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A 180-Million-Year Record of Sea Level and Ice Volume Variations from Continental Margin and Deep-Sea Isotopic Records

BY KENNETH G. MILLER, GREGORY S. MOUNTAIN, JAMES D. WRIGHT, AND JAMES V. BROWNING

Drilling conducted by the Integrated Ocean Drilling Program (IODP) on the inner, shallow part of the New Jersey shelf required the use of a three-legged lift boat. Not affected by tide or swell, a successful coring and downhole logging program through loosely consolidated shelf sediments was achieved. *Photo courtesy of IODP/ECORD*

ABSTRACT. The geologic record provides constraints on the rates, amplitudes, and mechanisms controlling globally averaged (eustatic) and relative (eustatic plus subsidence/uplift) changes of sea level on various time scales. On geological time scales, global sea level changes are tied primarily to long-term (10^7–10^8-year scale) tectonism and short-term (10^3–10^6-year scale) changes in continental ice volume, though recent studies also illustrate the importance of tectonism on 10^6-year time scales. The history of 10^6-year scale eustatic changes has been controversial; the most widely used sea level curves agree with independently derived estimates with regard to the ages of sea level falls, but depart significantly from more recent studies with regard to amplitudes. We present a 180-million-year history of sea level changes. A global sea level rise of 120 m followed the Last Glacial Maximum, with rates that exceeded 10 times the modern rate of rise (> 40 mm yr^{-1} versus ~ 3 mm yr^{-1}). The "ice ages" of the past 2.6 million years were due to growth/decay of large Northern Hemisphere ice sheets. Those of the past 780,000 years caused sea level changes that were large (> 100 m) and paced primarily by the ~100,000 year eccentricity cycle; smaller changes (typically < 60 m) prior to this time were paced primarily by the 41,000-year tilt cycle. The growth and decay of a continental-scale ice sheet in Antarctica caused 50–60-m variations on the 10^6-year scale beginning ~ 33.5 million years ago. Prior to this time, Earth had been a warm, high-CO_2 "greenhouse" world that was largely ice-free back to 260 million years ago, though recent evidence suggests that 15–25-m sea level changes may have been caused by the growth and decay of small, ephemeral continental ice sheets.

INTRODUCTION

Sea level change has captured the imagination of geologists since early studies documented great inundations of the continents that occurred numerous times during the Phanerozoic Era (the past 543 million years; Suess, 1888; Sloss, 1963). Continental floodings (termed transgressions) and subsequent withdrawals of the sea (termed regressions) are expressed in the sedimentary record of continental cratons and their margins; these transgressions and regressions have been attributed both to global sea level changes and uplift/subsidence of the continents. Reconstructing the timing, amplitude, and rates of sea level changes is challenging because sedimentation on continents and their margins is controlled by globally averaged sea level change (eustasy) and subsidence/uplift (due to tectonism, isostasy, and compaction), the combined effects of which result in changes of "relative sea level" (Posamentier et al., 1988). In addition, the position of the shoreline is controlled by relative sea level combined with variations in sediment supply. Thus, a transgression could be the result of a global sea level rise; subsidence on local, regional, or continental scales; or a reduction in sediment supply relative to its rate of removal (see papers in Payton, 1977).

Suess (1888) first used the term eustasy to refer to global sea level changes, and most geologists use this term loosely without properly considering reference level. For example, Posamentier et al. (1988) defined eustasy as sea level change with respect to the center of the earth, despite the fact that gravitational effects cause sea level highs and lows of more than 180 m relative to Earth's center. Engelhart et al. (2011, in this issue) discuss geodial effects on glacial isostatic adjustment (GIA) and properly define relative sea level as the sum of global sea level (including water and ocean volume changes), glacial isostatic adjustment, tectonism (including active and passive thermal subsidence and local isostatic loading), and local effects (e.g., compaction). On the million-year and longer time scales, GIA effects can be neglected, but to understand eustasy versus relative changes on shorter time scales (especially hundreds to ten-thousand-year scales), GIA effects must be modeled (see Tamisiea and Mitrovica, 2011, in this issue). For example, during the Last Glacial Maximum, relative sea level in Barbados was measured as a 120-m change in water depth below present (Fairbanks, 1989). Most geologists have incorrectly assumed that the entire ocean would respond to Airy loading by the addition of 120 m of water during deglaciation, and that global sea level rise would be about two-thirds of this figure due to isostatic adjustment (i.e., 80 m of globally averaged sea level rise). However, if the elastic and viscous response of the whole Earth to ice sheet melting and water loading is taken into account, this assumption is not correct; whole Earth models of globally averaged sea level that account for this response yield estimates for the Last Glacial Maximum of 127 m (Peltier and Fairbanks, 2005) to ~ 130 m (Yokoyama et al., 2001) below present. On very long time scales (10 to 100 Myr), relative uplift and subsidence of entire continents, a process called epeirogeny, make selection of a reference level uncertain (Bond, 1979; Harrison, 1990).

"UNDERSTANDING EUSTATIC MECHANISMS PROVIDES FUNDAMENTAL INSIGHTS INTO EARTH PROCESSES BECAUSE GLOBAL SEA LEVEL VARIATIONS RESULT FROM CHANGES IN THE VOLUME OF WATER IN THE OCEAN AND/OR THE VOLUME OF OCEAN BASINS."

Understanding eustatic mechanisms (Figure 1) provides fundamental insights into Earth processes because global sea level variations result from changes in the volume of water in the ocean and/or the volume of ocean basins. Long-term (10^7–10^8 years) sea level changes are slow (< 10 m Myr^{-1}) and have been related to changes in oceanic crust production, particularly high seafloor-spreading rates, which supposedly caused very high (250 m) sea level in the Late Cretaceous (e.g., Pitman and Golovchenko, 1983). The assumption of high seafloor spreading rates and an attendant Cretaceous (~ 80 million years ago) sea level peak has been challenged (Rowley, 2002; Cogné and Humler, 2006). Recent reconstructions of seafloor spreading appear to validate a Cretaceous global sea level peak of ~170 m (Müller et al., 2008) due to greater oceanic crust production rates, but this work and all long-term ocean volume and attendant tectono-eustatic estimates suffer from trying to reconstruct areal distributions of seafloor that was destroyed long ago.

