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Synchroneity of major late Neogene sea level fluctuations and paleoceanographically controlled changes as recorded by two carbonate platforms

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Abstract. Shallow-water carbonate systems are reliable recorders of sea level fluctuations and changes in ambient seawater conditions. Drilling results from Ocean Drilling Program (ODP) Legs 133 and 166 indicate that the timing of late Neogene sedimentary breaks triggered by sea level lowerings is synchronous in the sedimentary successions of the Queensland Plateau and the Great Bahama Bank. This synchrony indicates that these sea level changes were eustatic in origin. The carbonate platforms were also affected by contemporary, paleoceanographically controlled fluctuations in carbonate production. Paleoceanographic changes are recorded at 10.7, 3.6, and 1.7 – 2.0 Ma. At the Queensland Plateau, sea surface temperature shifts are documented by shifts from tropical to temperate carbonates (10.7 Ma) and vice versa (3.6 Ma); the modern tropical platform was established at 2.0-1.8 Ma. At Great Bahama Bank, changes were registered in compositional variations of platform-derived sediment, such as major occurrence of peloids (3.6 Ma) and higher rates of neritic carbonate input (1.7 Ma). The synchroneity of these changes attests to the far-field effects of modifications in the oceanographic circulation on shallow-water, low-latitude carbonate production.

1. Introduction

The Cenozoic was the time of the evolution of the icehouse world [*Shackleton and Kennett*, 1975]. During this time, fluctuations in polar ice volume apparently controlled eustatic (global sea level) variations [*Miller et al.*, 1991]. Glaciations, as deduced from the marine oxygen isotope record, corresponded to global sea level lows or drops [*Miller et al.*, 1998]. Carbonate platforms are reliable recorders of sea level fluctuations and water mass changes [*Schlager*, 1992]. Carbonate platform interior facies allow identification of the former position of sea level through texture, biotic, and diagenetic features. Periplatform deposits record sea level-driven processes of the inner platform through compositional and geometrical changes [*Schlager et al*, 1994]. Paleoceanographic changes are registered by fluctuations in the composition of shallow-water carbonate production, which is intimately linked to water mass properties [*James and Kendall*, 1992].

With the results of two transects drilled in shallow-water carbonate platforms (Ocean Drilling Program (ODP) Leg 133, Queensland Plateau and ODP Leg 166, Great Bahama Bank), the opportunity arose to compare Neogene sea level and paleoceanographic records in two ocean basins, the Pacific and the Atlantic. The Queensland Plateau is located in the low-latitude western Pacific, and the Great Bahama Bank lies in the low-latitude North Atlantic (Figure 1). Both carbonate platforms had a complex individual evolution. However, we will demonstrate that major sea level changes synchronously influenced the growth of these buildups. Synchronous events also affected the quality of the carbonate factory, indicating not only a global sea level signal but also suggesting far-field effects of the Miocene-Pliocene reorganization of global ocean current patterns.

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2. Methods and Data

The northeast Australian carbonate province, including the Queensland Plateau and the Great Barrier Reef, was extensively studied during ODP Leg 133 [*Davies et al.*, 1991]. Locations of drill sites at the Queensland Plateau are shown in Figure 1, and carbonate platform geometry at the southern tip of the plateau is shown in Figure 2. The Great Bahama Bank was subject of a multiplatform drilling project (ODP Legs 101 and 166 as well as platform interior shallow-water drilling [*Austin et al.*, 1986; *Eberli et al*, 1997; *Ginsburg*, 2000]). Position of drill sites and platform interior geometries as imaged in a seismic line are presented in Figures 1 and 2.

The sedimentary successions of both carbonate platforms are punctuated by sequence boundaries (Figures 2 and 3). In addition, changes in composition and sedimentation rates indicate changes of the shallow-water carbonate factory (Fig-

