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16. THE RECORD OF NEOGENE SEA-LEVEL CHANGES IN THE PROGRADING CARBONATES ALONG THE BAHAMAS TRANSECT—LEG 166 SYNTHESIS[1]

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ABSTRACT

The Bahamas Transect was designed to assess the response of the carbonate depositional system to sea-level changes and to evaluate the relationship between the sedimentary and oxygen isotope records of Neogene sea-level changes in order to establish a causal link between glacio-eustasy and the stratigraphic pattern. In addition, the timing of unconformity-bounded sequences and the question of chronostratigraphic significance of seismic sequence boundaries were of special interest.

Cores from seven sites drilled during Leg 166 along the western Great Bahama Bank retrieved the sedimentary record and the timing of high- and low-frequency sea-level changes throughout the Neogene. Facies successions within the cores contain indications of sea-level changes on two different scales.

First, there are high-frequency alternations between meter-thick layers with platform-derived material and thin layers with more pelagic sediments. Carbonate-rich intervals are interpreted to reflect periods of high sea level, whereas the thin intervals correspond to times of increased pelagic and siliciclastic input during sea-level lowstands. The duration of these alternations (20–40 k.y.) correlates with orbitally induced high-frequency climate and sea-level changes.

Second, longer term sea-level changes with a duration of 0.5–2.0 m.y. are also recorded in slope deposits along the Great Bahama Bank. Alternating high (up to 20 cm/k.y.) and low (<2 cm/k.y.) sedimentation rates record a long-term pattern of bank flooding with concomitant shedding to the slope as well as periods of bank exposure with reduced shallow-water carbonate production, upper slope erosion, and largely pelagic sedimentation in the basin. The longer term changes coincide with progradation pulses that are imaged on the seismic data as depositional sequences. The internal facies architecture of these carbonate depositional sequences displays five major elements. In the undathem, or the platform top, the sediments are arranged in shallow-water packages separated by exposure horizons. Thick bulges of the prograding pulses are characterized by fine-grained platform-derived material that accumulates on the upper slope. The middle to lower slope has a variable facies assemblage consisting of periplatform, pelagic, and redeposited carbonates. Small-scale channeling and lobes of turbidites produce irregular depositional surfaces. At the toe-of-slope, redeposited carbonates accumulate during both sea-level highstands and lowstands. These carbonate turbidite series are arranged in mounded lobes with feeder channels. The distal portion of the sequences is dominated by cyclic marl/limestone alternations with few turbidites.

The ages of the 17 observed Neogene seismic sequence boundaries yielded an excellent correlation between sites, documenting the age consistency of the sequence boundaries and chronostratigraphic significance of the seismic reflections. The ages of the sequences along the Bahamas Transect provide a data set that, in conjunction with data sets from other margins, will eventually solve the question about global synchronous longer term sea-level changes.

A comparison between the sedimentary and isotope records reveals a discrepancy in the frequency of sea-level changes. Oxygen isotopes record sea-level changes at an obliquity frequency, whereas resistivity and gamma-ray values record sea-level changes dominated by orbital precession. These precessional cycles are packaged into longer term cycles of eccentricity (100, 400, and 2000 k.y.).

INTRODUCTION

Although sea-level fluctuations are known to have occurred throughout Earth's history, their controls, global synchrony, amplitudes, rates, and effects are still largely unknown. The reason for the uncertainty in assessing each of these parameters is the complex interaction between eustasy, subsidence, and sediment supply. Different methods and approaches have been used to separate each parameter, producing a variety of results that are often controversial (e.g., Miller et al., 1998). Much of the controversy is caused by the conflicting results of the methods used. For example, estimates on the amplitudes of sea-level changes based on the sedimentary record usually yield much higher values than those relying on the stable isotope proxy (Pitman and Golovchenko, 1983; Haq et al., 1987; Miller et al., 1985). There is no doubt that the changing sea level leaves its record in the sedimentary bodies of continental margins. The sequence stratigraphic concept postulates that each global sea-level change creates a characteristic sequence of sediments that can be correlated with sedimentary basins around the world (Vail et al., 1977). In addition, the concept proposes that a predictable facies succession would develop within each sequence. The sequence stratigraphic concept relies on the following assumptions:

1. Stratal surfaces that are imaged by seismic reflections coincide with depositional surfaces and are essentially time lines.
2. Eustasy is the dominant control over sea-level changes, whereas local tectonism is merely amplifying or buffering the global signal.
3. Global sea-level falls are synchronous and produce unconformities that can be correlated worldwide.
4. Facies successions and stratal architecture are controlled by sea level and follow a predictable pattern.

The sequence stratigraphic concept and its facies models have been controversial ever since they were proposed (Pitman and Golovchenko, 1983; Miall, 1986; Summerhayes, 1986; Cloetingh, 1986; Cathles and Hallam, 1991). The controversies surrounding sequence stratigraphy reflect the unresolved problems of the sea-level issue. Two main problems are (1) the difficulty in separating the role of tectonic subsidence from eustasy in creating unconformity bound-

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ed sequences and (2) the difficulty in assessing the synchrony of sea-level changes in different ocean basins. Also, few data sets exist that test the assumptions of the concept. The Ocean Drilling Program (ODP) has set a priority to address such key questions surrounding sea-level changes by using a variety of approaches (COSOD II, 1987; Sea-Level Working Group (SL-WG) Report, 1992). The SL-WG (1992) recommended drilling transects of holes across several continental margins as a potentially best strategy.

ODP Leg 166 is one of these transects. The seven drilling sites of the Bahamas Transect along the western margin of the Great Bahama Bank (Fig. 1) also offered the unique opportunity to apply three independent ways of addressing problems of sea-level changes. First, the modern Great Bahama Bank is a flat-topped platform on a passive continental margin, and its flat top records sea level as a dipstick. Second, cores from the proximal portion of the transect indicate that the prograding sequences record sea-level changes in their facies and stratigraphic architecture (Eberli et al., 1997; in press). Third, the correlative deep-water deposits in the Straits of Florida encode the $\delta^{18}O$ proxy of sea-level changes in their foraminiferal assemblages. The combination of these three methods could potentially evaluate with a much higher confidence the relationships between depositional patterns vs. seismic reflection geometry and the frequency of glacioeustasy as recorded in the oxygen isotope record vs. the cyclo- and sequence stratigraphic depositional units.

The Bahamas Transect was designed to address four main sea-level objectives. The aim of this synthesis chapter is to briefly outline each of these objectives and describe the results that were obtained on board the *JOIDES Resolution* during Leg 166 and the postcruise scientific research related to Leg 166. The drilling along the Bahamas Transect has generated a wealth of data regarding the sedimentary record of carbonates with respect to sea-level changes—in particular concerning the question of highstand and lowstand shedding of carbonates. Results from biostratigraphic dating document the chronostratigraphic significance of seismic sequence boundaries, corroborating one of the fundamental assumptions of seismic sequence stratigraphy that stratal surfaces are essentially time synchronous (Vail et al., 1980). Ages of the sequence boundaries in the Bahamas will be compared with those at the New Jersey margin (Miller et al., 1996) and the global sea-level chart (Haq et al., 1987). An interesting discrepancy in the frequency of high-frequency sea-level changes between the sedimentary record and the oxygen isotope record will be discussed.

The amplitude of sea-level change in the Neogene is not considered here. The Leg 166 transect sites are all in deep water and thus are not suitable for such an analysis.

