The limited link between accommodation space, sediment thickness, and inner platform facies distribution (Holocene–Pleistocene, Bahamas)

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Abstract

Cyclic facies variations in shallow-water carbonate platforms often show repetitive facies patterns that are frequently interpreted to reflect the sedimentary response to variations in sea-level related to changes in climate linked to orbital variations, the Milankovitch frequencies. Whether these shallow-marine carbonates represent a complete infill of accommodation space, or are subtidal cycles, has been discussed in numerous papers. The extent to which the thickness of a single depositional cycle is a direct measure of the amplitude of relative sea-level change is not fully understood. New shallow seismic data from Great Bahama Bank reveal that accommodation space created during the Holocene sea-level rise is not filled in a predictable way. Three seismic horizons were identified: the seabed, the Pleistocene top, and a horizon within the Pleistocene. Depth surface and thickness maps of the Holocene and Pleistocene layers were combined with 326 in situ water-depth measurements to assess the upper limit of the present accommodation space. The analysis showed that accommodation space and Holocene sediment thickness, and water depth are not correlated. In addition, the actual water depth and inner platform facies distribution showed no straightforward link. The energy distribution across the shallow-water platform appears to control the facies type rather than water depth. Mud-dominated sediments prevail in shallow low-energy areas protected by a topographic barrier, whereas mud-free coarse-grained sediments mainly occur in deeper areas with hydrodynamic energy induced by strong tidal currents, ocean water influx, and winds. Hence, the uneven energy distribution not only results in unpredictable differences in the carbonate-cycle thickness on the platform but also to a water depth independent facies distribution pattern within the inner platform. Therefore, care should be taken when deducing sea-level signals from inner platform facies distribution and sediment thickness patterns on ancient platforms.

KEYWORDS

Accommodation space, Great Bahama Bank, Holocene, Milankovitch cycles, Pleistocene, sea-level change, shallow-water carbonate cycles

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INTRODUCTION

The Great Bahama Bank (GBB) is a flat-topped shallow-marine carbonate platform that has served as a major modern example for understanding the processes of both modern and ancient carbonate sedimentation (Schlager & Ginsburg, 1981). Its sedimentation patterns have formed the basis for many geological models and reservoir analogues. From such patterns, Fischer (1964) inferred the importance of climate variations from Milankovitch frequency in the cyclicity of Triassic shallow-marine carbonate deposits. To assess the accommodation space created by subsequent sea-level rises, Fischer constructed plots in which the cycle thickness is plotted against cycle number (proxy for time) and corrected for subsidence. Cycle thickness in excess of the subsidence is then taken as the amount of accommodation space created by sea-level rise (Fischer, 1964; Goldhammer, Dunn, & Hardie, 1987, 1990; Osleger & Read, 1991; Sadler, Osleger, & Montañez, 1993). The Fischer-plot method combined with spectral analysis of the cyclicity led to numerous studies (Cozzi, Hinnov, & Hardie, 2005; Goldhammer et al., 1987; Hinnov & Goldhammer, 1991; Husinec, Basch, Rose, & Read, 2008; Read & Goldhammer, 1988) that discuss the presence of orbitally controlled sea-level oscillations with Milankovitch frequencies within Triassic shallow-water carbonates. Inference that variation in cycle thickness records variation in the amplitude of sea-level rise was based on the principal assumption that each carbonate cycle represents the complete infill of accommodation space during sea-level rise and is marked by a shallowing-upward facies succession that terminates in an exposure surface. Other studies have disputed the notion that full-length Milankovitch frequencies are recorded in the platform cycles of Triassic carbonate platforms and have provided very strong evidence for the presence of sub-Milankovitch cyclicity (Brack, Mundil, Oberli, Meier, & Rieber, 1996; Mundil et al., 2003; Reijmer, Sprenger, Ten Kate, Schlager, & Krystyn, 1994; Schwarzacher, 1993; Schwarzacher & Haas, 1986; Zühlke, Bechstädts, & Mundil, 2003). All of these studies provided the foundation for cyclostratigraphic studies in shallow-marine carbonates, which assessed simultaneously Milankovitch cyclicity and the amplitude of sea-level changes (Kerans & Tinker, 1997). Other authors, however, argued strongly that processes of peritidal carbonate accumulation are stochastic, indicating that that the thickness frequencies of these deposits did not carry a signature of rhythmic eustatic forcing (Drummond & Wilkinson, 1993; Wilkinson, Drummond, Rothman, & Diedrich, 1997).

Several studies (Bergman, Westphal, Janson, Poiriez, & Eberli, 2010; Boss & Rasmussen, 1995; Eberli, 2013) pointed out that uncertainties do occur when assuming that stacked cycle thicknesses and facies variations correlate with the cyclic changes in water depth. Studies of the GBB as a modern example show that the Holocene sediment infill of the available accommodation space is a recent feature west of Andros Island (Mallof & Grotzinger, 2012) and the major part of the platform has remained unfilled (Bergman et al., 2010; Boss & Rasmussen, 1995). For ancient carbonate platforms, similar observations were made suggesting that infill of accommodation space was a more random process, e.g., the Maiella platform margin (Central Italy; Eberli, 2013), the Latemar limestone platform (northern Italy; Kemp, Manen, Pollitt, & Burgess, 2016), and the Cambrian and Ordovician peritidal sequences exposed throughout the south-central Appalachians (Wilkinson, Diedrich, & Drummond, 1996). In these studies, unpredictable variations were found as variable or incomplete cycle thickness, variable cycle frequency, and absence of a shallowing-upward trend within the cycle (Eberli, 2013; Kemp et al., 2016; Wilkinson et al., 1996). Other uncertainties relate to the partial erosion of sediment infilling accommodation space during sea-level fall as well as facies-dependent variations in sediment compaction (Strasser, Pittet, Hillgärtner, & Pasquier, 1999). Hence, evaluating relationships between the rates of carbonate deposition, facies distribution, and ambient accommodation space remains challenging. This study aims to examine the relationships between accommodation space, sediment thickness, and facies distribution on a modern platform where sea-level history, water depth, and sediment types are well constrained.