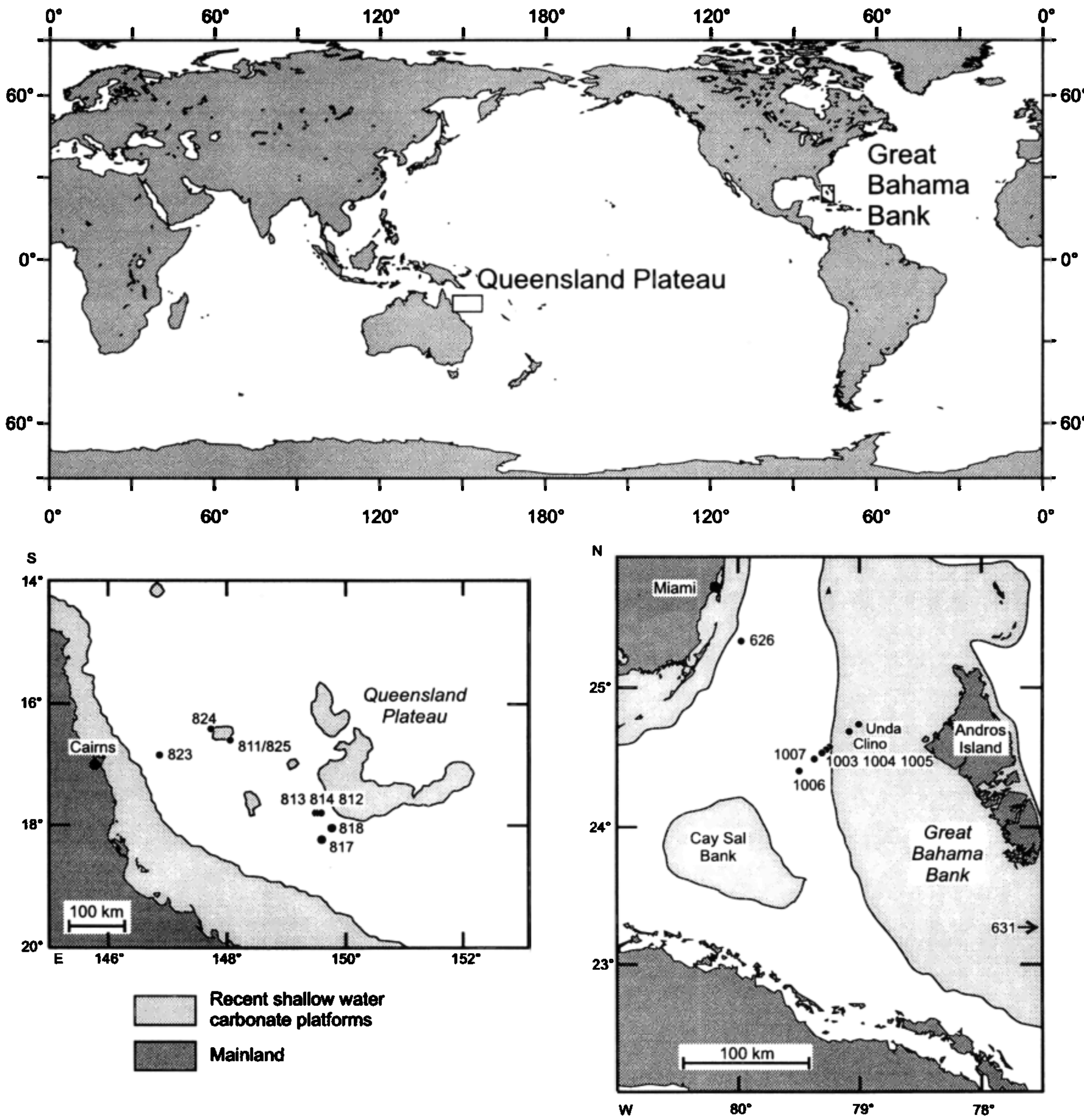

Figure 1. Map showing locations of the Queensland Plateau in the western Pacific Ocean and Great Bahama Bank in the northern Atlantic Ocean.

ure 3). The sequence boundaries are generated by sea level lowstands [*Betzler et al.*, 1993, 1999; *Eberli et al.*, 1997]. Recognition of these sequence boundaries is based on combined interpretation of depositional geometries on seismic lines, sedimentologic and petrographic analysis, down hole log interpretation, and micropaleontological studies. In inner platform settings the boundaries are placed at the lowest point of relative sea level, as deduced from depositional geometries, microfossil assemblages, and exposure surfaces. In periplatform settings, depositional geometries, changes in particle composition, and the positions of sequence boundaries were used to characterize sea level-driven flooding versus exposure of the platforms [*Davies et al.*, 1991; *Betzler et al.*, 1995, 2000; *Eberli et al.*, 1997].

Recognition of paleoceanographic changes at the Queensland Plateau and Great Bahama Bank relies on seismic (Figure 2), sedimentological, petrographical, micropaleontological, and geochemical data [*Betzler et al.*, 1993, 1995, 1999; *Isern et al.*, 1993, 1996]. Shallow-water carbonate production is a function of the ambient seawater conditions with the main controlling factor being water temperature [*James and Kendall*, 1992; *Jones and Desrochers*, 1992]. This is, for example, well documented for the global distribution of one important modern carbonate platform element: the zooxanthellate coral reefs. *Kleypas et al.* [1999] show that water temperature and the covarying aragonite saturation together with light penetration are the reef-limiting factors rather than nutrient levels. Thus paleoceanographic variations basically control carbonate production in the low-latitude shallow-water realm.

