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Bahamian carbonate platform development in response to sea-level changes and the closure of the Isthmus of Panama

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Abstract In this paper we show that the development of the sediment architecture at the leeward toe-of-slope of Great Bahama Bank (Ocean Drilling Project Leg 166, Bahama Transect) during the last 6 Ma is not only a response to sea-level fluctuations, but also to major paleo-oceanographic and climatic changes. A major sequence boundary close to the Miocene/Pliocene boundary (dated at 5.6–5.4 Ma) is interpreted to reflect a major sea-level drop that was followed by a sea-level rise, which led to the re-flooding of the Mediterranean Sea at the end of the Messinian and increasing sea-surface temperatures at Great Bahama Bank. Distinct erosional horizons occurred during the Pliocene (dated at 4.6 and 3.3–3.6 Ma) related to sea-level change and the intensification of the Gulf Stream when the emergence of the Isthmus of Panama reached a critical threshold. The Gulf Stream brings warm, saline and nutrient-poor waters to the Bahamas. Starting at the Early–Late Pliocene boundary at 3.6 Ma this paleo-oceanographic reorganization in combination with enhanced sea-level fluctuations associated with the Late Pliocene main intensification in Northern Hemisphere Glaciation (since 3.2 Ma) led to (1) a gradual change from a ramp-type to a flat-topped type morphology, and (2) a change from a skeletal to a non-skeletal-dominated sedimentary system (mainly peloidal). Increased sea-level fluctuations during the second half of the Pleistocene led to an intensified high stand-shedding depositional pattern within the surrounding basins.

Keywords Bahamas · Carbonate platform evolution · Paleo-oceanography · Miocene–Holocene · Sequence stratigraphy

Introduction

Extensive coral reefs grow in the warm pool of the tropical oceans (West Pacific, Western Atlantic, Indian Ocean). In the tropical oceans, the trade winds, which are diverted by the Coriolis force, blow from east to west. As a result, nutrient-poor, warm surface waters pile up at the western boundary of the continents, which leads to a deepening of the thermocline and reduced mixing with deeper water from below. Therefore, the geographical distribution of land and ocean will have severe consequences on coral reef growth and platform development. In the present-day Atlantic, warm surface waters from the equatorial region are driven into the Caribbean, where they warm up, become more saline, and eventually flow north in the Gulf Stream, which forms the Western Boundary Current of the subtropical North Atlantic Gyre. This, in turn, drives the thermohaline circulation (warm water cools and sinks in the Arctic Ocean).

During the last years, our knowledge of how the carbonate platform of Great Bahama Bank (GBB) responded to sea-level changes was expanded from the Quaternary time slice (e.g., Beach and Ginsburg 1980; Schlager and Ginsburg 1981; Mullins et al. 1984; Droxler and Schlager 1985; Droxler et al. 1988; Reijmer et al. 1988; McNeill 1989) to the entire Neogene based on the Ocean Drilling Project Leg 166 and the Great Bahama Bank Drilling Project results (Eberli et al. 1994, 1997a, 1997b; Betzler et al. 1999). Relying on core, log, and seismic data, it was shown that the sedimentary succession of the bank is subdivided by sequence boundaries generated

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during sea-level lowstands (Eberli and Ginsburg 1987, 1989). During sea-level highstands, GBB exported sediment, which was produced in the bank-interior, towards the platform flank. There are, however, sedimentary changes in the sedimentary evolution of GBB that are not only controlled by sea-level fluctuations. These changes, such as a Pliocene geometric turnover from a distally steepened ramp to a flat-topped platform (Eberli and Ginsburg 1987, 1989; McNeill 1989; Betzler et al. 1999), or a Pliocene change from skeletal-dominated to muddy, peloid-rich deposits (Reijmer et al. 1992; Westphal et al. 1999; Kenter et al. 2001), indicate profound re-organization of the shallow water carbonate factory. The way in which carbonate is produced in the shallow water carbonate factory relies on the ambient water-mass properties (e.g., Schlager 1992). The water-mass distribution in the area of GBB is controlled by the Gulf Stream, which, at present, bathes the Bahamas in warm and saline surface waters from the Caribbean. The Gulf Stream evolved stepwise from a precursor current system during the Neogene (Raymo et al. 1992, 1996; Haug and Tiedemann 1998) with the main controlling factor of this development being the closure of the Panama Isthmus (Keigwin 1982; Haug and Tiedemann 1998). Before the closure of the Isthmus of Panama, much of the warm waters from the Caribbean must have entered the Pacific Ocean because the trade winds would drive them there.