OBJECTIVE 1: TIMING OF SEQUENCE BOUNDARIES AND RELATIVE SEA-LEVEL CHANGES

Chronostratigraphic Significance of Seismic Reflections

One of the main assumptions of seismic sequence stratigraphy is that seismic reflections follow depositional surfaces. As such they are essentially time lines, and have chronostratigraphic significance (Vail et al., 1977). High-resolution seismic data from the Equatorial Pacific were some of the first data sets in the public domain to corroborate this assumption (Mayer, 1979a, 1979b; Mayer et al., 1986). However, several studies of seismic modeling show that under certain circumstances these preconditions might sometimes be violated (Rudolph et al., 1989; Schlager and Stafleu, 1993; Stafleu et al., 1994; Anselmetti et al., 1997). A good seismic data set and good core coverage along seismic lines are needed to evaluate the time consistency of seismic reflections. Very few data sets fulfill these criteria. The high-resolution seismic Line 106 along the Bahamas Transect and the five continuously cored drill holes of Leg 166 in combination with the precise time-to-depth conversion from the check-shot survey provide such a data set. Dating of the seismic reflections allows for a test of chronostratigraphic significance of the seismic reflections and,

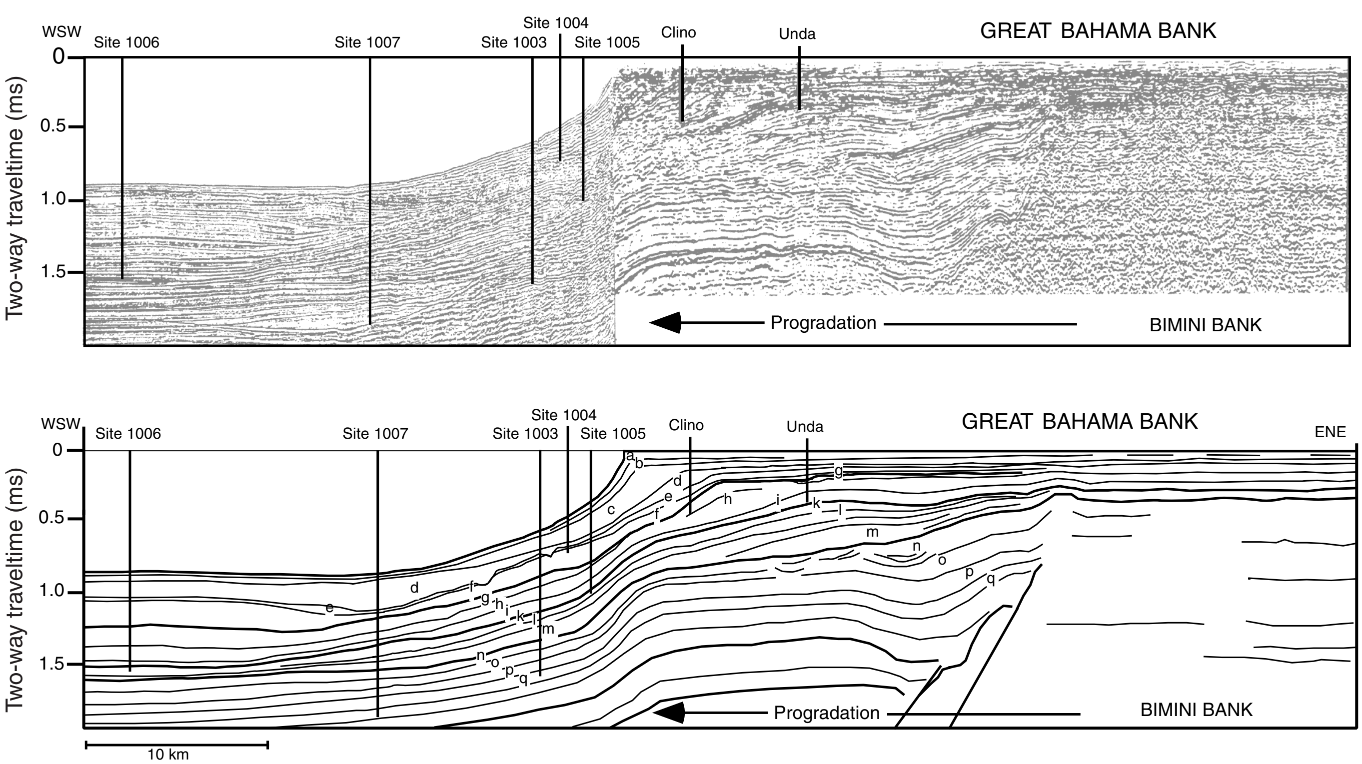

Figure 1. Location of five Leg 166 sites and the drill holes Unda and Clino along the Bahamas Transect on the seismic line and a schematic line drawing of interpreted seismic sequences.

thus, the seismic sequence stratigraphic concept for the investigated carbonate platform margin setting.

The ages of the drilled cores of Leg 166 were determined by the shipboard party (Eberli, Swart, Malone, et al., 1997) using calcareous nannofossils and planktonic foraminifers. Postcruise work refined these ages. For every site across the entire transect, the average maximum age offset of all seismic sequence boundaries amounts to 0.32 Ma (Table 1; Anselmetti et al., in press) and thus lies within the combined range of seismic and biostratigraphic resolution. It is remarkable that all Neogene seismic horizons can be traced from the middle of the Straits of Florida up to the Great Bahama Bank with high chronostratigraphic accuracy, thus confirming the concept that seismic reflections represent time lines. Consequently, even the drift deposits maintain their biostratigraphic integrity although ocean currents transported the sediment to the drift. The seismic reflections thus correlate across the depositional facies transitions and boundaries without changing their chronostratigraphic positions.

Comparison to the Global Sea-Level Curve

The well-defined ages of the sequence boundaries along the Bahamas Transect (Table 1) can be compared to the eustatic sea-level curve of Haq et al. (1987) (Fig. 2). The eustatic curve has been adjusted to the Berggren et al. (1995) time scale to allow a comparison to the ages of the sequence boundaries along the Bahamas Transect that were also dated with the Berggren et al. (1995) time scale. Approximately two-thirds of the ages of sequence boundaries coincide well with proposed sea-level falls on the eustatic sea-level curve. Because local tectonics and sediment supply influence the position and resolution of sea-level falls, this correlation is remarkably high. Most of the known major sea-level falls in the Neogene are recorded in the strata along the Bahamas Transect. Examples include the sea-level fall in the earliest Miocene, the first two falls in the middle Miocene, the fall at the Miocene/Pliocene boundary, and most of the Pliocene–Pleistocene major sea-level falls (Fig. 2). There are also, however, some notable differences. Sequence Boundary O is a well-expressed boundary positioned on an overall sea-level rise on the Haq et al. (1987) curve (Fig. 2). This sea-level rise, 18 m.y. ago, has been recognized in the South Atlantic (Abreu and Anderson, 1998) and along the New Jersey margin (Miller et al., 1998). Other sequence boundary ages differ only slightly from the proposed eustatic lows. Most of these shifts are toward younger ages and fall within early rises of the eustatic curve. At this point, it is not possible to evaluate whether the ages on the eustatic curve need to be adjusted or if the ages along the Bahamas Transect are shifted because of local causes. At any rate, the precise dating along the Bahamas Transect has produced an important data set to assess global synchrony of third-order sea-level changes. Other excellent data sets such as the New Jersey margin transect are needed to complete this task.