In our comparison we rely on high-accuracy dating of individual events in both carbonate platforms. This accuracy is

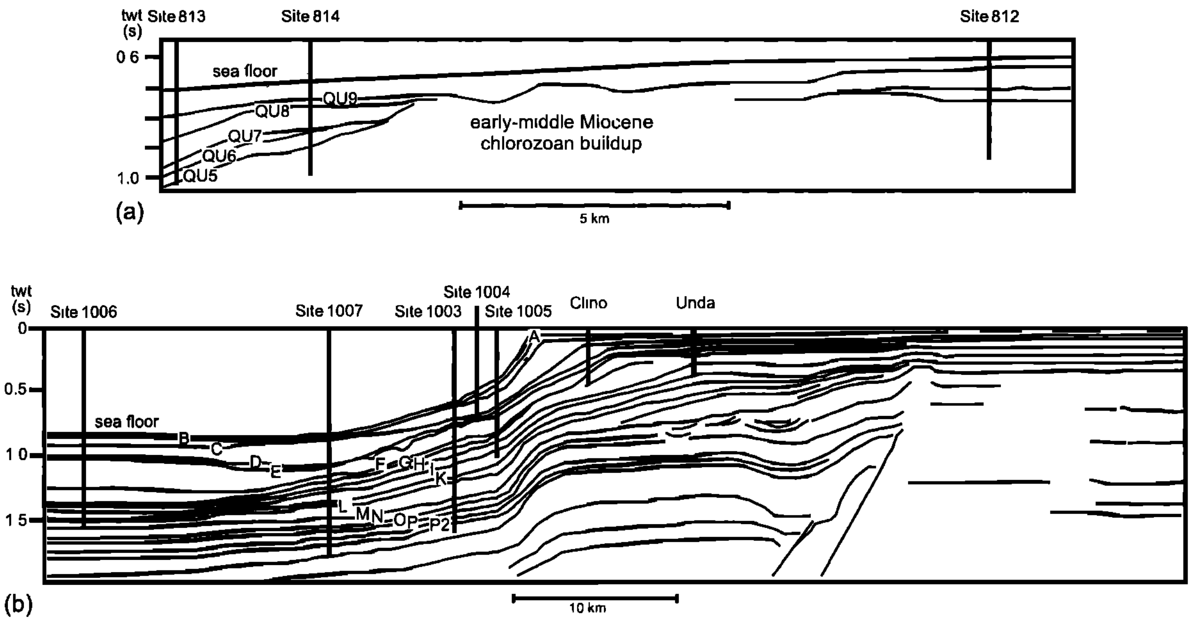

Figure 2. Carbonate platform geometry in one of the seismic lines at the southern part of the Queensland Plateau (a) showing late Miocene–early Pliocene sequence boundaries [modified after *Betzler*, 1997] and (b) sequence boundaries at Great Bahama Bank [modified after *Eberli et al.*, 1997]

possible by drilling of shallow-to-deeper water transects because dating errors of sedimentary breaks along such a transect is minimal since aberrant age dates (e.g., reworking of microfossils) can be recognized and average dates for certain surfaces can be produced.

The age model used for the two carbonate platforms is shown in Figure 4. At the Queensland Plateau, dating of the sedimentary successions is based on calcareous nannoplankton and planktonic foraminiferal datums [*Davies et al.*, 1991; *Betzler et al.*, 1993, 1995; *Betzler*, 1997; *Gartner et al*, 1993a, 1993b; *Kroon*, 1993; *Wei and Gartner*, 1993]. In pelagic and hemipelagic deposits, sampling distance for calcareous nannofossils was 1.5 m, and it was 3 m for planktonic foraminifers. Lower and middle Miocene platform interior strata were additionally dated with large benthic foraminifers [*Betzler et al.*, 1993; *Gartner et al.*, 1993a]. The ages of all datums were converted to the *Berggren et al* [1995] timescale (Figure 4). The age inaccuracies for respective sequence boundaries and events resulting from sampling resolution are marked with boxes in Figure 3. The age assignments of the Great Bahama Bank deposits rely on calcareous nannoplankton and planktonic foraminifer datums [*Eberli et al.*, 1997; *Wright and Kroon*, 2000; *Kroon et al.*, 2000] calibrated against the *Berggren et al.* [1995] timescale. In contrast to the data from the Queensland Plateau, age assignments of sequence boundaries and events are well constrained throughout the entire succession at the Bahamas [*Eberli et al.*, 1997; *Anselmetti et al.*, 2000]. Ages were tested by cyclostratigraphic analysis in the basinal Site 1006 [*Kroon et al*, 2000]. The maximum temporal deviation for sequence boundaries as derived by these methods is 200 ka., that is, one eccentricity cycle above or below of the sequence boundary [*Kroon et al.*, 2000]. The respective inaccuracies are marked by boxes in Figure 3.

