THE ROLE OF ODP IN UNDERSTANDING THE CAUSES AND EFFECTS OF GLOBAL SEA-LEVEL CHANGE

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"Much of the record of historical geology from Cambrian time onward has been that 'the seas came in and the seas went out.'"

P.B. King, 1959, The Evolution of North America: Princeton, NJ, Princeton University Press, p. 6

ODP AND THE SEA-LEVEL PROBLEM

The Ocean Drilling Program (ODP) continues to pursue the long-standing challenge of understanding global sea level (eustatic) change and its effects on the stratigraphic record. Scientists and non-scientists agree that changes of this fundamental boundary between land and sea have profound impacts on the distribution of sediments, sources of mineral and water resources, the stability of nearshore ecosystems, and the safety of shoreline population centers. Therefore, understanding the rates, magnitudes and mechanisms controlling sea-level change has direct societal relevance. Determining this information is a challenging task because eustasy is complexly intertwined with the interacting effects of local basin history, sediment supply, and climate.

Oxygen isotopic measurements of deep-sea foraminifers provide a proxy of global sea level changes caused by the waxing and waning of continental ice sheets. The Deep Sea Drilling Project (DSDP) and ODP recovered long, continuous Cenozoic deep-sea sections suitable for $\delta^{18}O$ studies. However, the $\delta^{18}O$ record is a function of both temperature and ice volume changes; glacio-eustasy can be estimated only by assuming a thermal history. Consequently, it is necessary to calibrate this deep-sea proxy with a more direct record of sea level change.

Another method for deriving past sea levels is to use tropical coral reef and atoll records. The growth surfaces of ancient coral reefs provide a close approximation of sea level ("fossil sunshine") and reef records provide an excellent record of rising sea levels (e.g., Fairbanks, 1989). However, reef growth ceases during sea level falls, and the resultant karst surfaces are less useful for deriving a sea level history. Reef records also can be difficult to core and date successfully from a dynamically-positioned drillship such as the *JOIDES Resolution*.

Continental margins contain an extremely long (billion year) sedimentary record that directly records the effects of sea level change. However, the margin record is complicated by tectonics (subsidence/uplift) and changes in sediment supply. Sea level falls and tectonic changes both produce discrete, unconformity-bounded units on continental margins known as sequences. Sequences are the fundamental building blocks of the stratigraphic record. Researchers at Exxon Production and Research (EPR) made a revolutionary breakthrough in using seismic reflection profiles to identify sequences, an assumption tested by ODP, and to produce eustatic estimates using stratigraphic records (e.g., Vail et al., 1977).

Publication of the EPR sea level curve in the late 1970s spurred interest in eustatic history. DSDP first ventured into the sea level game by drilling the Irish (Leg 80) and New Jersey (Legs 93 and 95) passive continental margins specifically to test the "Vail curve". Whereas these legs were successful in dating sequences, they were relegated to water depths >1000 m, far from direct stratigraphic effects of sea level change at shallower depths. In the meantime, researchers at EPR broadened the application of sequence stratigraphy to include outcrop, well, and seismic studies. This effort greatly increased the number of potential Triassic to Recent sea level events, and produced a second generation sea level curve (e.g., Haq et al., 1987). The pioneering work of EPR remained controversial because the fundamental methods used to produce the curves were in question (e.g., Christie-Blick et al., 1990; Miall, 1991), and their data base was largely proprietary.

In the early days of ODP, the community realized that integrated studies with publically available data sets were needed to evaluate eustatic changes. COSOD II (July 1987), a JOI/USSAC Workshop (1989), and the JOIDES Sea Level Working Group (1992) all recognized that sea level studies require a global array of data obtainable from ocean drilling. These groups identified four goals: 1) test the synchrony of sea level events; 2) estimate the amplitudes of changes; 3) evaluate various models that seek to explain the stratigraphic response to sea level oscillations; and 4) determine the mechanisms that control sea level. They recommended a three-fold approach to sea level studies, incorporating data from passive continental margins transects, deep-sea $\delta^{18}O$ records, and reef terraces and atolls. One recommendation was to compare sea level changes during the Oligocene to Recent "Icehouse World," when glacio-eustatic changes were clearly operating, and the older mid-Cretaceous to Eocene "Greenhouse World," a time that was then thought to be ice-free.

