INVEST White Paper - Global Sea-Level Changes and Effects

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Abstract

This white paper is based on a workshop report (Fulthorpe et al., 2008a) that identifies two fundamental objectives for sea-level studies: 1) determine the pattern of global sea-level (eustatic) change and identify and quantify the mechanisms responsible for eustatic change through geological time, and 2) define the sedimentary and sequence stratigraphic responses to eustatic change in siliciclastic, carbonates and mixed depositional settings. Strategies for achieving these objectives include applying a drilling transect approach (integrating offshore and onshore drilling transects) to both icehouse and greenhouse targets and extending the approach to active margins to complement ongoing passive-margin drilling.

Only through IODP drilling can we decipher the origin of the preserved stratigraphic record on continental margins and, in particular, quantify the record of global sea-level change (eustasy). Continental margin sediments, deposited within a few hundred meters of sea level, contain a direct record of eustatic fluctuations. However, these deposits are also a response to local forcing, e.g., vertical tectonism, sediment type and rate of supply (climatically or tectonically controlled), ocean currents, physiography, isostasy and compaction. Such controls vary temporally and spatially and all interact with eustasy to produce the stratigraphic record of beds and sequences. Deciphering these complex process interactions to read the long-term (Mesozoic through Cenozoic) record of earth history preserved within continental margins requires sufficient seismic coverage to constrain three-dimensional sequence stratigraphic architectures together with scientific ocean drilling to calibrate seismic interpretations. Drilling on widely separated margins is required to demonstrate global synchrony. Shallow-water (<200 m) drilling on shelves poses unique problems and may require Mission Specific Platforms.

Introduction

One of the most societally-relevant objectives of the earth sciences is to understand the history and impact of global sea-level (eustatic) fluctuations at different time scales. Over a third of the world's population lives within 100 km of a coastline. One tenth of the global population, and 13 per cent of the world's urban population live in the Low Elevation Coastal Zone (≤10 m above sea level), which covers only 2 per cent of the world's land area (McGranahan et al., 2007). Reconstruction of global mean sea level since 1870 indicates a 20th century rate of sea-level rise of 1.7 ± 0.3 mm yr^{-1} and a significant acceleration of sea-level rise of 0.013 ± 0.006 mm yr^{-2} (Church and White, 2006), in part due to anthropogenic influences. Satellite observations in the last decade show that rates have increased since 1993 to 3.3±0.4 mm/yr (Cazenave and Nerem, 2004). IPCC (2007) gives a best estimate of sea-level rise of as much as 50 cm in the next 100 years. Remote-sensing data suggest that ice sheets currently contribute little to sea-level rise. However, dynamical instabilities in response to climate warming may cause faster ice-mass loss (Cazenave, 2006). Rahmstorf et al. (2007) show that sea-level observations are tracking at the high end of the IPCC estimates and conclude that 80 cm, and perhaps >1 m, is the most likely global rise by 2100. In some of the most heavily populated areas (e.g., the U.S. Atlantic seaboard) relative sea-level rise exceeds 4 mm/yr (Psuty and Collins, 1996) due to combined effects of eustasy and subsidence. While such rates are gradual on a human time scale, the geological record shows that they can increase dramatically (e.g., >2 m in a century; Fairbanks, 1989; Bard et al., 1990); in addition, the retreat of shorelines can be erratic and rapid even under conditions of moderate global rises of sea level. Based on climate models and analogies with past conditions, a total sea-level rise of ~2 m by 2100 would only occur under extreme conditions; 0.8 m is most likely (Pfeffer et al., 2008).

The geologic record provides an opportunity to quantify the timing, amplitudes, rates, mechanisms/controls, and effects (stratigraphic response) of eustatic change (Figures 1, 2 and 3). In order to predict the effects of potential future eustatic trends and to assess anthropogenic influence, it is vital to document how the earth system has operated during past abrupt climate changes and under past conditions of extreme climate forcing and to constrain the eustatic response to elevated CO_2 levels. For example, determining how sea-level varied in response to past intervals of global warming, e.g., marine isotope stages 5e (Thompson and Goldstein, 2005), 11 (Droxler et al., 2003), 31 (Scherer et al., 2008);"mid " Pliocene warmth (Draut et al., 2003; Naish et al., 2008; Raymo et al., 2009), the middle Miocene climate optimum, the early Eocene (Zachos et al., 2001), and the Late Cretaceous (Abreu et al., 1998; Miller et al. 2005a,b; Bornemann et al., 2008), will provide a baseline for evaluation of the eustatic and societal impacts of future climate trends. To do so, we must understand how various mechanisms yield specific eustatic responses. Furthermore, understanding how process interactions produce the preserved stratigraphy of beds and sequences is fundamental to deciphering the long-term geologic and climatic history recorded by sediments in a variety of marine sedimentary basins. These environments are also economically and strategically important: testing predictive sequence models has proven potential for identifying oil and gas resources and for ground water/pollution remediation issues. Such research also helps to achieve the long-sought goal of predicting margin lithologies in the absence of drilling (i.e., Vail and Mitchum, 1977). Finally, quantifying the history of sea-level change provides data of direct use to researchers in other disciplines because of the relationships between eustasy and ice-sheet growth and decay, ocean temperature, nutrients and ocean productivity, ocean chemistry, carbon burial, and inorganic carbon precipitation (Figure 4), as well as global tectonism (Harrison, 1990; Müller et al., 2008).