The primary mechanism for changing the amount of water in the ocean is the growth and decay of continental ice sheets that produce high-amplitude, rapid sea level changes (up to 200 m and > 40 m kyr^{-1}; Figure 1). Pitman and Golovchenko (1983) outlined other processes for changing global sea level as summarized below and illustrated by Figure 1 (Miller et al., 2005a). On the 100-million-year time scale, changes in production of juvenile water and its sequestration into the mantle at subduction zones can be assumed to be in steady state (i.e., unchanged). Other processes of changing water volume (desiccation and inundation of marginal seas, thermal expansion and contraction of seawater, and variations in groundwater and lake storage) can cause rapid global sea level changes (10 m kyr^{-1}), but with low amplitudes (~ 5–10 m; Jacobs and Sahagian, 1993). Large-scale changes in ocean sedimentation (e.g., building the Indus Fan due to Himalayan erosion) cause slow, moderate-amplitude (60 m) changes (10 m Myr^{-1}); continental crustal shortening (e.g., building the Himalayas) causes slow, moderate-amplitude falls (tens of meters, 10 m Myr^{-1}; Pitman and Golovchenko, 1983). Volcanism associated with the creation of large igneous provinces (LIPs)—massive volumes of lava erupted over geologically brief periods in the ocean—produces moderately rapid rises, but slow falls, due to thermal subsidence (10 m Myr^{-1}); Pitman and Golovchenko (1983) assumed rates of up to 50 m in less than one million years based on extrusion of very large LIPs like the Ontong-Java Plateau (i.e., 50 x 10^6 km^3). However, their estimates were too high because they did not account for isostatic compensation, which would reduce maximum rates of rise to ~ 15 m Myr^{-1}.

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RECONSTRUCTING SEA LEVEL WITH REEFS AND OXYGEN ISOTOPES

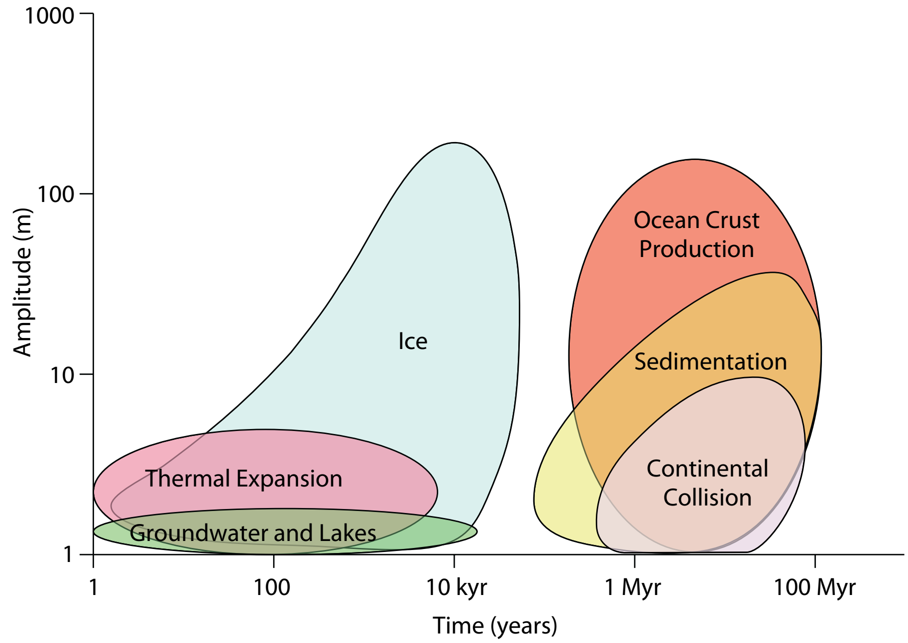

Figure 1. Mechanisms for sea level change. *Modified after Miller et al. (2005a)*

Ancient sea level can be reconstructed on 10^4–10^6-year scales by studying coral reef records, the $\delta^{18}O$ proxy of ice volume, and continental margin sequences. Precise dating of corals by U-Th provides high-resolution (±5 m) sea level records over the last few hundred thousand years (e.g., Fairbanks, 1989). By estimating uplift rates of coral terraces, studies show that sea level at the last interglacial (~ 125,000 years ago) was 7 ± 2 m above present (summary in Kopp et al., 2009). Understanding the position of sea level at the Last Glacial Maximum (20,000–26,000 years ago) requires sampling of corals that are now below sea level. Drilling of reefs in Barbados and Tahiti has shown a rise in excess of 40 mm yr^{-1} during the last deglaciation (Melt Water Pulse [MWP] 1a; ~ 14,000 years ago; Fairbanks, 1989; Yokoyama and Esat, 2011, in this issue); this rate is 10 times the current rate of sea level rise of 3.2 ± 0.4 mm yr^{-1} for 1993–2010 (http://sealevel.colorado.edu). However, coral records are difficult to obtain, date, and model subsidence beyond a few hundred thousand years and yield minimal constraints on the older record (a notable exception is the Pliocene of Enewetak; Wardlaw and Quinn, 1991).

Oxygen isotope measurements of marine carbonates provide a proxy for temperature and ice volume. Oxygen isotope values are expressed in $\delta^{18}O$ notation in per mille (‰), reflecting the ratio of the heavier ^{18}O to lighter ^{16}O. Carbonate $\delta^{18}O$ values vary inversely with temperature due to a thermodynamic effect, whereas variations in seawater $\delta^{18}O$ result from global ice volume and local evaporation/precipitation differences. Ice sheets preferentially store the lighter isotope ^{16}O, and their growth results in higher $\delta^{18}O$ values in the ocean. Growth of the Laurentide Ice Sheet lowered sea level 120 m by 20,000 years ago and increased global seawater $\delta^{18}O$ values by ~ 1.2‰ (Fairbanks, 1989). Conversely, melting the present-day global inventory of ice (~ 25 x 10^6 km^3 and 64 m of sea level equivalent; Lythe et al., 2001) would raise global $\delta^{18}O$ values by ~ 0.9‰ (Shackleton and Kennett, 1975). Oxygen isotopes measured in marine carbonates vary with periods that track the Milankovitch cycles. This pacemaker of climate and ice volume provides astronomical chronologies with better than ten-thousand-year resolution (Martinson et al., 1987) that have been extended through the Pliocene (~ 5.2 million years ago; Lisiecki and Raymo, 2005) and are being extended into the Late Cretaceous.