We show, how this paleo-oceanographic reorganization affected the evolution of the sediment deposition in the vicinity of GBB in addition to sea-level changes.

Database

ODP Leg 166 drilled seven sites at the margin of Great Bahama Bank and in the Straits of Florida (Fig. 1; Eberli et al. 1997b), in addition to two boreholes in the bank-interior (Clino and Unda; Eberli et al. 1997a; Fig. 1). The sedimentological interpretation given in this paper relies on core description (Eberli et al. 1997b) and on seismic interpretation (Betzler et al. 1999; Anselmetti et al. 2000).

Planktonic foraminiferal and nannofossil biostratigraphic events were used for dating the sediments (Arai and Sato 2000; Kroon et al. 2000a, 2000b; Wright and Kroon 2000).

Results and discussion

Since the late Miocene, a series of events mark the sedimentary and seismic records of the Bahamian carbonate platform, and these are shown in Figs. 2, 3 and 4.

Miocene/Pliocene boundary; SSB-F (5.4–5.6 Ma)

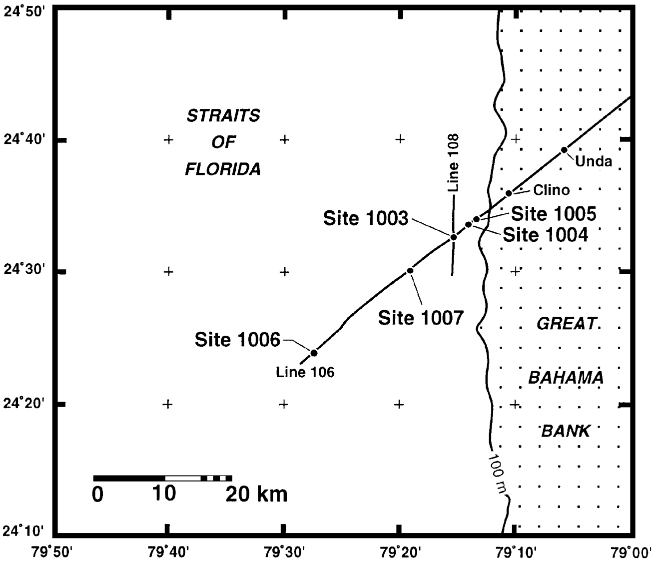
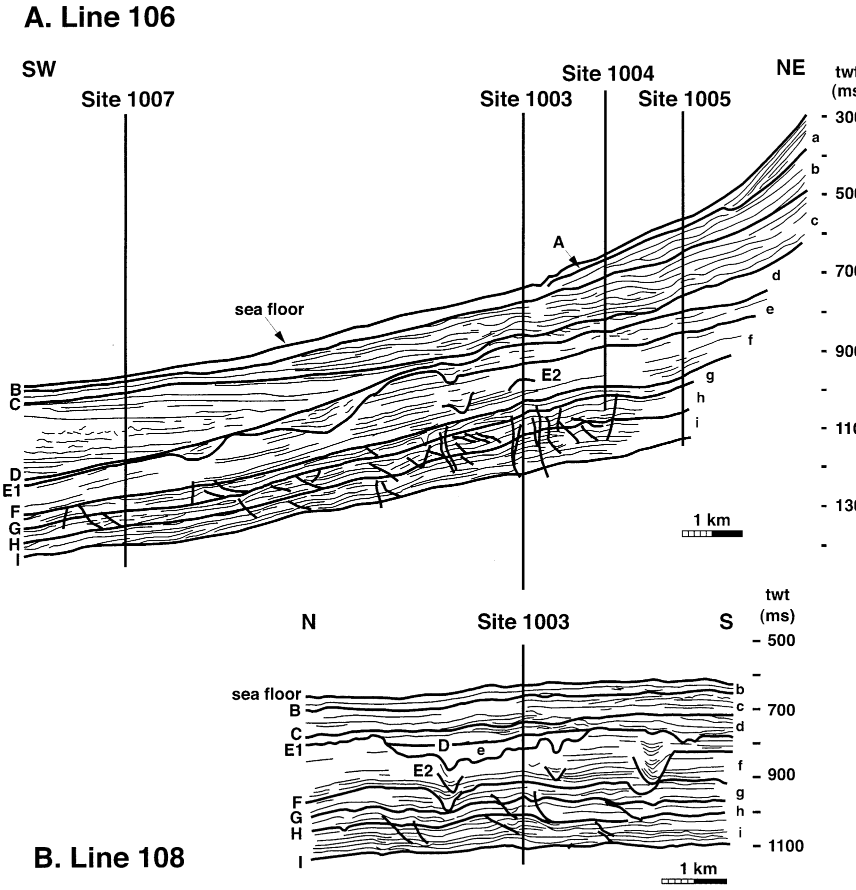