To address these issues, ODP had to drill in a setting that would be technically difficult for the *JOIDES*

Resolution: shallow-water, thickly sedimented continental shelves. Dynamic positioning within 3% of ambient water depth required by pipe strength is difficult in shallow water. Maintaining a 470-ft drillship in position over a target to ±1 to 3 m is a challenge even in the days of differential Global Positioning System (GPS) satellites. Hole stability in caving sands demands setting long casing strings, a virtually impossible task in such shallow water from a floating platform. Most importantly, drilling without blowout prevention in this environment demands addressing stringent safety and pollution prevention issues.

ODP accepted these challenges and ventured into shallow water, using the siliciclastic margin off the east coast of the U.S. as its test case. Leg 150 was designed to drill the New Jersey continental shelf and slope, targeting Miocene prograding, clinoformal sequences. However, safety considerations relegated actual efforts to the slope. The leg was successful in firmly dating Eocene to Recent sequences that were then tied to the deep-sea $\delta^{18}O$ proxy (Fig. 1; see summary and Fig. 7a in Miller et al., 1998). Despite this success, the lack of direct information on shallow-water facies precluded estimates of sea level amplitudes from Leg 150 drilling.

ODP demonstrated flexibility and innovation after Leg 150 by approving shallow shelf drilling during Leg 174A after an intense safety evaluation. Several sites into Pleistocene-uppermost middle Miocene strata on the New Jersey outer shelf sampled a few critical facies, and it was shown that the breakpoint or rollover approximates a paleo-shelf edge in 30 to 40 m of water. Another exciting result was the sampling of very thick (~550 m) marine Pleistocene sequences on the upper slope that were traced landward to the shelf boreholes where shallow-water strata were also sampled. However, Leg 174A was limited by poor recovery and lost bottom hole assemblies due to caving sands.

Recognizing that sea level objectives require transects across margins, ODP endorsed drilling onshore as part of an integrated study. Leg 150 slope drilling was

