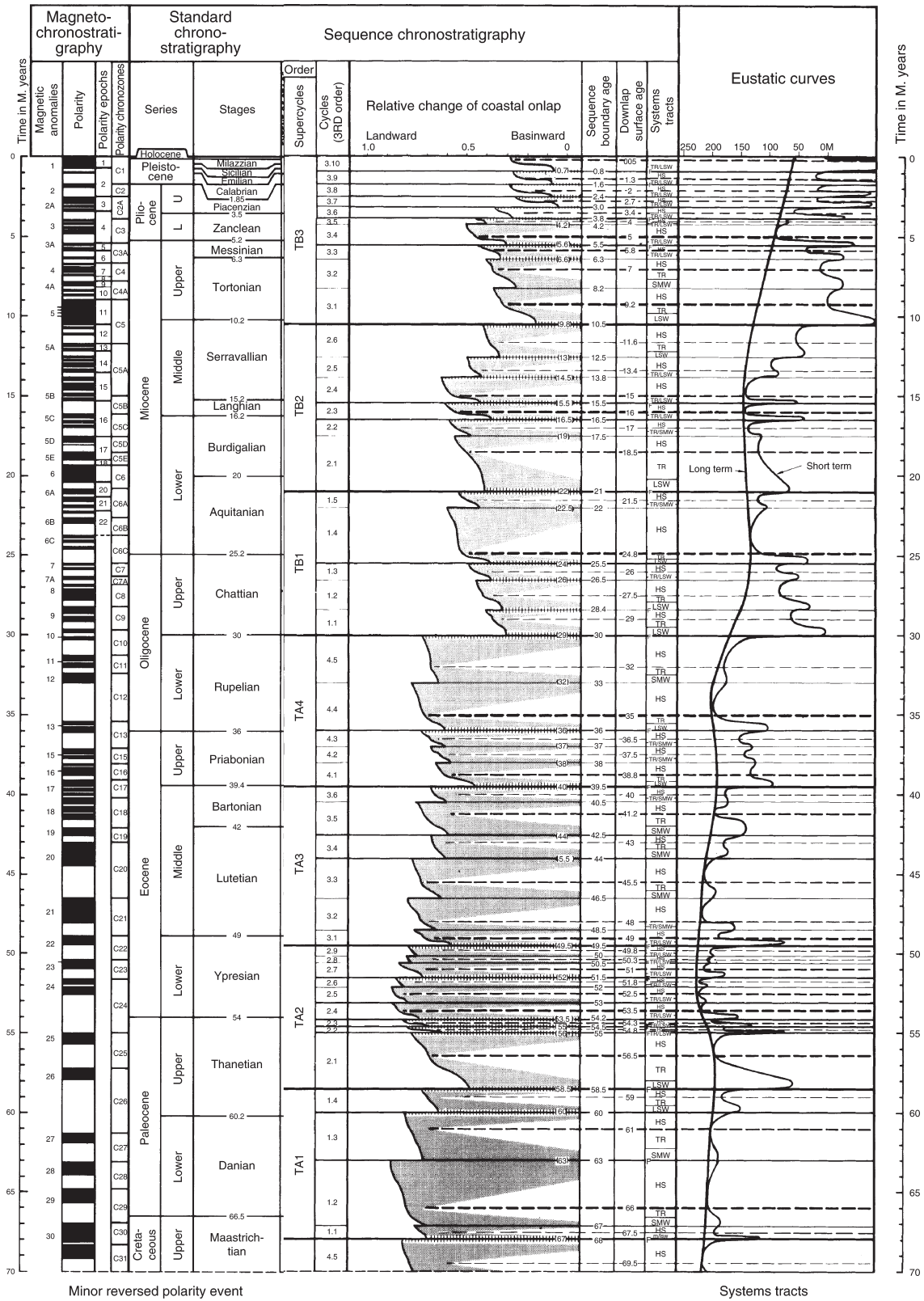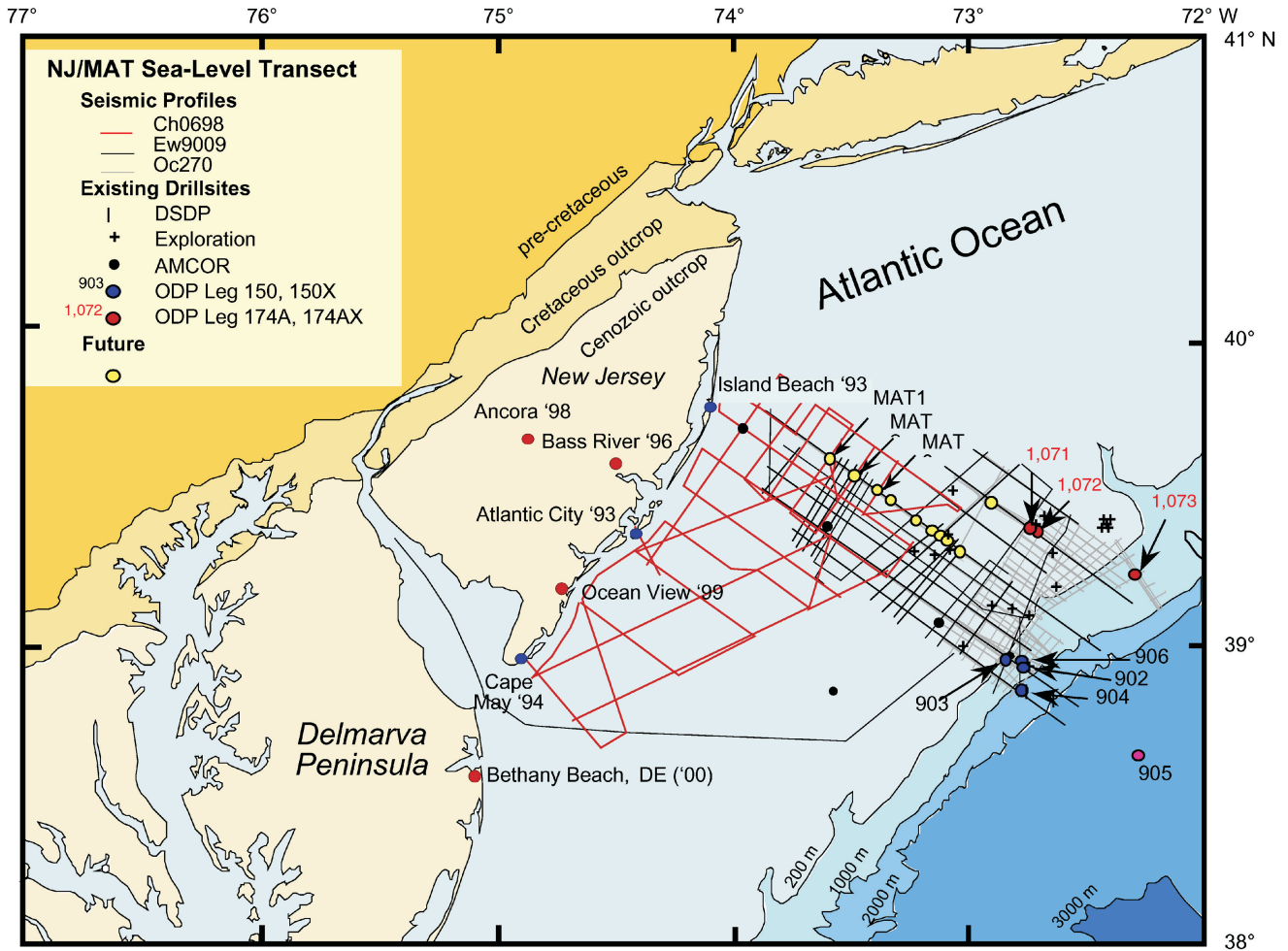**Figure S4** Cenozoic portion of the Haq et al. (1987) sea-level record.