Fig. 1 Map showing position of boreholes from ODP Leg 166, the Bahama Drilling Project as well as seismic lines 106 and 108 used in this study (modified from Eberli et al. 1997b)

The switch from a relative smooth ramp type of depositional environment to an incised slope combined with a different type of sedimentation pattern marks the end of the Miocene. The large-scale sedimentation pattern along the Bahamian transect shows a major eastward back-stepping of the shallow-water platform and reflects a sea-level rise following a sea-level fall at the end of the Miocene, which resulted in major progradation of the western margin of Great Bahama Bank in the Pliocene (Eberli et al. 1997b). A clear seismic sequence boundary (SSB) marks the sea-level fall and subsequent rise (Eberli et al. 1997b). The age of this SSB-F (Fig. 2) varies from 5.6 Ma at Site 1005, to 5.4 Ma at Site 1007 (Eberli et al. 1997b; Eberli 2000). The geometry of SSB-F is characterized by a gullied slope, which originated during a sea-level lowstand (Fig. 2B; Betzler et al. 1999; Anselmetti et al. 2000). Strong independent evidence for this is provided by a Pacific benthic oxygen isotope record, which is indicative of changes in global ice volume (sea level) and deep-water temperature (site 846, Shackleton et al. 1995). A long-term decrease in oxygen isotope values suggests a sea-level rise of 5.7–5.5 Ma assuming that the temperature of the deep Pacific Ocean remained nearly constant during this time. Moreover, the eustatic sea-level curves of Haq et al. (1987) and Eberli and Ginsburg (1989) also point to a significant sea-level rise during this time. This sea-level rise marks the end of the Messinian and, possibly, led to a first reflooding at 5.5 Ma and final inundation of the Mediterranean Sea at 5.33 Ma, as discussed in Shackleton et al. (1995), McKenzie et al. (1999), and Hodell et al. (2001; Fig. 4).

The Miocene–Pliocene transition at Sites 1005, 1007, and Clino is marked by a sedimentological change from a cyclic alternation of cemented–non-cemented biowackestones to an interval with poorly differentiated unlithified mud- to wackestones. This change to a more

Fig. 2 Interpretation of seismic lines 106 and 108 showing the geometries, sequence boundaries (capitals), and seismic units (lower case; modified from Betzler et al. 1999). Line 106 runs oblique and line 108 parallel to the bank edge on the western leeward side of the Bahamas. See Fig. 1 for location. Seismic patterns that precede the seismic sequence boundary F (*SSB-F*) with its parallel reflectors differs significantly from the complex pattern following this SSB



mud-dominated sedimentary system suggests a shift to rising surface water temperatures (McKenzie et al. 1999; Betzler et al. 2000). Consistent with this, the geometries also point to a strengthening of the predecessor of the Gulf Stream in the Strait of Florida.