The variations in thickness of the Holocene sediments on the western GBB and Little Bahama Bank have been measured at several locations (Beach & Ginsburg, 1980; Boss, 1994; Cruz, 2008; Harris, 1979; Rankey & Doolittle, 1992), but not yet in the western area of GBB. In the present study, the variations in sediment thicknesses for the Holocene and upper Pleistocene are mapped and modelled using a high-resolution 2D-seismic survey covering the length and width of the western portion of GBB. These variations were related to the in situ water-depth measurements and facies analysis of Reijmer et al. (2009). To test the assumption whether sediment thickness is related to variations in sea-level, two questions need to be answered: (i) does a correlation exist between the Holocene cycle thickness and the present-day water depth, and if not, (ii) what are the dominant factors controlling sediment thickness on GBB? Data discussed in this study demonstrate the lack of correlation between the Holocene sediment thickness, facies type, and accommodation space (i.e., water depth). They strongly suggest that the hydrodynamic energy level within the lagoon determines the infill of accommodation space and the facies distribution pattern. The results document that using cycle thickness and facies
change of shallow-marine carbonates as a measure for the amplitude of relative sea-level change should be treated with great care.

2 | GEOLOGICAL AND DEPOSITIONAL SETTING

Great Bahama Bank, the largest carbonate platform within the Bahamian archipelago, is located on the south-eastern continental margin of the North-American plate (Cloud, 1962; Purdy, 1963a; Smith, 1940) (Figure 1). The Pleistocene and Holocene evolution of GBB relates to repeated platform growth during sea-level highstands (Aurell, McNeill, Guyomard, & Kindler, 1995; Beach & Ginsburg, 1980; Kievman, 1998; Manfrino & Ginsburg, 2001) combined with typical highstand shedding of platform sediments into the surrounding basins (Betzler, Reijmer, Bernet, Eberli, & Anslemetti, 1999; Droxler & Schlager, 1985; Reijmer, Schlager, Bosscher, Beets, & McNeill, 1992; Reijmer, Schlager, & Droxler, 1988; Schlager, Reijmer, & Droxler, 1994). During sea-level lowstands, karst horizons developed on the platform surface due to subaerial exposure (Kievman, 1998; Manfrino & Ginsburg, 2001; McNeill, Grammer, & Williams, 1998). These horizons can easily be traced in seismic sections due to their strong reflections (Cruz, 2008).

Extensive research has been carried out to determine the modern facies distribution on GBB (Harris, Purkis, Ellis, Swart, & Reijmer, 2015; Purdy, 1963a, 1963b; Reijmer et al., 2009; Traverse & Ginsburg, 1966). The maps in Figure 2 show that nonskeletal, mud-dominated sediments mark the inner platform, whereas skeletal, coarse-grained sediments dominate at the platform edge (Enos, 1974; Purdy, 1963a, 1963b; Reijmer et al., 2009). Very fine-grained sediments occur in protected areas, such as the lee side of Andros (Maloof & Grotzinger, 2012). In agreement with earlier studies, Reijmer et al. (2009) and Harris et al. (2015) suggested that the sediment distribution of GBB is a result of a combination of factors that control the energy distribution across the platform and thus the type of sedimentation, tidal velocities, the dominant wind directions, wave energy, and the interaction with the inherited Pleistocene topography.

3 | METHODS

3.1 | Acquisition

The data set consists of 13 high-resolution shallow seismic lines with a total length of approximately 560 km that are either north–south or east–west orientated (Figure 1). The seismic survey was carried out with a X-STAR Full SpectrumTM Digital Sub-Bottom Profiler transmitting a FM pulse with 20 ms of length and a linear sweep of 2–10 kHz bandwidth during the GBB Geolithochem expedition in September 2007: 13 seismic surveys (yellow numbers) consisting of 201 SEGY-lines with 326 in situ water-depth measurements; measured every 1.67 km. Map modified after Reijmer et al. (2009)