Separating the effects of ice volume from temperature is a challenge. Deep-sea (below the thermocline) $\delta^{18}O$ values vary less than those in the ocean's mixed layer because the latter is influenced by regional differences in evaporation and precipitation. Consequently, ice volume changes are recorded by $\delta^{18}O$ values of deep-sea benthic foraminifera. However, despite relative stability in the deep sea, changes in deep ocean temperatures also affect deep-sea benthic foraminiferal $\delta^{18}O$ records. During the late Pleistocene, ice volume controlled two-thirds of the measured variability in benthic foraminiferal $\delta^{18}O$ records, while temperature variations accounted for the other one-third (Fairbanks, 1989). For example, deep-sea benthic foraminifera show a ~ 1.75‰ decrease during the last deglaciation, which reflects a 120-m sea level rise (~ 1.2‰) and a ~ 2°C warming (~ 0.55‰; Fairbanks, 1989; Figure 2). The pattern of glacial-interglacial temperature changes follows a previously established hysteresis loop between two stable modes of operation (Chappell and Shackleton, 1986; Wright et al., 2009). Cold, near-freezing deepwater conditions characterize most of the past 130,000 years, punctuated by two warm intervals (Figure 2), which suggests that there were few deepwater temperature changes during much of the Pleistocene and that scaling $\delta^{18}O$ to sea level is possible (Figure 3).

Miller et al. (2005a) scaled benthic foraminiferal $\delta^{18}O$ to sea level for the past 9 million years, making minimal assumptions about temperature change (i.e., a cooling of 2°C during the late Pliocene). We update this estimate using the stacked benthic foraminiferal $\delta^{18}O$ records of Lisiecki and Raymo (2005; Figure 3). However, such scaling suffers not only from peak interglacial warming but also from longer-term temperature changes. In fact, benthic foraminiferal $\delta^{18}O$ records of the past 50 million years show a 4‰ increase (Figure 4) that must reflect mostly cooling because only ~ 1.0‰ of the increase can be due to ice volume (Miller et al., 2005a). Thus, the long-term $\delta^{18}O$ record reflects ~ 12°C of cooling, complicating the use of $\delta^{18}O$ as an ice volume indicator beyond the Pliocene-Pleistocene (recent work of authors Miller and Wright and colleagues).

Deep-sea benthic foraminiferal $\delta^{18}O$ variations can be used as evidence for ice volume changes during the pre-Pliocene, but for the reasons described above, they cannot yield precise global sea level estimates. For example, Miller et al. (1996, 2005a) linked $\delta^{18}O$ increases to other proxies for sea level fall for the "icehouse world" of the past 33.5 million years when large ice sheets existed. Miller et al. (2003, 2005b) similarly linked sea level falls with $\delta^{18}O$ increases for the "greenhouse world" of the Cretaceous to Eocene. Although this is a time when the presence of continental ice sheets is hotly debated, these researchers postulated the existence of small ice sheets, as discussed below.

Scientific ocean drilling has provided a global array of deep-sea cores that have yielded numerous $\delta^{18}O$ records for the Late Cretaceous to Cenozoic (see syntheses of Zachos et al., 2001, and Cramer et al., 2009, 2011), though separating ice volume from temperature in these $\delta^{18}O$ records is progressively more uncertain prior to the Plio-Pleistocene. Mg to Ca ratios have come into use to provide a paleothermometer that accounts for the temperature component in deep-sea benthic foraminiferal $\delta^{18}O$ records, which can then be read as an ice volume/sea level record (e.g., Sosdian and Rosenthal, 2009). However, the errors in the Mg/Ca approach are large (~ 1–2°C or 20–40 m sea level equivalent for one record; recent work of authors Miller and Wright and colleagues), and $\delta^{18}O$ and Mg/Ca records cannot be used to provide an unequivocal sea level record earlier than the Pliocene. For this information, we must look to the sedimentary record of sea level change.

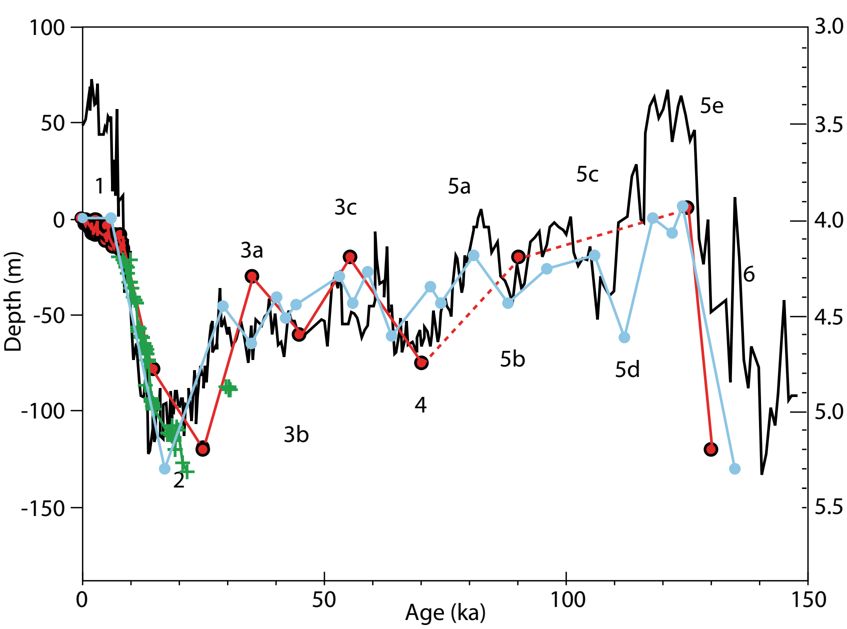

Figure 2. Late Pleistocene sea level and $\delta^{18}O$ (eastern Pacific piston core V19-30; Shackleton et al., 1983) records (mid-Atlantic US margin, solid red circles; Huon Peninsula, Papua New Guinea, blue; Barbados, green) showing excellent agreement except for the Holocene Chron 1 and Marine Isotope Chron 5e where the prediction from scaling $\delta^{18}O$ is too high. ka = thousands of years ago. *After Wright et al. (2009)*