2.1. Queensland Plateau Events

The breaks in the Queensland Plateau strata are defined in inner platform and periplatform deposits drilled during ODP Leg 133. From bottom to top, the events are numbered QU1 to QU12 (Figure 3 and Table 1). Low core recovery and fragmentary age control in tropical reef deposits provide a fragmentary record of the lower to middle Miocene of the Queensland Plateau. Deposits of this time interval are punctuated by sequence boundaries QU1 - QU4 (Sites 811/825, 824, and 813) (Figure 3). Age control of deposits is better for the upper Miocene deposits. The most important event, a turnover from a tropical rimmed platform to a non tropical, warm-temperate ramp occurred during the early late Miocene at 10.7 Ma (QU5, Figures 2 and 3). This is indicated by a change in biofacies from a chlorozoan assemblage to a bryomol association with large benthic foraminifers [*Betzler et al*, 1995] and by oxygen isotopes of planktonic foraminifers [*Isern et al*, 1993, 1996]. Warm-temperate water bryomol carbonates formed during the late Miocene and early Pliocene. In this interval, several sequence boundaries in the platform interior deposits and the periplatform sediments (QU6-QU9) (Figures 2 and 3) indicate major sea level changes during this time [*Davies et al.*, 1991; *Betzler et al*, 1995; *Betzler*, 1997].

At the lower/upper Pliocene boundary (3.6 Ma) a return into warmer water carbonate production (QU9) is indicated by higher carbonate sediment export rates in the periplatform area and concomitant occurrence of tropical calcareous green algae (Sites 811/825, 824, 817, and 818 [*Davies et al.*, 1991; *Droxler et al*, 1993; *Cotillon et al*, 1994; *Betzler*, 1997]). A final and major turnover occurred during the latest Pliocene at 2.0 to 1.8 Ma. It shows a stepwise increase in diversity of shallow-water carbonate producers (e.g., benthic foraminiferal associations), indicating installation of a typical modern tropi-