OBJECTIVE 2: STRATIGRAPHIC RESPONSE OF CARBONATES TO SEA-LEVEL CHANGES

In the icehouse world of the Neogene, waxing and waning of polar ice sheets have caused numerous high-amplitude sea-level changes. The $\delta^{18}O$ content of planktonic and benthic foraminifers has been shown to be an excellent proxy record for sea-level changes that are related to orbitally controlled climate cycles (e.g., Hays et al., 1976; Miller et al., 1987, 1991; Tiedemann et al., 1994). Carbonates can be an equally good recorder of high-frequency sea-level changes. Facies analysis enables water-depth estimates, usually to within 10 m. This helps determine paleobathymetry and, thus, amplitude of relative sea-level changes (Kendall and Schlager, 1981; Schlager, 1981). Shallowing-upward cycles in shallow-water carbonates have often been interpreted as the sedimentological record of successive high-frequency sea-level changes (Fischer, 1964; Grotzinger, 1986; Goldhammer et al., 1987; Strasser, 1988). Likewise, marl/limestone alternations have been considered the record of successive high-frequency sea-level changes on the slopes and in the basin surrounding shallow-water platforms (Fischer, 1991; Fischer et al., 1991). This comparison reveals an interesting discrepancy. Spectral analyses of the oxygen isotope data indicate that Earth's obliquity is the major control on glaciation and, therefore, on sea-level changes (Hays et al., 1976; Ruddiman et al., 1986; Raymo et al., 1990). Similar analyses of the sedimentary cycles, however, suggest that precession is the controlling orbital parameter (e.g., Hinnov and Goldhammer, 1991). This discrepancy is also present in the material from Leg 166 that allows a direct comparison of the $\delta^{18}O$ and the sedimentological record.

Table 1. Ages of seismic sequence boundaries calculated using biostratigraphic datums and extrapolated sedimentation rates between datums.

SSB	Site 1006	Site 1007	Site 1003	Site 1004	Site 1005	Estimated age	Maximal offset
A			0.09	0.16	0.1	0.1	0.07
B			0.25	0.73	0.6	0.6	0.5
C	1.8	1.5-1.7	1.2-1.6	1.7	1.6	1.7	0.2
D	3.1	3.2-4.2	3.1	2.6	2.9	3.1	0.6
E	3.6	3.2-4.2	3.8		3.6	3.6	0.2
F	5.4	5.5-6.4	5.6		6.0	5.4	0.6
G	8.7	8.8	6.2-8.7		6.2-8.8	8.7	0.1
H	9.4	9.4	9.0		9.3	9.4	0.4
I	10.7	10.9	10.6		10.2	10.7	0.7
K	12.4	12.2	12.2			12.2	0.2
L	12.7	12.5	12.7			12.7	0.2
M		15.1	13.6-15.1			15.1	0.0
N		16.2-16.4	15.9			15.9	0.3
O		18.2	18.4			18.3	0.2
P		19.4	19.2			19.4	0.2
P2		23.2	19.4-22.5			23.2	0.7
Q		23.7				23.7	—
R							
							Average Δt: 0.32

Notes: SSB = seismic sequence boundary. All ages given in Ma. Ages of the boundaries remain consistent along the transect, indicating the chronostratigraphic significance of seismic reflections.

Sea-level changes of a lower frequency are recorded as unconformity-bounded depositional sequences at the continental margins. The carbonate environment records alterations in climate and relative change in sea level in its own characteristic way, resulting in a system-specific depositional sequence architecture (Sarg, 1988; Eberli and Ginsburg, 1989; Schlager, 1992). Flat-topped carbonate platforms and shelves produce and export more sediment during sea-level highstands. How important the highstand shedding is in controlling sequence architecture has been a matter of debate. In particular, the amount and architecture of carbonate turbidites in such settings has been controversial (e.g., Droxler and Schlager, 1985; Sarg, 1988; Schlager, 1992). The five sites along the Bahamas Transect together with the seismic data have produced a comprehensive data set that gives a better understanding of the sedimentary record of both high- and low-frequency sea-level changes.

High-Frequency Sea-Level Changes

Cores along the Bahamas Transect display the record of high-frequency sea-level changes along the entire depositional profile (Fig. 3). With the completion of the transect, it is now possible to document the lithologic expression of these sea-level changes in the different depositional environments. The precisely dated, continuous, and expanded section at the basinal Site 1006 for the first time provides a direct correlation between (1) the sedimentary record and the oxygen isotope record of high-frequency sea-level changes back to the Miocene and (McKenzie et al., 1999; Kroon et al., Chap. 2, and Rendle et al., Chap. 6, both this volume) (2) the seismic stratigraphic record of lower frequency sea-level changes.

On the banktop, in the cores of Unda and Clino, shallow-water carbonate packages are separated by subaerial exposure horizons

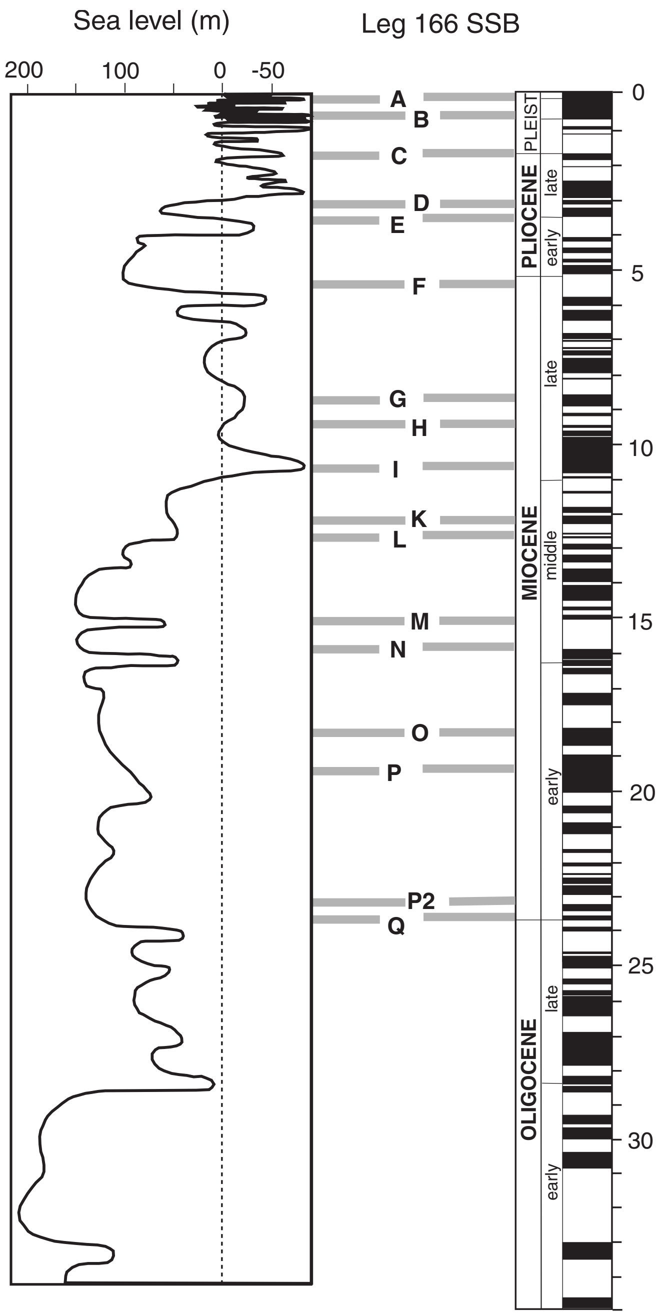

Figure 2. Comparison of ages of seismic sequence boundaries (SSB) on the Great Bahama Bank with the global cycle chart of Haq et al. (1987). The chart is adjusted to the Berggren et al. (1995) time scale. Approximately two-thirds of the sequence boundaries coincide with proposed sea-level lowstands.

(Kievman, 1996, 1998). These individual sediment packages generally do not show a shallowing-upward trend in their facies; instead, exposure is observed on a variety of platform facies. Eight exposure horizons are found in the top section back to the Brunhes/Matuyama boundary at 0.8 Ma, which seems to suggest that during each of the last eight high-amplitude sea-level fluctuations, a sedimentary unit was deposited on the platform top (Kievman, 1998). This finding provides a Quaternary analogue for studies that attribute rhythmic bedding of Mesozoic shallow-water carbonates to sea-level fluctuations in the Milankovitch frequency band (Fischer, 1991).