The challenge is considerable, because eustatic effects are complexly intertwined with processes of basin subsidence and sediment supply (e.g., Cloetingh et al., 1985; Karner, 1986; Posamentier et al., 1988; Christie-Blick et al., 1990; Reynolds et al., 1991; Christie-Blick and Driscoll, 1995; Kominz et al., 1998; Kominz and Pekar, 2001). Extracting the eustatic signal requires integrated onshore/offshore drilling transects involving global retrieval of cores representing multiple timeframes and depositional settings, including siliciclastic, carbonate and mixed systems (Figure 3).

Sea Level and Scientific Drilling

Various ODP-related groups developed strategies for studying eustasy on orbital (>19 kyr) and longer time scales (Imbrie et al., 1987; Watkins and Mountain, 1990; JOIDES, 1992). These strategies have begun to be implemented with drilling transects across the New Jersey margin (Legs 150, 150X, 174A, and 174AX), the Bahamas (Leg 166 and mission-specific platform sites) and a targeted sea-level amplitude experiment on the Marion Plateau, Northeast Australia (Leg 194). However, an effective, coordinated strategy requires that additional margin transects be drilled. To promote such drilling and to assess recent drilling advances, including the use of mission-specific platforms (MSP; e.g., IODP Expeditions 310, 313 and 325) and joint onshore-offshore drilling, together with new views on the roles of tectonics and sediment dynamics, a new international workshop was sponsored by Consortium for Ocean Leadership, ICDP, IODP, DOSECC and Chevron (Fulthorpe et al. 2008a,b). The workshop set out strategies to achieve the two fundamental objectives.

Objective 1: Determining the pattern of eustatic change and identifying and quantifying the mechanisms responsible for eustatic change through geological time.

1) Refining timing, amplitudes and mechanisms of icehouse (Oligocene-Recent) eustatic change. Understanding the mechanisms that drive eustatic change requires knowledge of the timing, amplitudes and rates of global sea-level change (Figure 1). It also requires information on climate and paleoceanography, mainly derived from proxy records (Figure 4), and tectonic mechanisms that control the volume of the oceans (Müller et al., 2008).

ODP results to date have demonstrated that global sea-level changes over the past 42 myr can be explained, in part, by growth and decay of continental ice sheets (glacioeustasy; Miller, Mountain, et al., 1996; Eberli, Swart, Malone, et al., 1997; Eberli, 2000). Such drilling has principally addressed the timing of sea-level change, and has also determined that sequence boundaries indeed represent time lines as predicted in the sequence stratigraphic model (Eberli, Swart, Malone, et al., 1997; Betzler et al., 2000). However, our understanding of how climate change influences sea-level, even during this "icehouse" period of large ice sheets, is incomplete. In particular, there are still uncertainties surrounding the hierarchy of eustatic and sequence periodicities, and particularly the origins of sequences with durations of >1 myr, which do not appear to conform to long-period (1.2 and 2.4 myr) astronomical variations (Miller et al., 2005a). It is surprising that modulation by the 1.2 myr-long tilt cycle is not a dominant periodicity in icehouse sea-level records, because it has been shown that the short 41 kyr tilt cycle dominates the ice-volume record of the past 34+ my (Zachos et al., 2001). The 2.4 myr very long eccentricity cycle dominates carbon isotopic records throughout the Cretaceous to Cenozoic through its effects on the carbon system and might be expected to be influenced by sea-level changes. Spectral analysis of the Miller et al. (2005a) sea-level records shows that variations occur with an as-yet-unexplained, persistent 3 myr beat that may be either an interference between the 1.2 and 2.4 myr cycles or be an artifact of an undersampled sea-level signal. This intriguing relationship bears investigation because the million-year-scale sea-level signal can be shown to be a composite of 41-kyr tilt cycles, at least for the icehouse world (Miller et al., 2005a).

Moreover, sea-level amplitudes during this period have not yet been adequately constrained. One approach for determining eustatic amplitudes, applied with success to the Oligocene of New Jersey margin, involves combining sequence stratigraphic and backstripping analyses (Figure 5; Kominz and Pekar, 2001; 2002; Pekar and Kominz, 2001). The resulting sea-level curve (Figure 2; Kominz et al., 2008; Browning et al., 2008) represents the best current estimate, but it is still incomplete because lowstand sediments were not recovered, introducing uncertainty to amplitude estimates, and use of 1D backstripping. Possibly as a result, the Miocene part of the New Jersey sea-level curve does not appear to correspond well to the globally recognized stratigraphic signature of the Neogene (Figure 6; Bartek et al., 1991) or to $\delta^{18}O$ records that have been corrected for paleotemperatures to yield an improved record of ice-volume fluctuations (Billups and Schrag, 2002; Lear et al., 2004; Westerhold et al., 2005 Figure 6).

Finally, estimates of the amplitudes of eustatic change from backstripping at one location (e.g., New Jersey; Miller et al., 2005a; Kominz et al., 2008; Browning et al., 2008) require confirmation through application of this procedure to strata on distant continents (e.g., Carter et al., 1991). Future scientific drilling must therefore include additional drilling for icehouse eustatic objectives. Ideally, two and three-dimensional backstripping procedures would improve amplitude estimates (e.g., Kominz and Pekar, 2001). These approaches require good regional seismic coverage and a well-constrained, regional, sequence stratigraphic framework, including data that can only be obtained from cores.