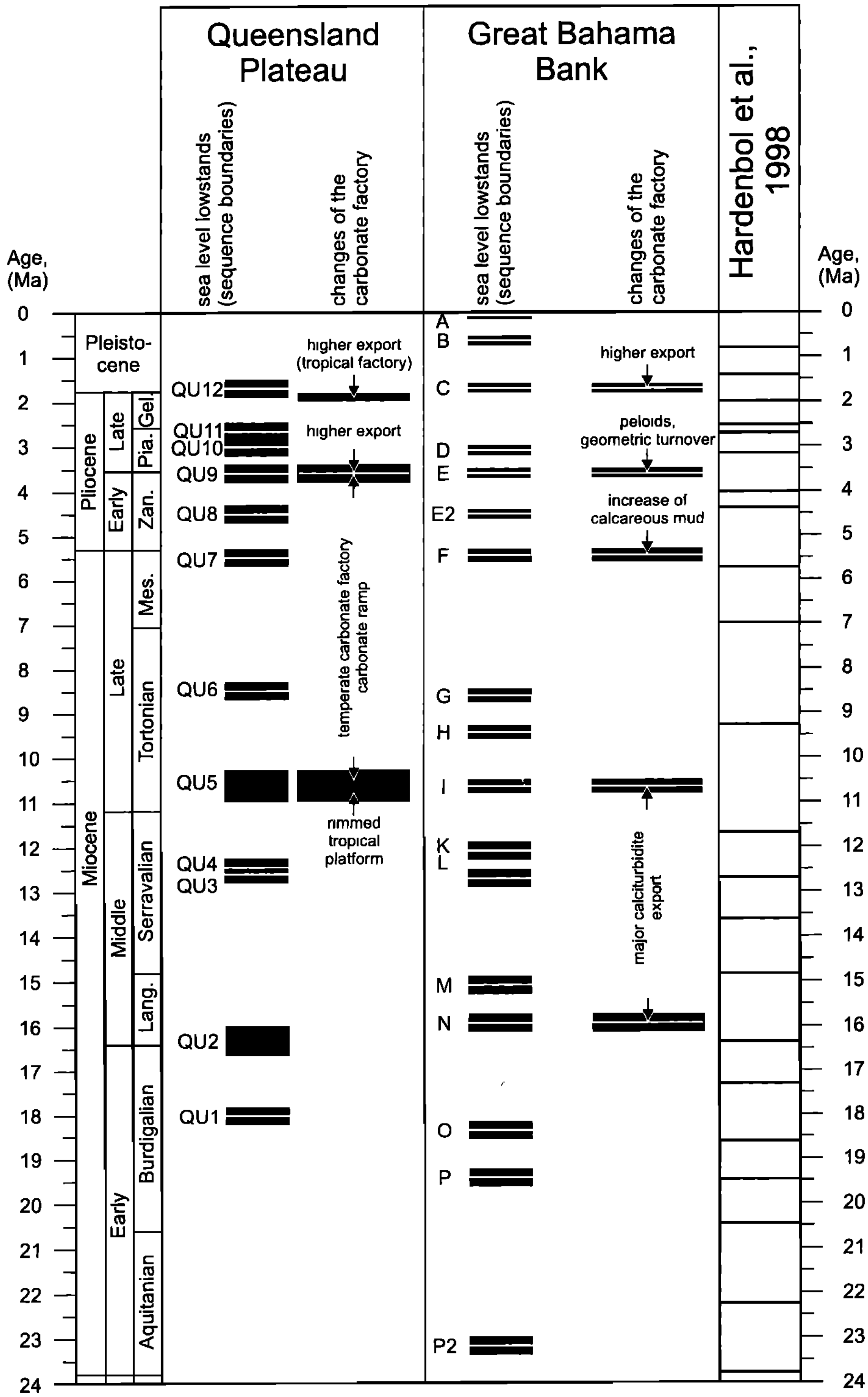

Figure 3. Neogene sequence boundaries of the Queensland Plateau and Great Bahama Bank and major changes in shallow-water carbonate production. Timescale is after *Berggren et al* [1995] Sequence boundaries A-P2 are after *Eberli et al.* [1997], and E2 is after *Betzler et al.* [1999] Black boxes indicate age uncertainties

cal Indo-pacific reef carbonate production (QU12, Sites 811/825, 824 [*Betzler*, 1997]).

2.2. Great Bahama Bank Events

The Neogene architecture and evolution of Great Bahama Bank is documented on seismic lines [*Eberli and Ginsburg*, 1987, 1989; *Eberli et al.*, 1997] (Figure 2), cores recovered during ODP Legs 101 [*Austin et al.*, 1986] and 166 [*Eberli et al.*, 1997], and during the Bahamas Drilling Project [*Ginsburg*, 2000]. Data are mostly from periplatform deposits with additional information from the boreholes Unda and Clino drilled on the platform interior [*Eberli et al.*, 1997;