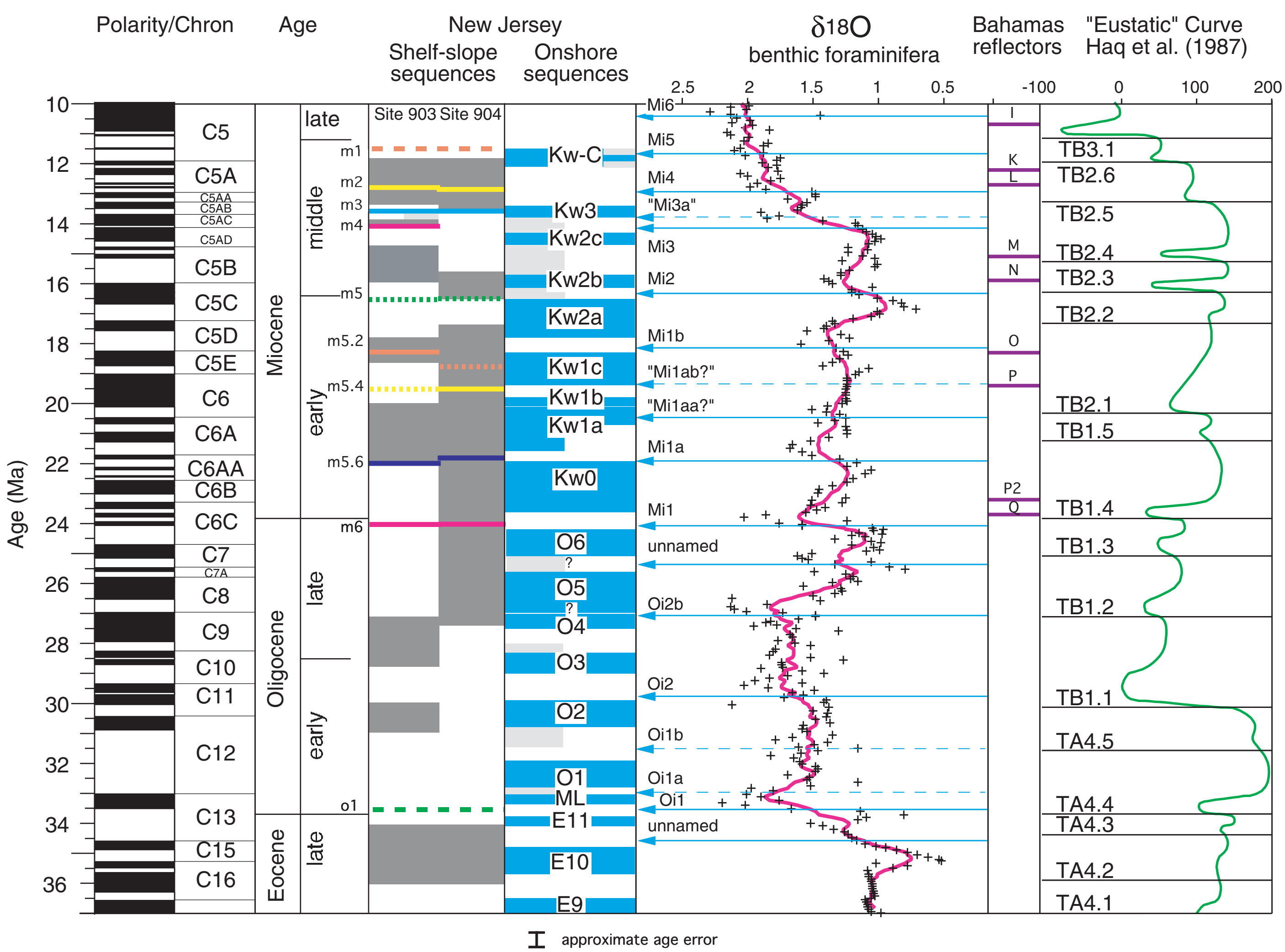

Figure 1. *Revised age comparison of Oligocene-Miocene slope sequences, onshore sequences, oxygen isotopes, Bahamia carbonate margin reflections, and the inferred eustatic record of Haq et al. (1987). After Miller et al. (1998).*

coupled to an onshore New Jersey drilling program, "Leg 150X." The ability to use telescoping casing strings, make short coring runs, and control weight-on-bit resulted in high core recovery despite the coarse-grained, unconsolidated sediments. This onshore "leg" sampled critical updip facies (Miller et al., 1998) that correlate with sequences on the slope (Fig. 1) and, with the $\delta^{18}O$ proxy of glacio-eustasy (Figs. 1 and 2), demonstrating not only that the sequences were regional, but also tied to a global proxy. Onshore New Jersey drilling continued with Leg 174AX drilling. One surprising result is that the Late Cretaceous to Eocene might not have been ice-free, as was previously widely assumed because sequence boundaries correlate with evidence for $\delta^{18}O$ glacio-eustatic lowering (Fig. 2). Studies of onshore boreholes provided estimates of eustatic variations using one- and two-dimensional backstripping (Kominz and Pekar, 2001; Fig. 3). Nevertheless, onshore drilling only sampled updip facies and missed critical lowstand deposits that are now buried beneath the continental shelf. Sampling these facies will probably require a supplementary drilling platform such as a jack-up rig. While ODP was struggling to drill on heavily sedimented siliciclastic margins, drilling also was proceeding on carbonate margins along Australia and the Bahamas and isolated northwest Pacific atolls. Legs 143 and 144 targeted the sea level records contained within atoll carbonate platforms in the northwest Pacific, but were plagued by poor core recovery. However, downhole log records were used in conjunction with available core to demonstrate the existence of sea level fluctuations during the Cretaceous, although evidence of eustatic control is equivocal.

