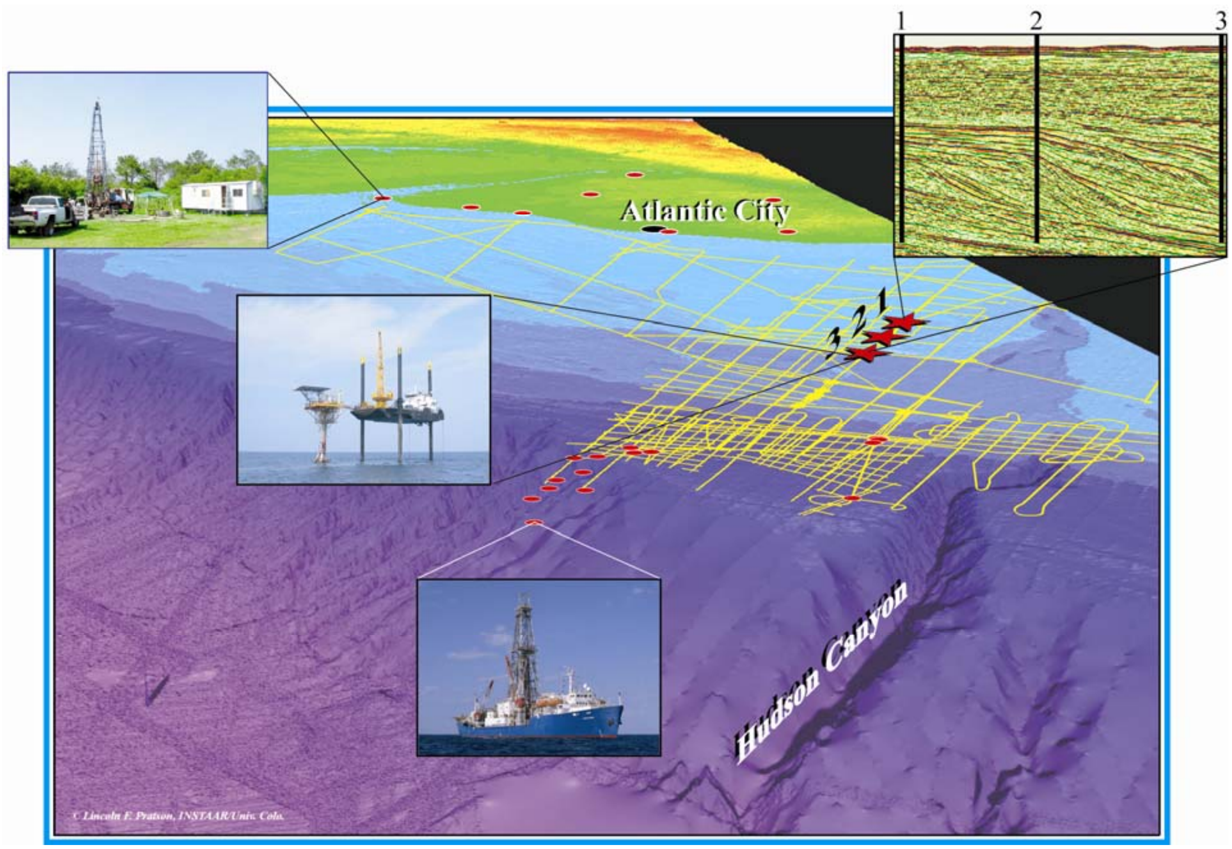
Drilling to Decipher Long-Term Sea-Level Changes and Effects



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Drilling to Decipher Long-Term Sea-Level Changes and Effects

Workshop Sponsors

Consortium for Ocean Leadership, ICDP, IODP, DOSECC, Chevron

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Cover image illustrates multi-platform scientific drilling of the New Jersey coastal plain, continental shelf and slope (courtesy of Greg Mountain, Rutgers University).

SUMMARY

Results of scientific drilling during the last fifteen years, coupled with the advent of new drilling technologies, provide the impetus for reassessing the strategies for understanding global sea-level change and its impact on the stratigraphic record. The principal objectives of sea-level research are identified as:

- *Determining the pattern of global sea-level change (eustasy) through Earth history and identifying and quantifying the mechanisms responsible for eustatic change through geological time.* Determination of eustatic timing, amplitudes and rates are essential prerequisites to assessing mechanisms, as is incorporation of results derived from proxy records.
- *Defining the sedimentary and sequence stratigraphic responses to eustatic change in siliciclastic, carbonate and mixed depositional settings.* This also necessitates deciphering the complex interactions between eustasy and local processes, particularly rates of vertical tectonism (uplift, subsidence) and sediment supply.

Scientific drilling is an essential tool for achieving these objectives because sediments representing key paleoenvironments and time periods are seldom adequately exposed in outcrop. Furthermore, outcrop sections cannot sufficiently constrain the three dimensionality of stratigraphic architecture that is characteristic of passive margins and other sedimentary basins.

The strategy developed at this workshop involves the following components:

1) *A focus on both icehouse and greenhouse objectives.* Most scientific drilling for sea-level objectives has focused on the Oligocene - Recent, icehouse interval. Our understanding of icehouse eustasy, particularly amplitudes, remains incomplete and further drilling is needed. However, onshore drilling of the New Jersey coastal plain has begun to document greenhouse eustasy and, in particular, to address the nature and significance of possible Cretaceous to early Eocene glaciation. Expanded study of greenhouse eustasy is required.

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

- Integration of onshore (e.g., ICDP, DOSECC) and offshore (IODP, DOSECC) drilling. The record of icehouse eustasy is best preserved offshore, e.g., on continental margins, but the older, greenhouse, record tends to be preserved and drillable beneath coastal plains or in onshore basins (e.g., the Western Interior Seaway). Onshore drilling is therefore expected to play an increasingly important role in sea-level studies.
- Drilling of sufficient boreholes, including multiple transects where necessary, and incorporation of sufficient seismic control to constrain three-dimensional stratigraphic architecture.
- Maximizing core recovery by using appropriate drilling technology (e.g., casing, mud) and platforms (e.g., Mission Specific Platforms [MSPs]) and by adapting coring strategies as needed, e.g., short advances of XCB, use of diamond coring.

3) Recognizing the value of addressing both passive and active margin settings. For example, the stratigraphic expression of sea-level change in active foreland basins in the U.S. and

Canadian western interior basins is superlative, though these stratigraphic records incorporate the effects of both eustasy and tectonism.

4) Incorporating a focus on high resolution (10^3-10^5 yr) glacial-interglacial cycles (e.g., the last 130 kyr). Examination of margins with high stratigraphic resolution will allow evaluation of the interaction of eustasy and other processes (e.g., Papua New Guinea; Jorry et al., 2008; Francis et al., submitted), and integration with process-oriented modeling (e.g., physical and mathematical modeling done as part of the Margins and Intermargins Initiatives).

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. Conversely, these research programs will also gain necessary insights from a well constrained eustatic history.

It is intended that this workshop report will serve as a guide to proponents of future scientific drilling proposals, to IODP and/or ICDP, designed to study global sea-level history.

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 coastal areas that lie within just 10 m above sea level (the Low Elevation Coastal Zone, or LECZ) 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 the rates have increased since 1993 to 3.3 ± 0.4 mm/yr (Cazenave and Nerem, 2004). Remote-sensing data suggest that ice sheets currently contribute little to sea-level rise. Best estimates are that sea level could rise by as much as 50 cm in the next 100 years (IPCC, 2007). 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 global sea-level rise and subsidence. While such rates are gradual on a human time scale, the geological record shows that they can increase rapidly and 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.

The geologic record provides an opportunity to quantify the timing, amplitudes, rates, mechanisms/controls, and effects (stratigraphic response) of eustatic change (Figures 1 and 2). This information, in turn, provides a baseline for predicting future global sea-level changes and assessing anthropogenic influences. In order to understand the effects of potential future eustatic trends, it is vital to document how the earth system has operated during past abrupt climate changes (e.g., the last and penultimate deglaciations) 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 chrons 5e (Thompson and Goldstein, 2005), 11 (Droxler et al., 2003), 31 (Scherer et al., 2008);"mid " Pliocene warmth (Draut et al., 2003)), the early part of the late Miocene, the early part of the middle Miocene peak warmth and middle Miocene climate optimum, the late Oligocene, the early Eocene, and the Late Cretaceous (Abreu et al., 1998; Miller et al. 2005a, b Bornemann et al., 2008), will provide a means to evaluate the eustatic impact of future climate trends. Understanding how processes/mechanisms yield specific eustatic responses will therefore improve our understanding the societal impact of the resulting sea-level changes. 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

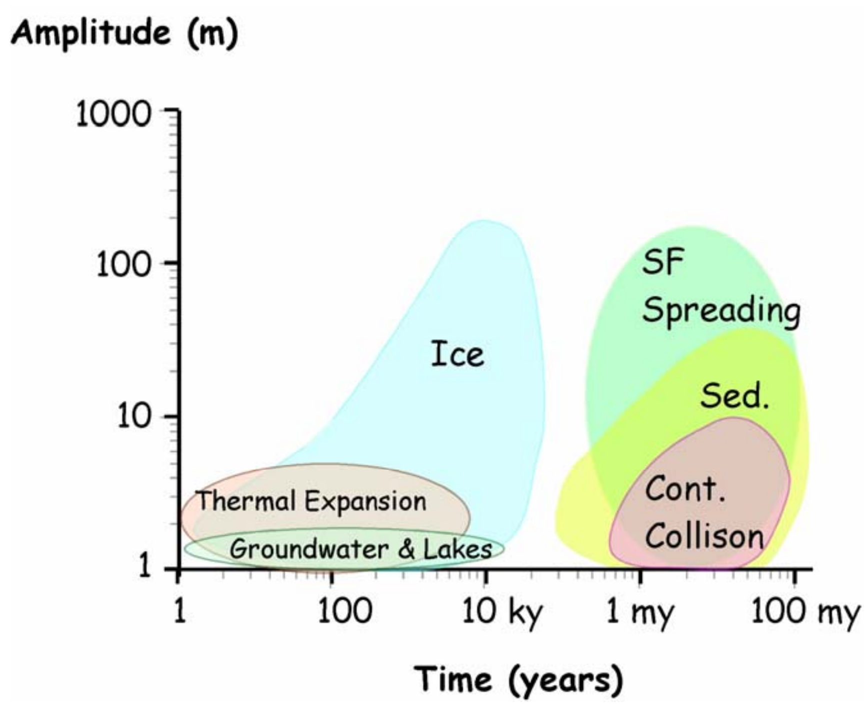

Figure 1. The mechanisms that generate eustatic change operate on different time scales and generate different magnitudes of sea-level change. These variations in conjunction with proxy data may be used to determine the causal mechanisms of eustatic change. (Modified from Miller et al., 2005a.)

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, a concept pioneered by the Exxon group (i.e., Vail and Mitchum, 1977). Finally, constraining the history of sea-level change provides data of direct use to researchers in other disciplines because of the complex relationships between eustasy and ice-sheet growth and decay, nutrients and ocean productivity, carbon storage and ocean chemistry.