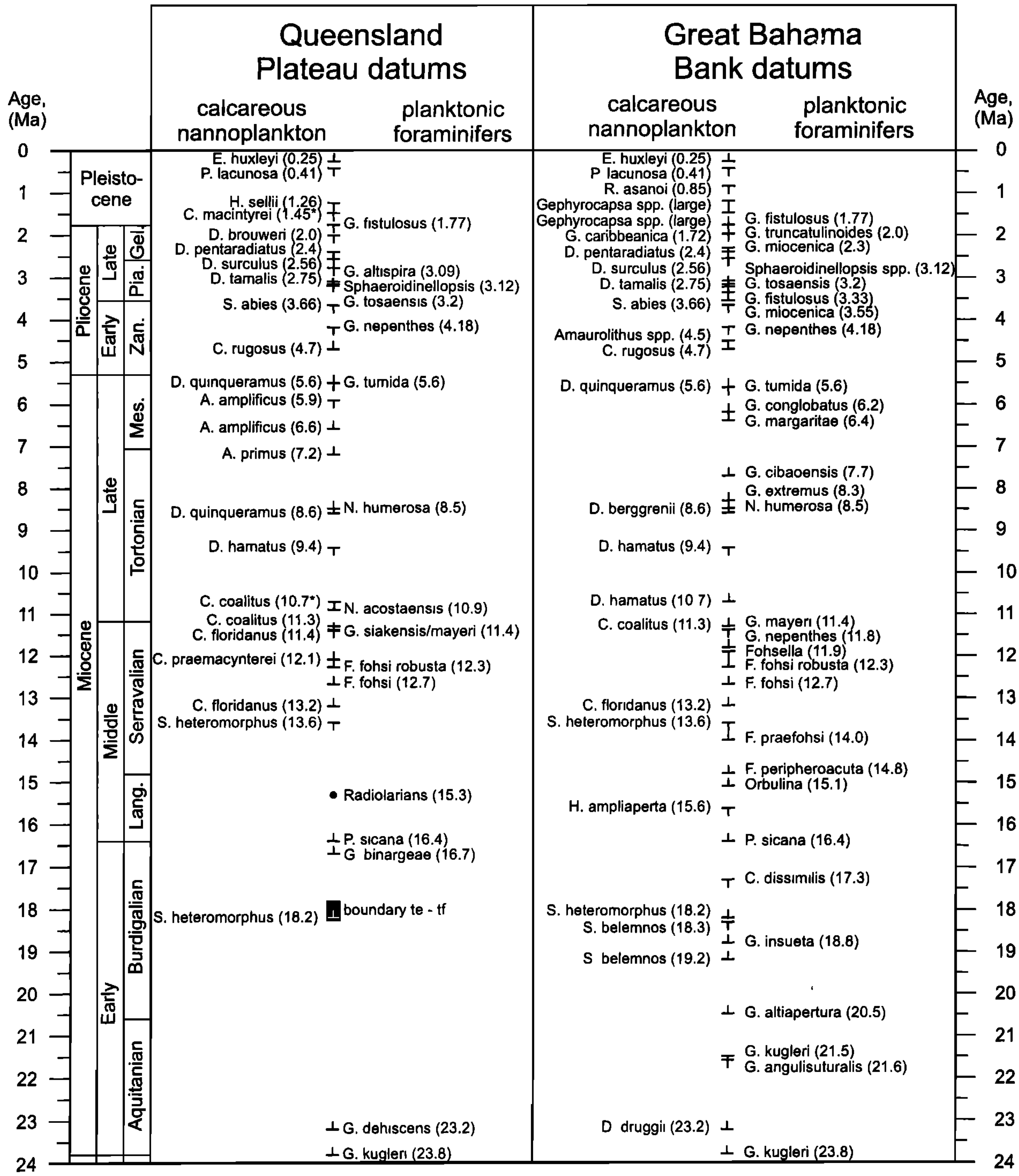

Figure 4. Age models used at the Queensland Plateau and at Great Bahama Bank. Age of datums are converted to the *Berggren et al.* [1995] timescale. Asterisks indicate datums not discussed in *Berggren et al.* [1995]. These ages are after *Gartner et al.* [1993a]. Boundary te-tf refers to East Indian Letter Stage Classification of large benthic foraminifers. See text for further discussion

Ginsburg, 2000]. Seventeen Neogene sequence boundaries are recognized on the seismic profiles [*Eberli et al.*, 1997] (Figures 2 and 3, and Table 1) and were penetrated during ODP Leg 166 [*Eberli et al.*, 1997; *Betzler et al*,. 1999].

In addition to sea level lowstands that produce sequence boundaries A-P2, several other events affected production and export of Great Bahama Bank carbonate sediments during the Neogene (Figure 3). In the first case, the amount of sediment redeposition along the carbonate platform flank varies. During the early Miocene, slope and basinal areas [*Eberli et al.*, 1997] are dominated by periplatform ooze deposition. In contrast, major amounts of calciturbidites were exported to the slope and toe of slope during the middle Miocene [*Fulthorpe and Melillo*, 1988; *Eberli et al*, 1997; *Betzler et al*, 1999]. This interval coincides at least partly with the Abaco Event, a middle Miocene sedimentary interval dominated by

Table 1. Ages of Events at Queensland Plateau and Great Bahama Bank

Queensland Plateau				Great Bahama Bank			
Sedimentary Breaks, Sequence Boundaries	Age, Ma	Changes of the Carbonate Factory	Age, Ma	Sedimentary Breaks, Sequence Boundaries	Age, Ma	Changes of the Carbonate Factory	Age, Ma
				A	0.1		
				B	0.6		
QU12	1.7	*Calcarina / Halimeda*	1.8-2.0	C	1.7	higher export	1.7
QU11	2.7						
QU10	3.0			D	3.1		
QU9	3.6	temperate → tropical	3.6	E	3.6	onset peloids	3.6
QU8	4.5			E2	4.5		
QU7	5.5			F	5.4	increase calcareous mud	5.4
QU6	8.5			G	8.7		
				H	9.4		
QU5	10.3-11	tropical → temperate	10.3-11	I	10.7	top major turbidite export	10.7
				K	12.2		
QU4	12.4			L	12.7		
QU3	12.6						
				M	15.1		
QU2	16-16.7			N	15.9	onset major turbidite export	15.9
QU1	18.0			O	18.3		
				P	19.4		
				P2	23.2		

calcareous redeposition at the Blake Plateau [*Bliefnick et al.*, 1983; *Fulthorpe and Melillo*, 1988]. This major calciturbidite shedding ceased during the earliest late Miocene (10.7 Ma), and sedimentation dominated by periplatform ooze was reinitiated. The increased turbidite shedding along the flank of Great Bahama Bank correlates with the global, long-term late middle Miocene sea level lowering [*Betzler et al.*, 2000].