On the slopes and in the basins surrounding the Great Bahama Bank, aragonite cycles and turbidite composition are equally good indicators of high-frequency sea-level fluctuations (Droxler et al., 1983; Reijmer et al., 1988; Haddad et al., 1993). In particular, aragonite content has been shown to closely monitor orbitally induced climate changes. Some scientists interpret the variations as a result of increased dissolution (Droxler et al., 1983), while others consider these variations a result of fluctuations in neritic input to the off-bank areas during interglacial times (Kier and Pilkey, 1971; Boardman and Neumann, 1984; Reijmer et al., 1988; Milliman et al., 1993). Rendle et al. (Chap. 6, this volume), based on cores retrieved during Leg 166, favor the input interpretation based on the facts that (1) their investigated cores at Sites 1003 and 1006 are from water depths deemed too shallow for aragonite dissolution (658 and 481 m) and (2) banktop-derived aragonite needles are most abundant during the interglacials along the entire transect. The mineralogical assemblage during glacial times (identified by oxygen isotope signals) shows a decreased amount of aragonite of 48% on average, whereas high- and low-magnesium calcite, dolomite, quartz, and insolubles account for the rest of the assemblage (Rendle et al., Chap. 6, this volume). The fact that aragonite does not decrease further indicates that production of neritic components never ceased completely during glacial periods.

The comprehensive data set collected during Leg 166, consisting of high-recovery cores, precisely dated sections, and a continuous suite of logs, helps evaluate these sea-level controlled cycles throughout the Neogene. A typical unlithified cycle (Pleistocene–Pliocene) consists of a unit of aragonite-rich, neritic carbonates followed by an interval of aragonite-poor carbonates rich in pelagic foraminifers, nannofossils, and siliciclastics. Miocene cycles consist of decimeter- to meter-scale alternations between light gray, better cemented limestone and dark gray, less cemented, compacted marl/marlstone (Betzler et al., 1999; Frank and Bernet, in press). The platform-derived sediment in the cycles is interpreted as being produced during the highstand of sea level when the platform was flooded, whereas the increased amount of pelagic and siliciclastic sediments are interpreted as being deposited during sea-level lowstands. With increasing distance from the platform margin, these carbonate cycles evolve into typical marl/limestone alternations (Fig. 3). At the basinal sites of Leg 166 (1006 and 1007), pulses of aragonite-rich neritic sediments are separated by dark clay and quartz-rich layers that contain as much as 80% clay, quartz, organic material, and detrital dolomite in aragonite-poor nannofossil ooze. The highly decreased amounts of neritic material in these layers indicate deposition during times when the carbonate production on the bank was reduced, as during sea-level lowstands. Betzler et al. (1999) propose that the marly portion of the cycles could also form during the transgression and represent a condensed interval. In both interpretations, however, each marl/limestone alternation is believed to have formed during one high-frequency cycle of sea-level fall and rise. The amplitudes of these changes might be relatively small. On a flat-topped platform, a sea-level fall of 5–10 m would be sufficient to significantly reduce the production of neritic components.

The cycles can be recognized in the cores and on logs. In particular, resistivity and gamma logs can record these alternations continuously (Eberli, Swart, Malone, et al., 1997; Isern et al., in press; Williams and Pirmez, 1999; Bernet, 2000). The physical properties of the two intervals are different in the uncemented portions of the cores and alter with ongoing diagenesis (Isern et al., in press; Frank and Bernet, in press; Bernet, 2000). Petrographic and isotopic analyses clearly show that the original composition is controlling the lithification processes and burial diagenesis (Frank and Bernet, in press). The disparity in the diagenetic potential of the different layers (i.e., the neritic- vs. the pelagic-dominated intervals) controls subsequent diagenesis. Therefore, burial diagenesis enhances the initial sedimentary differences but is not responsible for creating marl/limestone alternations. The enhancement by diagenesis also increases the response

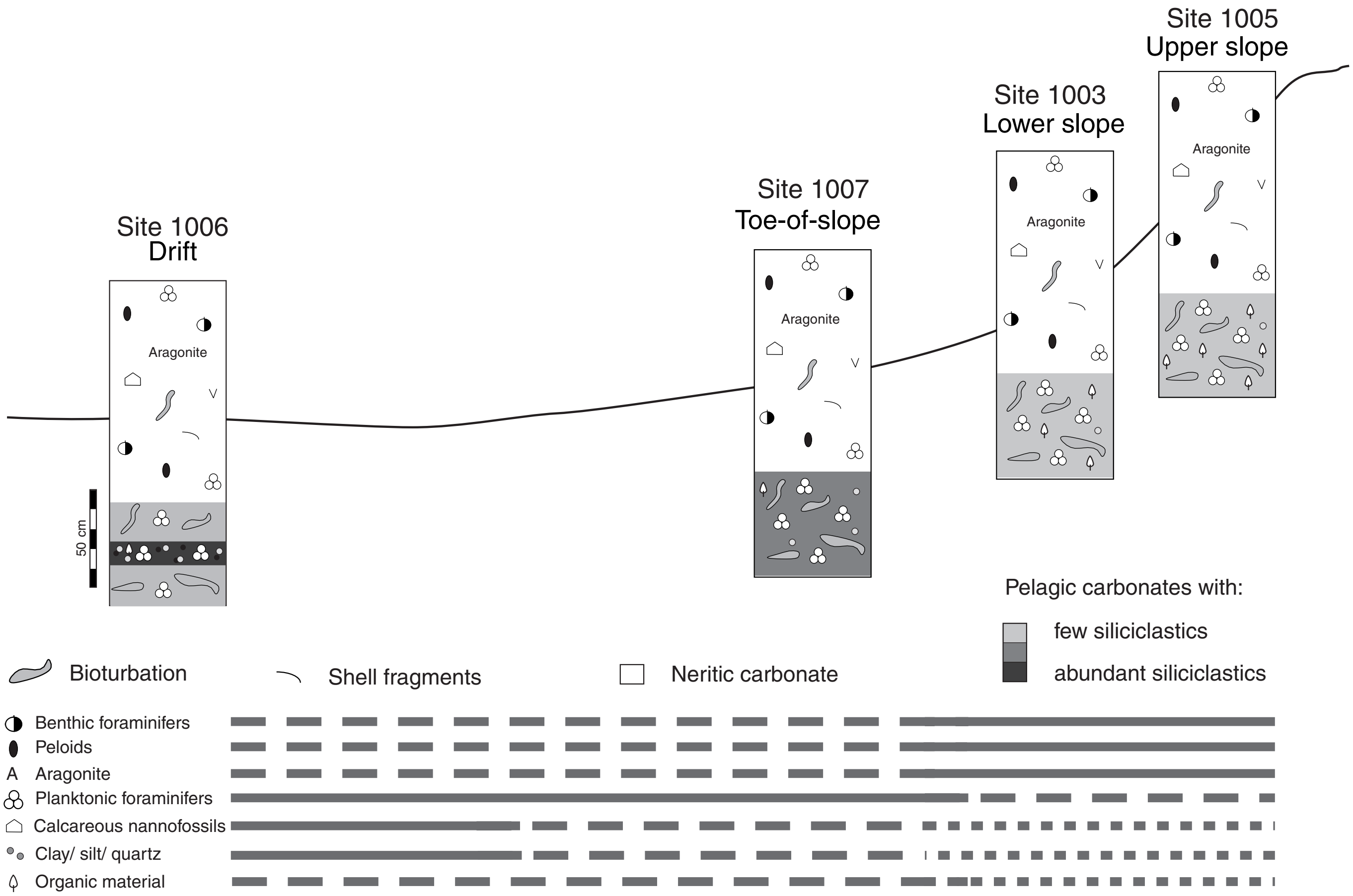

Figure 3. Decimeter- to meter-scale alternations of light-colored ooze/chalk/limestone and dark-colored marl/marlstone along the Bahamas Transect are interpreted as the record of high-frequency sea-level fluctuations. The neritic portion is judged to have been deposited during sea-level highstands, whereas the marls are lowstand and/or transgressive deposits (modified from Bernet, 2000).

in geophysical logs. For example, resistivity values are high in the carbonate-rich portion of the cycle and low in the siliciclastic portion, and gamma-ray signals record the marly intervals (Williams and Pirmez, 1999; Bernet, 2000).