Early Pliocene; SSB-E2 (4.6 Ma)

Seismic sequence *e* contains Early Pliocene sediments (Fig. 2; Eberli et al. 1997b; Betzler et al. 1999) and exhibits distinct erosional horizons at about 4.6 Ma (SSB-E2). SSB-E2 may result from a sea-level lowstand. This boundary agrees with an increase in oxygen isotope values (Shackleton et al. 1995) and thus relates to a sea-level drop. Comparisons of benthic oxygen isotope records from the Caribbean, Atlantic, and Pacific (e.g.,

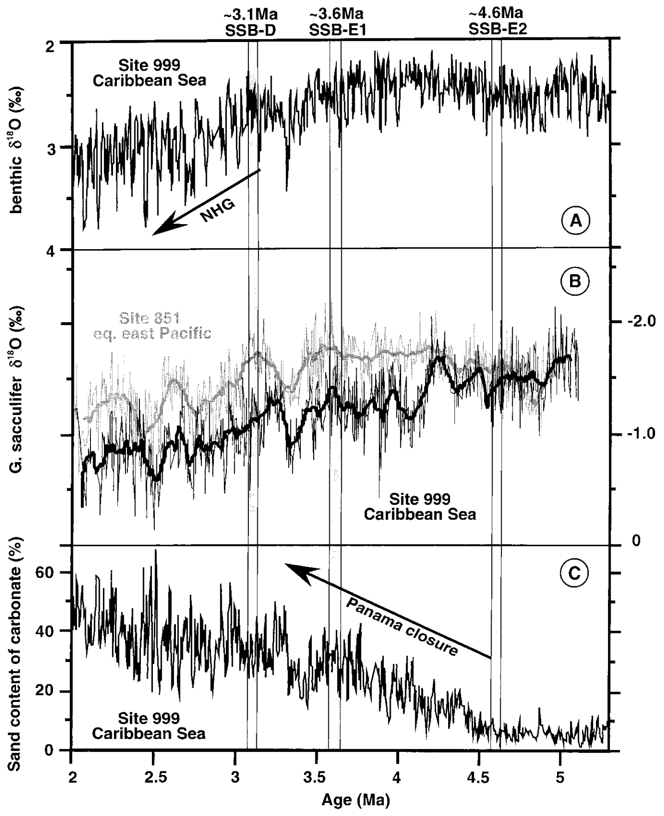


Fig. 3A–C Paleo-oceanographic proxy data indicating the main steps in Panama closure and onset of Northern Hemisphere Glaciation (*NHG*). **A** Benthic oxygen isotope record (*C. wuellerstorfi*) from ODP Site 999, Caribbean Sea; **B** original and raw data (*thick line* 15-point running average) pelagic oxygen isotopes (*G. sacculifer*) Pacific and Caribbean; **C** sand content of carbonate ODP Site 999, Caribbean Sea. Figure modified after Cannariato and Ravelo 1997; Driscoll and Haug 1998; Haug and Tiedemann 1998; Haug et al. 2001. Position of seismic sequence boundaries *E-2*, *E-1*, and *D* are indicated