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

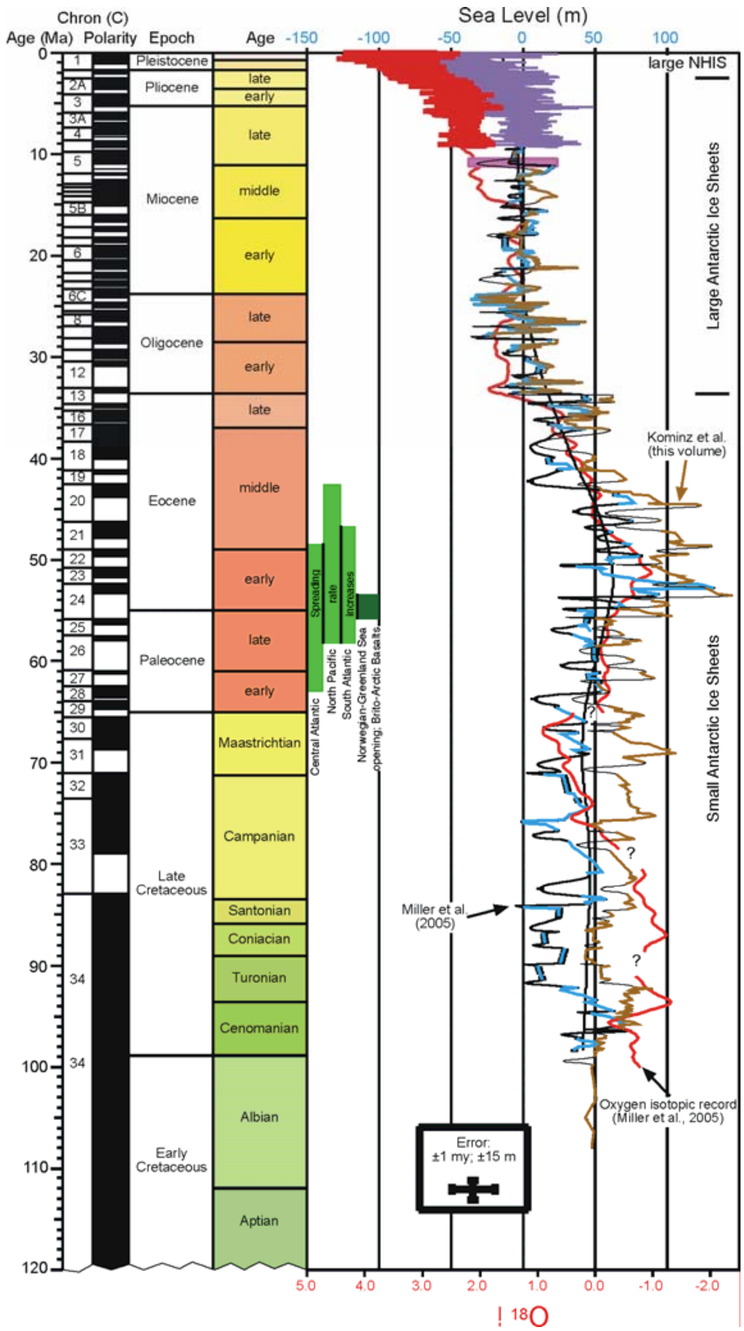

Figure 2. Global sea level (light blue) for the interval 7 to 100 Ma derived by backstripping data. Revised backstripped sea-level curve based on 7 new wells and new age and paleoenvironmental data for the 5 coreholes used to derive the light blue curve is plotted in brown (Kominz et al., in press). Global sea level (purple) for the interval 0 to 7 Ma derived from δ^{18}O, shown in red for a benthic foraminiferal d^{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., in press).

representing multiple timeframes and depositional settings, including siliciclastic, carbonate and mixed systems (Figure 3). Fundamental to the approaches recommended by our workshop are to: 1) enhance our understanding of eustatic timing, amplitudes, rates and stratigraphic response during the icehouse period, when glacioeustasy is known to be the principal eustatic mechanism, and; 2) begin an aggressive program to understand the mechanisms responsible for greenhouse eustasy and how they relate to climatic trends and stratigraphic response.

BACKGROUND

Determining the timing and amplitudes of global sea-level change and the role of eustasy in the generation and preservation of stratigraphy were prominent goals of ODP (COSOD II, 1987; Long Range Plan, JOI, Inc., 1996) and continues to be a focus of the IODP Initial Science Plan under the "Environmental Change, Processes and Effects" theme (IWG, 2001). Various ODP-related groups have 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; Mountain, Miller, Blum, et al., 1994; Miller et al., 1994; Austin, Christie-Blick, Malone, et al., 1998; Miller et al., 1998), the Bahamas (Leg 166 and mission-specific platform sites; Eberli, Swart, Malone, et al., 1997) and a targeted sea-level amplitude experiment on the Marion Plateau, Northeast Australia (Leg 194; Isern, Anselmetti, Blum et al., 2001). However, as stressed by previous groups, an effective, coordinated strategy requires that additional margin transects be drilled. In addition, it has been fifteen years since the last of these groups, the Sea-Level Working Group (JOIDES, 1992), discussed goals and strategies of sea-level research. Recent drilling advances, including the use of mission-specific platforms (MSP), together with new views on the roles of tectonics and sediment dynamics, required that the scientific community re-evaluate the fundamental assumptions of sea-level studies.

As a follow-up to the SEALAIX Symposium: *Sea-Level Changes: Records, Processes and Modeling* (September 2006, Presqu'Ile de Giens, France; conveners G. Camoin, A.W. Droxler, C.S. Fulthorpe and K.G. Miller), an international workshop of over 50 participants was held in Salt Lake City, Utah (8-10 October 2007) and sponsored by: Consortium for Ocean Leadership (formerly Joint Oceanographic Institutions), the International Continental Scientific Drilling Program (ICDP), Integrated Ocean Drilling Program (IODP), Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC) and Chevron. The purpose of the workshop was to: 1) review results of ODP drilling for sea-level objectives; 2) reevaluate principles and strategies for constraining genetic links between eustatic change and Earth system processes and for defining the relative roles of eustasy versus local processes in building the stratigraphic record; and 3) identify possible geographical areas and time intervals for future IODP drilling transects.

Workshop Organization

A series of presentations on scientific drilling organizations (IODP, ICDP and DOSECC) was followed by keynote scientific talks given by Ken Miller, Michelle Kominz, André Droxler and Vitor Abreu. A series of short, three-minute presentations by participants completed the first day of the workshop. The subsequent day and a half was devoted to breakout-group discussions and review of those discussions in plenary session. Posters were presented and discussed during scheduled breaks.

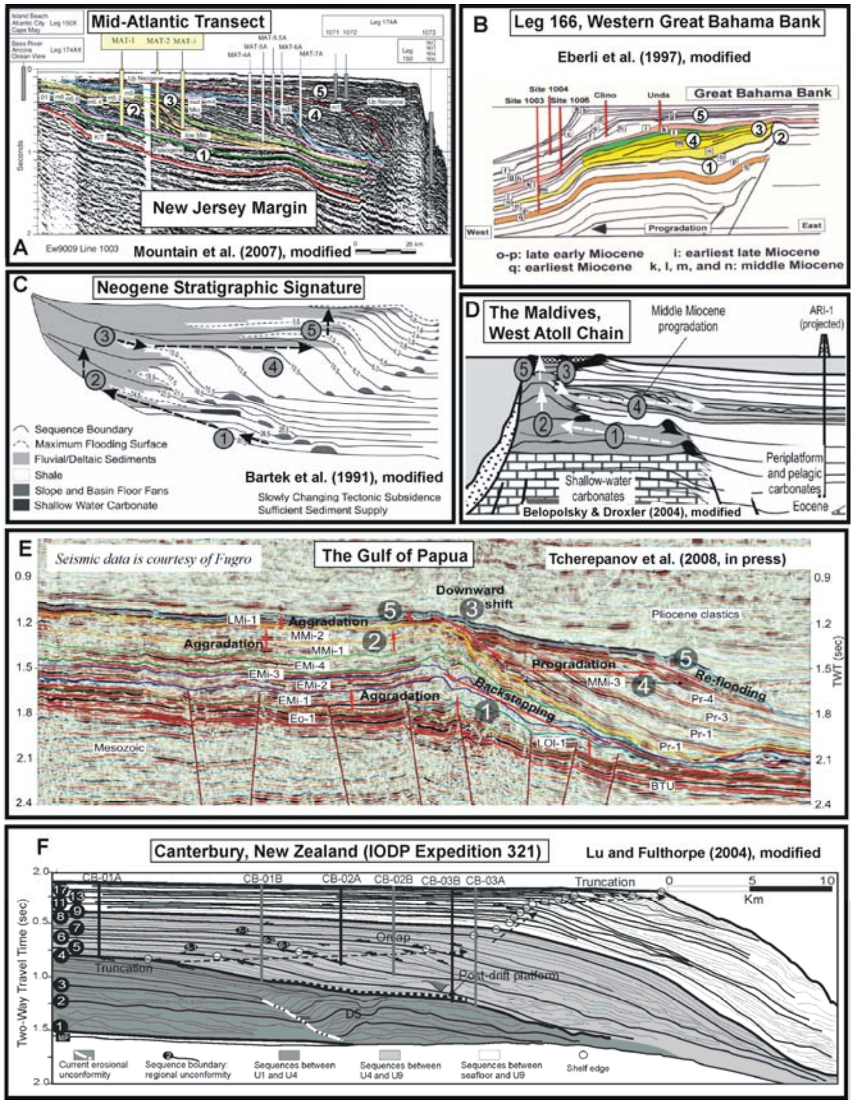

Figure 3. A. Middle Atlantic Transect (MAT) off New Jersey, showing proposed drillsites (modified from Mountain, et al., 2007) targeting a Paleogene-Pleistocene prograding clinoform succession. MAT has been drilled on the slope (ODP Leg 150; sites not shown) and shelf (Leg 174A; sites along strike from MAT8 and 9A), as well as on the Coastal Plain (Legs 150X and 174AX). Inner shelf drilling (MAT 1-3) is planned as a Mission-Specific Platform IODP Expedition 313. B. Line drawing (modified from Eberli, Swart, Malone, 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., in press). F. A future sea-level transect: line drawing of interpreted sequences, offshore Canterbury Basin, New Zealand, showing proposed IODP sites, scheduled for drilling as IODP Expedition 317 (modified from Lu and Fulthorpe, 2004).

Three breakout groups were asked to consider the following issues:

1) *Eustatic Mechanisms*: Relationship between recorded sea-level cyclicity and eustatic mechanisms through time. The hierarchy of global cyclicity (20 ky to 2.4 my and longer). Geochemical and other proxies. Timing and rates of eustatic change (chronostratigraphy). Eustatic amplitudes (paleobathymetry; backstripping, forward modeling) and what they tell us about mechanisms. (Co-Chairs: Michelle Kominz, Andy Gale)

2) *Deciphering the Stratigraphic Record*: Investigating the stratigraphic response to eustasy through a sedimentary process approach in icehouse, transitional and greenhouse worlds. What do we already know and what do we need to find out about the origins of the stratigraphic record? Influence of sediment supply, tectonism (including active margins). This group was further subdivided into:

A) Siliciclastics (Co-Chairs: Stephen Hesselbo, John Jaeger)

B) Carbonate and Mixed Systems (Co-Chairs: Rick Sarg, Bill Thompson)

All groups were also asked to consider issues such as:

Drilling program design to achieve objectives, general characteristics of ideal locations (number and layout of sites, offshore and onshore), pre-drilling data requirements (e.g., is there a need for 3D seismic data?), specific target areas, number of drilling expeditions needed, technology requirements (onshore and offshore), funding possibilities and alternative funding sources (e.g., industry).

BREAKOUT GROUP 1. EUSTASY AS A RECORD OF EARTH SYSTEM PROCESSES: EUSTATIC MECHANISMS

Determining eustatic mechanisms has always been a primary goal of IODP's sea-level studies (Imbrie et al., 1987; Watkins and Mountain, 1990; JOIDES, 1992). 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. In turn, such quantification of eustatic change will contribute to other areas of the earth sciences by helping to constrain such processes as ice-sheet growth and decay, ocean temperatures, carbon burial, and inorganic carbon precipitation in carbonates (Figure 4) as well as global tectonism (Harrison, 1990): sea level is important for the study of tectonic processes, because it is the datum against which vertical tectonic movements are measured.