The recognition of these alternations in logs and cores throughout the Neogene has major implications for two reasons. First, it shows that such marl/limestone alternations often found in the ancient rock record may be the result of changes in input of both the carbonates and the siliciclastics that are controlled by climate and sea-level changes (Bernet et al., 1998; Frank and Bernet, in press; Betzler et al., 1999). In addition, the uninterrupted recovery of these alternations from an unlithified to a lithified stage reveal for the first time their diagenetic behavior from early to burial diagenesis with pressure solution (Frank and Bernet, in press). Limestone beds are usually early cemented and little compacted. Their isotopic and petrographic characteristics are interpreted to reflect cement precipitation from cold seawater during the first ~100–200 m of burial. In the adjacent marlstones, diagenesis is inhibited because of higher proportions of insoluble materials, in spite of significant compaction and pressure solution during burial (Frank and Bernet, in press). Aragonite, for example, is still present in Miocene marlstones, whereas the limestones are completely altered to low-Mg calcite (Eberli, Swart, Malone, et al., 1997). This indicates that the diagenesis of the limestones and marlstones is not coeval and that limestones are formed before the marls undergo their alternations. Consequently, it is not likely that the formation of marl/limestone alternations is the result of a process in which carbonate dissolution in the marls would lead to precipitation in the limestones. With these results in hand, there seems to be less room to explain these alternations as produced solely by diagenesis (Ricken, 1986; Bathurst, 1987). Our results instead corroborated the findings of Diester-Haass (1991) that Neogene marl/limestone alternations result from diagenetically altered input variations produced by glacial–interglacial fluctuations in sea level, climate, and ocean circulation.

Second, the continuous record of the logs allows for a frequency analysis of the alternations and a comparison with the isotope record. Spectral analyses of resistivity and gamma-ray data of marl/limestone alternations from the Santaren Channel (Leg 166) show strong power spectra at 23 and 19 k.y. throughout most of the Miocene and Pliocene (Fig. 4; Bernet et al., 1998; Kroon et al., Chap. 15, this volume). This frequency is in concert with orbital precession but is in contrast to the obliquity frequency of glacial cycles recorded by stable isotope data (see below).

Low-Frequency Sea-Level Changes

The recognition that fluctuating sea level divides the strata in genetically related units not only makes sequence stratigraphy a method to date sequence boundaries and global sea-level changes (see above) but also adds a predictive capability to sequence stratigraphy that is lacking in the other stratigraphic methods. By combining depositional models with time, sequence stratigraphy is capable of documenting the dynamics in a depositional system and, therefore, the distribution and architecture of facies belts through time (Vail et al., 1977; Sarg,

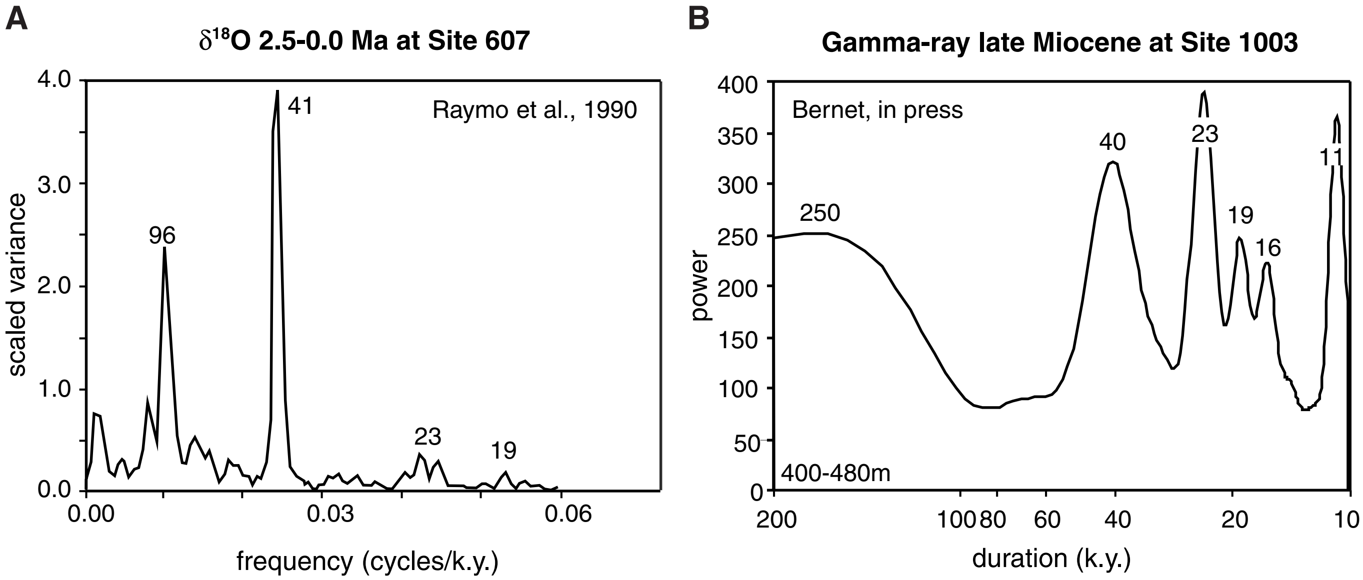

Figure 4. Two spectral analyses using the Blackman-Tukey method. **A.** $\delta^{18}O$ spectrum of Site 607 shows that $\delta^{18}O$ variations indicative for glaciations occur at the primary Milankovitch frequencies. Obliquity, however, is the dominant frequency (Raymo et al., 1990). **B.** Gamma-ray spectrum of Miocene marl/limestone alternations at Site 1003 produces frequencies at 40, 23, 19, 16, and 11 k.y. The strongest peak occurs at 23 k.y., indicating the dominance of orbital precession on these sedimentary cycles (Bernet, 2000). For further discussion, see the text.

1988; Handford and Loucks, 1993). The sequence architecture in each depositional system is controlled by the sea-level change that acts with other variables such as climate, subsidence, and sediment supply. These parameters largely control the depositional character of sedimentary rocks (sediment and facies type, geometry, continuity, etc.) and thus the resulting sequence architecture. Carbonate environments, for example, record changes in climate and relative sea level in a characteristic way, resulting in a system-specific depositional sequence architecture (Sarg, 1988; Eberli and Ginsburg, 1989; Schlager, 1992; Handford and Loucks, 1993). The difference between the carbonate and siliciclastic systems arises because the flat-topped carbonate platforms and shelves can produce and thus export more sediment during sea-level highstands when they are flooded. Export of sediment during sea-level highstands (known as highstand shedding) places the carbonate environment 180° out of phase with the siliciclastic environment where most of the sediment is exported into deeper water during sea-level lowstands (known as lowstand shedding) (Schlager and Chermak, 1979; Mullins, 1983; Droxler and Schlager, 1985).

The degree to which these differences influence the facies distribution in carbonate systems has been a matter of debate (Mullins, 1983; Schlager, 1991). There is general agreement that carbonate depositional sequences, like their siliciclastic counterparts, are unconformity-bounded depositional packages. Indeed, every sequence boundary along the Bahamas Transect was identified by a seismic unconformity at or near the platform margin (Eberli et al., 1997; in press). In the cores of Leg 166, each one of these boundaries coincided with a change in facies in one or more holes (Eberli et al., 1997). The internal sequence architecture is more controversial. Many scientists argue that as a result of highstand shedding, carbonate sequences develop relatively thin sediment packages during sea-level lowstands (lowstand system tracts) with small or nonexisting turbidite fan systems (Schlager, 1991). Others believe that platforms are also eroded and these erosional products would form lowstand turbidite fans (Sarg, 1988; Jacquin et al., 1991).