SEQUENCES ON CONTINENTAL MARGINS AND EPICONTINENTAL SEAS

The continents and their margins contain over a billion-year record of sea level changes in unconformity-bounded units called sequences. Sloss (1963) first documented that 10–100-million-year scale transgressive and regressive sequences correlated from continent to continent, and hence may be global. Peter Vail, a former student of Sloss's working at Exxon Production Research Company (EPR), and colleagues extended these observations to marine seismic reflection profiles where they identified and correlated global changes in what they termed "coastal onlap" (Vail et al., 1977). Their claim that patterns of coastal onlap tracked changes in global sea level sparked a renewed effort into the study of basin history and the geologic impact of sea level change. Many geologists, particularly within the oil and gas industry, have embraced sea level curves produced by Vail and EPR in the 1970s (Payton, 1977) and 1980s (Haq et al., 1987). Within that initial volume (Payton, 1977) and its subsequent update (Wilgus et al., 1988), there were three breakthroughs: (1) the realization that unconformity-bounded sedimentary units (sequences) are the building blocks of the stratigraphic record on margins; (2) seismic profiles can be used to image unconformities; and (3) these unconformities correlate interregionally and thus are formed in response to global sea level falls on the million-year scale. The first two of these hypotheses have been largely validated. Nevertheless, the sea level curves EPR produced (Vail et al., 1977; Haq et al., 1987) have been the center of controversy (e.g., Christie-Blick et al., 1990; Miall, 1992), largely due to concerns surrounding the first two steps EPR made in developing a global sea level record: (1) to demonstrate interregional correlation, the stratigraphic record must be dated at the appropriate resolution, in this case better than one million years; and (2) to be a reliable measure of eustatic amplitude, the paleowater depth history must have the effects of compaction, loading, and tectonic subsidence removed. Whereas the age and number of sea level falls proposed by EPR agrees with published recent estimates, the amplitude and shape of the other published curves do not (Miller et al., 1996, 2005a; John et al., 2011).

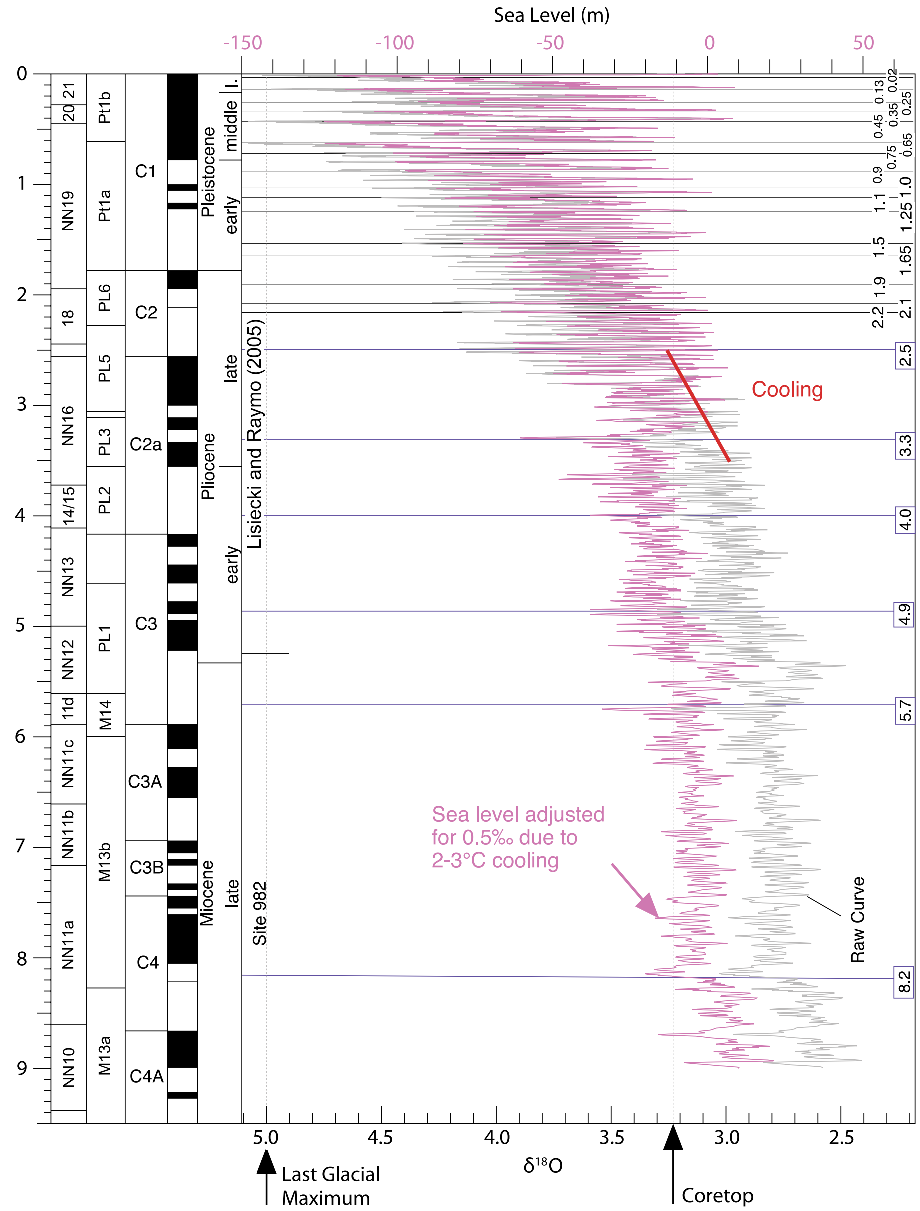

Figure 3. Sea level record for the past 9 million years generated from benthic foraminiferal $\delta^{18}O$ using the Lisiecki and Raymo (2004) stack to 5.2 million years ago and Ocean Drilling Program Site 982 from 5.25–9 million years ago records (Hodell et al., 2001). The authors scaled assuming 67% ice volume and 33% temperature, and they account for long-term temperature changes by incrementing a 2°C temperature increase between 2.5 and 3.5 million years ago.

The EPR sea level compilations were based on geological data from many areas of the world from which an impression was obtained concerning relative size of sea level fall and subsequent rise (Vail et al., 1977). The relative curve was scaled to Pitman's (1978)