Figure S5 Map showing seismic profiles and boreholes, New Jersey sea-level transect.

have extended back to 100 MyBP (Late Cretaceous; Miller et al., 2003).

Seismic profiles provide a means of imaging strata like a sonogram images structures within the human body. Seismic profiles exhibit stratigraphic geometries resulting from erosion, potentially due to sea-level lowerings ("sequence boundaries"). The seismic surfaces reveal themselves in borehole sediments as erosion surfaces. The New Jersey Transect dated these sequence boundaries by drilling in relatively deep water (400–1,400 m) on the continental slope and rise and using various tools for age control (fossils, magnetostratigraphy, Sr-isotopic stratigraphy). Drilling onshore in New Jersey also dated these sequences in a more proximal nearshore to paleo-shelf setting, where time gaps or hiatuses were longer. Nevertheless, the onshore hiatuses (white gaps between blue boxes; Figure S6) correlate remarkably well with offshore sequence boundaries (m1, m2, etc. on Figure S6). This establishes a regional correlation between these hiatuses and associated sequence boundaries, and a relation to at least regional-scale sea-level lowerings.

Comparison of the New Jersey sequence stratigraphic record with oxygen isotopes provides a link between regional sea-level lowerings and global changes in ice volume (hence sea level) for the past 34 Ma (Figure S6). Oxygen isotopic ($\delta^{18}O$) increases in deep-sea Atlantic cores correlate with the sea-level lowerings in New Jersey (Figure S6). This demonstrates that a significant portion of oxygen isotopic changes must be attributed to changes in ice volume. Still, we cannot precisely determine the extent of the role of ice growth versus cooling of bottom waters on any individual $\delta^{18}O$ increase. For example, a large $\delta^{18}O$ increase occurred across the Oligocene/Miocene boundary (ca. 23 Ma), correlating with the m6 continental slope and the O6/Kw0 onshore sequence boundaries (Figure S6). If this were attributed entirely to ice volume (presumably from Antarctic ice, because Northern Hemisphere Ice Sheets did not begin to grow until late Miocene to Pliocene), this change would be equivalent to a 90 m eustatic sea level drop. It is likely however, that bottom waters cooled at the same time as the glaciation; during the Quaternary, about two-third of the $\delta^{18}O$ signal is controlled by ice volume and one-third by temperature (Fairbanks, 1989). Applying this rule of thumb to the older record indicates about 60 m, not 90 m, of eustatic lowering; however, it is still possible that the temperature effects were larger and sea level change would have been correspondingly less.
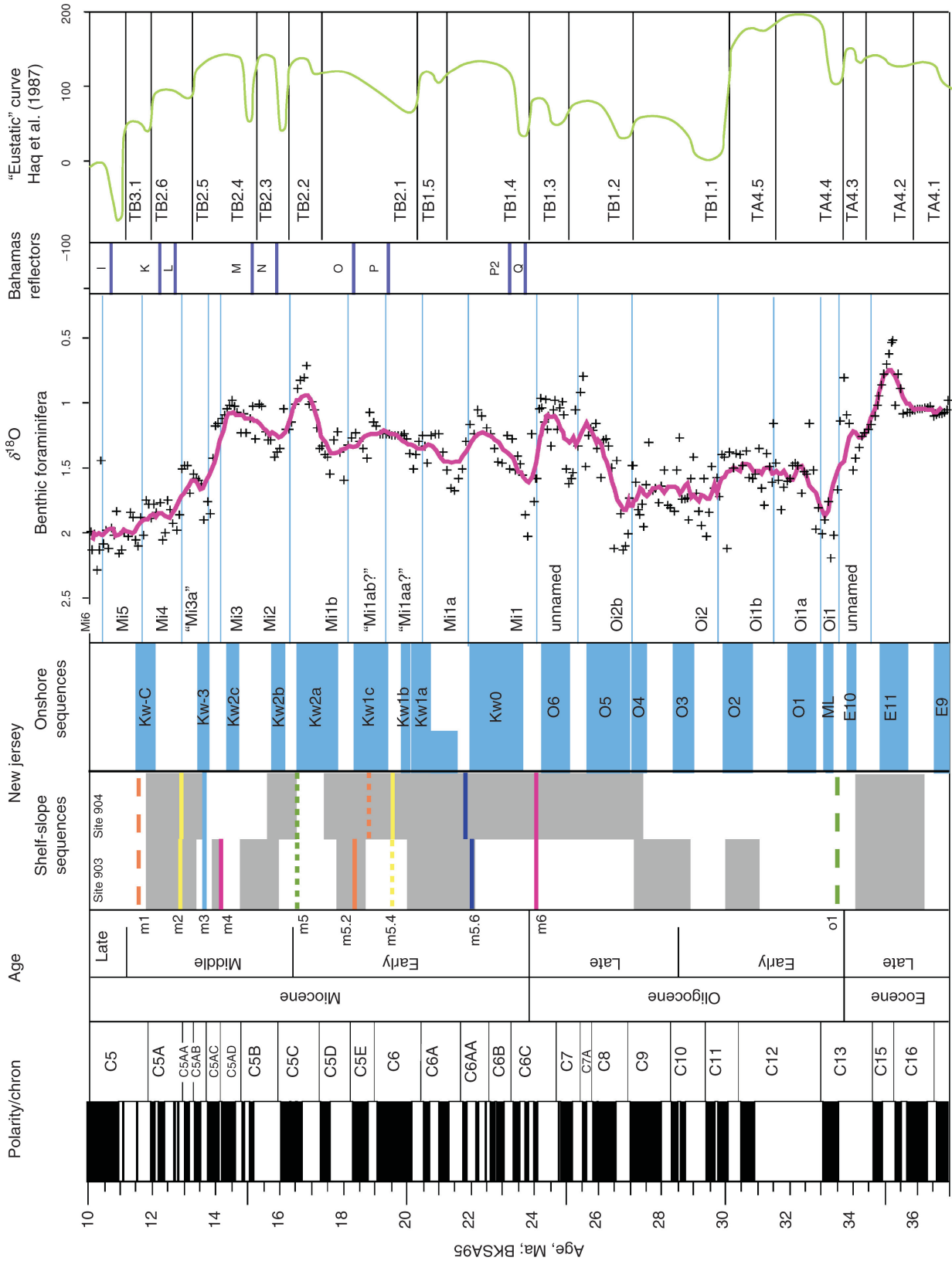
Figure S6 Comparison of offshore New Jersey, onshore New Jersey, global oxygen isotopes, ages of Bahamas reflections, and Haq et al. (1987) sea-level record (Miller et al., 1998).