Objectives

In order to determine the timing, rates and amplitudes of eustatic changes and use those results to infer the underlying mechanisms, we must answer key questions:

1) Can we consistently identify and precisely date signatures of eustatic changes of different durations? Do sea-level cycles occur as discrete and definable quanta throughout geological time? This must be evaluated at multiple timescales:
    - Long-term (>10 myr) versus million-year and shorter cycles (e.g., Hays and Pitman, 1974; Hallam, 1984)

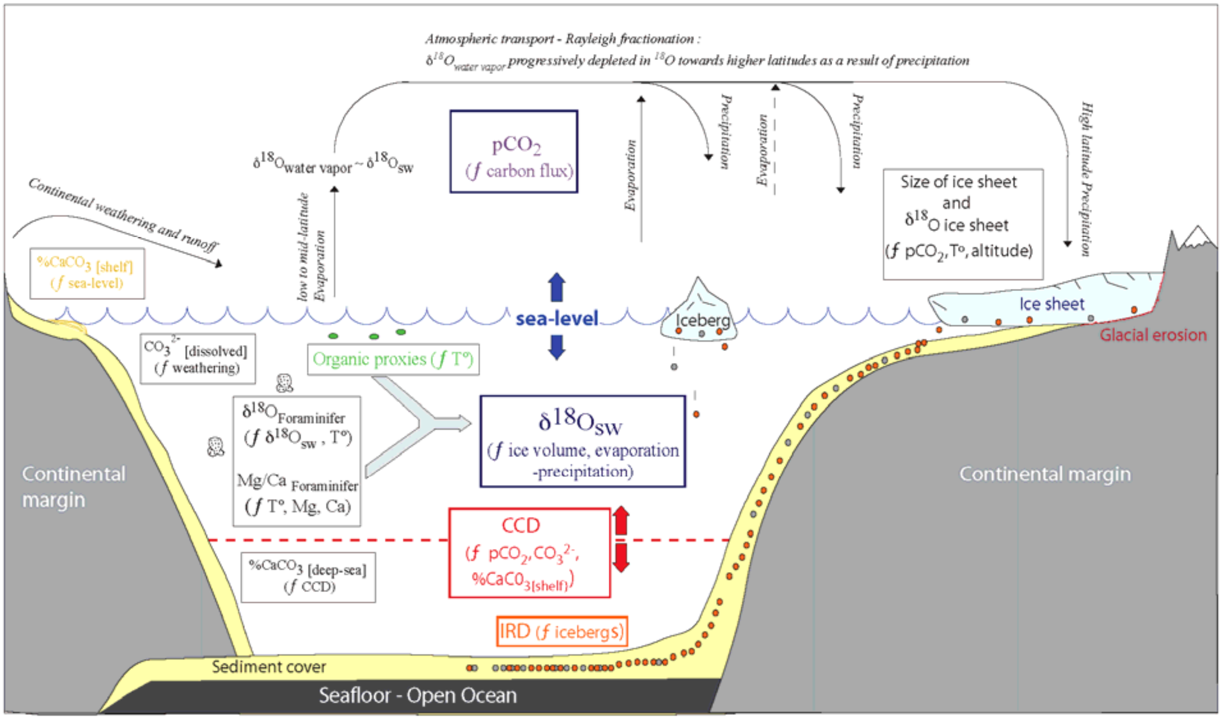

Figure 4. Schematic figure illustrating how deep-sea geochemical records can be used to understand mechanisms of past eustatic changes by analogy to the modern ocean. During atmospheric transport from low to high latitudes water vapor becomes progressively more depleted in ^{18}O, and ice sheets have 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 accumulation and burial on the shelf, which can in turn impact atmospheric CO_2. 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. (From M. Kominz, personal communication.)

- Milankovitch-scale: short- (20-40 ka), intermediate (100-400 ka) and long- (1.2-2.4 myr) period. Are recorded cycles driven by orbital forcing? (Hays et al., 1977; Olsen and Kent, 1999)
- Sub-Milankovitch. Studies have highlighted the importance of sub-orbital scale climate variability (e.g., the Younger Dryas, Heinrich events and Dansgaard-Oeschger events, e.g., Bond et al., 1999), but our understanding of causes of millennial and high-frequency changes and their links to sea-level remain vague, e.g., sea level changes during MIS-3 (Chappell, 2002; Siddall et al., 2003),

2) Can we quantify amplitudes and rates of eustatic change?

   - Are amplitude and rate estimates of regional sea-level changes consistent between basins, and therefore measures of a eustatic signal?
   - Are amplitude and rate estimates consistent when derived from different methodological approaches?

3) Can we distinguish causal factors using timing, amplitudes and rates (Figure 1)?

   - Rapid rates, but small amplitude: thermal expansion of sea water.
   - Rapid rates and small to large amplitude: glacioeustasy.
     - Can we separate ice mass contributions, e.g., single hemisphere versus bipolar, high altitude glaciers, East vs. West Antarctic ice sheets?
     - Can we quantify the dynamic nature of ice mass contributions?
   - Slow rates, small to large amplitude: tectonics and sedimentation.

4) Can we distinguish the relative contributions of different causal mechanisms under different climate states (e.g., icehouse vs. greenhouse)?

   - Need to reconcile numerical climate modeling with the geological record of eustatic change under variable boundary conditions (e.g., pCO_2, ocean circulation, weathering, paleogeography, paleoaltitude, marine and terrestrial biosphere).

These questions must be addressed in both icehouse and greenhouse time periods.

1) Refining timing, amplitudes and mechanisms of icehouse (Oligocene-Recent) eustatic change.

Glacioeustasy provides the dominant eustatic mechanism during the icehouse. In addition, high-resolution chronologies allow for integration with climatic, biogeochemical, physical oceanographic and landscape evolution records. 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; Eberli et al., 2002). Eustatic timing has been fairly well established at the million-year timescale during this period.

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, that has applied with success to the 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; Browning et al., in press) represents the best current estimate, but it is still incomplete because lowstand sediments were not recovered, introducing uncertainty to estimated amplitudes. Possibly as a result, the Miocene part of the New Jersey sea-level curve does not appear to correspond as well to the globally recognized stratigraphic signature of the Neogene as other eustatic curves (Figure 6; Bartek et al., 1991). Furthermore, the New Jersey curve also differs from $\delta^{18}O$ records that have been corrected for paleotemperatures and are therefore an improved record of ice-volume fluctuations (Billups and Schrag, 2002; Lear et al., 2004) and which do correspond well to the stratigraphic signature of the Neogene (Figure 6).

Finally, estimates of the amplitudes of eustatic change from one-dimensional backstripping at one location (e.g., New Jersey; Miller et al., 2005a; Kominz et al., in press; Browning et al., in press) requires supplemental 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., Steckler et al., 1999; 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.

Though we are beginning to unlock the mysteries of icehouse sea-level changes, our understanding of eustatic change during the preceding "greenhouse" world of the Triassic to early Eocene is controversial. For example, the Late Cretaceous has been reconstructed as a greenhouse world with warm polar climates (Bice et al., 2006), and most studies have assumed the absence of 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 (Kominz et al., 1998; Van Sickel et al., 2004; Miller et al., 2003; 2005a,b; Bornemann et al., 2008) have indicated large (tens of meters), short-period (<1 myr) Late Cretaceous global sea-level (eustatic) fluctuations (Figure 2). In addition, second- (~10 my), third- (1-5 my) and fourth-

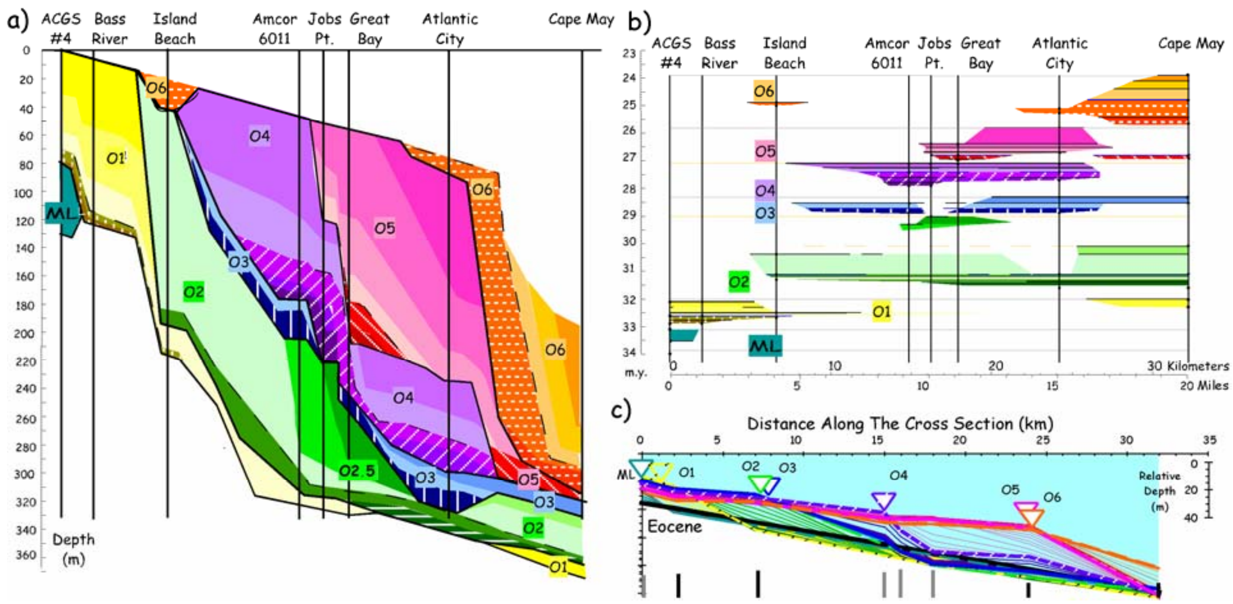

Figure 5. In order to determine sea-level change from a marginal marine setting we recommend at least two-dimensional sequence stratigraphic backstripping. An example of some of data required for two-dimensional sequence stratigraphic backstripping from Kominz and Pekar (2001 and 2002) is shown for illustration. **A.** Chronostratigraphic chart 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.** Sequence model for New Jersey coastal plain Oligocene sequences. Patterns and lines as described above. **C.** Geometry of horizons identified in A and B after performing geohistory analysis plotted on same vertical scale as B. 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.)

(~0.5 my) order sequences can apparently 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).

There are two solutions to this enigma: 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). Pitman and Golovchenko (1983) noted that the only mechanism that can explain such rapid eustatic changes is glacioeustasy. Matthews (1984) based on sea-level records and his reinterpretation of the $\delta^{18}O$ record, postulated the presence of intermittent ice sheets in the Cretaceous. Similarly, Stoll and Schrag (2000) interpreted Cretaceous bulk isotopic fluctuations as reflecting growth and decay of ice sheets.

ODP and ICDP drilling onshore New Jersey (Leg 174AX) have provided a detailed record of Cretaceous to early Eocene sequences. This record quantifies high amplitudes and rates of eustatic change (>25 m in <1 myr) in the Late Cretaceous to Eocene greenhouse world. Based on this sea-level history, Miller et al. (2003, 2005a,b) have proposed that ice sheets existed for geologically short intervals (i.e., lasting ~100 ky) during the Late Cretaceous-Eocene. This view can be reconciled with previous assumptions of an ice-free Greenhouse world. Eustatic changes on the 10^6 y scale were typically ~15-30 m in the Late Cretaceous-Eocene (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). These results are leading to a reassessment of our concepts of "icehouse" and "greenhouse". Greenhouse ice sheets were probably ephemeral, and for the most part Antarctica lacked ice sheets during the greenhouse world except for these cool/cold periods, dubbed "cool snaps" by Royer et al. (2004).

However, although such indirect evidence for ephemeral ice sheets is growing, there is, as yet, 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 need for additional high-resolution stratigraphic records from the greenhouse period.

Nevertheless, second- (~10 my), third- (1-5 my) and fourth- (~0.5 my) order sequences can be widely correlated between tectonically active and passive regions (e.g., Western Interior Seaway, Europe, India) suggesting eustatic control. In addition, the Toarcian oceanic anoxic event (OAE) is associated with a sharp negative carbon isotope excursion (actually 2 excursions) indicating global control.

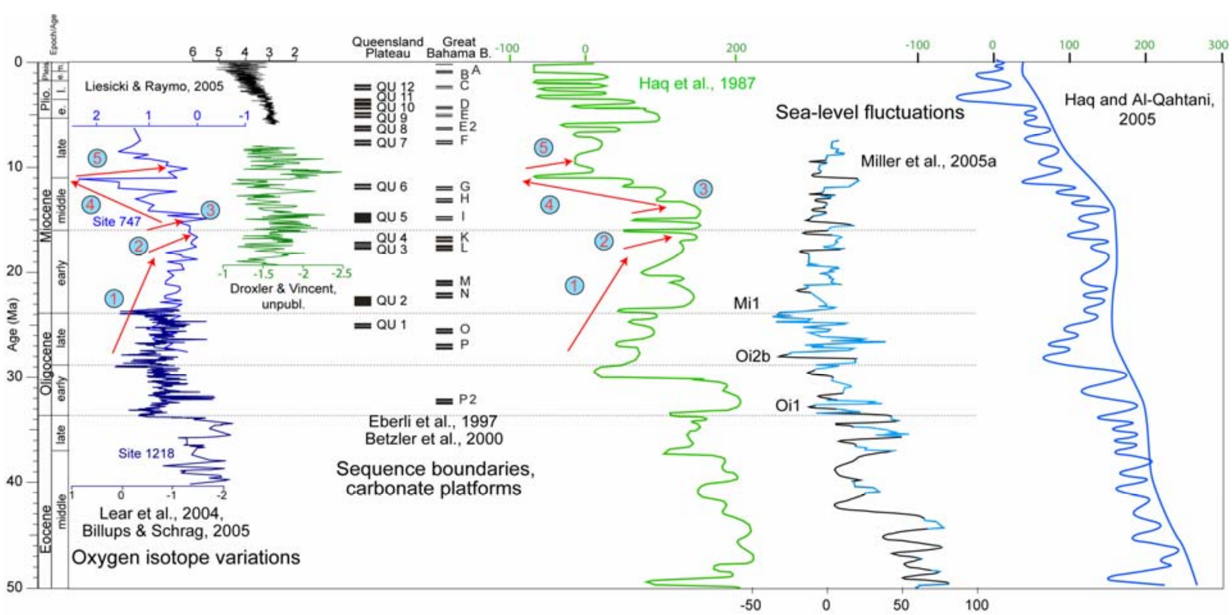

Figure 6. Oxygen isotopic and eustatic curves showing correspondence to the stratigraphic signature of the Neogene (red arrows and numbers 1-5; see Figure 3). The Miller et al. (2005a) eustatic curve from the New Jersey margin does not conform precisely to the global signature, particularly in the middle and late Miocene. (From A. Droxler, personal communication.)