The Bahamas Transect was designed to document the facies variations related to sea-level oscillations from shallow water to a water depth of ~600 m. This range allows a full assessment of the sedimentary response of carbonates to sea-level changes and, in particular, an assessment of the amount of highstand vs. lowstand shedding. Core data and seismic analyses now document a much more complicated picture than previously expected (Betzler et al., 1999; Bernet et al., Chap. 5, this volume). The distribution of turbidites within sedimentary sequences varies strongly. Generally, turbidites are clustered at the upper and/or lower portions of the sequences, indicating deposition of carbonate turbidites during both the highstand and lowstand of sea level and a suppression of turbidite sedimentation during transgressions. To complicate matters, highstand and lowstand turbidites seem to be deposited at different locations on the slope. Fifty percent more highstand turbidites (309 vs. 209) were deposited at the lower slope (Site 1003) than at the toe-of-slope (Site 1007), but twice as many lowstand turbidites were deposited at the toe-of-slope than at the lower slope (Bernet et al., Chap. 5, this volume). In addition, depocenters change from a lower slope position in the early and middle Miocene to a toe-of-slope position in the late Miocene and early Pliocene, probably as a result of the change in slope geometry from concave to more convex (Betzler et al., 1999).

Highstand and lowstand turbidites can be distinguished by slight differences in composition. In general, highstand turbidites contain abundant shallow-water allochems such as green algae, red algae, shallow-water benthic foraminifers (miliolids), and intraclasts. In lowstand turbidites, shallow-water allochems are often negligible but consist mostly of planktonic foraminifers and micrite. These compositional differences are similar to the well-documented Quaternary turbidites along the steep-sided Great Bahama Bank. Throughout most of the Neogene, however, the Great Bahama Bank had more of a ramplike geometry. This morphology resulted in reduced production of shallow-water sediment but not a complete shut-off. It also explains the abundance of lowstand turbidites in the older sequences (Fig. 5). Betzler et al. (1999) propose the following model for calciturbidite deposition during a third-order sea-level fluctuation. The lowering of sea level produces redeposition along the distally steepened ramp of the Great Bahama Bank. With progressive flooding, turbidite shedding is suppressed or reduced. During sea-level highstand, decreased accommodation space on the bank results in increased off-bank transport and renewed turbidite deposition.

Figure 5 shows the distribution of highstand sediments along the Bahamas transect. The lowstand and transgressive portion of the seis-

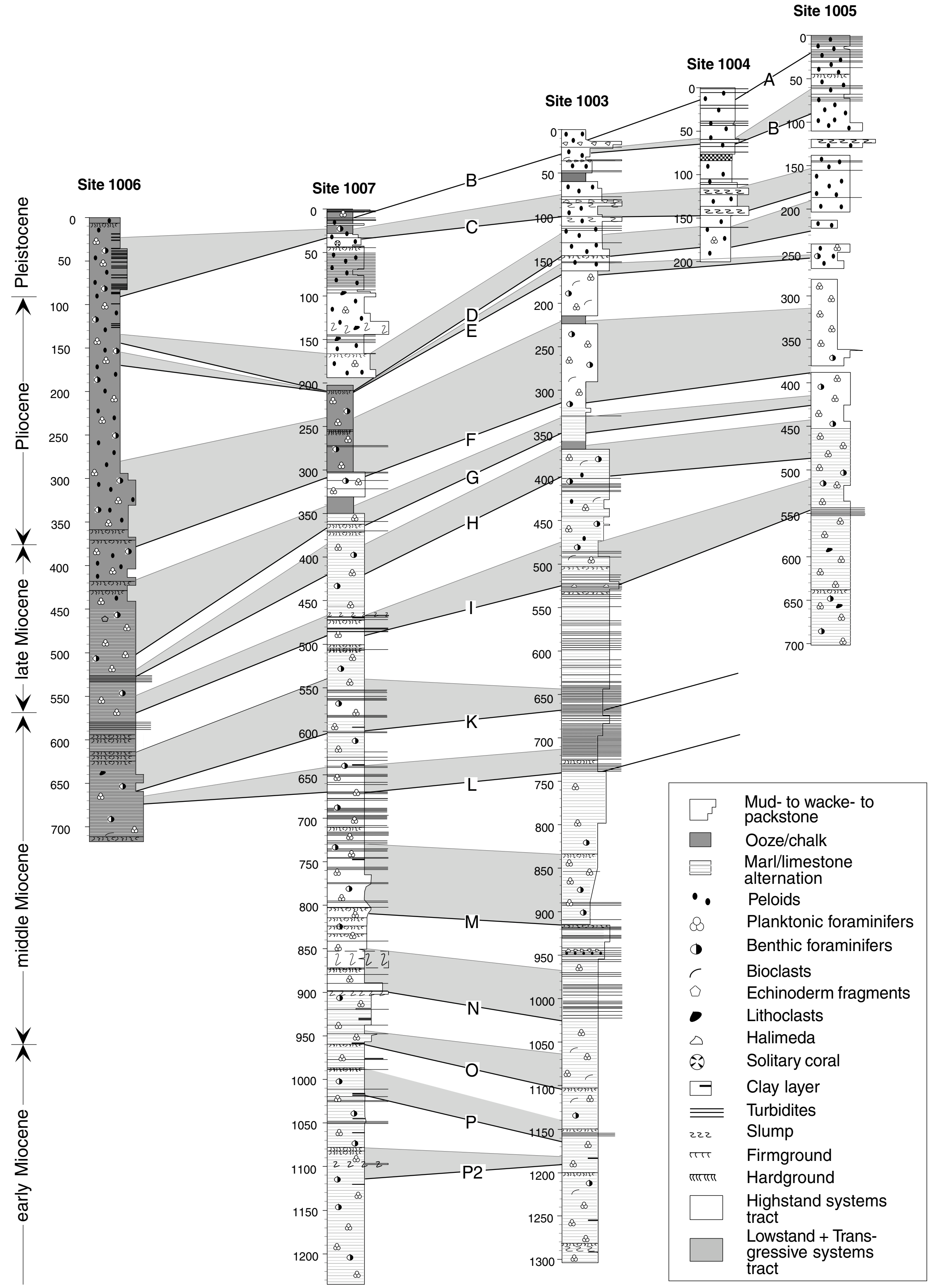

Figure 5. Comparison of thickness of the highstand deposits along the Bahamas Transect with sediments of the lowstand and transgressive intervals, which are treated as one unit (shaded areas). The youngest sequences deposited during times of a steep-sided platform have a thick highstand interval; in older sequences, lowstand and transgressive portions reach considerable thicknesses. A–P2 are sequence boundaries (modified from Bernet, 2000).

mic sequences are grouped together into one unit (Bernet, 2000). The separation of highstand into lowstand/transgressive systems tracts is based on mineralogical criteria and gamma-ray peaks. The onset of increased aragonite and/or high-Mg calcite is taken as an indicator of the onset of platform top production (i.e., as a sea-level highstand). A gamma peak often coincides with this mineralogical transition, and this criterion is used in the older strata to separate the highstand systems tract from the lowstand and transgressive systems tracts, which are not separable in most sequences (Bernet, 2000). Using these criteria, the highstand portion of the sequences is approximately half of the volume of the sequences except in the youngest sequences, where it is significantly thicker. The thickening of the highstand systems tract is probably related to the transformation of the bank morphology from a steepened ramp into a steep-sided platform.