2) Challenging the paradigm of a stable, ice-free "greenhouse" climate. The Late Cretaceous has been considered a greenhouse world with warm polar climates (Bice et al., 2006) and lacking polar ice sheets (e.g., Huber et al, 1995). However, the work of Exxon Production Research Company (Vail and Mitchum, 1977; Haq et al., 1987) and more recent publications (Van Sickel et al., 2004; Miller et al., 2003; 2005a,b; Bornemann et al., 2008) indicate large (tens of meters), short-period (<1 myr) Late Cretaceous eustatic fluctuations (Figure 2). In addition, second- (~10 my), third- (1-5 my) and fourth- (~0.5 my) order sequences can be correlated widely between tectonically active and passive regions (e.g., Western Interior Seaway, Europe and India; Gale et al., 2002) suggesting eustatic control.

Glacioeustasy is the only known mechanism for producing such large, rapid eustatic changes (Donovan and Jones, 1979; Figure 1). Therefore, either eustatic mechanisms are not fully understood, or there were ice sheets throughout much of the Triassic to early Eocene (e.g., Stoll and Schrag, 1996, 2000; Abreu et al., 1998; Miller et al., 2003, 2005a,b; Bornemann et al., 2008). ODP and ICDP drilling onshore New Jersey (Leg 174AX) have provided a detailed record that quantifies high eustatic amplitudes and rates (>25 m in <1 myr) during the Late Cretaceous to Eocene. Miller et al. (2003, 2005a,b) have therefore proposed that ice sheets existed for geologically short intervals (i.e., lasting ~100 ky) during this period. Eustatic changes on the 10^6 y scale were typically ~15-30 m from ca. 100-33.8 Ma, suggesting growth and decay of small- to medium-sized (10-15 x 10^6 km^3) ephemeral Antarctic ice sheets (Miller et al., 2005a,b). However, there is no physical evidence for Late Cretaceous to early Eocene ice sheets.

A particular difficulty is that other data indicate warm global temperatures for much of this interval, for example very warm Albian-Santonian sea surface temperatures in the tropical Atlantic (Forster et al., 2007). There is therefore a strong need for additional high-resolution stratigraphic records from the greenhouse period.

Objective 2: Defining the sedimentary and sequence stratigraphic responses to eustatic change in siliciclastic, carbonates and mixed depositional settings.

The stratal geometries that define sedimentary sequences worldwide (Mitchum et al., 1977; Haq et al., 1987) result from a complex interplay of processes acting in three dimensions. Eustasy competes with climatic and paleoceanographic variations, tectonism, rates and modes of sediment supply and submarine current activity to influence relative sea-level and shoreline position and hence stratal formation and preservation. Understanding margin sedimentation, therefore, requires evaluation of multiple processes (including eustasy) at various temporal and spatial scales (Nittrouer and Kravitz, 1995).

Nevertheless, industry and academic studies have established that unconformity-bounded sequences are indeed the building blocks of the stratigraphic record (see summary in Christie-Blick and Driscoll, 1995), as first proposed by Vail and Mitchum (1977), and that they can occur in predictable patterns (Figure 3). For example, the geometric signature of stratigraphic sequences along continental margins for the last 30 Ma is observed globally in both siliciclastics and carbonates (Figure 3E; Bartek et al., 1991; Tcherepanov et al., 2008a, b). However, the heart of this section, the early and middle Miocene, has not yet been calibrated by sampling, mainly because of past difficulties faced by *JOIDES Resolution* when drilling on continental shelves. The fundamental assumptions and predictive capabilities of sequence models can only be tested by drilling on shallow continental shelves where (3D) sedimentary geometries are constrained by seismic data (e.g., Kominz and Pekar, 2002). Furthermore, because of the multiple forcing mechanisms responsible for the stratigraphic record, stratigraphic response must be defined in diverse time periods and settings, both tectonic (passive and active margins) and sedimentary.

Siliciclastic Margins. Siliciclastic sediments are excellent sea-level markers because they are both highly sensitive indicators of shoreline position and are globally widespread. It is essential to define the specific sedimentary processes (depositional, transportational and erosional) responsible for the stratigraphic record and to distinguish the responses of these processes to eustasy from their responses to local forcing. This process-based approach must be a component of future drilling-based sea-level research.

The stratigraphic record comprises both surfaces and intervening sedimentary units. In offshore work, surfaces are often defined initially using seismic profiles and later calibrated by coring (Figure 3); only coring can provide the lithofacies and biofacies of the intervening units. Predictive sequence stratigraphic models (Posamentier et al., 1988; Van Wagoner et al. 1988; Vail et al, 1991) are based on simple assumptions about how facies respond to relative sea-level changes that have yet to be adequately tested. Real world complexity arises from the additional influence of local forcing and the resulting three-dimensionality of sequence architectures. Future drilling to investigate the stratigraphic response to eustasy must therefore evaluate the contributions of tectonism and sediment supply. In addition, geometrical variations must be constrained by pre-drilling seismic surveys.

Carbonate Platforms and Margins. Carbonates are also excellent and unique sea-level markers because carbonate facies are depth-dependent owing to the importance of sunlight to many carbonate-secreting organisms. The relationship of these systems to the carbon cycle allows direct correlation of climatic and eustatic signals. In addition, multiple dating techniques are available for carbonates (including ^{14}C, U/Th, Sr, U/Pb, biostratigraphy and magnetostratigraphy). This enables examination of a wide spectrum of sea-level change, from millennial scale to tens of millions of years.