ODP drilling has been successful in dating sequences on carbonate margins, particularly in the Bahamas during Leg 166. Despite the differences in sedimentation style between carbonate and siliciclastic margins, ODP drilling documented that similar-aged unconformities occur in the Miocene in both carbonate (Australian and Bahamas) and siliciclastic (New Jersey) settings (Fig. 1). Bahamas drilling during Leg 166 and supplementary platform drilling also showed that a carbonate bank flank environment could develop sequences that are

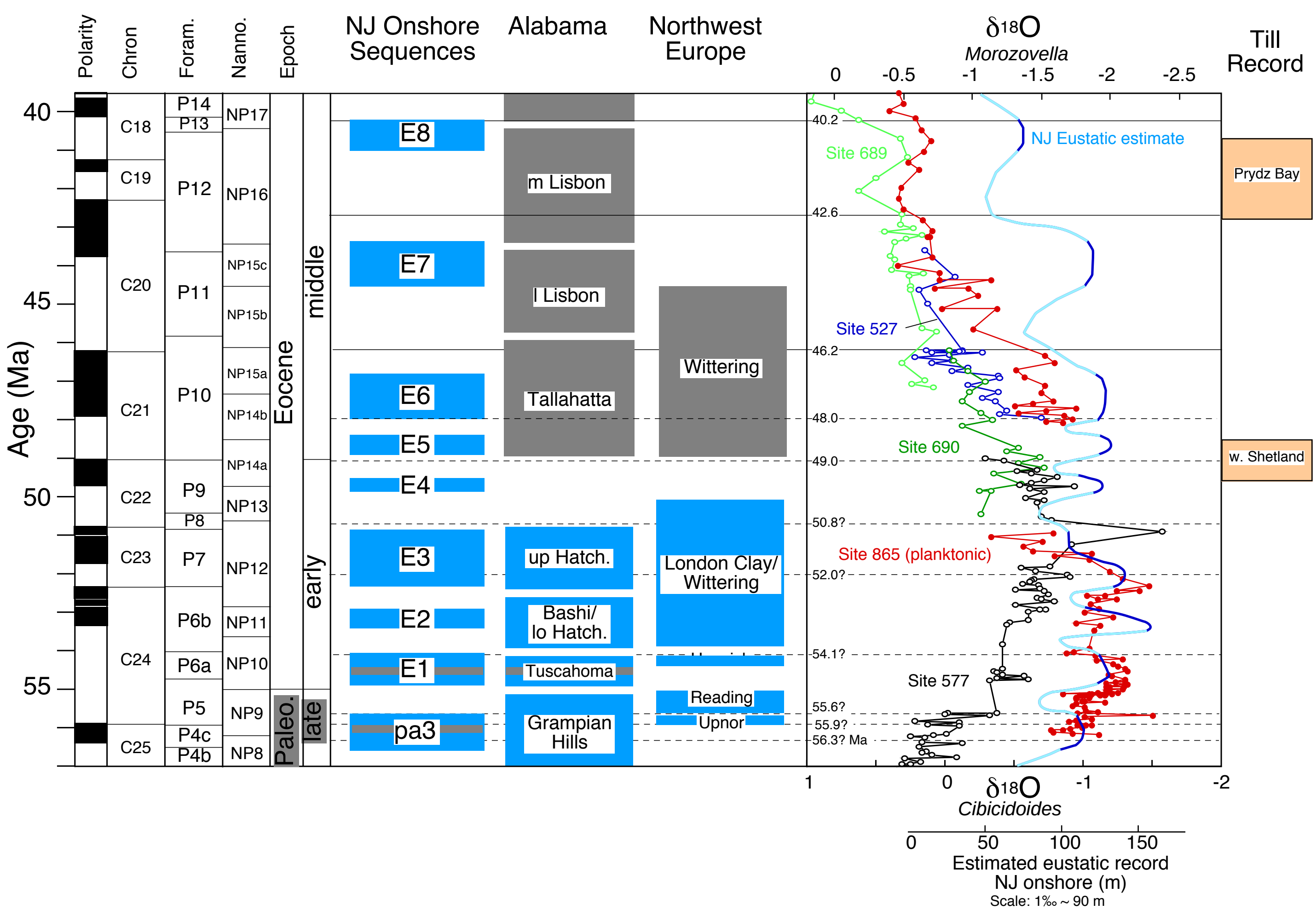

Figure 2. Comparison of Eocene onshore sequences (New Jersey, Alabama and northwest Europe), oxygen isotopes, New Jersey backstripped estimates, and till records in high southern latitudes. Blue boxes indicate time represented by sediments. Gray boxes indicate uncertain chronology. Modified by J.V. Browning and K.G. Miller (in prep.) after Miller et al. (1998) using backstripped estimates of Kominz et al. (1998)(solid blue) and scaling the lowstands (hiatuses onshore) to the oxygen isotopic record.

remarkably similar in character to those characterizing siliciclastic margins.