Calibration of cores along the complete transect makes it possible to define the facies from the proximal to the distal portion of the seismic sequences along the Bahamas Transect. The internal facies architecture of these carbonate depositional sequences displays five major elements (Fig. 6). In the undathem, or the platform top, the sediments are arranged in shallow-water packages separated by exposure horizons (Kievman, 1996; 1998). Very few of these packages display a shallowing-upward succession, although most of them are capped by an exposure horizon (Kievman, 1996). The uppermost slope at borehole Clino is characterized by thick sections of fine-grained, platform-derived material. Hardgrounds and firmgrounds associated with thin intervals of coarser grained skeletal packstone to grainstone indicate changes of sedimentation rates and sequence boundaries in this environment (Eberli et al., 1997; Kenter et al., in press). At Site 1005, the most proximal site drilled on the upper slope during Leg 166, a similar sedimentary succession consists of unlithified to partially lithified wackestones and slightly coarser grained intervals composed of packstones and grainstones. Compositional variations document an alternating pattern of bank flooding, concomitant shedding to the slope with periods of exposed banks, a shutdown of shallow-water carbonate production, and largely pelagic sedimentation (Eberli, Swart, Malone, et al., 1997). These pulses of sedimentation produce the prograding clinoforms seen on seismic data (Fig. 1). Few mass gravity flows are deposited at the proximal sites. Most of the platform-derived turbidites bypassed the upper slope. In this upper slope setting, incisions are common. They form a series of canyons perpendicular to the platform edge (Fig. 7A; Anselmetti et al., in press). Major incisions mark several seismic sequence boundaries; for example, at the Miocene/Pliocene and the early/late Pliocene boundaries (Fig. 7A).

On the middle to lower slope (Site 1003), sedimentation is more variable. Sedimentary units consist of either fine-grained, more neritic sediments; pelagic deposits; or turbidite successions. Channels and incisions are more abundant but of smaller dimension. The variability in facies and small-scale channeling is reflected in the seismic facies that shows a characteristic, discontinuous seismic reflection pattern (Fig. 7B; Anselmetti et al., in press). Seismic sequence boundaries correlate with breaks in the pulses of progradation.

The toe-of-slope (Site 1007) is the main depositional location for redeposited carbonates that accumulate during both sea-level highstands and lowstands (Bernet et al., Chap. 5, this volume; Betzler et al., 1999). The turbidite lenses are discontinuous within the marl/limestone alternations that form the background sedimentation. Seismic data that were calibrated with the core data reveal that the turbidite lenses are arranged in mounded lobes that partly coalesce (Betzler et al., 1999; Anselmetti et al., in press). Internal geometry of some of the lobes can be interpreted as a feeder channel. Canyon incisions on the upper and middle slope could act as a point source for some of these channels (Fig. 7A).

The distal portion of the sequences is dominated by cyclic marl/limestone alternations with few turbidites. In addition, drift deposits dominate the basinal sediments from the late middle Miocene onward (12.4 Ma) at the Bahamas Transect.

OBJECTIVE 3: THE LOW-LATITUDE ISOTOPE RECORD OF NEOGENE SEA-LEVEL CHANGES AND ITS RELATION TO THE SEDIMENTARY RECORD

Before the Pleistocene, climatic rhythms producing Northern Hemisphere glaciations were dominated by a 41-k.y. frequency (Fig. 4A; Ruddiman et al., 1986, Raymo et al., 1990). Whole-core magnetic susceptibility data, however, reveal that in the Indian Ocean, Pliocene climate variability before 2.5 Ma responded to precessional changes in insolation with periodicities of 23 and 19 k.y. (Bloemendal and deMenocal, 1989). Sediments and isotope data from the low-latitude Bahamas (Leg 166) indicate a similar discrepancy between the sedimentary and the isotope records. Oxygen isotopes record sea-level changes at an obliquity frequency, whereas resistivity and gamma-ray values record sea-level changes dominated by orbital precession (Fig. 4).

Spectral analysis of resistivity and gamma-ray data of marl/limestone alternations from the Santaren Channel (Leg 166) show that the sedimentary rhythm of marl/limestone alternations is in concert with orbital precession, indicating sea-level changes of this frequency (Fig. 4). In contrast, the frequency spectrum of oxygen isotope data from planktonic foraminifers from the same core clearly displays a dominant obliquity frequency (Fig. 4A; Ruddiman and McIntyre, 1984; Raymo et al., 1990). We speculate that both frequencies of sea level existed throughout most of the Neogene.

However, there is also a strong peak in the power spectrum at 11 ka. For example, in the late Miocene section at Site 1003 (Fig. 4), Kroon et al. (Chap. 15, this volume) report two resistivity log peaks within each precessional cycle in Unit 2 (3.6 to 4.6 Ma) at Site 1006, indicating an 11-k.y. duration of each cycle. Counting the middle Miocene cycles from 738 to 915 meters below seafloor at Site 1003 also rendered 11 k.y. duration (Bernet, 2000). Sedimentary cycles of 11 k.y. duration are known from the continental tropics and are attributed to climate changes within the precessional orbital cycle (Olson, 1990; Short et al., 1991). If the marl/limestone alternations were indeed the result of fluctuating sea level, it would imply that these climate changes produced high-frequency, low-amplitude (5–10 m) sea-level changes. The precessional signal is also present in the frequency spectrum from oxygen isotopes of Site 1006 (J. Wright, pers. comm., 1999) and as a minor peak in many oxygen isotope spectra (e.g., Raymo et al., 1990). The Earth's precession could theoretically lead to an alternating intensification of glacial buildup on the North and South Poles, causing small-scale sea-level changes with an 11-k.y. cyclicity. However, this cyclicity has not yet been detected in the oxygen isotope record of the Bahamas Transect.

Sea-level changes can be orbitally induced and created by changes in the ice volume at the poles. Oxygen isotopes indicate that obliquity forces created the largest changes in ice volume. However, smaller scale changes might occur and be recorded in shallow-water carbonates in the tropical realm. The shallow-water carbonates are sensitive indicators capable of recording sea-level changes of a few meters. Such changes require only a small amount of ice volume modification that might be undetected in oxygen isotope values of pelagic sediments because of low sedimentation rates. Where sedimentation rates are high, oxygen isotopes from the sediment drift in the Santaren Channel do indeed display precessional and obliquity periodicity in the frequency spectrum. Sea-level changes of precessional frequency probably transpire for most of the Neogene and dominate the sedimentary record in low latitudes. This result also explains the dominance of precession found in ancient shallow-water carbonate cycles. Site 1006, the most distal site of the transect, is positioned on a thick sediment drift (Fig. 1). These drift deposits provide a continuous and expanded section for most of the Neogene section. Fine biostratigraphy, the basis for a biocyclostratigraphy, has been established at this site (Eberli, Swart, Malone, et al., 1997; Wright and Kroon, Chap. 1,