Continental margin transects (Figure 3) have the advantage that stratigraphic architectures are constrained by seismic data. However, they are complemented by tropical reefs and atolls, which provide the most reliable geological estimates of relative sea-level by dating "fossil sunshine" (e.g., shallow dwelling corals). Coral reefs are of crucial importance to resolving the rates of millennial-scale eustatic changes, to clarifying the mechanisms that drive glacial-interglacial cycles and to constraining geophysical models. Coral reefs provide unparalleled records of sea-level amplitudes, particularly for the middle to late Pleistocene. For example, drilling reefs on Barbados has provided a precise estimate for the last eustatic lowstand (120±5 m below present at 18 ka; Fairbanks, 1989; Bard et al., 1990; Peltier and Fairbanks, 2006). Shallow-water drilling of coral reefs remains challenging due to recovery problems, but is necessary to allow high-resolution study of recent climate changes and contribute to estimates of the future behavior of the Earth system on societal timescales. This approach was employed during MSP IODP Expedition 310 off Tahiti (Camoin, Iryu, McInroy, 2007a, b). Drilling reefs older than the Pleistocene for sea-level studies has been plagued by problems in recovery (e.g., the experience of guyot drilling on Legs 143 and 144), but MSPs could breathe new life into this approach.

Strategies

1) *A focus on both icehouse and greenhouse objectives.*

2) Drilling transect approach. This approach, tested on the New Jersey margin and Great Bahama Bank, with scheduled drilling off New Zealand (Figure 3F), must be enhanced by:

a) Integration of onshore (e.g., ICDP, DOSECC) and offshore (IODP, DOSECC) drilling. The record of icehouse eustasy is best preserved offshore, but the greenhouse record tends to be preserved and drillable beneath coastal plains or in onshore basins.

b) Sufficiently numerous boreholes, including multiple transects where necessary, and sufficient seismic control to constrain and calibrate 3D stratigraphic architecture.

c) Maximizing core recovery by using appropriate technology (e.g., casing, mud) and platforms (MSPs) and coring strategies, e.g., short advances of XCB

3) Drilling both passive and active margin settings. For example, the stratigraphic expression of sea-level change in U.S. and Canadian western interior foreland basins is superlative, though the records incorporate the effects of both eustasy and tectonism.

4) High resolution (10^3-10^5 yr) glacial-interglacial cycles (e.g., the last 130 kyr). High resolution studies allow evaluation of the interaction of eustasy with other processes and integration with process oriented modeling.

5) Coordination with drilling operations designed to address other objectives. Sea-level studies can benefit greatly from the results of research into, for example, paleoclimate, carbon cycling, and ice-sheet dynamics (Figure 4). Conversely, these research programs will also gain necessary insights from a well constrained eustatic history.

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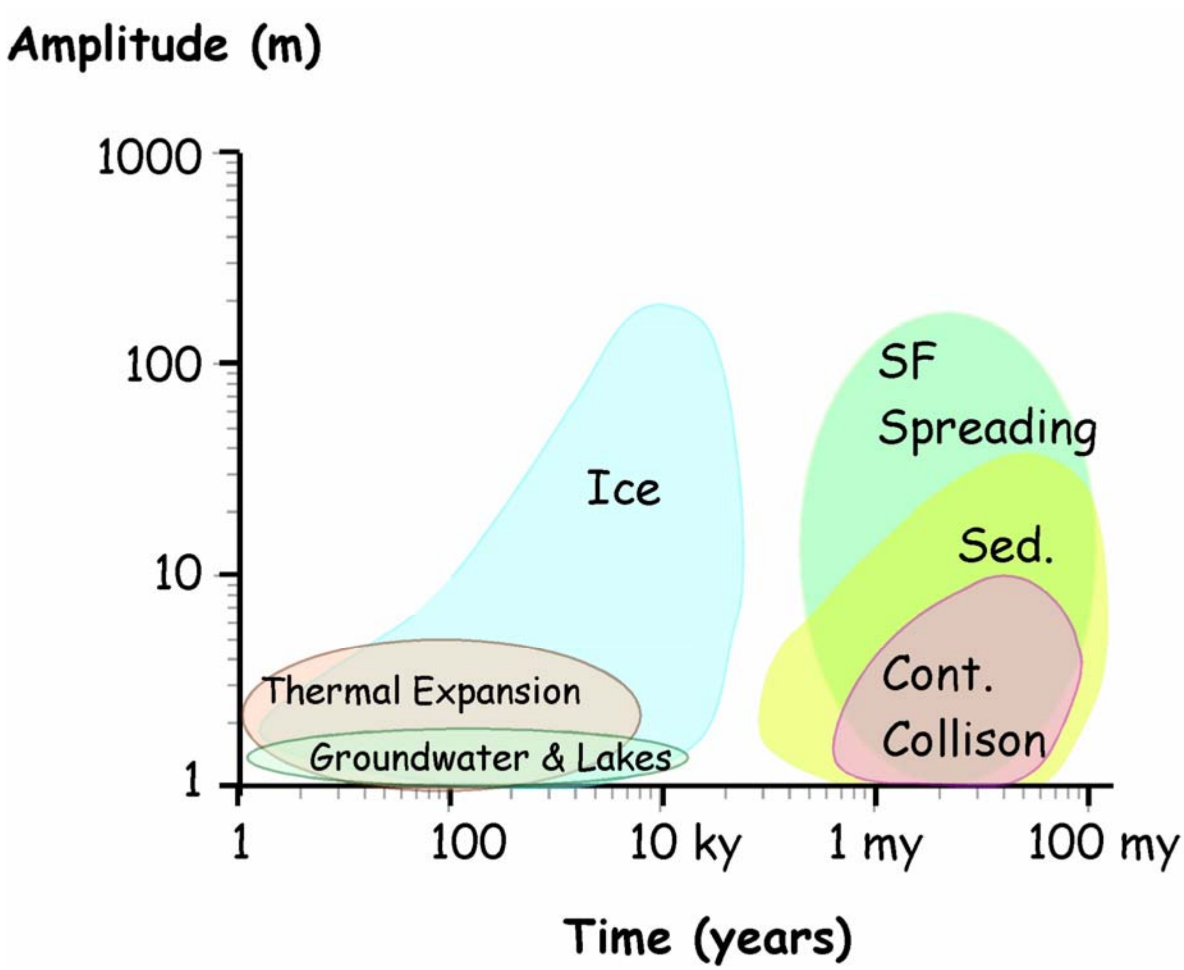