Thus there are a number of reasons for drilling Cretaceous to early Eocene successions for sea-level objectives:

- The first-order problem is to confirm the existence of globally synchronous sea-level change during this period and define the timescales (e.g., frequencies or orders) at which Greenhouse sea-level change was eustatic.
- Constrain the amplitudes of Greenhouse eustasy at all timescales. For example, it is unclear whether global sea level during the Paleogene (early Eocene) was higher than the Cretaceous peak (Cenomanian-Turonian). Late Cretaceous to middle Miocene amplitudes have been derived from New Jersey margin onshore drilling results, but the error bars are significant and amplitudes and rates need to be tested elsewhere (Van Sickel et al., 2004; Carter et al., 1991).
- Determine whether elevated pCO_2 and global warmth can coexist with ice sheets, no matter how small and ephemeral. What is the pCO_2 threshold required for ice sheet growth?
- Clarify the relationships among sea-level change and carbon-cycle processes (erosion, nutrients, pCO_2, productivity, positive and negative feedbacks, carbon burial vs. erosion, carbonate deposition).
- Define the links between eustasy and climate. For example, how did eustasy force, or respond to, transient climatic events such as Oceanic Anoxic Events and the Paleocene/Eocene Thermal Maximum (PETM)?

Strategy

Continental Margin Transects

The drilling of transects of boreholes across continental margins, also recommended by earlier workshops (COSOD II, 1987; Watkins and Mountain, 1990; JOIDES, 1992) is fundamental to the goals of assessing eustatic mechanisms (Breakout Group 1) and also to defining the stratigraphic responses to eustasy (Figure 3; Breakout Groups 2A and B).

The need for drilling transects of boreholes across continental margins arises in part because sequences are three-dimensional units whose lithofacies and biofacies cannot be defined by a single borehole. In addition, transects are also needed to determine eustatic timing and amplitudes 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, Browning et al., 2006). The strategy therefore involves drilling margins worldwide to evaluate global synchroneity, by correlation among multiple basins and with the oxygen isotopic record, and to document stratigraphic responses in diverse tectonic and depositional settings, including carbonate, siliciclastic and mixed siliciclastic-carbonate sedimentary systems on both continental and oceanic crust. This approach has guided ODP efforts off New Jersey (Leg 150; Mountain, Miller et al., 1994; Miller and Mountain, 1994; Leg 174A; Austin, Christie-Blick et al., 1998; Legs 150X and 174AX; Miller et al., 1994; Miller, Sugarman, Browning, et al., 1998) and the Bahamas (Leg 166; Eberli, Swart, et al., 1997), and continues to influence IODP planning (e.g., New Jersey IODP Expedition 313 and Canterbury Basin Expedition 317). Most of this drilling focused on the Neogene icehouse period (Miller et al., 1991), during which high-resolution chronological control is available and glacial cycles provide a well understood mechanism for eustatic change, calibrated by the deep-ocean oxygen isotope record. Scientific drilling has also focused on passive continental margins, where tectonic influence is minimized.

The transect approach integrates seismic profiles and multiple boreholes (Figure 3). Seismic profiles provide sequence architecture, seismic facies and morphologic constraints on depositional processes and tectonism. A drilling transect is required to document: 1) ages of sequence stratigraphic surfaces, including sequence-bounding unconformities, or their correlative conformities, and maximum flooding surfaces; 2) facies and lithologies comprising each sequence; 3) porosity, cementation and diagenesis, and 4) paleo-water depths from benthic biofacies. Two-dimensional modeling of these data within the sequence stratigraphic framework allows estimation of eustatic amplitudes because the form of the tectonic component of subsidence is known for passive margins (Kominz and Pekar, 2001). Ideally, transects should extend from sites onshore across the modern inner shelf to the outer shelf, and onto the modern slope in order to sample the maximum range of sequence ages.

The goal is to drill target sequences in at least two locations. 1) Drilling immediately landward of clinoform break or rollover, representing the paleo-shelf edge, provides information on facies and paleodepths at the break. Such paleo-water depth estimates are essential for determination of eustatic amplitudes (Moore et al., 1987; Greenlee and Moore, 1988; Kominz and Pekar, 2001; Pekar and Kominz, 2001; Pekar et al., 2002). In practice, distances of sites from individual clinoform breaks will necessarily vary. Two-dimensional backstripping will enable use of data from sites farther landward to constrain water depths at the clinoform break. 2) Drilling on the slope for paleoenvironment and facies of the lowstand systems tract. This is also essential for eustatic amplitude estimation in the event that sea level fell below the preceding paleo-shelf edge. Increased abundance of pelagic microfossils in such settings provides sequence boundary ages. The ideal location for dating is near the clinoform toe, to minimize the hiatus at the sequence boundary (Christie-Blick et al., 1998), but locations higher on the slope may be necessary to reduce drilling depths (e.g., location of Leg 174A New Jersey margin Site 1072 relative to sequence boundary m1(s); Austin, Christie-Blick, Malone, et al., 1998). In addition, locations on the slope will provide better constrained paleo-water depths, which are likely to be poorly constrained at clinoform toes. A further reason for drilling higher on the slope is that seismic correlation from clinoform toes landward to the clinoform front and shelf is difficult on all margins, because the section basinward of clinoform toes is condensed and landward divergence of reflections contributes to mis-ties.

Use of Transects to Estimate Eustatic Amplitudes

We still do not fully understand eustatic amplitudes, rates, and mechanisms on all timescales. A broad-ranging, integrated approach, perhaps analogous to the IODP "mission" concept, is necessary to determine the linkages among eustasy, climate and tectonics under a range of climatic conditions.

The absolute amplitudes of eustatic change can be extracted from geological records. Three approaches have been used. The carbonate "dipstick" approach involves dating fossil reefs and yields good eustatic amplitude records for last glacial cycle. However, uncertainties increase as the record is extended into the Pleistocene and farther back in time, mainly because of the difficulty of recovering reef sediments from a floating platform. A second technique is based on estimation of the position of coastal onlap and led to the Haq et al. (1987) eustatic curve. However, this method is problematic because of the difficulty in recognizing coastal versus marine onlap, partly because correlation between seismic facies and lithofacies are not unique. In addition, coastal facies are commonly not preserved, even at highstand.

The third approach has been applied with success to the New Jersey margin. It involves combining sequence stratigraphic and backstripping analyses (Kominz and Pekar, 2001 & 2002; Pekar and Kominz, 2001; Miller et al., 2005a). Both one-dimensional and two-dimensional backstripping approaches can be employed (Figure 5). Backstripping analysis reconstructs sea level amplitudes by removing the effects of tectonic subsidence, sediment loading and compaction. One-dimensional backstripping my give erroneous results when the flexural rigidity of the lithosphere and adjacent loads is not considered (e.g., Browning et al., 2006), or due to the fact that the entire section is not present at any single location (e.g., Van Sickel et al., 2004). Two-dimensional flexural backstripping eliminates many of these problems but introduces new ones. The first problem introduced involves data limitations – the two or three-dimensional model requires precise estimates across the data set as well as far-field estimates (e.g., Kominz and Pekar, 2001, 2002). These problems may be reduced, to a degree, by good regional seismic coverage and a well-constrained, regional, sequence stratigraphic framework. Assumptions regarding the rigidity of the basement with time and space are required as well as an understanding of the tectonic driving mechanisms beneath the study area. The input data required to minimize uncertainty are considerable and involve both drilling results and supporting data. Carbonate systems offer particularly good opportunities to constrain eustatic amplitudes because they are such sensitive responders to climate/sea level change. However, the procedure has not yet been applied in a carbonate setting.

Drilling Results Required

Among drilling requirements, maximum core recovery in all lithologies is fundamental. Coring strategies should be adapted to maximize recovery, e.g., by using short advances by XCB, and using appropriate technology and platforms (casing, mud, MSP, *Resolution*, land-based drilling). Core recovery governs the potential for meeting other needs, including:

1) *High resolution stratigraphic control with error estimates.* Errors in age control can significantly affect the amplitudes of eustatic fluctuations, as well as their timing, because they shift sequence boundaries relative to the long-term tectonic subsidence curve. As an example, the most significant differences in sea-level estimates between the Van Sickel et al. (2004) and the Miller et al. (2005a) New Jersey sea level curves were due to improved dating of sequences by Miller et al., (2005a). Age resolution is maximized when multiple dating techniques are applied in parallel. Effective techniques for age estimation include:

- Biostratigraphy (foraminifera, nannofossils, radiolaria, palinomorphs).
- Magnetostratigraphy, Sr–isotope stratigraphy, cyclostratigraphy, C-isotope stratigraphy.
- Radiogenic dating of ash beds.

2) *Paleobathymetry with error estimates.* Paleobathymetry is a key input to backstripping analyses, but uncertainties are significant and increase with paleo-water depth (e.g., Pekar and Kominz, 2001). Paleobathymetric estimates can be derived from:

- Benthic biofacies.

- Shallow marine deposits (corals, tidal facies)
- Seismic evidence of subaerial exposure (karst, paleo-shelf incision).
- Grain size analyses

3) *Compaction characteristics.* Decompaction of the sedimentary section requires knowledge of porosity variation with depth, as well as information on cementation and dissolution. This is one of the sources of uncertainty in backstripping. It is essential to have information about material both older (to basement) and younger (to the sediment surface) than the target interval, including estimates of the amount of material that has been removed by erosion.

Non-Drilling Data Requirements

1) *Tectonic history*

- Tectonic driving mechanism (e.g., thermal subsidence).
- Timing and magnitudes of tectonics. (e.g., Breakup age and amount of stretching if subsidence is thermal.)
- Flexural strength of the lithosphere. The effective elastic thickness (EET) and flexural rigidity of the lithosphere are required. Rheology, geotherm, strain rate and plate curvature of the lithosphere are the main influences on EET. These vary with time and location.

2) *Sequence stratigraphic interpretation.* The sequence stratigraphic framework for a basin is commonly derived from seismic data.

- 2-D seismic grids are generally sufficient to provide input for backstripping analyses. Profile spacings of no greater than 1-3 km are desirable, but even greater profile spacings may be sufficient to define sequence stratigraphy in relatively simple basins. However, more dense coverage, up to and including 3D seismic volumes, may be needed depending on other objectives (e.g., to allow application of seismic geomorphology to evaluate sedimentary processes).
- Seismic data can also be used to determine the depth to basement and estimate the location of ocean continent boundary
- Available borehole data from scientific or commercial drilling can complement seismic data in defining sequence stratigraphy. For example, well logs can reveal vertical and lateral shifts in facies and confirm identification of sequence boundaries and maximum flooding surfaces.

Deep-Sea Drilling and Proxy Records

In addition to direct determination of eustatic amplitudes from dedicated continental-margin transects, important complementary data can be obtained from deepwater sites drilled for paleoclimatic objectives. Recovery of complete high sedimentation rate pelagic and hemipelagic sediments can yield high-resolution paleontological and geochemical proxy records that can provide information relevant to assessment of eustatic mechanisms (Figure 4). Sea-level changes indicated by such indirect multi-proxy methods can be correlated with results from continental margin transects.

The principal proxy is the oxygen isotopic record. Sea-surface temperature (SST) and bottom-water temperature (BWT) allow estimation of the thermal expansion of seawater as a eustatic mechanism. However, the use of oxygen isotopes to determine global ice volume and hence constrain glacioeustasy as a mechanism is complicated by this effect of seawater temperature on oxygen isotopic fractionation. The temperature effect can be estimated using suitable approaches, for example through the use of independent temperature proxies, e.g., Mg/Ca, TEX86, etc. and comparison of coupled low-latitude planktonic and benthic isotopic records. Additional research is required to verify these methods.

These techniques allow investigation of the interaction between polar ice and paleoceanography, e.g., the "snow-gun" hypothesis of ice growth driven by high-latitude cooling. It is important to confirm that this relationship is observed in multiple data sets and to determine whether it holds true for different climatic regimes. The distribution, timing and provenance of ice-rafted debris (IRD) can help by constraining the timing, location and volume of ice sheets.