Other paleoceanographic changes are coeval with the formation of sequence boundaries [*Reijmer et al*, 1999]. Across the sequence boundary F, during the latest Miocene at 5.4 Ma, composition of the periplatform ooze changed from skeletal- to mud-dominated [*Eberli et al.*, 1997; *Betzler et al.*, 1999]. Similarly, above sequence boundary E (3.6 Ma) a further variation in sedimentation occurred with the onset of peloid occurrence [*Eberli et al*, 1997]. This event affected the entire Great Bahama Bank [*Beach and Ginsburg*, 1980; *Reijmer et al.*, 1992] and was also recorded at Little Bahama Bank between 3.3 and 3.6 Ma. [*McNeill et al.*, 1998]. On Great Bahama Bank this compositional change is also coeval with a geometric change of the platform from a ramp-like to a steep-sided morphology [*Eberli and Ginsburg*, 1987]. The youngest event in the sediments at western Great Bahama Bank is an increase of the periplatform sedimentation rates at 1.7 Ma [*Eberli et al.*, 1997], reflecting major progradation of the platform flank [*Eberli and Ginsburg*, 1987, 1989]. A synchronous increase of the periplatform sedimentation rates is also recorded in ODP Leg 101 drill sites 626 and 631 [*Austin et al.*, 1986].

3. Discussion and Interpretation

Both carbonate platforms have a complex individual evolution. However, major time-equivalent sea level changes and fluctuations in the carbonate factory affected both settings (Figure 3), pointing to global synchroneity of these events.

3.1. Sea Level Changes

The poor lower Miocene record at the Queensland Plateau prevents a comparison prior to QU1, i.e., 18 Ma. This sequence boundary is, within the age resolution, probably of the same age as sequence boundary O (18.3 Ma) on Great Bahama Bank . In the middle Miocene, there is a certain parallelism of events, especially between 13 and 12 Ma, when both platforms register closely spaced sequence boundaries (QU3, 4, L, K; Figure 3).

For the late Miocene, there is a very good correlation of sequence boundaries QU5 and I, QU6 and G as well as QU7 and F. Bahamas sequence boundary H, however, was not registered at the Queensland Plateau. In the Pliocene-Pleistocene interval a very good age correspondence exists between horizons QU8 and E2, QU9 and E, QU10 and D, and QU12 and C. This is contrasted by sequence boundaries QU11, B, and A, which only occur in one platform.

The isochroneity of sea level lowstands in two tectonically unrelated carbonate platforms is strong evidence for eustatic sea level changes as the controlling factor on large- to medium-scale (1-5 Ma) stratigraphic packaging. The timing of most of the currently recognized eustatic sea level fluctuations in these independent carbonate systems does, however, not seem to match as clearly with the timing of global sea level lowstands as proposed by *Haq et al* [1988] and *Hardenbol et al.* [1998] in the Mesozoic and Cenozoic Sequence Chronostratigraphic Chart (MCSSC) (Figure 3). This discrepancy may relate to the resolution of biostratigraphic dating. The accuracy of dating depends on a number of factors: (1) the number of biostratigraphic datum levels found, (2) the quality of the biostratigraphic events used. Factors such as abundance of the species play a role and the exact appearance or exit levels of a species should be quantified, which is hardly done owing to time constraints, and (3) consistency of sedimentation rates in between datum levels because the interpolation technique is used for the timing of a certain event. However, dating accuracy can be improved by repeating the exercise along transects to minimize errors and dismiss aberrant dates, and thus average dates of certain events can be calculated. Particularly, the basin sites or lower slope sites are useful where sedimentary packages are complete and conformable. Dating can be significantly improved by using Milankovitch cycles [*Kroon et al.,* 2000], such as off Great Bahama Bank. The basin sediments showed excellent cyclostratigraphy, which gave the opportunity to date within one eccentricity cycle on either side of the sequence boundary. The success of identifying synchroneity in the independent carbonate systems may be partly due to the transect approach and high sampling resolution for biostratigraphic analysis.

In addition, differences in age assignments of sequence boundaries in siliciclastic depositional systems (MCSSC) and carbonate depositional systems may arise from the different responses of these deposits during sea level fluctuations. Whereas siliciclastics shelves export major amounts of sediment to the basin during sea level lowerings, carbonate platform exposure during sea level lowstands leads to a very strong reduction or demise of carbonate production [*Droxler and Schlager*, 1985] and thus of carbonate export to the basin. Thus a siliciclastic system will export sediment toward the basin during forced regressions, whereas at this stage in a carbonate system a condensed section will form at the distal slope and toe of slope. Timing of input of sediments relative to the sea level cycle thus may affect the date of the sequence boundary as a result of the interpolation technique. This aspect only applies, however, for the time when Great Bahama Bank was a flat-topped platform because during the older distally steepened ramp stage, major amounts of basinal lowstand deposits occur [*Betzler et al*, 1999].