Figure 1. The mechanisms that generate eustatic change operate on different time scales and generate different magnitudes of sea level change. These variations in conjunction with proxy data may be used to determine the causal mechanisms of eustatic change. (Modified from Miller et al., 2005a.)

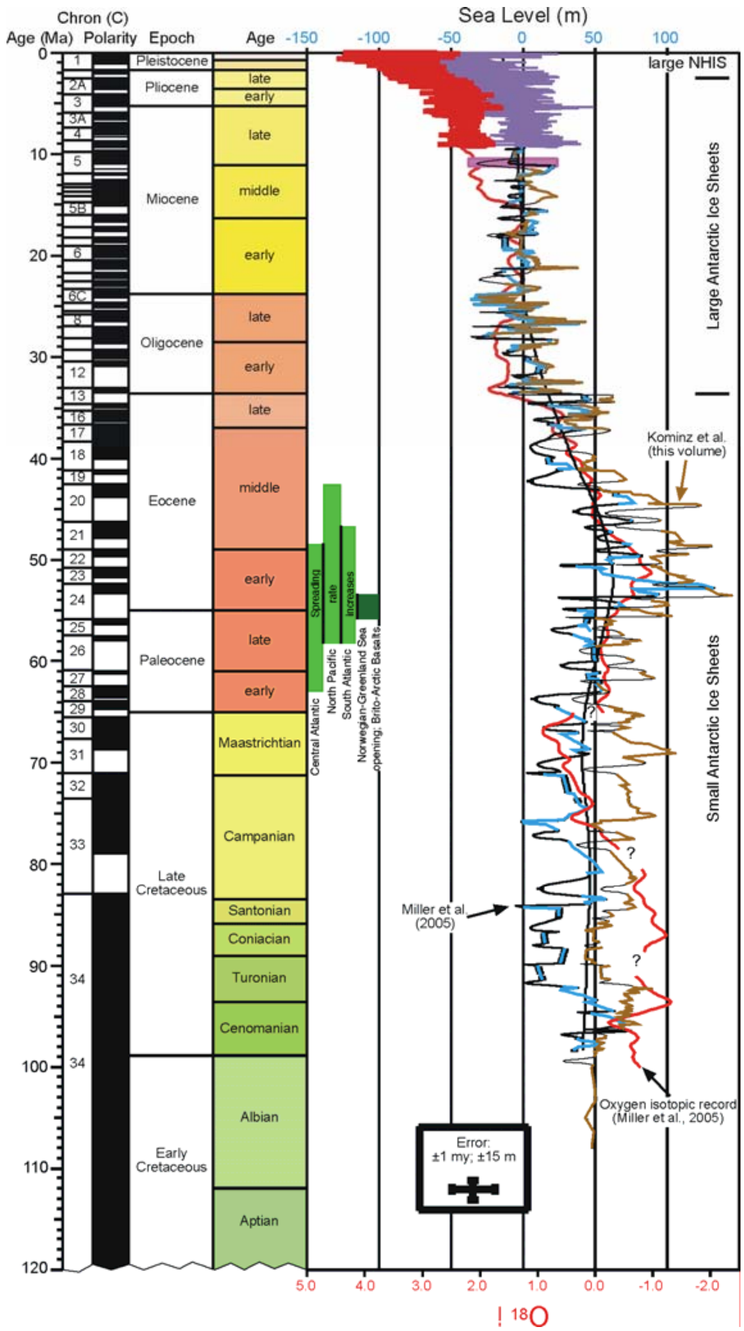

Figure 2. Global sea level (light blue) for the interval 7 to 100 Ma derived by backstripping data. Revised backstripped sea level curve based on 7 new wells and new age and paleoenvironmental data for the 5 coreholes used to derive the light blue curve is plotted in brown (Kominz et al., 2008). Global sea level (purple) for the interval 0 to 7 Ma derived from $\delta^{18}O$, shown in red for a benthic foraminiferal $\delta^{18}O$ synthesis from 0 to 100 Ma with the scale on the bottom axis (in parts per thousand, Miller et al., 2005a). The Miller et al. (2005a) backstripped sea level curve was smoothed with a 21-point Gaussian convolution filter to generate the smooth black curve. The pink box at`11 Ma is a sea-level estimate derived from the Marion Plateau (John et al., 2004). Light green boxes indicate times of spreading rate increases on various ocean ridges (Cande and Kent, 1992). Dark green box indicates the opening of the Norwegian-Greenland Sea and concomitant extrusion of basalts (modified from Browning et al., 2008).