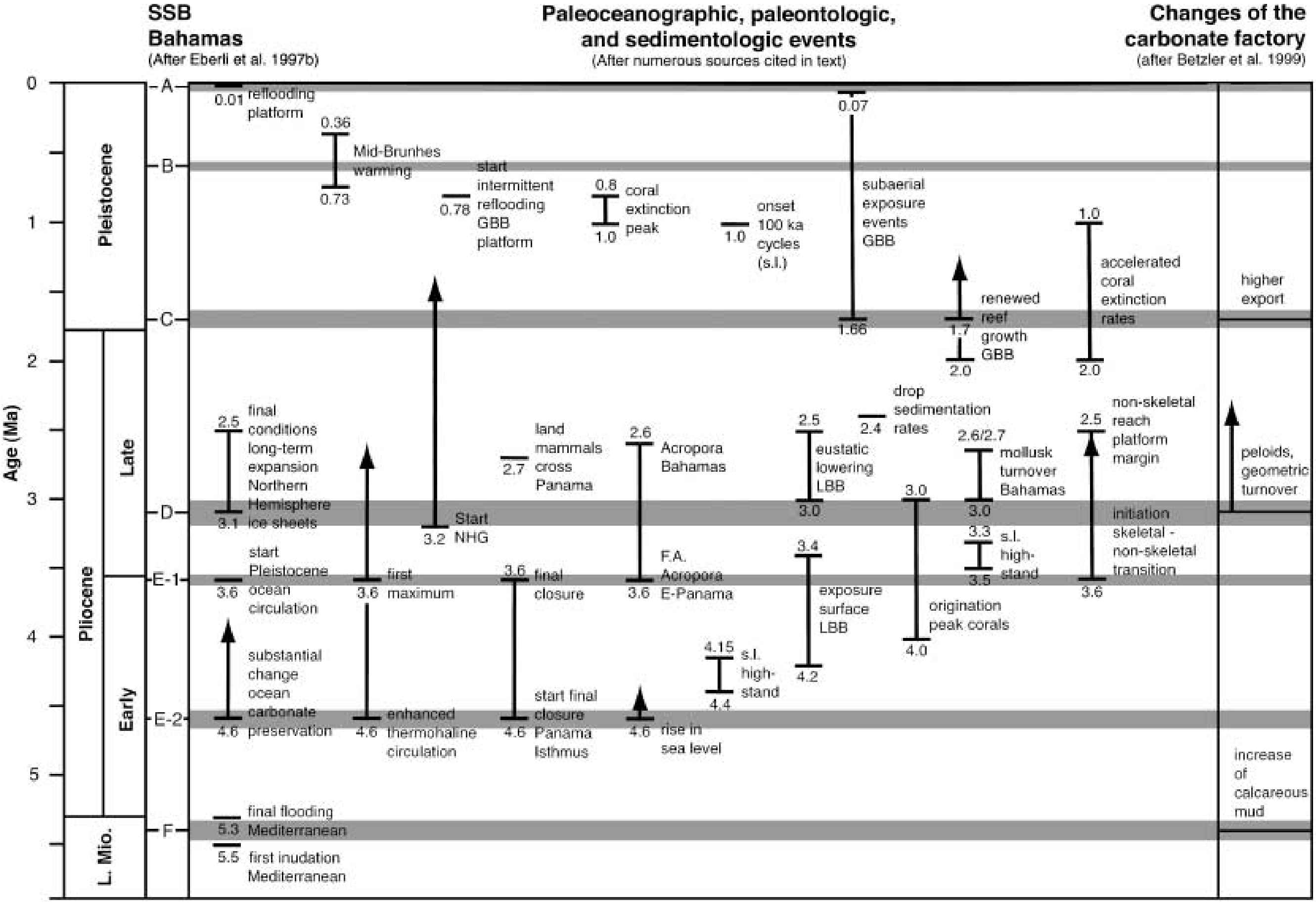


Fig. 4 Schematic overview of the events affecting the development of the carbonate platform of the Bahamas. Sources cited in text. *GBB* Great Bahama Bank; *LBB* Little Bahama Bank; *NHG* Northern Hemisphere Glaciation; *s.l.* sea level; *SSB* seismic sequence boundary

Tiedemann et al. 1994; Haug and Tiedemann 1998, Haug et al. 2001) can also be used to infer relative changes in sea level. A long-term global decrease in isotope values of about 0.4‰ suggests a rise in sea level from 4.6 to 4.4 Ma (Fig. 3; Haug and Tiedemann 1998). Evidence for this sea-level highstand is found at Little Bahama Bank (4.2 Ma; McNeill et al. 1998). This highstand lasted until 4.15 Ma, and was followed by a sea-level fall from 4.15–4 Ma. Sea level rises again from 4–3.9 Ma. A significant drop in sea level that is shown by similar trends does not occur before 3.6 Ma (Fig. 4).

This boundary at 4.6 Ma also marks a change in oceanographic conditions with increased deep-water ventilation and carbonate preservation, which shows the increased thermohaline circulation due to the closure of the Panama Isthmus (Fig. 3C; Keigwin 1982; Maier-Reimer et al. 1990; Tiedemann and Franz 1997; Haug and Tiedemann 1998; Billups et al. 1999).