Pelagic and neritic carbonate mass accumulation rates constitute other important proxy records that are related to CCD vertical depth migration (Barker et al., 2006; Droxler et al., 2003; Zeigler et al., 2003; Ridgwell et al., 2003). In addition, erosion rates, as indicated by mineralogic variations and Os, Sr and Nd, isotopes, can also respond in parallel with eustatic change.

Proxy records allow investigation of possible eustatic mechanisms through iterative integration of proxies and numerical modeling. However, the flow of information between researchers focusing on proxies from deep-sea sites and those investigating continental-margin eustatic records is not one-way. For example, continental-margin eustatic amplitude estimates provide information on ice-volume fluctuations that are of importance to paleoclimatologists and ice-sheet modelers.

Drilling Requirements

1) *Extensive geographic coverage.* Sites are required in different oceans and representing different water masses, including high-latitude sites and sediments that have been subject to different burial histories (to constrain diagenetic effects). A valuable ancillary effort will be assessment of available legacy core material and re-coring of critical sites where incomplete core recovery limits interpretation.

2) *High resolution stratigraphic control with error estimates.*

- Biostratigraphy (foraminifera, nannofossils, radiolaria, palinomorphs).
- Magnetostratigraphy, Sr–isotope stratigraphy, Cyclostratigraphy, C-isotope stratigraphy.
- Radiogenic dating of ash beds.

BREAKOUT GROUPS 2A AND 2B. DECIPHERING THE STRATIGRAPHIC RECORD

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 (Posamentier and Kolla, 2003). 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). However, predictive models of the distribution of sediments within unconformity-bounded sequences are based on assumptions about the importance of relative sea-level change (Posamentier et al., 1988; Vail et al., 1991) that have yet to be adequately tested.

Nevertheless, various 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 involves: (1) late Oligocene (Chattian) and early Miocene (Aquitanian) aggradation, back-stepping and drowning, (2) late early Miocene (Burdigalian) and earliest middle Miocene (early Langhian) aggradation, (3) earliest middle Miocene (late Langhian) downward shift of deposition, (4) middle Miocene (Serravallian) progradation, and (5) and (6) two stacked flooding and aggradational episodes in the late Miocene (Tortonian) and early Pliocene (Zanclean) separated by a late Miocene (Messinian) downward shift of deposition (Bartek et al., 1991). Although this pattern is observed globally in both siliciclastics and carbonates and can be explained by ice volume proxies (Figures 3 and 6; Bartek et al., 1991; Tcherepanov et al., 2008 and submitted), the heart of this section, the early and middle Miocene, has not yet been calibrated by ground truth, mainly because of past difficulties faced by *JOIDES Resolution* when drilling in shallow water on continental shelves. However, 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) and it is therefore vital to continue efforts to sample Neogene shelf sections.

Breakout Group 2A: Siliciclastic Sedimentary Systems

Sea Level-Climate Linkages and Impacts on Terrigenous Margins

Because of the complex interplay of forcing mechanisms responsible for the stratigraphic record, stratigraphic response must be defined in a diversity of time periods and settings, both tectonic and sedimentary. Siliciclastic sediments are excellent sea-level markers because they are both highly sensitive indicators of shoreline position and are globally widespread. However, 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 reflection profiles and later calibrated by coring (Figure 3). However, only coring can provide the lithofacies and biofacies of the intervening units. Sequence stratigraphic models of such units (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. However, the real world is rendered more complex by the additional influence of local forcing and the 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.

Tectonism

Tectonism exerts first-order control on stratigraphic geometries and facies by creating and destroying accommodation space and altering base level through tectonic uplift and subsidence. Isostatic loading and compaction also contribute to the creation of accommodation space, as does sediment mass distribution, which affects adjacent regions through crustal flexure. Quantification of vertical tectonism is an essential part of determining eustatic amplitudes, as discussed in the section concerning Breakout Group 1. Tectonism also influences stratigraphy by controlling uplift in the hinterland and thereby influencing sediment supply (see below). In addition, anticlinal structures can trap or divert sediment leading to depocenter migration.

Theoretical studies have shown that rates of subsidence and sediment supply, amplitude and frequency of eustasy, isostasy and sediment compaction can combine to cause sequence boundary formation to lead or lag the time of most rapid eustatic fall by up to $^{1}/_{4}$ cycle (Christie-Blick, 1991; Reynolds et al., 1991; Jordan and Flemings, 1991; Steckler et al., 1993). In addition to thermal and isostatic subsidence, in-plane stress has been shown to be theoretically capable of producing vertical displacements of the order of 100 m (Cloetingh et al., 1985; Karner, 1986; Cloetingh, 1988). However, flexural deformation of extensional basins produced by in-plane force variations is difficult to recognize and is, by itself, unlikely to represent an alternative mechanism to eustasy for generation of third- and higher-order sequences (Christie-Blick et al., 1990; Karner et al., 1993). In the absence of faulting or folding, therefore, tectonic effects alone cannot be expected to generate sequence boundaries, but can act to modulate, within a limited range, the timing and geometries of sequences of dominantly eustatic origin.

However, even when faulting and folding are present, eustatic and tectonic effects can be distinguished. This is indicated by work on the offshore Eel River Basin, northern California (Figure 7). The basin is in a forearc setting and subject to east-west convergence between the Gorda and North America plates as well as north-south compression associated with the northward migration of the Mendocino Triple Junction, currently located south of the basin. High-resolution MCS data reveal areally extensive regional unconformities coexisting with heavily incised, but localized, unconformities concentrated adjacent to a fault-cored anticline (Burger et al., 2002). Age control is limited, but nevertheless indicates that the regional unconformities are of eustatic origin since they correlate approximately with the oxygen isotope proxy record of Neogene glacioeustatic fluctuations (Figure 7). The numerous local unconformities, in contrast, are restricted to the vicinity of a site of structural deformation, and are inferred to be of purely tectonic origin, or the result of tectonic enhancement. They are probably a response to deformation and uplift caused by the northward migration of the triple junction (Burger et al., 2002). Interestingly, this work also shows that high-frequency repetition of unconformities is not by itself evidence for a eustatic origin and that tectonic processes cannot be presumed to operate only at lower frequencies (vs. the assumptions of Vail et al [1977] that tectonism operates on the 10^7 yr scale).

Elsewhere, the Wanganui Basin on the North Island of New Zealand, located above the subducting Pacific Plate, contains Pleistocene sequences that correlate with the deep-ocean oxygen isotopic record (Abbott and Carter, 1994; Naish and Kamp, 1997). Similarly, links between cycles of Pliocene limestone deposition and the oxygen isotopic record have been demonstrated in the forearc basin setting of eastern North Island (Kamp and Nelson, 1988).

Links to other communities

All of these studies indicate that a eustatic signal can potentially be both recorded and deciphered, even in a tectonically active area. An important corollary is that seismic surveys and drilling for eustatic objectives also have the potential to yield information about basin tectonic history through dating of uplift and subsidence events.

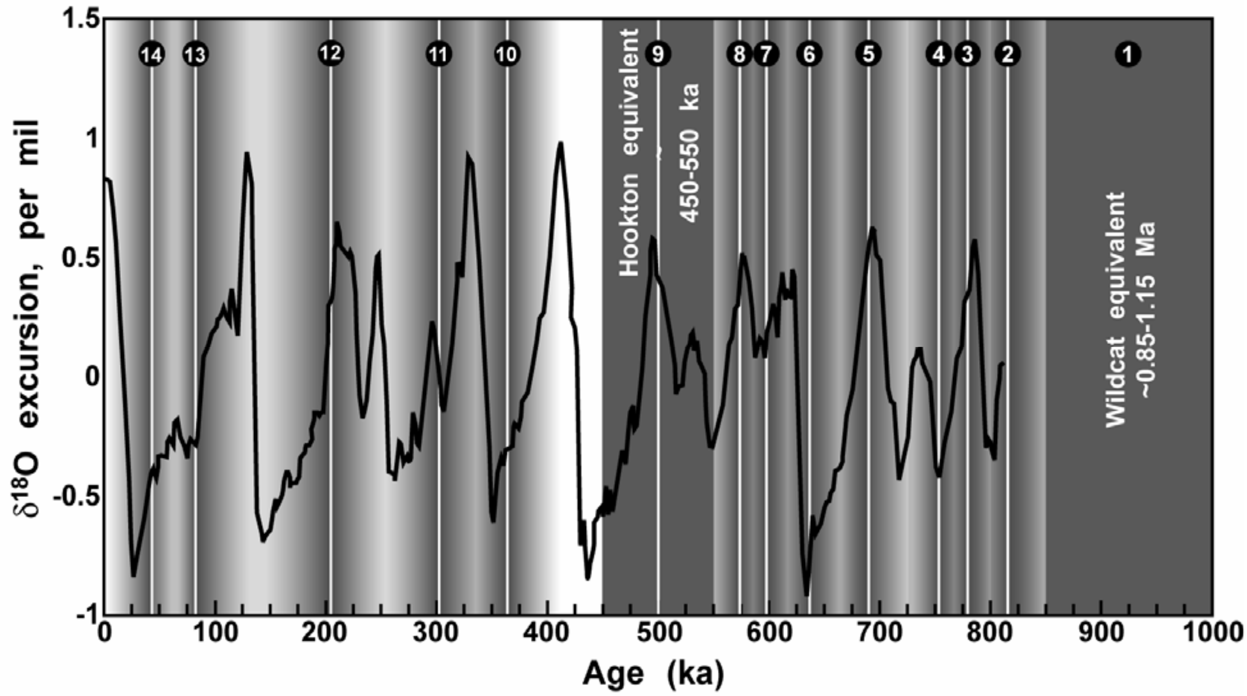

Figure 7. Stacked δ18O curve derived from fourteen different benthic records globally (Mederios et al., 2000). Vertical lines show estimated ages of Eel River Basin seismic unconformities and shading represents uncertainty in age estimates. Solid gray areas represent estimated hiatus lengths of the onshore Wildcat Unconformity and Hookton Datum (equivalent to Surfaces 1 and 9, respectively). The increased frequency of unconformity formation prior to ~550 ka, mimics the obliquity-dominated 41 kyr glacioeustatic cycles during that same interval. In contrast, after the Hookton Datum hiatus, the frequency of unconformity formation decreases, and generally coincides with the eccentricity-domimated 100 kyr cycles characteristic of that interval. The apparent correspondence between δ18O cyclicity and unconformity formation both before and after the orbitally-dominated transition implies that glacioeustacy controls the timing of formation of these surfaces. (Modified from Burger et al., 2002.)

Sediment Supply and Transport

Sediment supply is another of the primary controls that interacts with eustasy to produce the preserved stratigraphic record. However, sediment supply is only part of the story. Sequences record sediment accumulation at a particular location rather than supply. Under modern, highstand conditions most sediment is retained on the shelf, even in regions of very high sediment input, such as off the Amazon and Yangtze river mouths (Wright and Nittrouer, 1995;

Liu et al., 2006). Very few large rivers currently supply sediment directly to the deep sea: the modern Ganges/Brahmaputra river system is an exception.

The U.S. Office of Naval Research's STRATAFORM project, the European Union-funded EuroStrataform project, and NSF's MARGINS Source-to-Sink project have revealed the importance of sediment input from point and line sources (e.g., Eel, Rhone, Po, Fly, Waipaoa rivers) that creates highstand strata on modern margins. However, these projects also highlight how the influence of such point and line sources on preserved stratigraphy is muted by marine sediment transport processes. The Eel River point source does not develop a classic delta. Instead, point-source input is distributed by both along-shelf and along-slope sediment transport and also gradual downslope movement of mud to create a long-term record of well-developed clinoforms (Figure 8). Seismic interpretations and coring of the Oligocene-Neogene of the New Jersey (Fulthorpe and Austin, 1998; Fulthorpe et al., 1999; Monteverde et al., 2000; Pekar et al., 2003; Fulthorpe et al., in press; Monteverde et al., in press) and the Neogene Canterbury margin (Lu and Fulthorpe, 2004) also lack distinct evidence of point sources, although sequence thicknesses and geometries vary markedly along strike. This migration of depocenters is presumably in response to a combination of changes in the location of individual fluvial inputs, the volumes of sediment supplied from particular inputs, and redistribution of that sediment within the marine environment. However, in prograding clinoform successions, stratal formation is still controlled by downslope movement.

These results also re-emphasize that two-dimensional sequence models are idealizations and do not conform to a particular cross-section of a real margin except under fortuitous circumstances. Location relative to a dominant point source of sediment is one factor, because onlap has been postulated to develop best adjacent to, but not directly opposite, such sources (Driscoll and Karner, 1999). If timescales of along-strike transport (river avulsion, longshore transport, shelf and slope currents) are similar to those of eustatic forcing, a 3D perspective is essential.