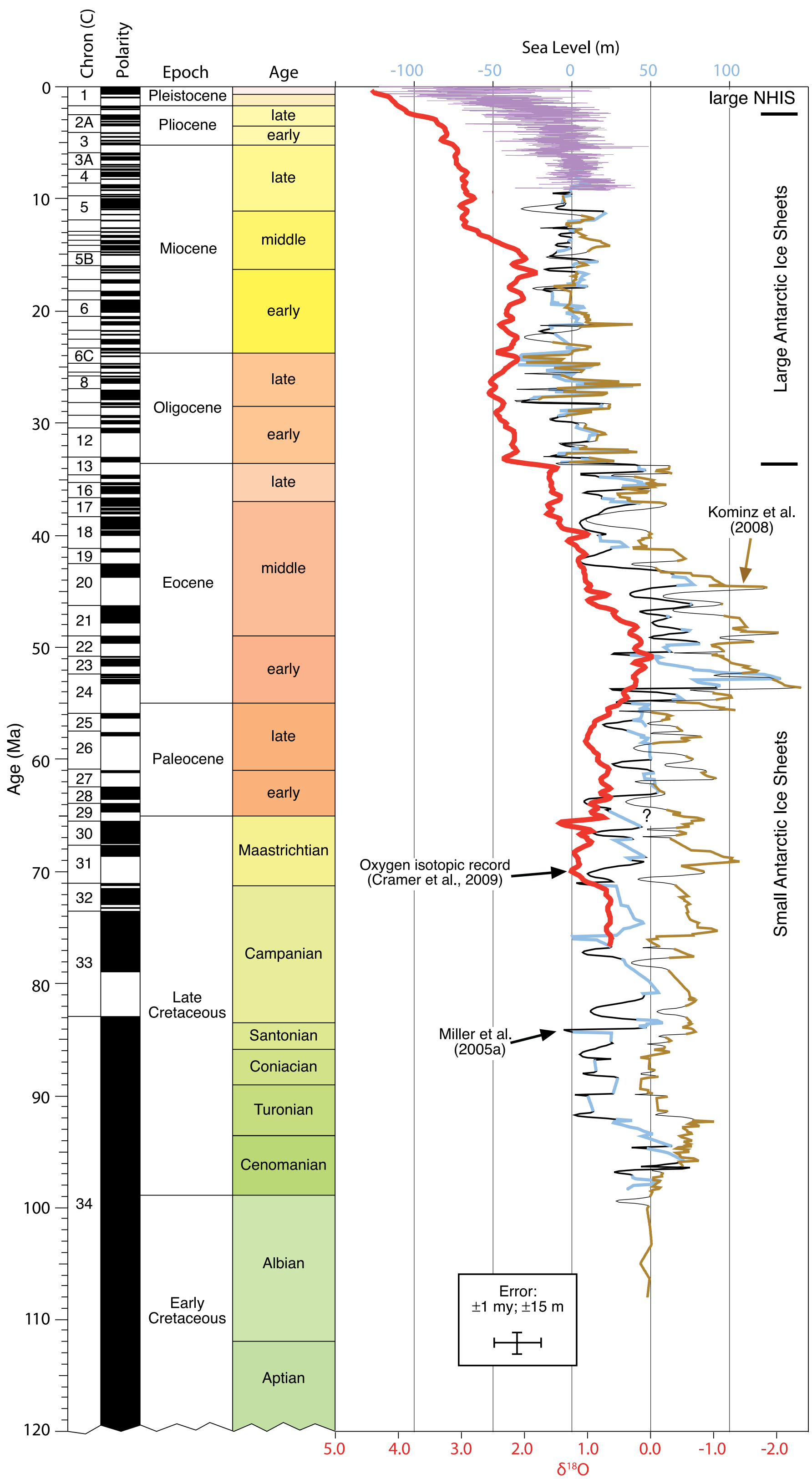

Figure 4. Sea level estimates derived from New Jersey (Miller et al., 2005a; Kominz et al., 2008) that provide a testable record of global sea level for the past 100 million years. The figure also shows the oxygen isotopic synthesis of Cramer et al. (2009). NHIS = Northern Hemisphere ice sheets. Ma = millions of years ago.

long-term (10^7-year) sea level estimate that peaked at ~ 250 m above present at 90 million years ago, elevations of flooding surfaces were scaled so that those on the million-year scale reached the envelope of the long-term curve, and lowstands were chosen to not exceed the depths of Pleistocene sea level falls except during the middle Oligocene (Vitor Abreu, EPR, *pers. comm.*, 2010). But as mentioned previously, little attempt was made to remove the effects of compaction, loading, and tectonically induced subsidence, and this approach has remained a source of controversy concerning the validity of global sea level histories derived in this manner (Christie-Blick et al., 1990).

Sea level events postulated for the Eocene-Oligocene transition illustrate problems with this approach. Vail et al. (1977) reported a 400-m sea level fall in the middle Oligocene and no sea level fall across the Eocene/Oligocene boundary; Haq et al. (1987) suggested a ~ 160-m middle Oligocene fall. Two decades of study have subsequently documented that the development of a near-modern-sized Antarctic ice sheet (e.g., Miller et al., 1991, 2005a; Zachos et al., 1996) in the earliest Oligocene resulted in a global sea level fall of ~ 55 m, with a fall of similar amplitude in the middle Oligocene (e.g., Miller et al., 2005a; Pekar et al., 2002). Thus, the amplitudes of the EPR records are too high by a factor of ~ 2–2.5 (Miller et al., 2005a; Pekar et al., 2002; John et al., 2011). Better estimates of the amplitudes of these sea level changes were derived from ocean drilling, which provided sea level records from the continental margins of New Jersey (Miller et al., 2005a) and Australia (John et al., 2004, 2011).

OCEAN DRILLING APPROACHES TO SEA LEVEL

The Deep Sea Drilling Project (DSDP) drilled the passive continental margins of Ireland (Leg 80) and New Jersey (Legs 93 and 95) attempting to "test the Vail curve." But, due to their deepwater locations (> 1 km), none of these sites provided constraints on the amplitude of past sea level change. Planning during the early Ocean Drilling Program (ODP) suggested drilling a global array of passive continental margin transects, deep-sea sites suitable for $\delta^{18}O$ studies, and coral reefs (Imbrie et al., 1987; Watkins and Mountain, 1990; JOIDES Sea-level Working Group, 1992). Four aspects for examining past sea level changes were targeted: (1) test their synchrony, (2) estimate their amplitudes, (3) determine their causal mechanism(s), and (4) evaluate various models for the stratigraphic response to sea level change.

Recognizing the importance of margin transects, ODP endorsed drilling onshore as well as offshore New Jersey in an integrated study. ODP Legs 150 (slope), 174A (outer shelf), and Leg 150X/174AX (onshore) dated sequence-bounding unconformities and tied them to $\delta^{18}O$ increases indicative of glacioeustatic falls (summaries in Miller et al., 1996, 2005a). Drilling onshore in New Jersey and Delaware by ODP Legs 150X and 174AX provided 13 sites that were dated using integrated $^{87}Sr/^{86}Sr$ techniques and biostratigraphy with a resolution of better than one million years (Browning et al., 2008). These data, together with interpretations of lithofacies and benthic foraminiferal biofacies, provided a chronology of water-depth changes that, in turn, were used to develop the first testable Late Cretaceous to Cenozoic global sea level curve (Figure 4; Miller et al., 2005a; Kominz et al., 2008). A global sea level estimate was derived using the inverse modeling technique termed backstripping, which progressively removes the effects of sediment compaction, loading, and thermal subsidence (Steckler and Watts, 1978; Kominz et al., 1998, 2008). Backstripping was done one dimensionally for the 11 coreholes, except for the latest Eocene to earliest Miocene where two-dimensional backstripping used a flexural model to link the sites (Kominz and Pekar, 2002; Pekar et al., 2002). Backstripping provides a measure of global sea level and nonthermal subsidence. Studies show that passive tectonic effects dominate the tectonic component of accommodation in New Jersey, including simple thermoflexural subsidence and Airy loading (Kominz et al., 1998,). Thus, the estimates derived (Figures 4–6) provide a working model for global sea level variations, with the acknowledgement that no one location or region can be used to constrain global sea level changes.