Drilling off Australia has provided insight into the effects of sea level change on the development of carbonate margins and platforms. Leg 133 demonstrated that eustatic fluctuations, paleoceanography, and subsidence controlled the initiation, growth, and demise of the Queensland Plateau, Great Barrier Reef, and Marion Plateau. Sequences seaward of the Great Barrier Reef slope contain a thick record of cyclically-deposited mixed carbonate-siliciclastic sequences. Deposition was controlled by sea level fluctuations modulated by the formation of the barrier reef system near the shelf edge (Feary et al., 1993). Leg 182 along the western Great Australian Bight was designed primarily to study cool-water carbonates, including evaluating the effects of sea level. It provided excellent Pliocene to Pleistocene records of a prograding carbonate shelf, documenting that sediment transport from the shelf to slope occurred during sea level falls, and that development of bryozoan-dominated mounds, the cool-water equivalents of coral reefs, occured only during lowstands (James et al., 2000). Leg 194 specifically targeted the amplitude of sea level change and was successful in providing an estimate of a major late middle Miocene eustatic lowering of 85 ± 30 m.

ODP ACHIEVEMENTS

Planning of and drilling during ODP Legs 133, 150, 150X, 166, 174A, 174AX, 182, and 194 resulted in the following accomplishments:

1) Proved that the age of sequence boundaries on margins can be determined to better than ± 0.5 million years (m.y.) and provided a chronology of eustatic lowering for the past 42 m.y. (Figs. 1 and 2);
2) Validated the transect approach of drilling passive continental margins and carbonate platforms (onshore, shelf, slope); future work should consider three-dimensionality by drilling of arrays (transects both perpendicular and parallel to depositional dip);
3) Tested and validated the assumption that the primary cause of impedance contrasts producing seismic reflections on continental margins are stratal surfaces including unconformities;
4) Demonstrated that middle Eocene-Miocene sequence boundaries correlate with $\delta^{18}O$ increases,