Climate, large-scale relief and drainage area exert fundamental controls on sediment creation and delivery to the coast (e.g., Milliman and Syvitski, 1992; Syvitski et al., 2003). Climate, and specifically basin-averaged temperature, has a strong influence on sediment production through the influence on weathering rates, soil formation, and in establishing feedbacks within polar (frozen soils, snow and ice melt dominated discharge), temperate (snow melt, increasing lapse rate, freeze–thaw cycles, increasing convective rainfall), and tropical (convective rainfall–monsoons and typhoons, soil formation, tropical canopy) settings (Syvitski et al., 2003). Because climate and glacio-eustacy are inherently linked, the silicilastic sedimentary record on continental margins should contain a signature of time-varying sediment supply influenced by glacio-eustatic changes in base level and climate change within drainage basins. Enhanced sediment accumulation and an increase in coarser sediment delivery to continental margins worldwide during the Plio-Pleistocene is ascribed to a transition from a period of climate stability in the Late Miocene/early Pliocene when sediment production reached an equilibrium between weathering rates and removal to a period of frequent and abrupt changes in temperature, precipitation and vegetation, which created a disequilibrium between production and removal (Hay et al., 1988; Peizhen et al., 2001). Once sediment has been produced, fluvial transport and storage (in lakes, coastal plains and estuaries) and its response to changes in base level become a factor. A central tenet of sequence stratigraphic models is that alluvial incision and increased sediment bypassing and delivery to the ocean occur during a fall in relative sea-level, followed by an aggrading phase during the ensuing sea-level rise. However, recent conceptual and

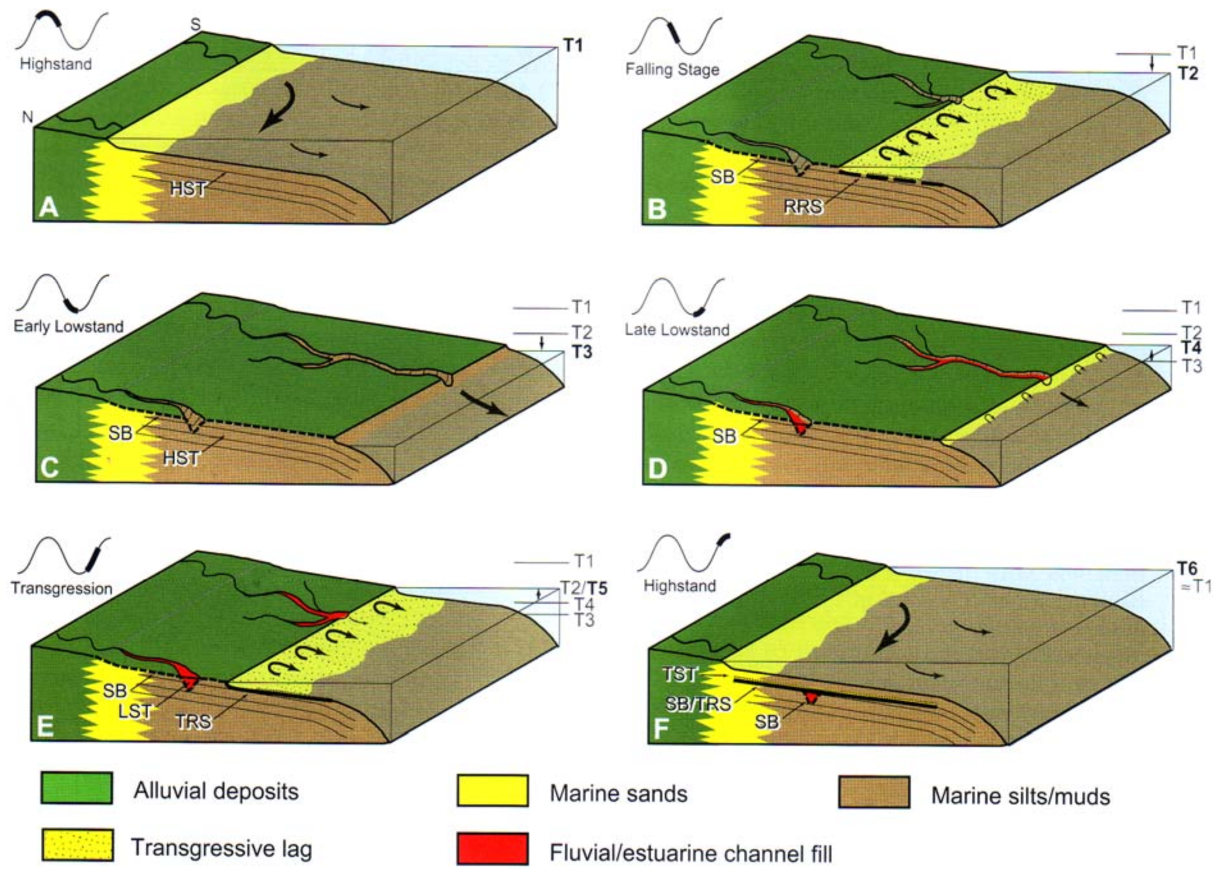

Figure 8. Proposed sequence stratigraphic model for the Eel River shelf, northern California. (A) Highstand – alongshelf-directed, nearshore and shallow marine sediment transport and deposition dominates, as at present. (B) Falling stage: shelf is progressively exposed, and a regressive ravinement forms by shoreface erosion as the shoreface crosses the shelf. The exposed shelf represents the lowstand sequence boundary. (C) Early lowstand – sea level falls below the shelf edge; sediments largely bypass shelf through fluvial channels. (D) Late lowstand:fluvial gradients decrease, initiating channel infilling basinward; shoreface erosion of the shelf resumes. (E) Transgression – shelf channels are progressively infilled basinward to landward; vigorous erosion forms a prominent transgressive ravinement as the shoreface crosses the shelf. Lowstand sediments and the sequence boundary are eroded in all but deeply incised areas. (F) Highstand: alongshelf deposition of sediments over the entire shelf resumes. Over most of the shelf, highstand deposits immediately overlie highstand sediments from the previous sequence. SB=sequence boundary; RRS=regressive ravinement surface; TRS=transgressive ravinement surface; SB/TRS=composite surface; HST=highstand systems tract; LST=lowstand systems tract; TST=transgressive systems tract (From Mountain et al., 2007; by permission of Wiley-Blackwell Publishing).

quantitative models and observations from Quaternary coastal plains instead predict and document that coastal plain rivers can aggrade during relative sea-level falls and that the occurrence of erosion and incision is a function of sediment supply, drainage basin geometry, and the rate of sea-level fall (e.g., Schumm, 1993; Leeder and Stewart, 1996; Blum and Tornquist, 2000; Browne and Naish; 2003; Swenson and Muto, 2007). Therefore, studies of offshore sequences should be linked to processes in the watersheds onshore. Offshore, climate and regional wind patterns influence longshore transport and storm frequency, intensity and wave base. Consequently, major changes in large-scale atmospheric circulation patterns between glacial and interglacial climates likely had a strong impact on regional wave and current dynamics, which would strongly modify the relative balance between downslope and along-margin sediment dispersal.

Tectonism also influences sediment supply through creation of mountain ranges and relief. Over-steepened slopes and mass movements, fractured rock, and frequent volcanic and earthquake activity result in the largest sediment yields from the highest-relief basins (Milliman and Syvitski, 1992). On 10^7-y time scales, temporal variability in tectonism results in renewed erosion and mass redistribution. An episode of uplift in the Appalachians is hypothesized to have led to the Miocene sediment influx recorded on the New Jersey margin (e.g, Poag and Sevon, 1989). However, a mid-Miocene sediment accumulation peak has been recognized globally and may reflect climatic forcing. Nevertheless, convergence at the Alpine Fault led to uplift of the Southern Alps in New Zealand and correlates with increased sediment accumulation in the offshore Canterbury Basin (Lu et al., 2005). Additional records of sediment accumulation rates are required for correlation with climatic, tectonic and eustatic trends in order to deconvolve the influence of these controls on sequence architecture.

Links to other communities

Stratigraphic response studies have important ties to several modeling communities. Firstly, the data collected to document stratigraphic response form direct inputs to numerical and physical stratigraphic models. In addition, the work of climate and physical oceanographic models can aid understanding of onshore erosion and offshore sediment transport and the interaction of mountain building, climate, and sea-level changes.

Seismic Control

Seismic control should ideally be sufficient to document along-strike variations in sediment input, transport, erosion and deposition. Seismic data can provide evidence for fluvial incision of paleoshelves, river avulsion, along-shelf and along-slope slope currents (through identification of sediment waves and drifts) and slope gullies and canyons if vertical resolution is sufficient (Figure 9). True 3D seismic data are ideal and allow application of seismic geomorphology to better resolve and map the incisions that constrain process and identify sequence boundaries. Commercial 3D surveys are potentially available from margins that have been subject to significant hydrocarbon exploration (e.g, the Australian Northwest Shelf). However, some margins of scientific importance (e.g., New Jersey, Canterbury, Maldives, northern California) have not received commercial 3D surveys. In such places, academic surveys are the only option (Figure 10). Academic 3D surveys are likely to be rare, because of their cost, and also of limited areal coverage. Nevertheless, they should be pursued for areas of particular scientific interest. Meanwhile, dense (~2-3 km profile spacing, or less) 2D seismic coverage can constrain margin three dimensionality sufficiently for drill-site location. Even less dense surveys (~5-10 km line spacing) may be sufficient on relatively simple margins and can provide adequate control for backstripping analyses (Figure 10). However, such 2D surveys provide only limited information on sedimentary processes, unless line spacings are as fine as 50-200 m to allow mapping of small shelf incisions and slope gullies.

Scientific Strategy

Margin complexity mandates the drilling transect approach of multiple boreholes across each margin, coupled with seismic coverage (Figure 3). More than one transect may be required on

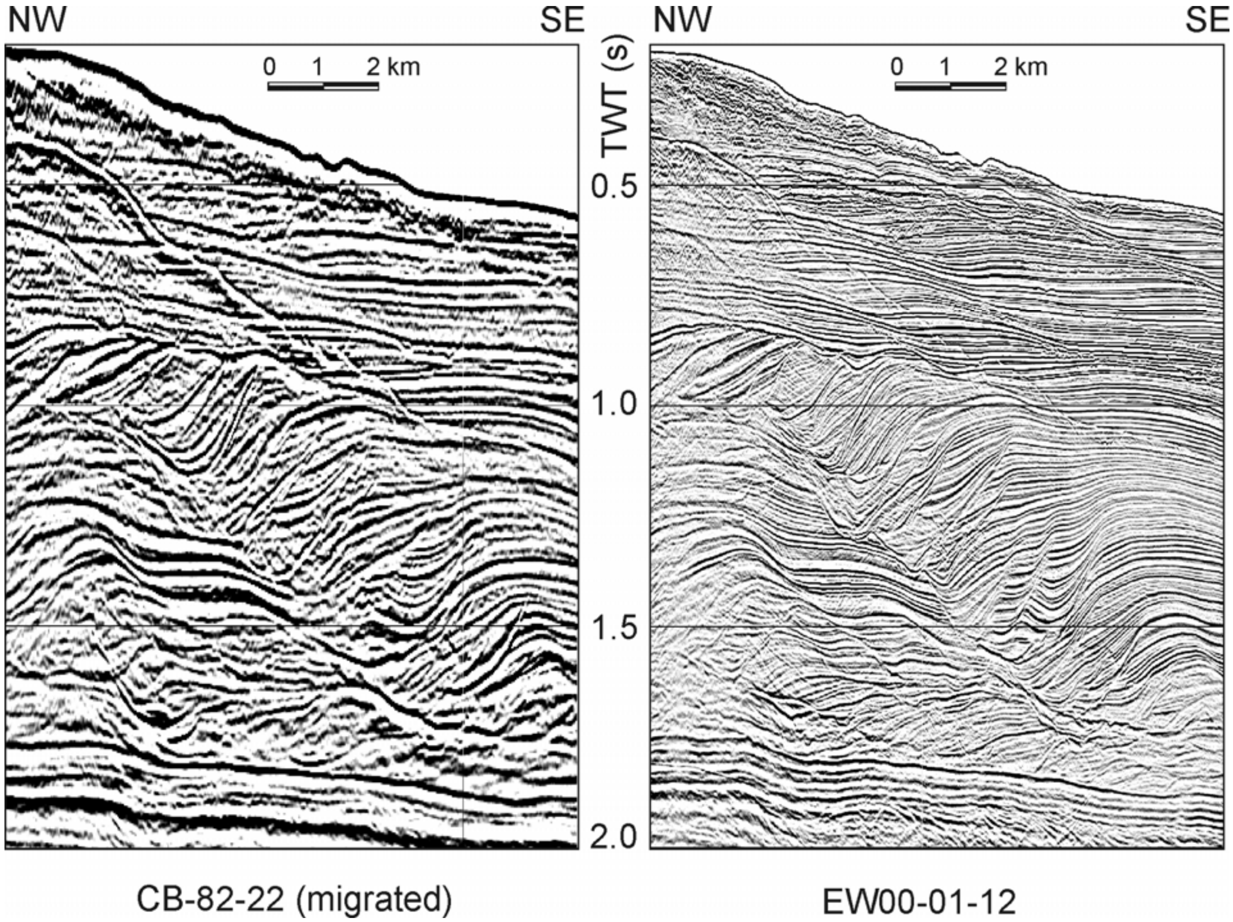

Figure 9. Comparison of commercial multichannel seismic (MCS) profile (left) and high-resolution MCS profile (right) aquired along the same track across a large sediment drift in the offshore Canterbury Basin, New Zealand (see also Figure 10 B), showing the improved imaging provided by a high-resolution survey using two 45/45 cu. in. GI air guns, a 12.5 m group interval (120 channels) and 1 ms sample interval. The commercial profile has a vertical resolution of ~20 m, whereas that of the high-resolution profile is ~5 m in the upper second (C. Fulthorpe, unpublished).

margins that exhibit marked along-strike variability through time. Such transects might consist of two coupled dip profiles or coupled dip and strike profiles. Ideally, margins should have experienced high sedimentation rates during the period of interest to maximize stratigraphic resolution. However, such high sedimentation rates should coincide with accommodation creation rates that are low enough to allow progradation in order to create the clinoform geometries optimal for sequence recognition.