Another interesting phenomenon is that the number of the Queensland Plateau and Great Bahama Bank sequence boundaries does not correspond to the postulated number of sea level lowstands in the MCSSC (Figure 3). Such inconsistencies between the sedimentary record in specific areas and the MCSSC, which is based on a composite record, were also observed, for example, by *Miall* [1992] or *Immenhauser and Scott* [1999] for different time intervals. These observations ask for more studies centered on dating and detailed reconstruction of past sea level changes.

3.2. Changes of the Carbonate Factory

At the Queensland Plateau, changes of shallow water carbonate production are largely sea surface temperature controlled and alternate between tropical and temperate (Figure 3). A slightly more southerly location of the Australian plate provided a reinforcement of the global, oceanographically controlled [*Pagani et al.*, 1999], late Miocene cooling at the Queensland Plateau [*Isern et al.*, 1996], triggering the turnover from the tropical rimmed platform to the warm-temperate ramp. Timing of the turnover at 10.7 Ma is coeval with the end of major calciturbiditic shedding at Great Bahama Bank. Although presently available data indicate that this turnoff is sea level controlled (see above), it has to be stressed that it also corresponds to the "carbonate crash" [*Lyle et al.*, 1995] recognized elsewhere in the Caribbean carbonate province at the middle-late Miocene boundary [*Sigurdsson et al.*, 1997]. This carbonate crash is interpreted to be a consequence of changes in oceanic circulation triggered by the closure of the Panama Isthmus [*Lyle et al*, 1995; *Sigurdsson et al.*, 1997].

Textural change of the Great Bahama Bank periplatform deposits at 5.4 Ma indicates that mud production became a major carbonate source in the shallow-water areas. Calcareous mud production in the Bahamas region is nowadays achieved through degradation of calcareous green algae and whitings. As both mud sources are temperature dependent [e.g., *James and Kendall*, 1992], with subtropical to temperate water temperatures reducing mud production rates, we interpret this change as a record of rising surface water temperatures. This interpretation is corroborated by the oxygen isotope record at Site 1006, which indicates a warming of the surface waters [*McKenzie et al.*, 1999]. The warming slightly predates the Pliocene warming recognized by *Tiedemann and Franz* [1997] in the oxygen isotope record of the western equatorial Atlantic. However, it correlates with a strengthening of the current system in the Strait of Florida [*Eberli et al.*, 1997; *Betzler et al.*, 1999] attesting for the enforcement of the "paleo-Gulf Stream", probably related to the closure process of the Panama Isthmus [*Reijmer et al.*, 1999]. This enforcement would produce the appropriate mechanism to raise surface water temperatures at Great Bahama Bank.

The next younger sedimentologic event at the Bahamas, the onset of peloid production and the geometric evolution from the ramp to a flat-topped platform, coincides with the switch from temperate to tropical conditions at the Queensland Plateau (Figure 3). In the northern Atlantic this event corresponds to a further intensification of the thermohaline circulation postulated by *Haug and Tiedemann* [1998] at 3.6 Ma. The age equivalent change to the tropical platform at the Queensland Plateau indicates a similar increase of water temperatures at this location. Although in both cases the event predates the "mid-Pliocene Warming", as described by *Raymo et al.* [1996], by roughly 0.5 Ma, we suggest that the change in shallow-water carbonate production reflects the Pliocene global reorganization of surface water currents triggered by an intensified conveyor belt [*Raymo et al*, 1996].

At 1.8–2.0 Ma, another change affected both carbonate platforms. In the case of the Queensland Plateau, such a change is assumed to reflect installation of a western Coral Sea warm pool [*Isern et al*, 1996], a feature which ultimately is controlled by the global oceanic circulation pattern. At Great Bahama Bank, higher periplatform sedimentation rates around 1.7 Ma reflect either higher neritic sediment production rates or a higher efficiency of sediment export from the platform interior. Both processes may have been achieved through intensification of the trade winds which, first raised sea surface temperatures (expansion of the warm water pool) and, second strengthened inner platform currents, thus promoting sediment transport to the leeward side of Great Bahama Bank.

Our results demonstrate the synchroneity of major late Miocene and Pliocene eustatic sea level changes in the tropical Atlantic and in the tropical Pacific. Our data and ages of global sea level lowstands, however, only moderately correlate with the ages postulated in the MCSSC [*Haq et al.*, 1988; *Hardenbol et al.*, 1998]. In addition to sea level changes, we recognize synchronous oceanographic and atmospheric circulation events in both areas, in particular, the stepwise strengthening of the conveyor belt and of warm-water pools, which gradually affected low-latitude shallow-water carbonate deposition. In fact, significant compositional and architectural changes are closely related to these events. This result provides new insights of the impact of climate change on such carbonate systems.

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