3.2 | Seismic analysis

Two important seismic horizons have been recognized in earlier studies (Cruz, 2008) in CHIRP data from the shallow GBB subsurface: the seabed and the Pleistocene top (karst). As it is assumed that the Holocene layer on GBB consists of a single carbonate cycle starting from the onset of an interglacial period with sea-level rise after the last
Pleistocene glacial period (Harris et al., 2015), the difference in depth between the seabed and top-Pleistocene surface represents the thickness of the Holocene sediments (Figure 3). A third horizon (Figure 3) can locally be recognized to occur below the top of the Pleistocene and is interpreted as a karst horizon during a period of exposure within the Pleistocene (Cruz, 2008). The identified horizons were transferred into depth surfaces in Petrel™ using a velocity model in which a P-wave velocity of 1,543 m/s was used for sea water (calculation in Supplementary Materials). The acoustic velocities for the Holocene and top-Pleistocene layer were based on averaged values obtained from petrophysical analyses on the deep drill holes Clino and Unda from the Bahamas Drilling Project (Anselmetti & Eberli, 1993), cores from Long Key and Stock Island in the Florida Keys (Anselmetti, Von Salis, Cunningham, & Eberli, 1997), and Leg 101 and 166 cores from the Ocean Drilling Project (Anselmetti, Eberli, & Ding, 2000; Kenter, Anselmetti, Kramer, Westphal, & Vandamme, 2002). For the Holocene layer, this resulted in a minimum P-wave velocity of 1,650 m/s for very fine wackestones and a maximum velocity of 1,850 m/s for grainstones (Figure 4). The top-Pleistocene sediments range from 3,200 m/s to 5,300 m/s (Anselmetti & Eberli, 1993), corresponding to the minimum and maximum P-wave velocities used in our velocity model for the second layer between the Pleistocene top and the within-Pleistocene karst horizon. A detailed description of the seismic processing and the thickness model can be found in the Supplementary Materials.

4 | RESULTS AND INTERPRETATION

4.1 | Seismic characteristics and sedimentary features

The seismic analysis shows three horizons in the shallow subsurface of GBB: the sea floor, the Pleistocene top, and a lower karst level, assumed to be of Pleistocene age (Figure 5). Multiples had to be treated with care during the seismic analysis, as they are not everywhere as obvious as shown in Figure 5C and D. The sea floor topography is rather flat in the north-eastern part of the platform, and slightly inclined with an overall south-westwards dip in the
Towards the south-west of the study area, the sea floor becomes more irregular, especially along the platform edge where hills are visible (Figure 5D). These hills form a continuous belt along the western margin of the platform (Line 13 in Figure 1) and occur in deeper water (>9 m) than the rest of the sediments in the study area.

The top-Pleistocene surface is irregular throughout the entire research area (Figure 5). Locally, sinkholes or potential channels created depressions in the Pleistocene top and cut through the karst level below (Figure 5B). In other areas, the top-Pleistocene surface forms hills or rock ridges, or elevated exposure surfaces that nearly reach the present-day sea floor (Figure 5E).

The within-Pleistocene karst level (Figure 5C, D and E) shows an irregular surface similar to the Pleistocene top. Likewise, sinkholes and channels form depressions in its surface (Figure 5C), while rock ridges or hills locally form elevated areas that interrupt the top-Pleistocene surface (Figure 5B). This karst level is not observed in the western area along and close to the margin (Line 12 and 13 in Figure 1) and in the most northern part (Line 1 and the northern part of Line 2 in Figure 1).

Since the seismic survey of this study only covers a small part of GBB, it is possible that some relationships are underestimated, such as a potential correlation between sediment thickness and facies type or between the water depth and type of facies. Incompleteness in the seismic survey furthermore led to extrapolation of the model towards its boundaries, and thus there is some uncertainty regarding the sediment thickness and water depth in these areas. Furthermore, the time-to-depth conversion caused uncertainties in the depth of each horizon and thus the layer thickness.

In this study, it was assumed that the Holocene layer was still unconsolidated and hence had very low acoustic velocities varying between 1,500 m/s and 1,800 m/s (Anselmetti & Eberli, 1993). The Pleistocene layer is likely to be consolidated, and thus a large range in acoustic properties (3,200 m/s to 5,300 m/s) between mud-dominated carbonates and mud-free coarse-grained carbonates may occur.

FIGURE 3 Composite line 9 2D-converted. (A) Seismic section showing the horizons of interest: the seabed, the Pleistocene top, and the within-Pleistocene karst horizon. Multiples from the seabed are locally present. (B) Seismic section with the volume attribute “Structural Smoothing” to provide increased layer continuity and signal/noise ratio without sacrificing the vertical resolution. Processing artefacts are indicated as well as a sinkhole in the Pleistocene top. (C) Portion of (A) showing how the horizons were picked. (D) Location of this seismic section indicated on the map of GBB (red)

FIGURE 4 Graphic representation of the model input. Left: $V_p$-values for the mud-dominated model. Right: $V_p$-values for the mud-free model
Since sedimentary cores of the shallow subsurface of GBB were not at our disposal, the horizons could not be tied to known core data to decrease these uncertainties. Nonetheless, the relative thickness variations throughout the platform remain the same regardless of the magnitude of the acoustic velocity. The facies distribution over the platform and the facies variations within the subsurface have not been considered, and thus can either exaggerate or diminish the measured thickness variations.

4.2 | Depth of the sea floor

The sea floor shows a trend of shallowing towards Andros Island and deepening towards the platform edges and interior (Figure 6). The sea floor is deepest (8 to 10 m) in the most northern part, in the western area where the hills or ridges occur, and in the south-western part of the study area (Figure 6). The depth map in Figure 6 is created by a time-to-depth conversion of the seabed horizon in Petrel™ with a similar V₀-value for both the mud-dominated model and the mud-free, coarse-grained model resulting in a single depth map.

4.3 | Depth of the Pleistocene top

Although the top-Pleistocene surface is more irregular than the present-day sea floor, it shows roughly the same morphology trend throughout the platform: it is shallowest in the centre of the study area towards Andros Island, and it is deepest in the north, along the western platform edge, and in the south-western part (Figure 7). The deepest values are outliers where sinkholes or deep depressions
formed by karst-related processes developed in the top-Pleistocene surface.