The above example illustrates the hazards of trying to estimate eustatic amplitudes from oxygen isotopic records. Though continental margin stratigraphic records are complicated by changes in subsidence, it is possible to evaluate subsidence histories using a method called backstripping. This method progressively removes the effects of compaction, sediment loading, and thermal subsidence; the residual provides an estimate of eustatic sea level (e.g., Kominz et al., 1998; Watts and Steckler, 1979). Backstripping requires estimates of age, sediment type (for decompaction), and paleowater depth; the latter is obtained from benthic foraminifera and lithologic data and is the greatest source of uncertainty. Kominz et al. (1998) and Van Sickel et al. (2004) backstripped individual onshore New Jersey boreholes ("1-dimensional" backstripping) and found amplitudes of 20–40 m. Two-dimensional backstripping (backstripping an entire profile using several boreholes) of ten latest Eocene to earliest Miocene sequences provided estimates of ~20–60 m eustatic lowerings (Kominz and Pekar, 2001). Both one and two dimensional backstripping yielded Oligocene-Miocene eustatic estimates that are lower than those published by the EPR group (e.g., Haq et al., 1987) by a factor of two or more (Kominz and Pekar, 2001; Van Sickel et al., 2004).

Studies of sea-level change must be global in scope and ODP has drilled on the Australian margin (Legs 133, 182, and 194) and the Bahamas (Leg 166). Despite the fundamental difference in sedimentation style between carbonate and siliciclastic margins, ODP drilling documented similar-Miocene unconformities in these diverse settings (Figure S6). Drilling in the Bahamas showed that the flanks of a carbonate bank environment develop sequences that are remarkably similar in character to those of siliciclastic margins (Eberli et al., 1997). Though tectonic effects (e.g., rapid subsidence) influence much of the northeast Australian region (Davies et al., 1993), consequences of global sea-level change on the evolution of the Marion Plateau and the Great Barrier Reef were evaluated. Drilling on the Australian margin by Leg 194 (Isern et al., 2002) provided an estimate of a major late middle Miocene eustatic lowering of 33 ± 12 m based on Airy (point) loading to 85 ± 30 assuming rigid crust (flexural loading). These wide ranges again illustrate the difficulty in estimating global sea-level amplitudes.