At the same time, a drastic acceleration of extinction and the origination of Caribbean corals occurred, which is characterized by the extinction of ~75% and the origination of 50% of the species living in the Caribbean today (e.g., Jackson et al. 1996; Budd and Johnson 1997; Budd et al. 1998). On Curaçao, this accelerated faunal turnover occurred over a 2–3-Ma period during the Early to Late Pliocene (Budd et al. 1998; Fig. 4).

Early Pliocene; SSB-E1 (3.6 Ma)

SSB-E1 forms the top of seismic sequence *f* and is dated 3.6 Ma at proximal Site 1005 and basinal Site 1006 (Eberli et al. 1997b). It displays deeply incised canyons that truncated clinoform reflectors along the slope of the platform (Betzler et al. 1999; Fig. 2). We argue here that the erosional horizon at 3.6 Ma may have originated from intensification or reorganization of the surface circulation, which led to a truncation in the sedimentary deposits. Increased platform export by density flows might additionally have caused erosion of the slope. At Little Bahama Bank, the Early/Late Pliocene boundary is marked by subaerial exposure, which is related to a lowering of sea level (4.2–3.4 Ma; McNeill et al. 1998; Fig. 4).

At 3.6 Ma, the isotope records show some evidence for a sea-level lowstand, which, compared to others after SSB-E2, appears to be minor (Fig. 3B). However it forms the last lowstand before a general rise in sea level that reached its maximum at 3.3/3.5 Ma (Fig. 3B).

More likely, the erosional horizons of SSB-E1 may have been caused by changing directions of surface currents above the platform and/or by intensification of the surface current. This suggestion is supported by paleo-oceanographic studies (Keigwin 1982; Tiedemann and Franz 1997; Haug and Tiedemann 1998; Fig. 3) and by results from numerical models (Maier-Reimer et al. 1990) that argue for an intensification of the Gulf Stream in response to the closure of the Isthmus of Panama. Shallowing of the sea way resulted in a surface-water salinity increase in the Caribbean and intensified the Gulf Stream, which led to enhanced North Atlantic deep and intermediate water formation and to a more vigorous ocean circulation that reached a first maximum at 3.6 Ma (Haug and Tiedemann 1998; Billups et al. 1999; Haug et al. 2001; Figs. 3C and 4). A first ventilation maximum in the Caribbean Sea was reached at 3.6 Ma and reflects the increased strength of less carbonate-corrosive northern component water masses (Fig. 3B). Within this seismic sequence, which shows up in the seismic data as a fairly thick unit (Fig. 2), the sedimentation rates for the individual sites increase sharply, which suggests increased productivity (Eberli et al. 1997b) in response to these oceanographic changes. The Gulf Stream brings warm, nutrient-poor and saline waters to the Bahamas in which corals thrive. A sea-level change alone could not have caused such a change, which makes the SSB-E1 at 3.6 Ma really unique. So, although the isotopes do show some evidence of a sea-level drop, the platform itself and its surrounding sediments suggest higher productivity because of increased sea surface temperatures caused by an intensified Gulf Stream.

The first appearance of the major reef-building coral *Acropora palmata* on the Caribbean side of the Isthmus of Panama was set at the Gauss chron 3.6–2.6 Ma (McNeill et al. 1997), which coincides with this change at SSB-E1 (Fig. 4). This switch in platform builders might form the first step towards the change in Bahamian platform morphology from a ramp to a rimmed flat-topped morphology that ultimately was completed at the Pliocene–Pleistocene boundary. Shallow-water fossils from both sides of the Panama–Costa Rica region (Coates et al. 1992) indicate that the closure of the Isthmus of Panama was almost complete at 3.6 Ma, but the final closure that allowed land mammal exchange was achieved at 2.7 Ma, and is coincident with the glacial-induced sea-level drop during the major intensification of the northern hemisphere ice-sheet growth (see below and Fig. 4).