Sediments have a range in $V_p$ between 1,500 and 1,800 m/s at the time of deposition (Anselmetti & Eberli, 1993). Therefore, the depth maps in Figure 7 were both created with a time-to-depth conversion in Petrel™ and minimum and maximum $V_p$-values of 3,200 m/s and 5,300 m/s, respectively, according to the $V_p$-range of consolidated Pleistocene sediments discussed by Anselmetti and Eberli (1993), resulting in two depth maps: one for mud-dominated sediments (Figure 7A) and one for mud-free coarse-grained sediments (Figure 7B).

The within-Pleistocene karst level is shallowest in the center of the study area and deepens towards the south-west. Sinkholes, possible channels, and the south-western corner of the study area exhibit the greatest depths (>20 m). The difference between the two maps is approximately 2 m for the minimum depths and 6 m for the maximum depths.

4.4 | Depth of the within-Pleistocene karst level

The within-Pleistocene karst level deepens towards the south-west and shallows towards Andros Island (Figure 8). This study will focus on the depth variations at and around the seismic lines; this is because of a Petrel™ induced bias with extrapolation towards the model edges lacking data coverage (e.g., Andros Island). The uppermost Pleistocene layer is modelled with a time-to-depth conversion in Petrel™ and minimum and maximum $V_p$-values of 3,200 m/s and 5,300 m/s, respectively, according to the $V_p$-range of consolidated Pleistocene sediments discussed by Anselmetti and Eberli (1993), resulting in two depth maps: one for mud-dominated sediments (Figure 8A) and one for mud-free coarse-grained sediments (Figure 8B).

4.5 | Thickness of the Holocene sediments on GBB

The Holocene layer on GBB is thinnest at the platform interior west of Andros Island, and thickens towards the platform edges and the south (Figure 9). The maximum values occur as outliers where sinkholes or potential channels created depressions in the Pleistocene top. The thickness maps in Figure 9 are created by a thickness calculation in Petrel™ using the difference between the depth maps of the seabed and the Pleistocene top for both the mud-dominated model (Figure 9A) and the mud-free coarse-grained model (Figure 9B). This results in a thickness difference of approximately 0.5 m, while the thickness distribution throughout the platform remains similar.

4.6 | Thickness of the uppermost Pleistocene layer

Figure 10 shows that the uppermost Pleistocene layer roughly thickens towards the south-west. Since the model is extrapolated towards Andros Island, we will not speculate about this area. The thickness maps (Figure 10) result from a calculation in Petrel™ that subtracted the lower Pleistocene surface from the top-Pleistocene surface. The depth of the within-Pleistocene surface was modelled with two different $V_0$-values for consolidated carbonate sediments resulting in two different thickness maps (Figure 10). Depending on the type of sediment, its acoustic properties change, and thus the thickness of the Pleistocene layer changes accordingly. Hence, the mud-dominated model results in an average layer thickness of 3.5 m (Figure 10A), and an average layer thickness of 5.5 m is proposed for the grainstone model (Figure 10B).
Based on the thickness maps and reflector depth estimates of the top-Pleistocene and within-Pleistocene reflectors, a correlation is proposed with the lithological variations as published by Beach and Ginsburg (1980). They described a core transect running along the GBB reef and lagoon, and Andros Island (Figure 11) in which two upper intervals of Holocene and Pleistocene age showed alternating unstratified wackestones, packstones, and grainstones (Beach & Ginsburg, 1980). The uppermost interval of the Lucayan Limestone, 0 to 10 m in core, is characterized by nonskeletal components, e.g., peloids and ooids, while the lower interval is dominated by skeletal components, 10 to 40 m in core (Beach & Ginsburg, 1980).

The depth estimate of 9 m for the top-Pleistocene reflector compares well with the values from the Petrel model with 8 m (Figure 7A) and 9 m (Figure 7B). The same holds for the thickness estimate for the Holocene sequence with 4 m (Figure 10) and the same value obtained in the Petrel estimate (compare Figure 11 with Figure 9). The value for the within-Pleistocene reflector, most likely representing the major lithological transition from nonskeletal dominated to skeletal dominated sediments in the Beach and Ginsburg (1980) profile, is slightly overestimated when interpreting the major lithological transition in the Beach and Ginsburg (1980) profile at ca. 16 m (Figure 11) compared to the Petrel values of 10 m (Figure 8A) or 13 to 14 m (Figure 8B). The thickness estimate of the uppermost Pleistocene sequence taken from the Beach and Ginsburg (1980) profile, however, agrees with the Petrel estimates; compare the 4 m shown in Figure 11 with the 3 m mudstone model of Figure 10A and the 5 m grainstone model of Figure 10B.