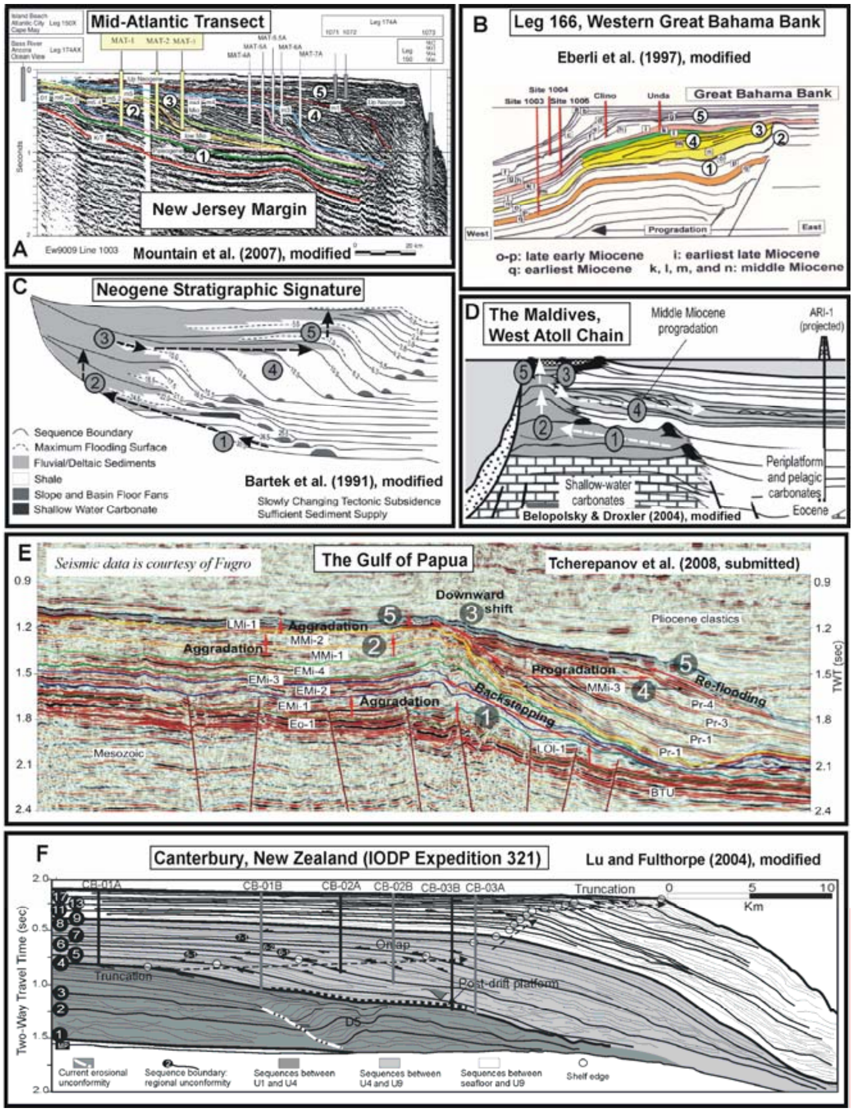

Figure 3. A. Middle Atlantic Transect (MAT) off New Jersey, showing proposed drillsites (modified from Mountain, et al., 2007) targeting a Paleogene-Pleistocene prograding clinoform succession. MAT has been drilled on the slope (ODP Leg 150; sites not shown) and shelf (Leg 174A; sites along strike from MAT8 and 9A), as well as on the Coastal Plain (Legs 150X and 174AX). Inner shelf sites (MAT 1-3) were drilled in summer 2009 as Mission-Specific Platform IODP Expedition 313. B. Line drawing (modified from Eberli, et al., 1997) of interpreted Great Bahama Bank sequences drilled during ODP Leg 166 (Sites 1003-1007) and the Bahamas Drilling Project (sites Clino and Unda). C. The stratigraphic signature of the Neogene (modified from Bartek et al., 1991). D) The Neogene stratigraphic signature along the West Maldives Inner Sea carbonate margin (modified from Belopolsky and Droxler, 2004). E) Neogene stratigraphic signature in the Gulf Of Papua represented by: 1) late Oligocene-early Miocene aggradation, backstepping and partial drowning; 2) late early Miocene-early middle Miocene vertical growth or aggradation; 3) middle Miocene downward shift of deposition; 4) late middle Miocene systematic lateral growth (progradation); 5) late Miocene-early Pliocene re-flooding and aggradation (Tcherepanov et al., 2008). F. A future sea-level transect: line drawing of interpreted sequences, offshore Canterbury Basin, New Zealand, showing proposed IODP sites, scheduled for drilling in November 2009 -January 2010 as IODP Expedition 317 (modified from Lu and Fulthorpe, 2004).