Late Pliocene; SSB-D (3.1 Ma)

SSB-D marks the upper boundary of a sedimentary unit infilling the pre-existing canyon topography (Fig. 2). It succeeds the sea-level highstand at 3.2 Ma (McNeill et al. 1998) and forms the transition to a sequence with large drift wedges and slump deposits, as can be seen at the toe-of slope (Site 1007). In addition, a sharp increase in the occurrence of pellets and aragonite needles can be observed in the Late Pliocene (Fig. 4; Eberli et al. 1997b; Betzler et al. 1999).

The Gulf Stream flow reached full power between 3.6 and 3.2 Ma (Haug and Tiedemann 1998; Fig. 3). The final conditions for amplification and continuation of the long-term expansions of the northern hemisphere ice sheets were reached between 3.1 and 2.5 Ma (Haug and Tiedemann 1998), after the necessary preconditions were met at 4.6–3.6 Ma by the formation of the Isthmus of Panama (Driscoll and Haug 1998; Fig. 3). Thus, strengthening of the thermohaline circulation intensified the northern hemisphere glaciation and ultimately lead to higher amplitude, high-frequency sea-level fluctuations.

Late Pliocene to Early Pleistocene; SSB-C (1.7 Ma)

The sediment accumulation rates for the proximal Sites 1005 to 1003, the interior of GBB at ODP sites 632 and 633, and other ODP Sites around GBB are high prior to 2.4 Ma (Upper Pliocene), but clearly drop in the Upper Pliocene (e.g., Droxler et al. 1988; McNeill et al. 1988; Schlager et al. 1988). At Site 1007, the rates increased, but this resulted from the deposition of platform-derived sediments that bypassed the upper slope and the accumulation of drift deposits (Eberli et al. 1997b). The geometry of this sediment package, pinching out towards the toe-of-slope, confirms this interpretation (Fig. 2; Betzler et al. 1999).

Within seismic sequence *c* a clear transition occurs in the composition of the Bahamian sediments from a skeletal-dominated carbonate system to a non-skeletal-dominated system. On the platform top, McNeill et al. (1998) dated this change as Early–Late Pliocene, at 3.6–2.6 Ma. Slope deposits at GBB (Westphal 1997; Westphal et al. 1999; Kenter et al. 2001) and basinal deposits (Exuma Sound; Reijmer et al. 1992) also display this profound sedimentological change, which can be related to the transition from a ramp-type of platform to a flat-topped stage (Fig. 4).

An extended period with frequent exposure of the platform lasted through much of the Late Pliocene and Early Pleistocene (Fig. 4; McNeill 1989; McNeill et al. 1998). The Upper Pliocene turnover from a ramp morphology to the flat-topped platform configuration, however, had an important consequence for the size of exposure of inner bank areas during sea-level lowstands. During the Upper Pliocene, subaerial exposure was largely restricted to the bank interior of GBB (Kievman 1998). The Early Pleistocene interval in core Unda and Clino, however, showed that the main part of the platform remained exposed during several sea-level oscillations (Kievman 1998). This exposure resulted in reduced sedimentation rates in the basins surrounding the platform (Schlager et al. 1988; Reijmer et al. 1992).

In cores Clino and Unda, SSB-C marks the base of renewed reef growth at 2.0–1.9 Ma since the Messinian (Eberli et al. 1997a). Reef growth continued until ~1.7 Ma (Unda), well into the Matuyama (1.7–0.8 Ma) at Clino. Accelerated extinction rates within the Caribbean reef-corals were once again observed for the period

2–1 Ma (Budd et al. 1996). The diachronous first appearance of *Acropora palmata*, within the Gauss chron (3.6–2.6 Ma) at Panama and at the Plio-Pleistocene boundary at the Bahamas (McNeill et al. 1997), displays the gradual spreading of this type of coral after the final closure of the Isthmus of Panama. Jackson (1997) registered an intense burst of extinction between 2.0 and 1.5 Ma when total diversity was reduced by nearly half (Fig. 4). The increased reef-coral diversity (Jackson 1997) in the Late Pliocene probably reflects the closure of the Isthmus, whereas the mass extinction must have some other climatic explanation. Changing oceanographic conditions must have influenced the different trends in the evolution of size and larval development, as shown by a variety of biota (e.g., gastropods, shrimps, epibenthic foraminifera). Allmon (2001), however, suggested that changes in nutrient conditions played a dominant role in causing the observed patterns of origination and extinction in the Pliocene–Pleistocene (e.g., Budd et al. 1996, 1998; Jackson 1997), although changes in temperature might have been important. These nutrient changes might have destroyed habitat conditions to result in enhanced speciation and extinction.