FIGURE 7 Depth top-Pleistocene surface (C.I. = 2 m). (A) Mud-dominated model. (B) Mud-free coarse-grained model. The differences in depth between A and B are approximately 0.5 m; both indicate a shallowing trend towards Andros Island. Seismic lines in white.
DISCUSSION

The aim of this study was to demonstrate that the assumptions of Fischer (1964), Goldhammer et al. (1987, 1990), Read and Goldhammer (1988), and Cozzi et al. (2005), that shallow-water carbonates fill their accommodation space completely during sea-level rise, and thus that cycle thickness is a measure of sea-level change, should be evaluated with great care. Other studies (Drummond & Wilkinson, 1993; Strasser et al., 1999; Wilkinson et al., 1997) showed that the assumption might be correct only when the cycle top is intertidal and erosion is absent, and when the sediment column has been decompacted. Often shallow-water carbonate sequences contain incomplete or missing cycles (Eberli, 2013; Kemp et al., 2016; Strasser, 2015). Many ancient carbonate platforms showed an exponential thickness frequency distribution (Drummond & Wilkinson, 1993; Wilkinson et al., 1997) disproving the occurrence of any periodic process within such cycles. Strasser et al. (1999) also discussed a series of scenarios that may result in variations in platform cycles like autocyclic processes mimicking allocyclic facies variations, the development of multiple sequences during one change of accommodation space, or reduced sediment production resulting in nondeposition or non-preservation. Other processes like variations in accommodation space when flooding an exposed carbonate platform or differential compaction of individual facies may result in thickness variations of the sedimentary cycles lacking a proper reflection of the available accommodation space. The new seismic data cover a total length of approximately 560 km crossing several facies belts on western GBB. Hence, in addition to visualizing the water-

FIGURE 8 Depth to the within-Pleistocene karst layer (C.I. = 4 m). (A) Mud-dominated model. (B) Mud-free coarse-grained model. The differences between A and B are ca. 2 m in minimum depths and 6 m in maximum depths. Highest values in the platform interior. Seismic lines in white.

5 | DISCUSSION
depth and sediment thickness variations, the data set can also be studied to evaluate the relationship between water depth and facies distribution.

5.1 | The Petrel™ model

The bathymetric map produced in this study (Figure 12B) is fairly consistent with that of Harris et al. (2015; Figure 12A) with regard to the position and contours of shallow and deep areas. The water depths from this study are ca. 2 m higher than those of Harris et al. (2015). The latter were based on a water colour—water depth proxy derived from satellite data while the data used in this study were directly measured at each sampling point. The greatest water depths (8 to 11 m) occur in the south-west of the study area and close to the platform margin in the west (Figure 12B). The shallow areas (3 to 6 m) are located in the northern part of the study area, in the proximity of Andros Island, and close to the platform rim in the west corresponding to the pattern observed on the bathymetric map of Harris et al. (2015) (Figure 12).

5.2 | Holocene sediment thickness, accommodation space, and facies distribution

Since Holocene sea-level rise has more or less stabilized and reached its maximum (Camoin & Webster, 2015; Thompson, Curran, Wilson, & White, 2011), ignoring greenhouse gas-related rise sea-level, it might be argued that the current accommodation space could be filled in the near future if sediment production on the platform remains at current levels. The peritidal carbonates positioned at the
western side of Andros Island showed a tidal influenced shallow-upward trend that started 1,200 years ago despite the fact that the area became flooded at ca. 4,500 years (Maloof & Grotzinger, 2012). So, the infill of accommodation space of that part of the platform in response to the postglacial rise in sea-level is only a recent phenomenon.

Several studies on Florida Bay (Bosence, 1989; Nelsen & Ginsburg, 1986; Stockman, Ginsburg, & Shinn, 1967) and Little Bahama Bank (Neumann & Land, 1975) have shown that recent carbonate sediment production exceeded the accommodation space of these settings and would be sufficient to fill the accommodation space of carbonate platforms like GBB during the 8,200 years since the onset of Holocene flooding (Boss & Rasmussen, 1995). Sediment export from GBB started 7,230 years BP and periplatform ooze was deposited on the western flank of GBB with sedimentation rates of up to 13.8 m/kyr (Roth & Reijmer, 2004, 2005). At 4.6 ka, sea-level was still −6 m below present values (Boss & Rasmussen, 1995; Roth & Reijmer, 2004). The last part of the Holocene sea-level rise was estimated at 1 to 1.5 m/kyr as of 9.6 ka to stabilization at 2.5 to 3 ka (e.g., Indian Ocean: Zinke et al., 2003b; Camoin, Montaggioni, & Braithwaite, 2004; Global overview: Camoin & Webster, 2015). Holocene sedimentation rates on GBB vary between 0.1 and 0.4 m/kyr for the northern part of GBB (Boss & Rasmussen, 1995) and are equal or somewhat less than those known from other carbonate platforms, for example, Mayotte in the Indian Ocean with 0.35 m/kyr (Zinke, Reijmer, & Thomassin, 2003a; Zinke et al., 2003b) and Belize with up to 0.8 m/kyr (Gischler, 2003). The introduction of currents on the GBB platform
as soon as it was flooded, identified by sediment export rates, also resulted in reduced platform sedimentation rates and prevented filling of large parts of the available accommodation space. The grain-size variations in the Holocene sediment wedge of GBB confirm that variations in current strength existed across the platform, which could be related to the strength and location of the trade wind system and oceanographic circulation (Roth & Reijmer, 2004, 2005).

A comparable scenario with high sediment export rates (Droxler & Schlager, 1985; Reijmer et al., 1988; Rendle-Bühring & Reijmer, 2005) and related currents sweeping the platform must have existed during the Pleistocene interglacial MIS 5e, a period with a similar sea-level rise as the modern with 2.6 m/kyr (Thompson et al., 2011). As discussed by Eberli (2013), the Pleistocene top would still be exposed if the accommodation space had filled up during

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**FIGURE 11** Location of core borings across Great Bahama Bank and associated profile showing the facies variations. Arrows mark the assumed positions of the top-Pleistocene and within-Pleistocene horizons present in the seismic profiles in Figures 3 and 5. After Beach and Ginsburg (1980)
the previous 5e sea-level highstand when sea-level was about 6–9 m higher than today (Hearty, Hollin, Neumann, O’Leary, & McCulloch, 2007).