Causes of sea level change

Drilling on the New Jersey, Bahamas, and Australian margins have firmly demonstrated that ice-volume changes have been one of the primary controls on sea-level change during the Icehouse world of the past 34 Myr. It is not surprising that this is true because ice-volume changes are the only known mechanism for causing the large (>10s m), rapid changes in sea level reported for this time interval. The close correspondence between the oxygen isotopic and continental margin records is testament to this linkage (Figure S6). However, what about the vast amounts of geologic time in which the Earth was presumably ice-free?

Sea level during the Cretaceous (144–65 Ma) was much higher than at present because of long-term changes in sea level. These long-term (10–100 Myr scale) sea-level changes have been largely controlled by tectonics. For example, during the warm interval of the middle Cretaceous (ca. 80–90 Ma), global sea level was between 100 (Miller et al., 2005) and 170 m (Müller et al., 2008) higher than today. However, such high sea levels cannot be explained by a warmer planet and the absence of ice sheets: even if all of the modern ice sheets were melted (an "ice-free Greenhouse world"), then sea-level would be only 73 m higher than today. Although the Cretaceous oceans were 10–12 °C warmer than today, thermal expansion could only account for another 10–13 m of rise. The generally accepted explanation for the high mid-Cretaceous sea levels is high sea-floor spreading rates; higher rates mean hotter crust, which expands, displacing seawater and causing long-term flooding of the continents (Hays and Pitman, 1973; Kominz, 1984). This pulse of mid-Cretaceous high seafloor spreading has been recently disputed (Rowley, 2002), though various stratigraphic data unequivocally show that relative to the continents, sea level was 100–250 m higher, based on backstripping in the former case (Watts and Steckler, 1979) and continental flooding in the latter (Sahagian et al., 1996). If not caused by high-sea floor spreading rates, the long-term flooding and subsequent retreat of the sea over the past 180 Myr could have been the result of the breakup of the supercontinent Pangea, beginning at 180 Ma, which may have led to overall subsidence of continents relative to the oceans during the Jurassic to mid-Cretaceous.

Even more puzzling than the long-term record is the observation that large (10s to 100 m), rapid (less than 1 Myr) sea-level changes occurred during the Triassic to middle Eocene (ca. 250–50 Ma), a time considered to be an ice-free Greenhouse (Haq et al., 1987; Hallam, 1992). Ice-volume changes (glacioeustasy) are the only known mechanism for producing large, rapid sea-level change (Pitman and Golovchenko, 1983). Although it has been believed in general that there were no significant ice sheets prior to the middle Eocene, Haq et al. (1987) delineated numerous Cretaceous to early Eocene sequence boundaries with associated large (>50 m), rapid (<1 Myr) sea-level lowerings. There are four explanations for this apparent paradox (Browning et al., 1996): (a) the Cretaceous to early Eocene sequences summarized by Haq et al. (1987) were restricted to local basin(s) and do not reflect eustasy (this is unlikely considering that many have been widely recognized; e.g., Aubry, 1985; Mancini and Tew, 1991, 1995; Olsson, 1991); (b) the sequences were controlled by low-amplitude sea-level changes (e.g., 10 m of lowering in 1 Myr can be explained by numerous mechanisms; Donovan and Jones, 1979); (c) mechanisms of sea-level change are not fully understood; and (d) there were ice sheets throughout much of the Cretaceous to early Eocene (e.g., Stoll and Schrag, 1996).