Pleistocene; SSB-B (0.6 Ma)

The intensification of the continental glaciations for the Pleistocene–Holocene resulted in sea-level changes with a stronger amplitude (e.g., Shackleton et al. 1984), which influenced the sedimentation patterns on and within the vicinity of the platform (e.g., Droxler et al. 1988; Reijmer et al. 1988). At the beginning of the Brunhes chron (approx. 0.8 Ma) the entire lee side of the platform was exposed (Kievman 1998). That study also reported that the number of discontinuity horizons along the Great Bahama Bank were in agreement with the number of sea-level oscillations, as known from the oxygen-isotope record for the Brunhes chron. The SSB-B also marks the transition in which the obliquity rhythm was progressively superseded by the 100,000-year period of orbital eccentricity that has dominated sea-level fluctuations since (Fig. 4; Shackleton et al. 1984; Ruddiman et al. 1986a, 1986b, 1989).

Reflooding of the platform occurred at 0.8 Ma (e.g., McNeill 1989; Reijmer et al. 1992). The sediments show a slight coarsening upward trend with increasing input of platform-derived grains such as aragonite needles (Eberli et al. 1997b). A sharp change in the sedimentation rates at Site 1007 shows the transition from a depositional to an erosional mode along the margin of Great Bahama Bank (Fig. 3; Rendle et al. 2000; Rendle and Reijmer 2001a).

A middle Pleistocene coral extinction peak at 1.0–0.8 Ma occurred in the western Caribbean at the same time and involved somewhat deeper water coral faunas in comparison with the Pliocene shallow-water coral extinction peak (Getty et al. 2001). Getty et al. (2001) proposed that the high-amplitude sea-level changes had a strong environmental impact on the habitat modification and thus coral extinction in the Caribbean Basin.

The massive production of ooids started at this time, and the development of a distinct shedding pattern related to flooding or exposure of the platform established itself in all Bahamian basins (e.g., Droxler and Schlager 1985; Reijmer et al. 1988; Schlager et al. 1994; Fig. 4). The sediments along the Bahamian Transect also show a typical highstand shedding pattern with alternating mud-dominated interglacial sediments and coarser grained glacial deposits (Rendle et al. 2000; Rendle and Reijmer 2001b).

Holocene/Pleistocene; SSB-A (0.1 Ma)

SSB-A marks the base of the Holocene sedimentary wedge at the western leeward side of GBB (Eberli et al. 1997b; Fig. 2). The sediments consist of platform-derived fine aragonite mud (Wilber et al. 1990; Rendle et al. 2000). Along the Bahamas Transect its thickness varies from 12 m at the proximal Site 1005 to almost 2 m at the distal Site 1006. This wedge shows the direct link between flooding of the platform and subsequent export of sediment produced within the shallow-water realm of the platform.

Conclusions

The timing of the Miocene to Holocene seismic sequence boundaries and sedimentation patterns along the Bahamian Transect not only register eustatic sea-level fluctuations, but also paleo-oceanographic events that affected the regional current regime as well as the global climatic system. The closure of the Isthmus of Panama played a major role in these sedimentological changes. Sediment-producing carbonate platforms are complex ecosystems, which are highly sensitive to changes in their environment, i.e., in the tropical warm pool regions. If this ecosystem changes, this should influence the sediment production.

One of the objectives of ODP Leg 166 was to evaluate whether there is a causal link between eustasy and sequence stratigraphic patterns. This study showed that an interactive process between sea-level variations, paleo-oceanographic changes and carbonate platform development shaped the margin of the Great Bahama Bank. Sea level generates many of the sequence boundaries, but the overall evolution of the Bahamian carbonate platform was governed by climate and paleo-oceanography.

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