Onshore New Jersey backstripping showed that long-term (10^7 yr) sea level changes were smaller than previously inferred, with a Cretaceous peak of ~ 75 m above modern sea level (Miller et al., 2005a), implying lower changes in oceanic crust production rates than previously assumed. Initial backstripping of Miller et al. (2005a) overestimated early subsidence; revised backstripping by Kominz et al. (2008) resulted in a higher Cretaceous peak of > 100 m, similar to the 120 m estimated by backstripping of wells off Nova Scotia, Canada, for the Late Cretaceous (Steckler and Watts, 1978; Figure 5). Moucha et al. (2008) and Müller et al. (2008) have proposed that epeirogenic uplift resulting from subduction of the Farallon slab beneath North America should have led to an underestimate of long-term sea level change in the New Jersey record. Comparison of records (Figure 5) indeed shows that New Jersey backstripping may underestimate sea level change on the 10^7-year scale. Müller et al. (2008) estimated the Late Cretaceous sea level peak at 175 m, but continental flooding records of Bond (1979) and Harrison (1990) suggested peak globally averaged sea levels of 140 ± 60 m and 150 m, respectively (Figure 4). We conclude that peak sea level in the Cretaceous

"BETTER ESTIMATES OF THE AMPLITUDES OF THESE SEA LEVEL CHANGES WERE DERIVED FROM OCEAN DRILLING, WHICH PROVIDED SEA LEVEL RECORDS FROM THE CONTINENTAL MARGINS OF NEW JERSEY AND AUSTRALIA."

was 150 ± 50 m (Figure 4). Though the longer-term (10^7-year scale) New Jersey record may have a ~ 50 m overprint due to the effects of the Farallon slab, interregional correlations and ties to the $\delta^{18}O$ record demonstrate that it is untainted by tectonic overprints at higher frequencies (10^6 yr).

The New Jersey record of icehouse world sea level changes (Oligocene and younger) agrees well with $\delta^{18}O$ changes (Miller et al., 2005a): $\delta^{18}O$ increases reflect glacially driven global sea level falls associated with sequence boundaries. During the Late Cretaceous to Eocene, backstripped estimates show that sea level changes varied from ~ 15–25 m, with a particularly large (40 m) fall at the Campanian/Maastrichtian boundary (~ 71.5 million years ago). As discussed below, the only mechanism that can explain such large and rapid changes is glacioeustasy.

ODP drilling has been conducted with success on other margins as well, but thus far in all cases offshore. The margins of Australia (Legs 133 and 194) and the Bahamas (Leg 166) provided sea level records from carbonate settings (see summaries in Betzler et al., 2000; John et al., 2004). Drilling documented that Miocene unconformities, progradation, and stacking patterns occur in both of these carbonate settings as they do in the siliciclastic sediments of New Jersey. Drilling along Marion Plateau during ODP Leg 194 provided a backstripped global sea level estimate of 57 ± 12 m for a major middle Miocene (~ 13.9–13.8 million years ago) lowering (John et al., 2004, 2011). In comparison, the Haq et al. (1987) record for this interval shows a lowering of > 100 m. Thus, both Marion Plateau and New Jersey backstripped estimates indicate that the Haq et al. (1987) sea level records were too high by a factor of two or more.

ODP drilling in all of these settings accomplished the following: (1) validated the transect approach, (2) confirmed that some impedance contrasts associated with diagnostic reflector terminations detected in seismic reflection profiles indeed match unconformities, (3) demonstrated interregional correlation of unconformities, suggesting that they are global, (4) determined the ages of sequence boundaries to better than ± 0.5 million years and provided a chronology of global sea level lowerings for the past 100 million years, (5) linked sequence boundaries directly to global $\delta^{18}O$ increases, demonstrating a causal relationship between sea level and ice volume, (6) provided evidence of possible small ice sheets during the Late Cretaceous-Eocene, and (7) showed that siliciclastic and carbonate margins yield comparable records of sea level change.

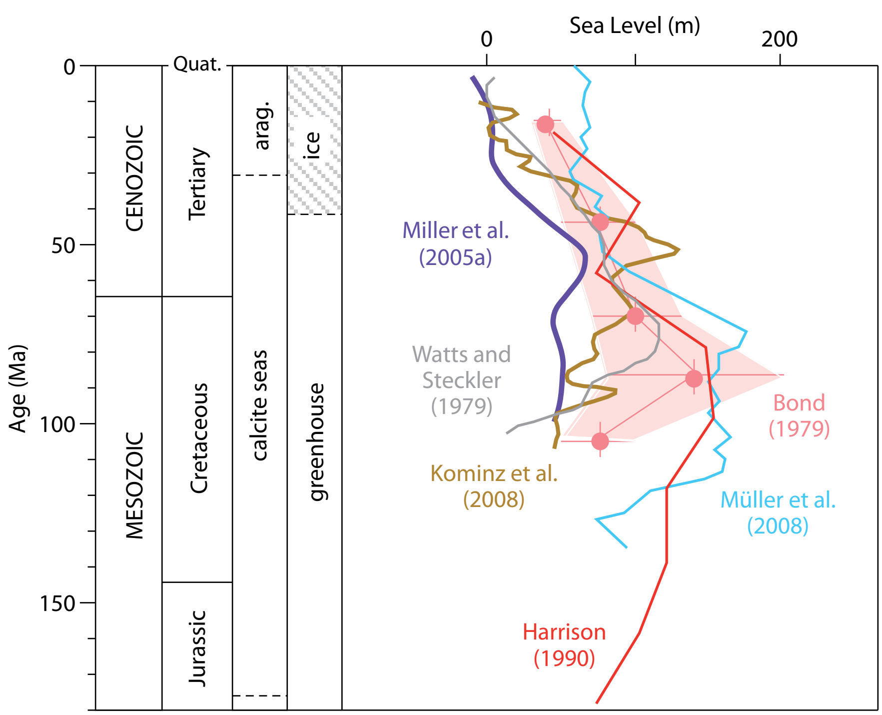

Figure 5. Long-term sea level estimates vary considerably but are in the range of 100–200 m for the peak at ca. 80 million years (versus the 250 m of Haq et al., 1987). Ma = millions of years ago. *Modified after Miller et al. (2005a)*