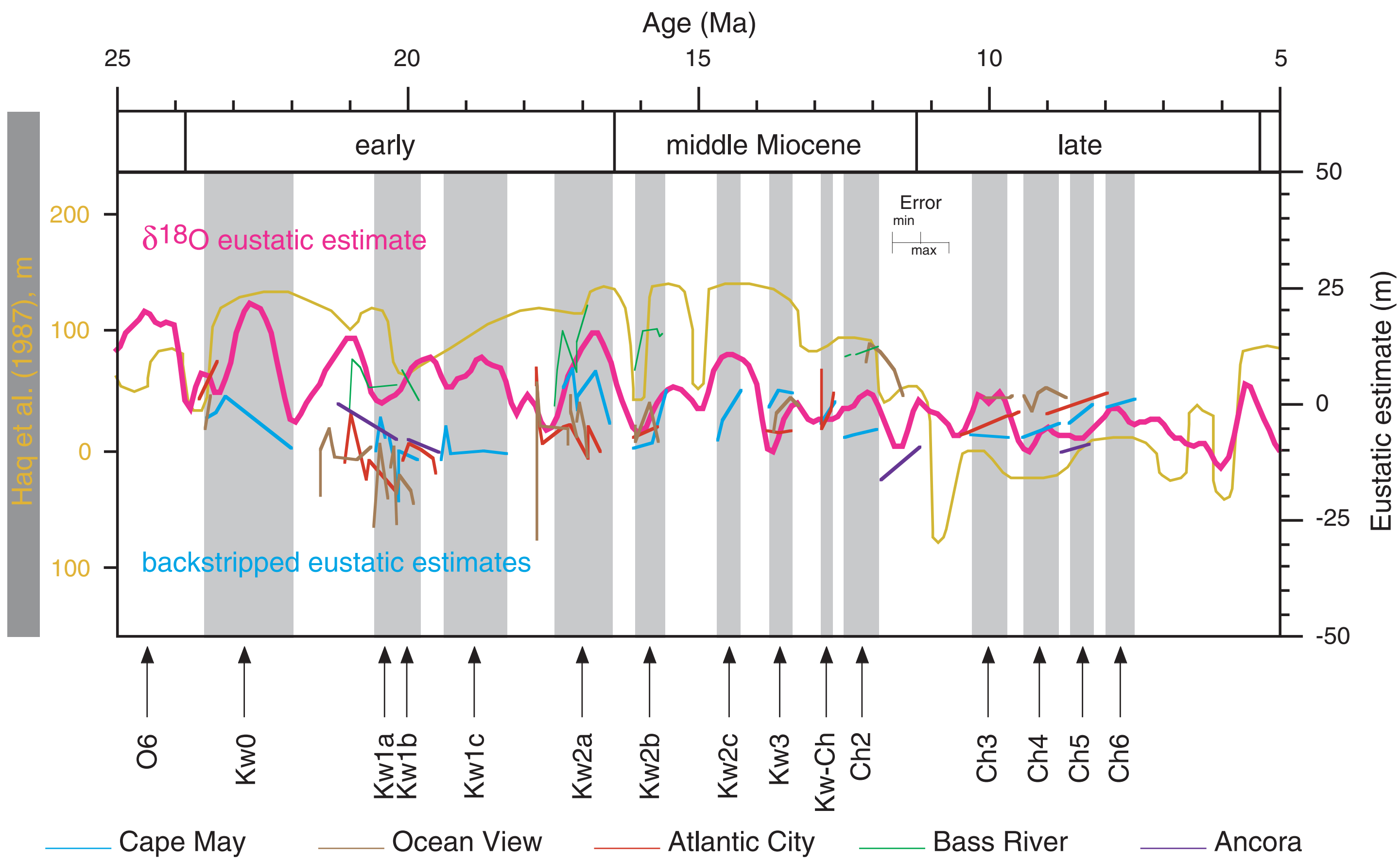

Figure 3. *Comparison of backstripped eustatic estimates from the New Jersey coastal plain (Legs 150X and 174AX; modified from Kominz et al., 1998) with an estimate using oxygen isotopes and the Haq et al. (1987) record. Note that the Haq et al. (1987) amplitudes are scaled to be one-quarter of the New Jersey and oxygen isotopic estimates (Miller et al., 1999; K.G. Miller, M.A. Kominz, J.D. Wright, and J.V. Browning, in prep.)*

linking the formation of sequence boundaries to glacioeustatic lowerings (Figs. 1 and 2);

5) Provided evidence that Late Cretaceous to middle Eocene times may have had small- to moderate-sized ice sheets (30% of modern ice volume), in addition to the moderate to large ice sheets of the past 42 m.y;
6) Showed that siliciclastic and carbonate margins yield correlatable, and in some cases comparable, records of sea level change (Fig. 1);
7) Evaluated the sedimentary response of both tropical and cool-water carbonate platforms to eustatic changes;
8) Provided preliminary amplitude estimates of approximately 20 to 85 m for m.y.-scale variations from the New Jersey margin that agree with oxygen isotopic estimates (Fig. 3), although they may be less than the best estimates derived from carbonate environments (85 ±30 m); and
9) Achieved orbital-scale, and, perhaps, suborbital-scale, stratigraphic resolution on continental slopes and carbonate platforms.

THE FUTURE

ODP has provided a chronology of sea level changes for the past 42 m.y., established a causal link between sequence boundaries on margins and eustatic lowerings, and made progress toward estimating eustatic amplitudes. Although ODP has drilled the New Jersey, Bahamas, and Australian margins, a lack of shallow-water drilling capability continues to limit understanding of global sea level change and sedimentary architecture. As a result, there are fundamental uncertainties in the rates, amplitudes, and mechanisms, for, and response to, eustatic change.