We propose a focus on two time periods reflecting different global climatic conditions:

1) Late Paleogene-Neogene-Quaternary – 'Icehouse'

There are fundamental needs to: 1) calibrate the lithofacies within the prograding continental-margin sequences characteristic of the Neogene (Bartek et al., 1991) and defined using seismic profiles (Figure 3) and 2) understand the interactions among processes that control the position of the shoreline: principally eustasy, vertical tectonism (uplift, subsidence) and sediment supply.

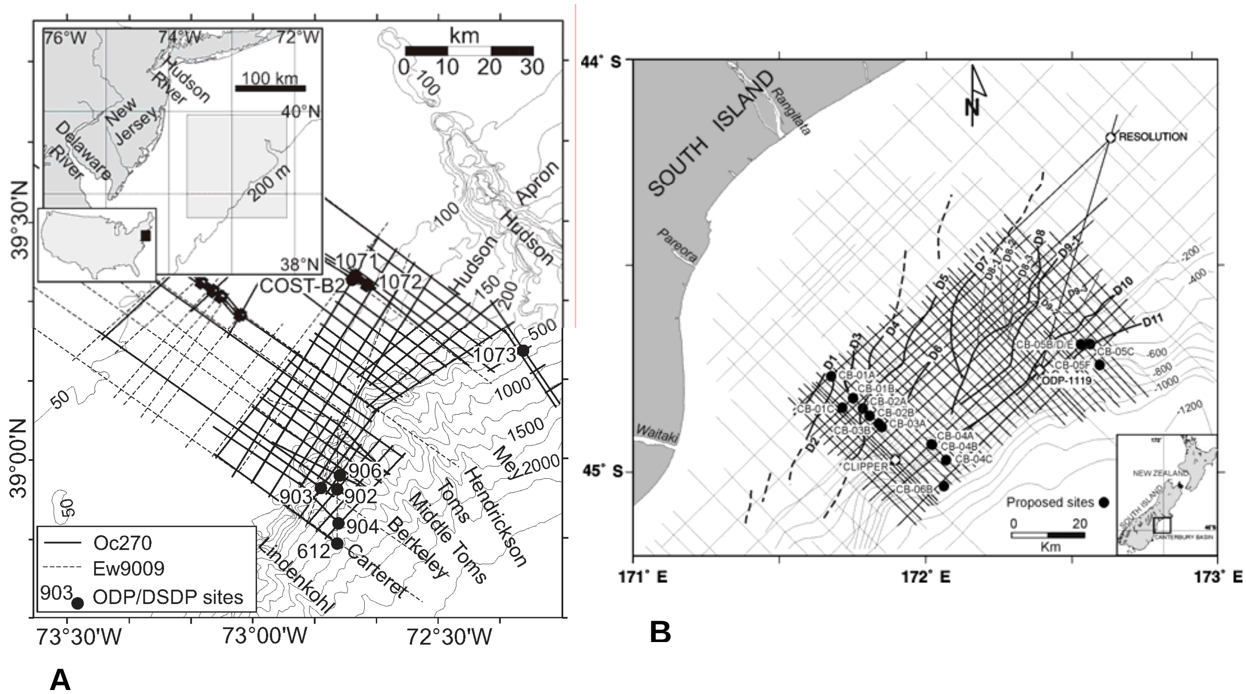

Figure 10. Two examples of seismic surveys in support of scientific ocean drilling for sea-level objectives. **A.** The New Jersey illustrating two academic seismic surveys acquired in this area for ODP Legs 150 and 174A. R/V *Maurice Ewing* cruise Ew9009 MCS collected relatively low-resolution (<80 Hz) profiles (dotted) in 1990. In 1995, R/V *Oceanus* cruise 270 (Oc270) collected high-resolution (30-240 Hz bandpass filter, 5 m vertical resolution in upper 0.1 s.), multichannel seismic (MCS) profiles (solid lines). Although the Oc270 coverage (dip profiles at 2-5 km spacings) is relatively dense coverage for an academic survey, by historical standards, and was adequate for site selection purposes, it is still insufficient to map paleoshelf incisions and even paleoslope canyons. A number of other academic surveys (e.g., ultra-high-resolution Chirp surveys) have also been carried out in this area. Bathymetry (meters) is from National Oceanic and Atmospheric Administration (1979). (Modified from Fulthorpe and Austin, in press.) **B** The Canterbury Basin, New Zealand (IODP Expedition 321). EW00-01 high-resolution MCS grid (thick straight lines) acquired in 2000 complements, low-resolution CB-82 commercial MCS grid (thin straight lines; see Figure 9 for a direct comparison of these data). Proposed drill sites, exploration wells Clipper and Resolution, and ODP Site 1119 are also shown, as is the distribution of seismically resolvable sediment drifts (D1 to D11; curved lines mark the crests of the drift mounds). Sediment drifts were identified on the CB-82 data, but could not be adequately mapped. Even the more dense (2-3 km dip profile spacings) EW00-01 profiles did not allow drift geometries to be completely constrained. True 3D data would be needed for that purpose. Bathymetric contours are in meters. (Modified from Lu and Fulthorpe, 2004.)

Integration with process-based margin studies will allow 3-D modeling of along-strike sediment geometries and sediment-transport processes. All of this should be testable on Milankovich and longer timescales. Indeed, a good place to begin to define the sedimentary response to eustasy would be to study the development of sedimentary architecture within well-constrained sea-level cycles that have undergone eccentricity (~400 and 100 kyr), obliquity (41 ka), and precessional (19/23 Ka) forcing. This would provide insights that would assist interpretation of stratigraphic response in other icehouse sequences. Mid-high latitude margin responses should be correlated with low-latitude carbonate and mixed siliciclastic/carbonate systems in different tectonic settings. Also, it is important to understand the role of ice sheets (including the onset of bipolar glaciation) and sea ice on climate and sediment delivery to margins.

Seismic stratigraphy, recognition of sequence boundaries and dating of surfaces is well established. New Jersey margin drilling has shown that eustasy is tied to positive oxygen isotopic excursions (Miller et al., 1996, 2005). However, questions remain about the processes of sequence boundary formation and the phase relations (lead and lags) between eustatic changes and erosional and maximum flooding. Formation of stratigraphic gaps in slope settings is particularly problematic and the roles of sediment by-pass versus vigorous along-slope currents need clarification (Lu and Fulthorpe, 2004). For example, rapid and erosive currents may be expected after changes in thermohaline circulation (e.g., Northern Component Water). In addition, the coastal onlap approach to establishing changes in sea-level amplitude remains largely untested because of the difficulty of recognizing coastal onlap from seismic data alone. Drilling is essential to ground-truth the lithofacies associated with the seismic signature of on-lap.

Furthermore, there is a need for comparable data from a siliciclastic margin distant from the Atlantic passive margin. This need should be met in the first instance by Canterbury Basin drilling (IODP Expedition 317; Figure 3). This will provide data that are complementary to those from New Jersey from sequences of similar age, but subject to different climatic, sediment supply, tectonic, and paleoceanographic regimes.

In addition, although passive margins are expected to remain the principal focus of eustatic studies, the ability of tectonically active margins to record a eustatic signal and the stratigraphic response to eustasy in tectonically active settings has not yet been evaluated by scientific drilling, although numerous seismic data sets suggest a strong eustatic control. Only scientific drilling can recover material to provide age control on key surfaces and strata packages to test for a correlation with global eustatic changes. A benefit of active margins is that outcrop-based records from uplifted sections may complement offshore drilling.

2) Jurassic/Cretaceous-Early Paleogene – 'Greenhouse'

Our understanding of the stratigraphic response to eustasy in the greenhouse world is limited by lack of a well-defined eustatic mechanism, as well as greater uncertainties about eustatic amplitudes and rates during this time period. Nevertheless, global correlation of second- (~10 my), third- (1-5 my) and fourth- (~0.5 my) order sequences suggests eustatic control.

Times of major eustatic sea-level change are commonly coupled with major climate change and perturbations in the carbon cycle. This is most obviously the case for the Jurassic and Cretaceous Oceanic Anoxic Events (e.g., Jenkyns, 1985; Gröcke et al. 1999). For these times, high-resolution carbon isotope stratigraphy provides a tool for correlation at sufficient resolution to assess relative ages of depositional sequences and thus also understanding relationships between sea-level change and carbon cycle processes (e.g., Hesselbo et al., 2007). The association between global anoxia and sea-level change is established but is not understood, even to the first degree. Additionally, integrated geochemical and palaeobiological data have potential to give information about linkages between climate change and sea-level change that can affect our interpretation of stratigraphic geometries for particular times, for example by identifying events during which sediment supply may have increased or decreased dramatically (e.g., Cohen et al. 2004; Hesselbo et al., 2007).

It is possible to address stratigraphic response to greenhouse eustasy by drilling onshore locations, such as in basins along the Cretaceous Western Interior Seaway. The Alberta Basin provides an excellent example of the type of location that might be targeted. The Alberta Basin is a foreland basin where relative sea-level rises and falls are irreconcilable with current understanding of tectonic processes and suggest eustatic control (Plint and Kreitner, 2007). The Alberta Basin already has a well-established sequence stratigraphic record, based on extensive outcrop exposure and a large public database (>300,000) of well logs and cores (mostly in reservoir facies). Results from continuous coring (perhaps by ICDP, possibly with industry collaboration) could confirm the possible glacioeustatic origin for late Cenomanian-middle Turonian sequences [and others – as there is a good marine record for mid Albian to Campanian] and provide a test of Greenhouse eustasy in a tectonically active basin. Carbon isotopes from both terrestrial and marine organic matter provide an important potential means of correlation of sequences in the Cretaceous Western Interior Seaway with sequences globally to test for synchroneity (cf. Gröcke et al., 2006). Leaf debris and/or palynofacies in such successions give potential for determining climate change and atmospheric CO_2 content in relation to sea level change. Ammonites, inoceramid bivalves, and ash fall deposits, together with analysis of cycle frequencies, may provide additional chronostratigraphic control.

Drilling Strategy and Targets

There is a broad consensus that the drilling transect strategy is effective and should be continued. Only this approach addresses the spatial variability of sequence architecture, lithofacies and biofacies. The New Jersey transect must be continued, by completion of IODP Expedition 313 MSP drilling. Canterbury Basin drilling (Expedition 317) will provide a complimentary transect (Figure 3).

The results of the New Jersey and New Zealand IODP expeditions will help shape the next step in the study of eustatic timing and amplitudes and the stratigraphic response to eustasy in the Neogene. Future options will include: 1) moving to new areas to further establish global synchronicity and further constrain stratigraphic response (Appendix I), or 2) additional drilling off New Jersey (e.g., to fill in the mid- and outer-shelf parts of the transect or to drill a second transect along strike to constrain 3D controls on margin architecture) and/or off New Zealand.