EVALUATING MARGIN RESPONSE

A major and ongoing objective of sea level studies is to understand how sequences are constructed in response to variations in global sea level, subsidence, and sediment supply in different tectonic and geographic settings (i.e., siliciclastic, carbonate bank, carbonate shelves along different continents). A characteristic pattern of sequences is a clinoform geometry that appears to develop when there is sufficient accommodation and sediment supply. The clinoform model of systems tracts predicts facies variations within sequences (Posamentier et al., 1988). These predictive models are based on some important untested assumptions (Fulthorpe et al., 2008). Our understanding of depositional environments within a clinoform are poorly known, but are critical to evaluating sea level change and predicting the distributions of reservoir sands and confining muds. For example, Greenlee and Moore (1988) illustrate that the assumption of shallow coastal versus marine onlap of the clinoform front introduces major uncertainties (> 50 m) into sea level estimates because it is not clear if they form in shallow (< 20 m) or deep water (up to 100 m; e.g., Cathro et al., 2003).

The Integrated Ocean Drilling Program (IODP) has continued to address the issue of the response of sedimentation on continental margins to sea level change by successfully drilling shallow water siliciclastic sequences with a mission-specific platform on the New Jersey shallow shelf (Expedition 313) and with *JOIDES Resolution* in New Zealand (Expedition 317). IODP Expedition 313 cored nearshore New Jersey lower to middle Miocene (24–14 million years ago) sequences that are poorly represented onshore but seismically well imaged nearshore; good recovery was obtained using a jack-up platform at three strategically placed sites in ~ 35 m of water (see opening-spread photo). Numerous early Miocene sea level cycles were recovered (http://publications.iodp.org/preliminary_report/313). Expedition 317 cored upper Miocene to Recent sequences in a transect of one slope and three shelf sites in the Canterbury Basin offshore of New Zealand (http://iodp.tamu.edu/scienceops/expeditions/canterbury_basin.html), providing a stratigraphic record of relative sea level cycles that are complementary to, albeit mostly younger than, the samples from New Jersey Expedition 313. Ongoing studies of these two classic areas will address development of facies models and sea level changes in these siliciclastic settings.

> "A MAJOR AND ONGOING OBJECTIVE OF SEA LEVEL STUDIES IS TO UNDERSTAND HOW SEQUENCES ARE CONSTRUCTED IN RESPONSE TO VARIATIONS IN GLOBAL SEA LEVEL, SUBSIDENCE, AND SEDIMENT SUPPLY IN DIFFERENT TECTONIC AND GEOGRAPHIC SETTINGS."

A 180-MILLION-YEAR HISTORY OF SEA LEVEL AND ICE VOLUME CHANGES

Comparison of 100 million years of backstripped records in New Jersey with those from the Russian platform (90–180 million years ago; Sahagian et al., 1996) allows extension of global sea level estimates back to the Early Jurassic (Figure 6) and development of a history of sea level and ice volume changes. Following Carboniferous glaciations, Earth entered a greenhouse state with high atmospheric CO_2 (> 1,000 ppm or > 3–4 times pre-anthropogenic levels; Royer et al., 2004). Yet, backstripped global sea level estimates from New Jersey and Russia show large (> 25 m) and rapid (< 1 million years) sea level changes in the Middle Jurassic to early Eocene (180–49 million years ago) greenhouse world. No known mechanism can explain the rapidity and amplitude of these changes other than growth and decay of continental ice sheets (Miller et al., 2005b; Figure 1). Examples of major global sea level falls associated with cool events in the greenhouse world ("cold snaps" of Royer et al., 2004) are as follows: (1) the late Pliensbachian (late Early Jurassic; ~ 185 million years ago) global sea level fall correlates with glendonites and other evidence of Siberian glaciation (Suana et al., 2010), though it lacks backstripped records; (2) the late Cenomanian–early Turonian was the warmest interval of the past 200 million years, yet it was bracketed by two inferred global sea level falls of ~ 25 m that were associated with two large (> 0.75‰) deep-sea $\delta^{18}O$ increases (92–93 million years ago, mid-Turonian, and 96 million years ago, mid-Cenomanian; Miller et al., 2005b); (3) the early/middle Eocene boundary was a major global fall associated with a $\delta^{18}O$ increase and the slide into the icehouse world of today (Browning et al., 1996; Miller et al., 1998).

Many mechanisms can cause regional sea level changes, and new evidence suggests that tectonically controlled changes can be rapid (e.g., Lovell, 2010). However, we argue that most of the events listed above are global. Glacially driven global sea level change is the only known mechanism that can account for such rapid changes because other hypothesized mechanisms are too slow or too small. Jacobs and Sahagian (1993) found that changes in land-based water storage in liquid form could account for 10 m of sea level variability at Milankovitch time scales, but it is difficult to explain 25 m in less than one million years without forming ice. Miller et al. (2005b) reconciled records of warm high latitudes with glacially driven global sea level changes by proposing that greenhouse world ice sheets generally reached maximum volumes of 8–12 x 10^6 km^3 (20–30 m global sea level equivalent) in Antarctica during the Late Cretaceous to Eocene, and in Siberia during the Jurassic to Early Cretaceous, but did not reach the coast. The physical evidence for these postulated ice sheets is thus not seen offshore of Antarctica, and today may be largely buried beneath 4 km of ice. This glacial mechanism for greenhouse world sea level changes remains controversial.

During the earliest Oligocene, a continental-scale ice sheet developed in Antarctica (Miller et al., 1991, 2005a; Zachos et al., 1996) associated with a fall of atmospheric CO_2 (Pagani et al., 2005). Oligocene to middle Miocene sea level changes are associated with large (~ 50–60 m) sea level falls on the million-year scale (i.e., the Oi and Mi isotope events of Miller et al., 1991) that have an apparent periodicity of 1.2 million years and may be paced by the long planetary tilt cycle (recent work of authors Miller, Browning, and Wright, and colleagues). This interpretation is consistent with a strong, persistent overprint of the 1.2-million-year tilt cycle on $\delta^{18}O$ records and a persistent dominance of 41,000-year tilt periods in the Milankovitch bandwidth (Zachos et al., 2001; Holbourn et al., 2007). The ice sheet nearly disappeared many times during the Oligocene to middle Miocene. During the middle Miocene, two major $\delta^{18}O$ increases (Mi3 and Mi4) culminated in the development of a near-permanent East Antarctic Ice Sheet. As a result, later middle Miocene to early Pliocene