Other studies (Cruz, 2008; Ginsburg, 2005; Harris, 1979; Rankey, Riegl, & Steffen, 2006; Reeder & Rankey, 2008) provided evidence that the Holocene sediments on GBB tend to fill the accommodation space at the high-energy margins where tidal ooid shoals (mud-poor packstone and grainstone) occur, while large parts of the inner platform realm remain unfilled. Reijmer et al. (2009) showed that mud-rich facies (mudstone, wackestone, and mud-rich packstone) mainly occur in deeper environments, and that mud-free coarse-grained facies (mud-poor packstone and grainstone) are most abundant at the platform edges, elevated areas in the platform interior and in the southern part of the platform. It is evident that the tidal ooid shoals fully fill the accommodation space (e.g., Cat Cay, Joulters Cay, south of the Tongue of the Ocean in Figure 2). However, mud-free coarse-grained facies occur throughout the entire range of water depths (Figure 13) and even occupy locations with the greatest water depths (10 to 11 m) in the southern platform interior of GBB (Figure 12A and B). Thus, mud-free coarse-grained sediments do not exclusively fill accommodation space.

Similar sedimentation patterns with filled atoll and platform edges and unfilled lagoons have been observed for the atolls of Belize in the Caribbean (Gischler, 2003), Mayotte (Zinke, Reijmer, & Thomassin, 2001; Zinke et al., 2003a, 2003b) and the Maldives (Gischler, 2006; Perry et al., 2013; Klostermann & Gischler, 2015) in the Indian Ocean, the Great Barrier Reef (Davies & Kinsey, 1977;
Harris, Vila-Concejo, & Webster, 2014; Purdy & Gischler, 2005) in the Coral Sea, and Bora Bora in the Pacific Ocean (Gischler et al., 2016; Isaack et al., 2016). For Cay Sal Bank (positioned west of GBB), Seranilla Bank (Triffleman, Hallock, & Hine, 1992), Cat Island Bank (Dominguez, Mullins, & Hine, 1988), and western Little Bahama Bank, Purkis et al. (2014) discussed that these carbonate platforms did not keep up with sea-level, while carbonate production on the platform did not keep up with sediment export, resulting in platforms that lack platform-margin reefs. So, being at what we may consider as the end of a depositional cycle, only limited parts of the lagoons and even the margins of various carbonate platforms and atolls are marked by a complete infill of accommodation space. Maloof and Grotzinger (2012) already showed that accommodation space of the GBB lagoon west of Andros Island was infilled, but whether this will be the end product remains open.

The occurrence of each facies type is highly random rather than restricted to a specific range in water depth (Figures 13 and 14), but whether this is because the present-day sediment distribution is not in equilibrium with water depth or if it reflects a mere random distribution, remains to be determined. Figure 13 shows a weak inverse trend of muddier sediments (i.e., mudstone, wackestone, and mud-rich packstone) prevailing in shallower areas, whereas the grainier mud-free sediments (i.e., mud-poor packstone and grainstone) predominate in deeper water. In addition, the facies map of Reijmer et al. (2009) shows a roughly concentric facies distribution in the lee of Andros Island rather than a random facies distribution (Figure 2B) accompanied by shallowing and thinning of the Holocene sediments towards Andros Island (Figures 9 and 12). Reijmer et al. (2009) measured a clear trend in decreasing grain size towards Andros Island with decreasing water energy functioning as a topographic barrier. On the other hand, grainier mud-free sediments are mainly deposited at places where an influx of water occurs such as in the southern part of GBB and along the platform edges (Cruz, 2008; Ginsburg, 2005; Harris, 1979; Purkis et al., 2017; Rankey et al., 2006). The mud-free coarse-grained sediments form the thickest part of the Holocene layer, whereas the fine-grained muddy sediments tend to be thinner. Nonetheless, areas with the thickest deposits consisting of grainy sediments also fail to fill the accommodation space. Figure 14 highlights total randomness in the occurrence of both the mud-rich and mud-poor facies and shows very clearly that each facies type occurs throughout the whole range of water depths with varying sediment thickness. The lack of a strong correlation between the types of facies, accommodation space, and sediment thickness imply that other factors—such as the inherited Pleistocene topography and present-day energy distribution due to tidal currents, waves, and prevailing wind directions—control the sedimentation rate and its distribution.

5.3 | The role of the Pleistocene topography

The inherited Pleistocene topography was addressed in previous studies (Eberli, 2013; Ginsburg, 2005; Harris et al., 2015; Reijmer et al., 2009) as one of the reasons that accommodation space on GBB has been filled in an irregular manner. Purdy (1961) suggested that the Cat Cay ooid shoals were deposited on a Pleistocene ridge; however,
Cruz (2008) as well as Sparks and Rankey (2013) for Lily Bank on Little Bahama Bank showed that these shoals were located next to the Pleistocene ridge and were deposited on a preexisting flat surface. Figure 5D demonstrates a similar depositional setting: the highly irregular hills or ridges along the western margin (Line 13 in Figure 1) accumulate on a fairly flat Pleistocene surface. This implies that sediment thickness is not related to a specific type of seabed relief but rather influenced by hydrodynamics (Sparks & Rankey, 2013). Another remarkable feature is that the Holocene sequence also infills valleys and sinkholes producing a smoothed present, sea-bottom topography (Figures 3 and 5B and C).