Rates of Sea Level Change

Though atoll drilling in Barbados has provided a detailed record of the rapid rise in sea level since 18 ka (Fairbanks, 1989), the maximum rates of rise remain uncertain. The Barbados record contains two rises of >30 m in one thousand years (k.y.) each, but other records indicate that rates may have been even faster. Drilling suitable targets on passive margins should resolve the rates of these millennial-scale changes, both in the Holocene and in the older record.

Amplitudes

Despite ODP's success, the amplitude of sea level change remains one of the thorniest problems in reconstructing past boundary conditions of the Earth. ODP has demonstrated that the 400 m eustatic variations published by Vail et al. (1977) or even the 140+ m variations published by Haq et al. (1997) are excessive. However, even in the Miocene, an interval sudied during six legs, amplitudes remain uncertain, ranging from 20 to 80 m to 85 ± 30 m. Nevertheless, results of drilling for amplitude determination are encouraging, and it is clear that drilling arrays of boreholes on different margins in different settings will allow two- and three-dimensional backstripping that will undoubtedly provide firmer constraints on the amplitudes of eustatic change.

Mechanism

While ODP has confirmed the importance of glacio-eustasy since 42 million years ago (Ma), other mechanisms were undoubtedly operative. For example, intraplane stress has been invoked as a possible mechanism explaining eustatic change (e.g., Cloetingh, 1988). Borehole arrays on margins targeting stratigraphic intervals with large global tectonic events can be used to evaluate this mechanism and other non-glacio-eustatic components. This approach may be particularly important for evaluating eustatic mechanisms for portions of Earth history that were essentially ice-free.

Using ODP drilling, we have pushed back the age of inception of continental glaciation into the Paleogene and possibly the Late Cretaceous. There are intervals such as the mid-Cretaceous through Triassic, for example, that must have been ice-free. Yet, large (>>10 m) and rapid (<< 1 m.y.) changes in sea level occurred during these intervals, not only as suggested by EPR workers (Haq et al., 1987), but also documented by others (e.g., Hallam's (1992) summary). The only known mechanism for causing these changes is glacio-eustasy. Additional potential mechanisms can be evaluated by comparing estimates of Cretaceous-early Eocene sea level variations with near- and far-field tectonic events, global $\delta^{18}O$ records, and other possible causal events (e.g., basin dessication, large igneous province formation).

Response

As we increasingly understand eustatic variations, we can begin to understand the interaction of processes that control margin stratal architecture, the geometry of stratal surfaces including sequence boundaries and intra-sequence stratal patterns. Nested acoustic images of continental margins reveal surfaces and seismic facies on various scales that reflect variations in eustasy, tectonics, and sediment supply. These effects can be evaluated by drilling margin sequences in different tectonic and sedimentary settings. The influence of tectonics can be evaluated by comparing the development of coeval sequences on passive margins, translational margins, and foreland basins. Facies models developed by EPR (Posamentier et al., 1988) and others potentially provide a means of predicting the distribution of sediments within sequences and resources such as oil and water. To develop and test predictive facies models, sequences and facies within sequences must be sampled on carbonate, mixed carbonate-siliciclastic, and siliciclastic margins across a wide spectrum of sediment inputs.

SEA LEVEL AND IODP

Ongoing efforts to understand global sea level changes and their effects on the stratigraphic record will require continued innovation and the use of new drilling tools. Despite valiant efforts, the *JOIDES Resolution* and its successor, a dynamically-positioned riserless drillship, will not be suitable platforms for drilling in shallow water and setting long casing strings. Supplementary alternative platforms such as jack-up rigs, semi-submersibles, and anchored geotechnical drillships will provide the right tools. The success of this approach was demonstrated by the Bahamas Drilling Project, an integral component of Leg 166 drilling. As we move into IODP, these supplementary platforms, and other mission-specific platforms for drilling in the Arctic Ocean and other challenging areas, should constitute the third leg of a stool, and complement drilling by the successor to the *JOIDES Resolution* and the riser drillship currently under construction for IODP.

ACKNOWLEDGEMENTS

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> "Oh, I could tell you why the ocean's near the shore,
> And then I'd sit, and think some more"
> *The Scarecrow, The Wizard of Oz (1939)*

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