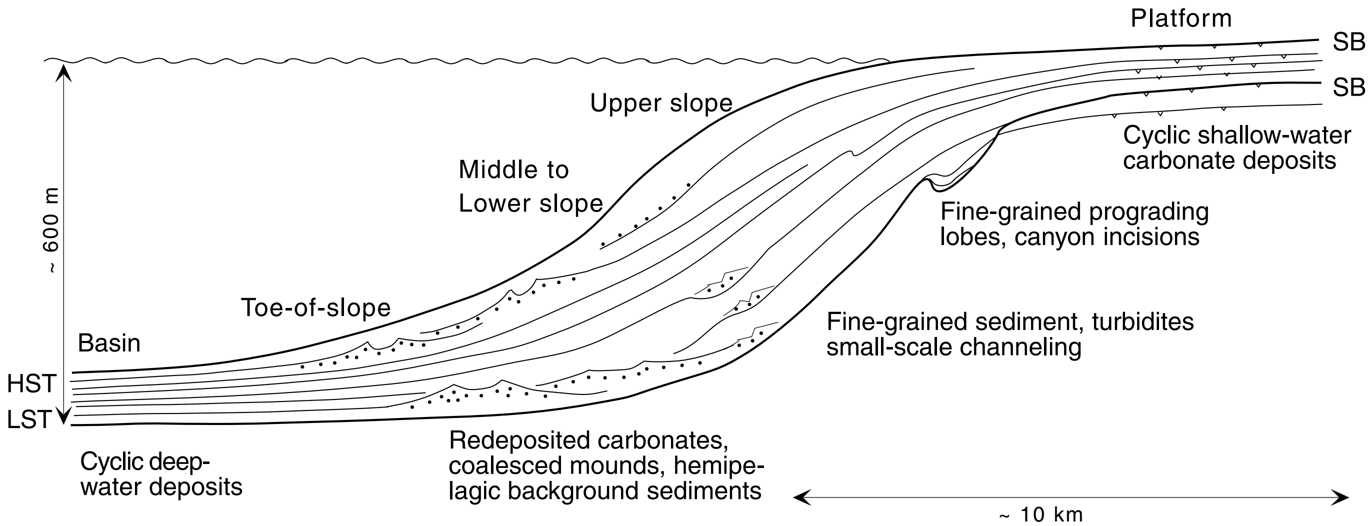

Figure 6. Schematic diagram of facies within a prograding sequence along the Great Bahama Bank. Five major depositional environments are recognized: (1) the platform top, composed of shallow-water carbonates separated by exposure horizons; (2) the upper slope, with thick bulges of fine-grained platform-derived material and channel incisions; (3) the middle to lower slope, with variable facies assemblages of peri-platform material, pelagic ooze, and redeposited carbonates with channels and lobes; (4) the toe-of-slope, the main depocenter for redeposited carbonate that accumulates in mounded lobes within marl/limestone alternations as background sediment; and (5) the distal portion of the sequences, dominated by cyclic marl/limestone alternations with few turbidites. SB = sequence boundary, HST = highstand systems tract, LST = lowstand systems tract.

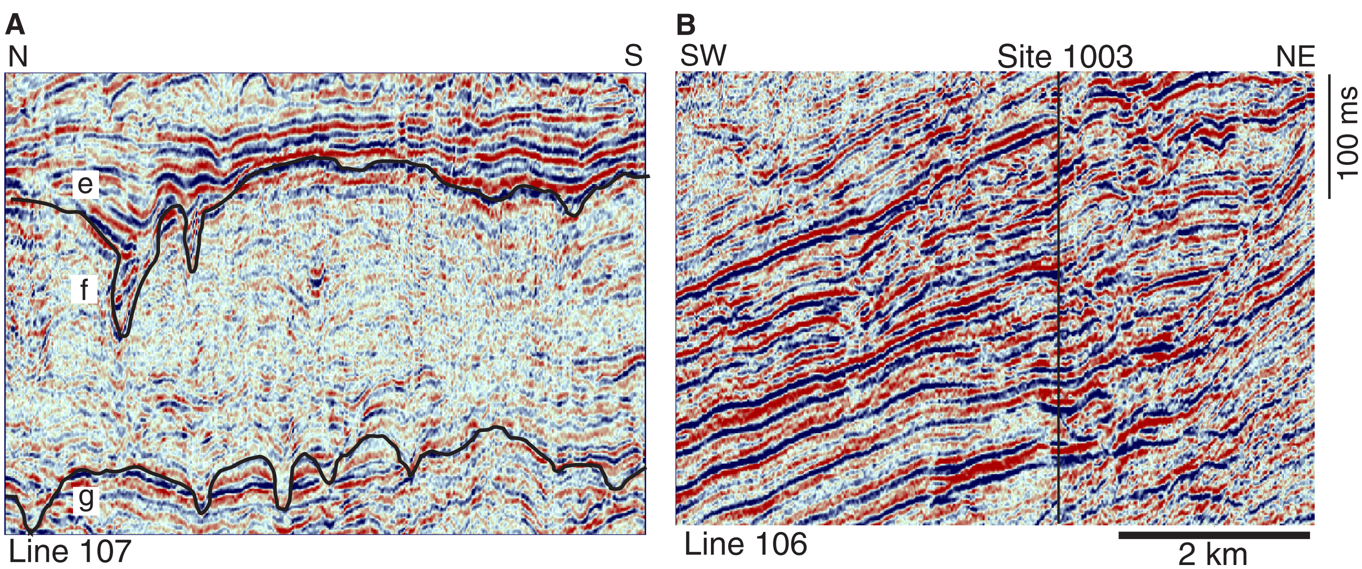

Figure 7. Seismic facies of the upper slope and middle to lower slope environment. **A.** Line 107 is a strike line parallel to the platform margin at the upper slope. The fine-grained platform-derived slope deposits form a nearly transparent seismic facies. Channel incisions of as much as 150 m punctuate this facies. Major incisions appear at the early/late Pliocene boundary (e/f) and the Miocene/Pliocene boundary (f/g). **B.** Line 106 is a dip line across Site 1003, displaying the discontinuous seismic facies of the middle to lower slope as a result of a high variability in facies and small-scale channeling (modified from Anselmetti et al., in press).

and Kroon et al., Chap. 15, both this volume). As mentioned above, the sedimentation in this drift on the slope of Great Bahama Bank is controlled by the precessional beat for most of the Neogene. Counting these cycles produces an accurate time scale and, thus, a sedimentation rate time scale (Kroon et al., Chap. 15, this volume). Spectral analysis of these sedimentation rates indicates a bundling of the precessional beats into longer term eccentricity cycles. The short-term eccentricity (~120 k.y.) and the long-term cycles of eccentricity (400 k.y.) are pervasive in the Miocene, but even the long-term 2-Ma eccentricity cycle is present (Kroon et al., Chap. 15, this volume). If these sedimentation rates are caused by changing sea level, this would be the first time that a mechanism could be documented by which the high-frequency cycles bundle into lower order (third-order) sea-level changes. Future work on stable isotopes will elucidate this process.

CONCLUSIONS

The drilling, coring, and logging of Leg 166 sites along the Bahamas Transect added important board data to the seismic images of the margin architecture and the two core borings on the platform top. The scientific results show the strength of the transect approach for addressing sea-level objectives, especially when the distal site can provide a link to the stable isotope proxy of sea-level changes. This approach has resulted in the following major results regarding sea-level changes in the Neogene:

1. The chronostratigraphic significance of seismic reflection is documented with unprecedented precision. This precision is achieved by using a check-shot survey at each site for an exact core-seismic correlation.
2. The facies succession in cores corroborate that the observed seismic sequences are the result of long-term sea-level changes.
3. Carbonate platforms shed turbidites during both lowstands and highstands of sea level, whereas transgressions produce a lull in shedding. For most of the Neogene, the ratio between highstand vs. lowstand turbidites is smaller than in the Quaternary. The increase of lowstand turbidites compared to the Quaternary (Schlager and Chermak, 1979; Droxler and Schlager, 1985) is related to the change in platform morphology from a steepened ramp to a steep-sided platform.
4. High-frequency sea-level changes are recorded in the sediments along the entire transect. On the platform top, these changes are expressed in shallow-water packages capped by exposure horizons. In the basin, they are seen as marl/limestone alternations.
5. Orbital precession is the dominant beat for high-frequency sea-level changes on the Great Bahama Bank throughout the Neogene. This finding is at odds with the stable isotope proxy that recognizes orbital obliquity as the dominant force.
6. Bundling of the precessional cycles into cycles of orbital eccentricity emerges as a mechanism to package the high-frequency cycles into the lower order, seismically imaged sequence.
7. The precisely dated sequence boundaries will be an important data set to assess global synchrony of long-term sea-level changes in the Neogene. Additional transects from other ocean basins, however, are needed to complete this task.

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