Arguably the most obvious influence of the Pleistocene topography is the effect that Andros Island has—as a preserved Pleistocene subaerial exposure surface—on the type of sediments: the western lee side of Andros Island is protected from strong tidal currents and the easterly trade winds. Consequently, this area predominately consists of mudstones and wackestones (Figure 14B). However, the negative topography (valleys, sinkholes) does not result in recognizable energy funnelling and thus does not influence the facies distribution. The latter pattern contrasts with the findings of Purkis et al. (2014) for Cay Sal Bank where the Holocene sediment thickness, the biotic, and the sediment distribution are controlled by the Pleistocene karst topography with its buried sinkholes.

5.4 | The uppermost Pleistocene sequence

The Pleistocene displays an increase in the number of sediment cycles and a concomitant cycle thickness decrease towards the platform interior (Figure 11; Anselmetti & Eberli, 1993; Beach & Ginsburg, 1980; Kievman, 1998). This trend of increasing thickness towards the platform margins is also seen in the thickness maps of the Holocene and uppermost Pleistocene layer (Figures 9 and 10). Thompson and Goldstein (2005) and Thompson et al.
(2011) pointed out that the MIS 5e sea-level highstand for the Bahamas is marked by two highstands separated by a lowstand, which might have produced more than one cycle on the platform top. This might explain why the uppermost Pleistocene layer in this study is not present across the entire extent of the study area (Figures 8 and 10).

The sea-level curve of Lisiecki and Raymo (2005) shows very clearly that the sea-level amplitude differs for each cycle throughout the Pleistocene. During MIS 5e, the sea-level was 6–9 m higher than modern sea-level (Hearty et al., 2007; Thompson & Goldstein, 2005), and hence when all accommodation space would have filled up during this period, the topography of the present-day platform would have been much higher and still would be entirely exposed. However, the only exposed Pleistocene remnants are the islands such as Andros Island and New Providence. On the other hand, sea-level was much lower than present during MIS 7 and most other MIS stages, e.g., 9, 11, during the Pleistocene, and thus sedimentation on the platform was limited or absent. Moreover, our study shows that the sediment thickness varied extensively throughout the platform during the last Pleistocene highstand MIS 5 (Figure 10). This is also seen in the cores from Unda and Clino (Anselmetti & Eberli, 1993).

5.5 | The within-Pleistocene reflector

The within-Pleistocene reflector present in most of the profiles most likely represents the transition from nonskeletal to skeletal dominated inner platform sediments as shown in the Beach and Ginsburg (1980) profile (Figure 11, lower arrow). The thickness estimate of the uppermost Pleistocene sequence shown in the Beach and Ginsburg (1980) depositional texture distribution (Figure 11) matches the Petrel estimates; compare the 4 m shown in Figure 11 with the 3 m calculation of the mudstone model (Figure 10A) and the 5 m of the grainstone model (Figure 10B). The facies change and associated diagenetic modifications of the original sediments apparently produced enough impedance contrast at this transition for it to show up in the seismic profiles.

5.6 | Water energy

While the data shown in Figures 12, 13 and 14 suggest a lack of correlation between facies type and water depth, the facies distribution seems to follow specific patterns when it comes to the water energy (Cruz, 2008; Purkis et al., 2017). In low-energy zones (e.g., inner platform and west of Andros Island), deposition is dominated by fine-grained mud-rich sediments. Mud-free sediments are deposited in high-energy areas where strong currents enter the platform; the southern and northern part of the platform, south of the Tongue of the Ocean and at Joulters Cay. Furthermore, both Reijmer et al. (2009) and Harris et al. (2015) address the influence of topography on energy distribution: areas that are protected by a topographic barrier such as Andros Island are shallower and are dominated by muddy sediments, whereas at places where strong tidal currents can freely enter the platform deeper water areas dominated by grainy mud-free deposition result (e.g., the northernmost part of GBB). While the facies distribution of Beach and Ginsburg (1980) shows across platform variations through time (Figure 11), there is no regular stack of facies repetitions with regular cycle thicknesses suggesting variations in the energy distribution across the platform through time.

5.7 | Accommodation space and cyclicity analysis

Based on satellite data and a comparison with earlier studies by Reijmer et al. (2009), Swart, Reijmer, and Otto (2009) and Harris et al. (2015), Purkis and Harris (2016) distinguished four types of accommodation space infill patterns on GBB, namely overfilled, filled, underfilled, and unfilled. In accordance with Harris et al. (2015), they also noted that facies distributions over GBB were not exclusively associated or linked to water depth. The distribution of islands played an important role in sediment distribution patterns and the infill of accommodation space. However, under the assumption that present-day sediment distribution is in equilibrium with present-day water depths, which cannot be demonstrated unequivocally, our study shows that unfilled and underfilled accommodation space has no direct link to the shallow-water facies distribution patterns.