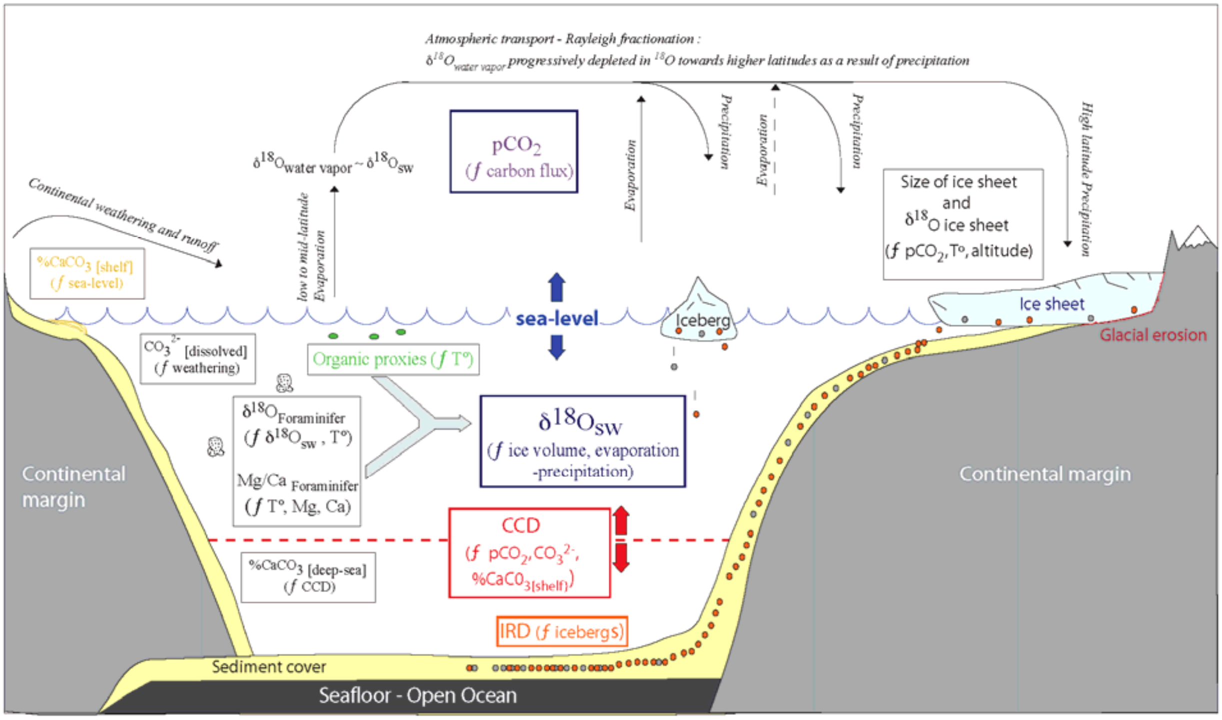

Figure 4. Schematic figure illustrating how deep-sea geochemical records can be used to understand mechanisms of past eustatic changes by analogy to the modern ocean. During atmospheric transport from low to high latitudes water vapor becomes progressively more depleted in ^{18}O, and ice sheets have a very negative $\delta^{18}O$ signature. The isotopic composition of high latitude ice sheets is a function of the magnitude of isotopic fractionation within the hydrological cycle, which in turn is dependent on pCO_2 and temperature, and could vary over geological timescales. Consequently, the $\delta^{18}O$ composition of seawater ($\delta^{18}O_{sw}$) is largely a function (f) of ice volume and regional evaporation and precipitation processes. Reconstructing $\delta^{18}O_{sw}$ in different ocean basins will highlight times of eustatic changes due to ice-volume fluctuations, as well as provide a record of the timing and amplitude of these changes. $\delta^{18}O_{sw}$ can be derived by combining the isotopic composition of foraminiferal calcite ("$\delta^{18}O_{Foraminifer}$") with independent temperature proxies (e.g. Mg/Ca for deep-water temperature, and TEX_{86} and alkenones for surface water temperatures). Subsequently, correlation of excursions in $\delta^{18}O_{sw}$ to more positive values with independent evidence of sea-level change can be taken as support for the operation of a glacio-eustatic mechanism. Open ocean sites can also provide more indirect evidences of the relative role of glacio-eustasy through geological time. The presence of ice rafted debris (IRD) in open ocean sediments indicates iceberg transport, and thus a significant volume of ice at sea level along continental margins. The waxing and waning of ice sheets is a function of high-latitude temperatures and atmospheric pCO_2, which also impact on the position of the carbonate compensation depth (CCD). Fluctuations in the CCD are recorded as variable carbonate contents (%$CaCO_3$) within deep-sea sediments and could be used as indirect evidences of glacial/interglacial alternations, as it is sensitive to changes in carbonate burial on the shelf. Finally, eustatic variations control the area of shelf submerged, thus indirectly impacting the type of rocks subjected to continental weathering, the amount of nutrients and carbonate ions delivered to the coastal ocean, and the area available for carbon burial on continental margins. Some isotope systems (Os, Nd and Sr) are available as proxies of continental weathering. The weathering processes ultimately have feedbacks on the carbon cycle, climate, and glacio-eustasy.