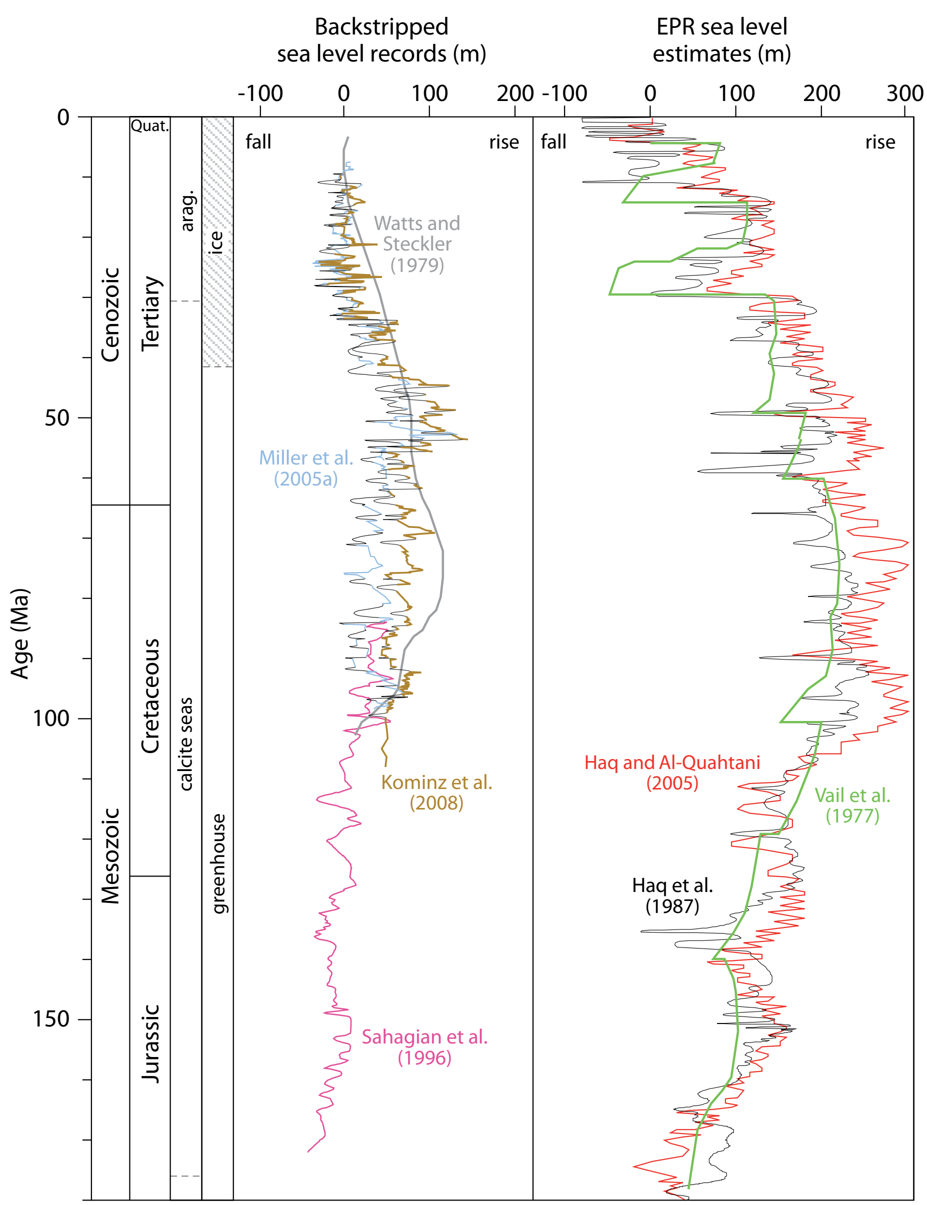

Figure 6. Comparison of backstripped sea level records from New Jersey (blue, Miller et al. 2005a; brown, Kominz et al., 2008), Russian platform (pink, Sahagian et al., 1996), and Scotian margin (gray, Steckler and Watts, 1979) with Exxon Production Research Company (EPR; green, Vail et al., 1977; black, Haq et al., 1987; maroon, Haq and Al-Qahtani, 2005). Note the much higher amplitude of the EPR estimates.

sea level variations were muted on the million-year scale. During the Pliocene to Brunhes (i.e., from 5.2–0.8 million years ago), the 41,000-year tilt cycle dominated Milankovitch-scale sea level cycles, a phenomenon that has not been fully explained because of the apparent lack of expected precessional (19,000/21,000 years) effects (see Raymo and Huybers, 2008). A sea level peak of ~ 20–25 m in the early Pliocene has been estimated on the basis of backstripping in New Zealand, Virginia, and Enewetak, as well as with the application of oxygen and Mg/Ca methods (recent work of authors Miller, Browning, and Wright and colleagues). This early Pliocene peak has been linked to atmospheric CO_2 values of roughly 400 ppm (Pagani et al., 2010). Beginning ~ 2.55 million years ago, large Northern Hemisphere ice sheets caused sea level changes of 50–100 m, leaving dropstones in the northern North Atlantic and marking the beginning of the "ice ages" (Shackleton et al., 1984; Lisiecki and Raymo, 2005). During the Bruhnes (last 780,000), growth and decay of very large Northern Hemisphere ice sheets occurred predominantly at ~ 100,000-year periods (Martinson et al., 1987); the dominance of this eccentricity cycle resists explanation. Large 100,000-year changes in ice sheets are not predicted by Milankovitch theory because the direct effects of eccentricity on radiation are small, and this beat must be explained by some nonlinear feedbacks in the climate system (e.g., Imbrie et al., 1993)

CONCLUSIONS

Sea level change is of great interest to the public and scientists alike, with links to many fields that include climate change, geochemistry, biogeochemical cycles, sedimentology, stratigraphy, biologic evolution, tectonophysics, basin evolution, and the search for resources (oil, gas, water, and carbon sequestration [CCS]). The ties to climate change are fundamental: sea level studies challenge the conventional view of much of Earth history as an ice-free "greenhouse." Facies models that incorporate the effects of cyclic changes in relative sea level yield predictions about sand versus mud distribution directly applicable to estimating reservoir/aquifer and cap rock/confining beds in hydrocarbon, groundwater, and CCS applications. Constraining global sea level history has important feedbacks into tectonophysics. Backstripping was developed to evaluate basin evolution, assuming sea level was known (e.g., the EPR record). ODP/IODP studies have demonstrated the inadequacy of sea level histories developed with inadequate regard for tectonism, loading, compaction, and other factors, while providing the way toward developing new eustatic estimates that can then be used to solve for tectonism.

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