Numerous studies analysing sediment thickness distributions of shallow-marine and peritidal carbonate deposits rely on the assumption that accommodation space is filled in across the entire shallow-water area (Burgess & Pollitt, 2012; Cozzi et al., 2005; Goldhammer et al., 1987; Hinnov & Goldhammer, 1991). In their discussion on generic cycle types, Soreghan and Dickinson (1994, 1995) emphasized that cycle thickness cannot be directly linked to magnitudes of eustatic sea-level change. Wilkinson, Frank, and Klein (1995), Wilkinson et al. (1997) highlighted that lithofacies composition and water depth may be unrelated and that changes in water depth may not be reflected in changes in lithofacies. Related studies have strongly argued for the stochastic nature of peritidal carbonate accumulation and discussed that the thickness frequencies of these deposits did not carry any influence of rhythmic eustatic forcing (Drummond & Wilkinson, 1993; Wilkinson et al., 1997). The facies distribution and sediment thickness observed along the depth transect shown in Figure 14 confirm the ideas discussed in the aforementioned studies of Drummond and Wilkinson (1993), and Wilkinson et al. (1995, 1997).
The observed variations in sediment facies and water depth may result from external forcing mechanisms overpowering the system-inherent signals (Rankey, 2002). Further variations may be caused by the migration of facies belts following or neglecting Walthers Law (Soreghan, 1997) or location-dependent facies zones, the so-called disobedient sediments of Ginsburg (2005). The end product may be a complex mosaic of sediment types draped over a depositional surface that changed repeatedly through time because of variations in eustatic, sedimentologic, and/or tectonic forcing (Rankey, 2004; Wilkinson & Drummond, 2004). For the GBB distinct variations in topography characterized, the depositional surface flooded during the Holocene sea-level rise (Boss & Rasmussen, 1995; Figure 7 this study). So, straight from the start varying physical conditions existed that ultimately resulted in the variations in sediment facies recorded along the sea bottom following the seismic profiles. Whether the Markov chain-based modelling experiments of Dyer, Maloof, Purkis, and Harris (2018) relate to the actual and ancient sediment behaviour, and associated facies distribution patterns on carbonate platforms remains questionable.

In his summary of the analysis of Berriasian platform cycles in the Swiss and French Jura, Strasser (2015) noted that thick elementary sequences occurred in the central parts of the platform sequences implying higher accommodation space, which might reflect specific hydrodynamics for this platform while such a one to one relationship was not found on GBB.

In various modelling studies, the assumption is made that carbonate accumulation on the platform top relates to water-depth dependent sediment production associated with various production profiles, e.g., euphotic, oligophotic, and aphotic (Burgess, 2016; Burgess & Pollitt, 2012; Hill, Wood, Curtis, & Tetzlaff, 2012; Kemp et al., 2016). The data from GBB, however, show that hydrodynamic processes play an important role in steering the sediment thickness distribution on the platform. This thus casts doubt on the accumulation pattern assumptions used in modelling studies. Kemp et al. (2016) noted that when modelling the infill of accommodation space and cycle completeness, nutrient availability, temperature and lateral transport were additional factors that should be considered besides the main processes, e.g., production rate, subsidence, erosion, and sea-level. Our study shows that the hydrodynamic patterns that develop on carbonate platforms through time after the platform is reflooded may be an important process in steering the infill of accommodation space. For the atolls of Belize (Gischler, 2003), Mayotte (Zinke et al., 2001, 2003a, 2003b), the Maldives (Klostermann & Gischler, 2015; Perry et al., 2013), the Great Barrier Reef (Purdy & Gischler, 2005), and Bora Bora (Gischler et al., 2016; Isaack et al., 2016), similar patterns were found. The Holocene flooding history of Cay Sal Bank, situated west of GBB, showed an even more dramatic scenario with a carbonate platform that did not keep up with sea-level while the hydrodynamics on the platform top resulted in enhanced sediment export outpacing carbonate production, resulting in a semi-drowned carbonate platform (Purkis et al., 2014). Hence, allocyclic control by climate variations and related wind and currents patterns appear to have a high impact on the sediment distribution patterns of individual carbonate platforms.

6 | CONCLUSIONS

New seismic data from the shallow subsurface of GBB show that the sedimentation cycle thicknesses of the studied shallow-marine carbonates are not in equilibrium with the amplitude of orbitally driven sea-level change and associated infill of accommodation space. The seismic analyses and surface modelling combined with in situ water-depth measurements revealed that sediment thickness is not related to water depth, and thus not to present-day accommodation space. In addition, it was disclosed that within the lagoon the type of facies is not restricted to a certain range of sediment thicknesses.

This study showed that the sediment distribution patterns and the associated facies types are controlled by energy distribution across the GBB platform, which is installed immediately during the reflooding of the platform and relies on the interplay between tidal currents, waves, prevailing wind directions, influx from ocean water, and the inherited topography. For the platform interior only, a weak correlation was observed between facies type and water depth in which coarse-grained mud-free sediments seem to prevail in deeper waters on the platform, but more data are needed to confirm this trend. The inherited Pleistocene topography influenced energy distribution on the platform in such a way that mud-dominated sediments are deposited in protected shallow-water areas (west of Andros Island), whereas grainy mud-free sediments predominate in areas where strong currents enter the platform, e.g., north of Andros, south of the Tongue of the Ocean, at Joulters Cay, and in the south-western part of GBB.

The sediment thickness distribution is highly unpredictable while the varying energy distribution leads to irregular sediment (re-) distribution as well as a steady and large off-bank transport of the sediments. These processes result in an incomplete sediment record of a single carbonate sedimentation cycle on the platform, which confirms earlier studies that highlighted that the sediment thickness of shallow-marine carbonates cannot be a direct measure for the amplitude of orbitally controlled sea-level change and the associated creation of accommodation space.
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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.