Drilling in New Jersey has recently provided a record of sea-level changes during the warm Late Cretaceous. These studies firmly document that large (>25 m), rapid (≪1 Myr) eustatic variations occurred in the Late Cretaceous, hinting at the presence of ice sheets in this supposedly ice-free Greenhouse world (Figure S7). Continuous coring recovered 11–14 Upper Cretaceous sequences at Bass River and Ancora, New Jersey that were dated by integrating Sr-isotopic and biostratigraphic data (age resolution ±0.5 Myr) and subsequently backstripped taking into account sediment loading, compaction, paleodepth, and thermo-flexural subsidence, providing a new sea-level estimate. The timing of Late Cretaceous sequence boundaries in New Jersey is similar to sea-level lowerings found by EPR (Haq et al., 1987), NW European sections (Hancock, 1993), and Russian sections (Sahagian et al., 1996), indicating a global cause (Figure S7). However, New Jersey and Russian Platform eustatic estimates are half of the EPR amplitude; the EPR record also differs in shape from the backstripped estimates. The use of the EPR record for the Late
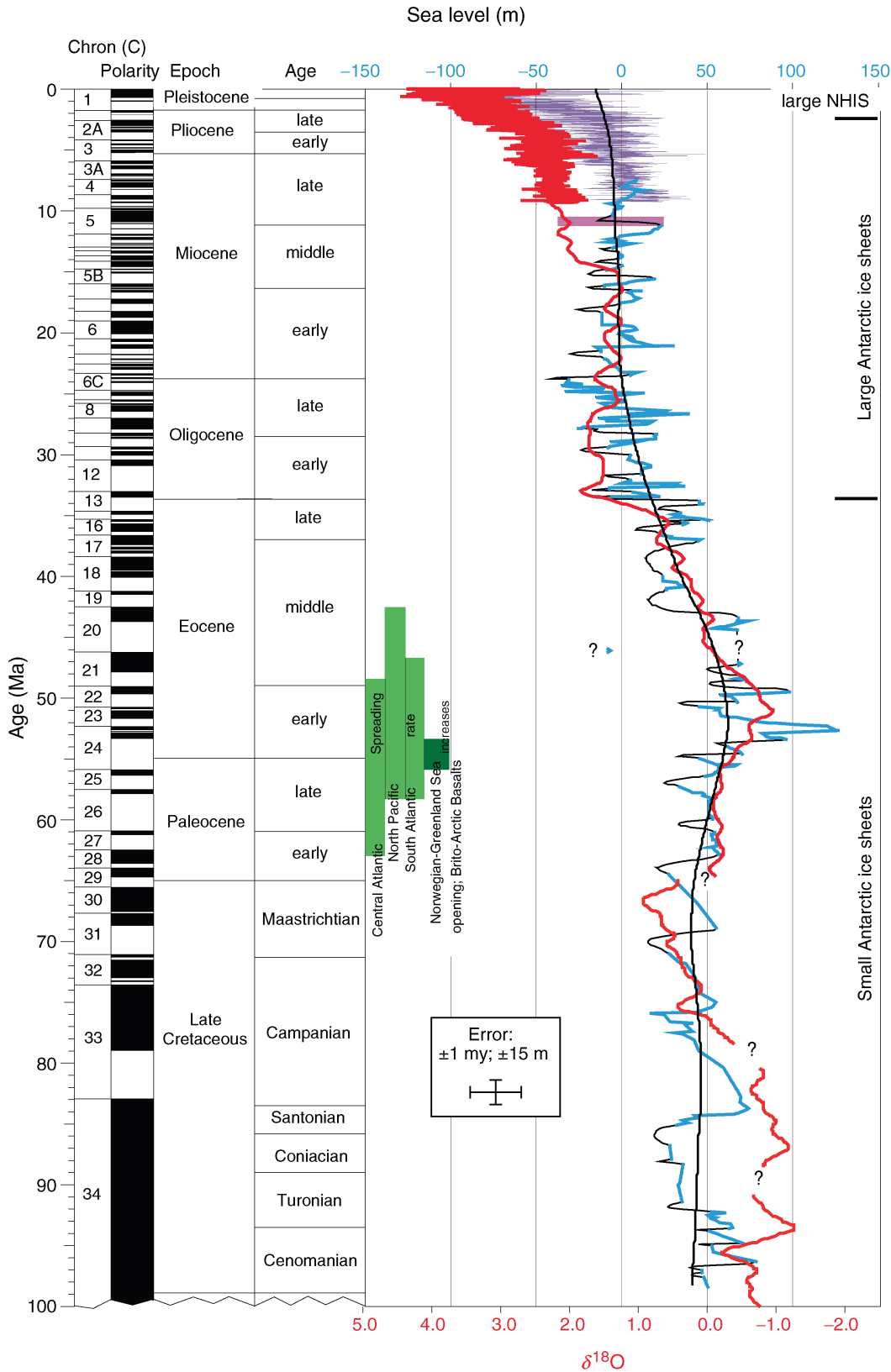
Figure S7 Comparison of Late Cretaceous deep-sea benthic foraminiferal δ^{18}O records, New Jersey composite sequences, relative sea level from NW Europe (Hancock, 1993), backstripped Russian platform record (Sahagian et al., 1996), the EPR eustatic estimate (Haq et al., 1987), backstripped R2 eustatic estimates for Bass River (*black*) and Ancora (*gray*) and our best estimate of eustatic changes (*heavy black line* constrained by data, *dashed* inferred). *Pink arrows* indicate positive δ^{18}O inflections (inferred cooling and/or ice volume increases) (after Miller et al., 2004).