Characteristics of Future Drilling Areas

Seismic data must be available, or plans made to collect such data, particularly in offshore drilling areas. The data should be of sufficient resolution to delineate the stratigraphic architectures to be calibrated by drilling and should provide a level of 3D stratigraphic control appropriate to the objectives (see above). Locations with high rates of sediment accumulation maximize the resolution of stratigraphic sequences. However, it should be possible to correlate from such areas to adjacent areas of lower accumulation where increased microfossil abundances provide optimal age control. Drilling techniques employed should ensure the highest recovery possible.

Strategies for icehouse and greenhouse climatic conditions may differ substantially. For example, greenhouse deposits are likely to be most accessible at drilling locations on modern inner shelves and coastal plains or other onshore locations, necessitating a linked ICDP-IODP approach. In contrast, icehouse deposits are generally preserved beneath modern mid- to outer-shelves and slopes. Access to MSPs for offshore sites in shallow water (<70 m) will be essential. It would be beneficial to explore links to industry as a resource for the scientific community. Such links can range from donation of seismic data to collaborative drilling operations.

Downhole Measurements

Logging is a critical component of the drilling strategy because of the likelihood of gaps in recovery in unconsolidated marginal-marine cohesionless sediments. Until such recovery problems are solved, logging while drilling (LWD) has advantages for siliciclastic margins.

Spectral gamma and the standard logging suite are essential. VSP, LWD (where appropriate) and FMS are highly desirable. Post-cruise high-resolution logging and U-channel measurements (paleomagnetic, sedimentary structures); scanning XRF may also be desirable.

BREAKOUT GROUP 2B: CARBONATE AND MIXED SYSTEMS

Carbonate Platforms and Margins

Carbonate sediments contain unique and important components of the records of sea-level timing, amplitude and stratigraphic response. Carbonates are excellent 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 range of frequencies of sea-level change, from millennial scale to tens of millions of years.

Continental margin transects (Figure 3) have the advantage that their stratigraphic architectures are well 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). The study of coral reefs is of crucial importance in attempts to resolve the rates of millennial-scale changes in sea level, to clarify the mechanisms that drive glacial-interglacial cycles and to constrain geophysical models. Coral reefs provide unparalleled records of sea-level amplitudes, particularly for the middle to late Pleistocene. For example, drilling reefs in 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 study of recent high-resolution climate changes and contribute to estimates of the future behavior of the Earth system on societal timescales. This approach was successfully employed during MSP IODP Expedition 310 off Tahiti (Camoin, Iryu, McInroy, 2007a, b).

Drilling reefs older than the Pleistocene for sea-level studies has suffered more from poor recovery. The principal effort has been the drilling of Cretaceous carbonates on guyots by ODP Legs 143 and 144 (Sager, Winterer, Firth, et al., 1993; Premoli-Silva, Haggerty, Rack, et al., 1993). This was an application of the “dipstick” approach, an attempt to recover the record of reef growth and exposure surfaces created in response to the combined effects of subsidence of the underlying volcanic edifice and global sea-level change. MSPs and ICDP onshore drilling of atolls could breathe new life into this approach.

Evaporites/Siliciclastics/Carbonates

Evaporites potentially represent an untapped, high-resolution archive of information on rapid sea-level fluctuations. However, recovering evaporites poses a challenge.

Mixed carbonate-siliciclastic systems have also received little attention as targets for scientific drilling. They provide the opportunity to sample carbonates related to early transgression growing on top of lowstand silisiclastic deposits. It may be possible to sample all three systems in a Mediterranean transect.

Multi-Expedition Multi-Location Approach

It will be necessary both to drill a range of time intervals and to drill each time period at multiple locations. This is because depositional conditions for carbonates change spatially as well as temporally (e.g., modern corals are dying at the equator as a result of increasing water temperature). Integration of both onshore (ICDP) and offshore drilling is also essential. For example, ICDP drilling of atolls could complement IODP drilling of guyots and platforms. New drilling technologies (e.g., MSPs) have improved the chances of success for drilling of atolls and guyots..

Icehouse and Greenhouse carbonate sediments must be drilled for correlation with siliciclastic sections. Within each interval, several themes are identified. Crucial time intervals and thematic objectives are:

Icehouse

- Last 3.5 million years

  Last glacial cycle and last 600 ky, including the mid Brunhes global establishment of modern reefs, other intervals of high sea level around MIS 34-31 (about 1.1 - 1.0 Ma; Scherer et al., 2008) and MIS 52-47 (about 1.5 - 1.4 Ma). The mid Pliocene warm interval in the early late Pliocene (3.3 - 2.7 Ma) has been particularly studied because it could represent future climate on an Earth with high atmospheric CO_2 (Ravelo et al. 2004)

- Oligocene - early Pliocene

  Early Pliocene climatic optimum, Messinian sea-level cycle, early late Miocene climatic optimum (Tortonian), early middle Miocene climatic optimum (Langhian), early late Oligocene sea-level fall, Eocene to Oligocene sea-level fall.

Greenhouse

- Early Eocene climatic optimum (PETM)
- Late Cretaceous

Drilling Strategy

Carbonate margin and platform geometries are well defined and allow selection of optimal drill-site locations for sea-level studies. However, poorly cemented, shallow-water carbonates have proved difficult to recover by ODP using the *JOIDES Resolution*. MSP drilling has been more successful (e.g., Tahiti drilling, IODP Expedition 310). Targeting well cemented intervals should improve recovery, as will carefully controlling weight on bit.

Drilling transects should sample carbonate platform interiors and margins, slopes, and slope toes (Figure 3). Lowstand sediments should ideally be sampled close to locations of onlap. Along-strike variability of sequence geometries may necessitate more than one drilling transect.

As for siliciclastics, seismic data are essential for selecting drill-site locations and constraining along-strike variations in sequence architecture. Survey requirements are the same as those for siliciclastics (see above). One potential difference is the use of seabed streamers to image shallow water platforms. High-quality seismic data (3D or dense 2D) of non-prospective Paleogene to Recent sections may be accessed through industry, depending on the country of origin.

FUTURE WORK

Future IODP drilling for sea-level objectives includes: Expedition 313, New Jersey inner shelf MSP drilling, scheduled for summer 2008, but now postponed, and Expedition 317, Canterbury Basin, New Zealand, scheduled for November 2008-January 2009. Great Barrier Reef drilling is tentatively planned for 2009. Additional drilling is essential to complement existing results and provide the necessary global correlations. In addition, these planned expeditions, and existing IODP proposals (e.g., Maldives, North West Australian Shelf, Gulf of Mexico - Southern Bank, Belize margin, Gulf of Papua) all address icehouse objectives. Such drilling is indeed vital, in particular to constrain icehouse eustatic amplitudes and to calibrate the stratigraphic signature of the Neogene (Bartek et al, 1991). However, the next phase of sea-level studies must include greenhouse objectives. We therefore encourage proponents to prepare and submit sea-level proposals for both offshore and onshore drilling focusing on the greenhouse world.

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APPENDIX 1

POTENTIAL DRILLING LOCATIONS

Potential locations for future drilling are presented in the tables below. The intent is neither to exclude locations that are not listed, nor to drill all of the locations listed. They are provided as examples as a guide to proponents of future drilling expeditions.

The locations are subdivided into the following categories: 1) siliciclastics, 2) active margins, 3) carbonates, and 4) proxy records. Examples covering greenhouse, transitional and icehouse objectives are included.

Information on sediment age, lithology, environment and suitability for addressing particular objectives is provided where this was available at time of writing.

Location	Age	Greenhouse or Icehouse	Lithology, Environment	Comments	Objectives (Breakout Group)		
					1	2A	2B
Siliciclastics							
New Jersey, Expedition 313	Miocene	I	Passive margin	Summer 2008 drilling. Also drilled on legs 150, 150X, 174A, 174AX. Onshore and offshore.	X	X	
Canterbury Basin, New Zealand, Expd. 317	Miocene - Recent	I	Passive margin	Incorporates along-strike currents, sediment drifts. Nov. 2008 drilling	X	X	
Japan		I	Passive and active margins			X	
Hampshire Basin	Eocene and Oligocene	I, transitional		Onshore transect. Excellent fossil preservarion.	X	X	
Pelotas Basin (Brazil margin)	Eocene - Recent	I, transitional	Passive margin	Conjugate with Namibian margin.	X	X	
Walvis Basin (West Africa)		I	Passive margin		X	X	
Cauvery Basin (SE Indian margin)	Mid-Cretaceous - Eocene	G	Passive margin	400 ky cycles onshore correlate with UK. Much drilling could be onshore. Good fossil preservation.	X	X	
Mazagan Plateau (NW Africa margin)	Cretaceous to Paleogene	G					
Main Pass	Neogene - Recent	I	Passive margin	Hydrocarbon province (drilling safety issue)	X	X	

Location	Age	Greenhouse, Icehouse	Lithology, Environment	Comments	Objectives (Breakout Group)		
					1	2A	2B
Active Margins							
Alberta Basin	Cretaceous	G	Siliciclastic foreland basin	Outcrops, abundant well logs, availability of seismic data uncertain. ICDP drilling would provide continuous cores.	X?	X	
Eel River Basin, northern California	Quaternary	I	Siliciclastic forearc basin	May resolve 100 ky cycles. Possible location for intensive study of a single cycle.	X	X	
Gulf of Papua	Quaternary	I	Mixed siliciclastic, carbonate	Source-to-sink site.	X	X	
North Island, New Zealand	Quaternary	I	Siliciclastic, forearc basin	Source-to-sink site.	X	X	

Location	Age	Greenhouse, Icehouse	Lithology, Environment	Comments	Objectives (Breakout Group)		
					1	2A	2B
Carbonates							
Great Barrier Reef	Quaternary	I	Barrier reef	Complements Tahiti (Expedition 310)	X		X
Atolls and Guyots	Cretaceous to Quaternary	G, I	Atolls, guyots	Use of MSPs offers new opportunities for success for this approach.	X		X
Belize	Neogene-Quaternary	I	Barrier reef, atoll		X		X
Maldives	Miocene - Recent	I	Carbonate platform	Mid-ocean platform with enclosed basin containing prograding sequences.	X		X
Australian North West Shelf	Oligocene - Recent	I	Carbonate and mixed passive margin	Carbonates with a siliciclastic interval. 3D commercial seismic data.	X		X
Other locations focusing on last 1 Ma	Quaternary	I	Carbonate	Hawaii, Ryukyus, Barbados, offshore South Texas, Gulf of Papua	X		X
Other Neogene locations	Neogene	I	Carbonate	South Florida, Eucla Shelf, Maiella	X		X

Location	Age	Greenhouse, Icehouse	Lithology, Environment	Comments	Objectives (Breakout Group)		
					1	2A	2B
Proxy Records							
Umbrian Basin, Italy	Cretaceous - Paleogene	G		Onshore. Calibration at astronomical timescales. Magneto-, bio-, chemo-stratigraphy.	X		
Crozet and Aghulas Plateau	Mid-Late Cretaceous	G			X		
Falkland Plateau	Mid-Late Cretaceous	G	Siliciclastic	Redrill Site 511 (clay with forams.	X		
Exmouth Plateau	Mid-Cretaceous - Eocene	G	Hemipelagic and pelagic carbonates	Redrill sites 762, 763, 766	X		
Ontong Java Plateau	Cretaceous - Recent	I, G	Pelagic carbonates.		X		
Wharton Basin	Extends to Jurassic	G			X		
East Timor Sea			Carbonates	Good seismic control	X		
Goban Spur	Cretaceous	G		Thick section	X		
Alpha Ridge, Arctic Ocean	Late Cret. (Campan. and older?)	G	Siliciclastic	Proposal exists. Organic-based paleotemperatures.	X		
NW Pacific: DeePac	Mid-Cretaceous	G	?, chert	Proposal exists. Need ability to recover chert.	X		
Greenland Sea	Paleogene (Eocene), Neogene	I, G, transitional		High-latitude transect; resample sites 913, 918; IRD.	X		

Location	Age	Greenhouse, Icehouse	Lithology, Environment	Comments	Objectives (Breakout Group)		
					1	2A	2B
Proxy Records (continued)							
Maud Rise	Maastrichtian - Oligocene	I, G, transitional	Chalk, ooze	High-latitude, Southern Ocean (Atlantic). IRD. Redrill Leg 113 Sites. Proposal exists.	X		
Kerguelen Plateau	Paleogene	G?, transitional?		High-latitude, Southern Ocean (Indian). IRD.	X		
Svalbard	Cretaceous - Eocene	G, transitional		Onshore. North of Arctic Circle, not well studied.	X		
Greenland, Ellesmere Island				Onshore	X		
Antarctic Peninsula				Onshore	X		
Russian Platform			Epicontinental Sea	Onshore. Need continuous cores for age control.	X		

Appendix II

Workshop Participants

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