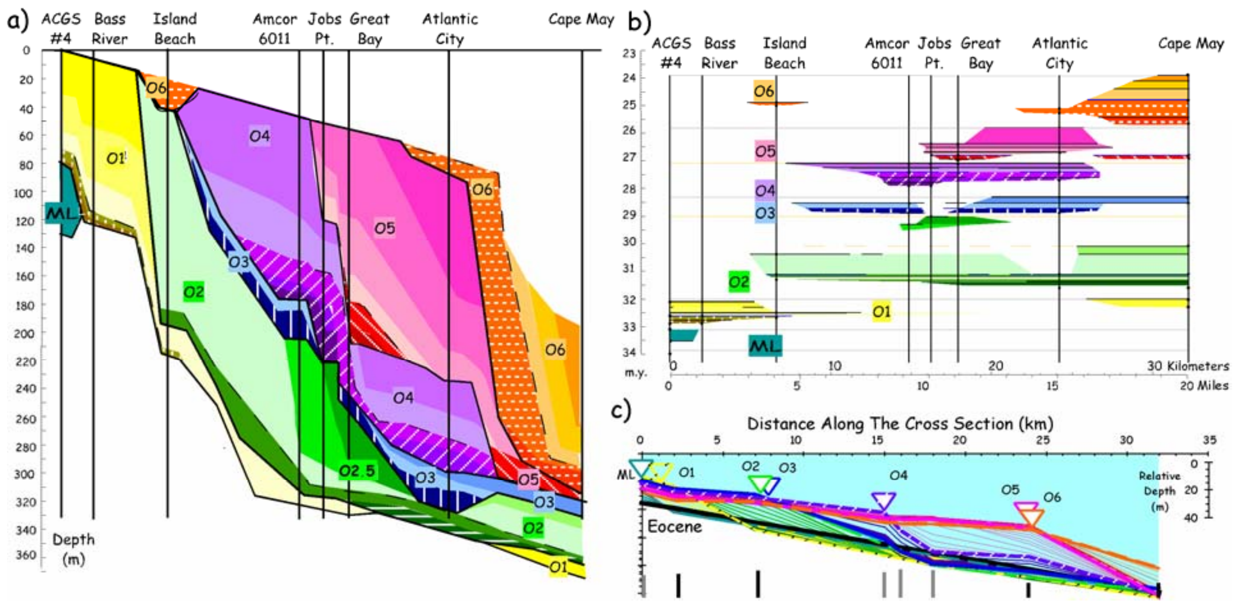

Figure 5. In order to determine sea-level change from a marginal marine setting we recommend at least two-dimensional sequence stratigraphic backstripping. An example of some of data required for two-dimensional sequence stratigraphic backstripping from Kominz and Pekar (2001 and 2002) is shown for illustration. **A.** Sequence model for New Jersey coastal plain Oligocene sequences. Solid colors represent highstand systems tracts while lowstand systems tracts are depicted by patterns. Vertical lines show well control. Modified from Kominz and Pekar (2002). **B.** Chronostratigraphic chart for New Jersey coastal plain Oligocene sequences. Patterns and lines correspond to those shown in A. **C.** Geometry of horizons identified in A and B after performing geohistory analysis plotted on same vertical scale as A. Sequences may be identified by colors, which reflect those A and B and the labeled offlap break points (inverted triangles) of the final horizon of each sequence. (Modified from Kominz and Pekar, 2002.)

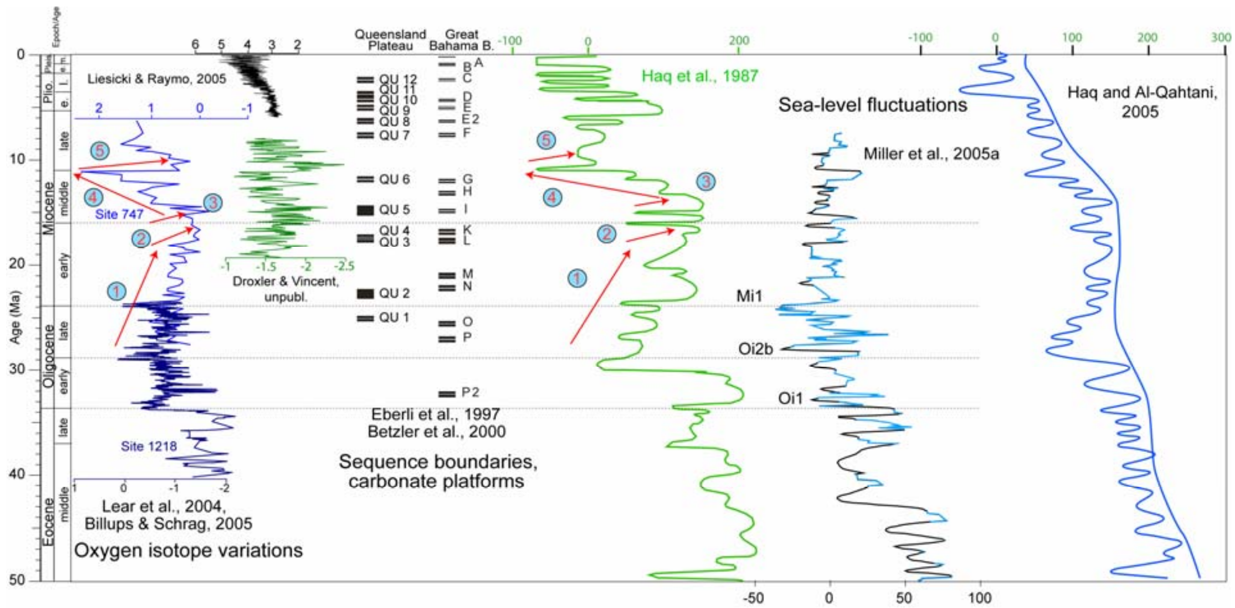

Figure 6. Oxygen isotopic and eustatic curves showing correspondence to the stratigraphic signature of the Neogene (red arrows; see Figure 3). The eustatic curve from the New Jersey margin does not conform precisely to the global signature.