Cretaceous should be abandoned; the New Jersey backstripped records provide the best substitute at this time.

The firm documentation of large (>25 m), rapid (<Myr) sea-level changes (Figure S7) indicates some glacioeustatic control during the Late Cretaceous. The apparent inconsistency with evidence for warm high latitudes during the Late Cretaceous can be explained by ephemeral (i.e., lasting ≪1 Myr) ice sheets (presumably in East Antarctica (EAIS)) with volumes approaching one-third to one-half of the modern EAIS (Miller et al., 1999) and intervening warm, ice-free intervals (Miller et al., 2003).

Oxygen isotopic comparisons with Late Cretaceous sequence boundaries have not attained the resolution needed to link the two datasets unequivocally, as has been done for the past 42 Myr (Miller et al., 1998a). Nevertheless, comparisons between Late Cretaceous sequence stratigraphy and δ^{18}O records are intriguing (Figure S7), further suggesting small ice sheets in this alleged Greenhouse World: (a) a major mid-Cenomanian sequence boundary (hiatus ca. 96–97 Myr ago) (see also Gale et al., 2002) correlates with a major (>1‰) δ^{18}O increase; (b) two minor δ^{18}O increases spanning the Cenomanian/Turonian boundary may correlate with sequence boundaries; (c) a mid-Turonian sea-level lowering (91.5–92 Ma) may correlate with a major increase in benthic foraminiferal δ^{18}O values (~1.0‰), although additional data are needed to determine the precise timing of the increase (Figure S7). Several other Coniacian-Campanian δ^{18}O increases (*dashed arrows*, Figure S7) may be related to sequence boundaries, but the data are too sparse to provide a firm correlation.

The EPR sea-level records (Vail et al., 1977; Haq et al., 1987) are major achievements for the Earth sciences. However, it is not surprising after 15–25 years, that we conclude that these previous sea-level estimates are not entirely correct in their shape and amplitudes. Methods for extracting sea level from stratigraphic data have advanced during this period and the scientific community has begun to document amplitudes of sea-level change with increased precision. Despite their limitations, the EPR curves stand the test of time as an approximate chronology (±1 Myr) of eustatic lowerings. Studies on the New Jersey and other continental margins have generally confirmed the number and approximate ages of sea-level lowerings of Haq et al. (1987) for the past 100 Myr (Figures S6, S7). In the absence of other datasets for the Triassic-Early Cretaceous, the Haq et al. (1987) record still provides the best estimate for the timing of eustatic lowerings. Although the timing can be estimated, the amplitudes of sea-level change during the Triassic-Early Cretaceous remain poorly constrained and the causal mechanisms for the large, rapid sea-level changes for this interval can only be explained by glacioeustasy. Is our understanding of causal mechanisms for global sea-level change flawed, or is our interpretation of a largely ice-free planet prior to 42 Ma incorrect?

ODP drilling has determined ages of sequence boundaries on continental margins to better than ±0.5 Myr and provided a chronology of eustatic lowering for the past 42 Myr (Figure S6). ODP has also validated the transect approach of drilling passive continental margins and carbonate platforms (onshore, shelf, slope). Additional integrated geological and geophysical studies of transects of margins are needed to address the history magnitude, and mechanisms of global sea level change over the past 250 Myr.

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Cross-references