Controls of depositional facies patterns on a modern carbonate platform: Insight from hydrodynamic modeling

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Abstract
Recent studies of Holocene deposits on Great Bahama Bank (GBB) have focused on mapping of sediment distribution, an analysis of the variable filling of accommodation space, a comparison between ooid sandbodies and an examination of whittings and mud production. Collectively, these studies provide insight into the variability in depositional facies that challenge outcrop and subsurface interpretations. Missing from these analyses, however, has been a scrutiny of the physical controls over deposition. To partially explore these controls, a hydrodynamic model forced by prevailing ocean hydrodynamics, tides, winds and atmospheric pressure was developed. Current intensity and direction can be examined at short time steps over 1 year, and GBB can be partitioned into zones of mean annual hydrodynamic energy. Areas of vigorous tidal exchange correspond to localities where platform margin ooid sand shoals have developed. There is a predictive relationship between increasing peak current velocity and increasing area of the sandbody for the Cat, Joulter and Schooners Cays and Tongue of the Ocean sites. A connection between platform-top hydrodynamics and the formation/suppression of whitings is evidenced west of Andros, suggesting a relationship between the production/deposition of platform-top muds and off-platform circulation. Filling of accommodation space can be partially related to platform topography and hydrodynamic flow. For instance, accommodation filling occurs locally along the platform margin by grainstones in areas of high tidal exchange as well as by mud accumulation leeward of islands. Conversely, the development of hiatal surfaces (sites of non-deposition) occurs in areas not sheltered by islands, such as the southern GBB, where platform-top currents are persistently vigorous. A broader understanding of platform-top currents and their diverse controls can aid interpretation of the rock record, including the type and distribution of platform-top sediments, the distribution of hiatal surfaces and, therefore, identification of locations which have the potential to host more complete depositional cycles.

KEYWORDS
accommodation, Great Bahama Bank, hydrodynamic model, ooids, whittings
1 | INTRODUCTION

Great Bahama Bank (GBB), a relatively flat-topped, isolated carbonate platform lying directly to the east of southern Florida, is a major modern location of carbonate deposition and a natural laboratory for investigating many facets of carbonate sedimentology. Decades of geological studies of various aspects of GBB have provided much of the understanding of processes of carbonate sedimentation and numerous geological models to illustrate depositional facies variations (summarized in Bathurst, 1975; James & Jones, 2016; Tucker & Wright, 1990). This immense platform covers an area of over 103,000 km$^2$ (590 km north–south extent and 160 km east–west), its margin extends for 3,088 km in length, and 60%, or 61,400 km$^2$, of the submerged portion of GBB lies in 5 m or less of water. Additionally, GBB displays a well-organized association of shallow, platform-top depositional environments across its breadth (Enos, 1974; Harris, Purkis, Ellis, Swart, & Reijmer, 2015; Kaczmarek, Hicks, Fullmer, Steffen, & Bachtel, 2010; Newell, Purdy, & Imbrie, 1960; Purdy, 1963a, 1963b; Purkis & Harris, 2016; Reijmer et al., 2009).

Recent investigations of Holocene sediments atop GBB have focused on: (a) platform-wide mapping of water depth (Figure 1a) and sediment distribution (Figure 1b) by Harris et al. (2015), (b) an examination of whitings occurrences and mud production, that is, the carbonate mud factory (Figure 1c) by Purkis et al. (2017), (c) a quantitative comparison between three key carbonate sandbodies that shows a range of depositional facies patterns, that is, the carbonate oolitic sand factory (Figure 1d) by Harris (2010) and Harris, Purkis, and Ellis (2011) and (d) a platform-wide assessment by Purkis and Harris (2016) showing where accommodation is filled and the facies responsible for the filling (Figure 1e). Collectively, these quantitative GIS-based studies were aimed to provide new insight into the variability in depositional facies in a preeminent modern setting, and to serve as analogues for outcrop and subsurface studies by providing a template that helps to address challenging subsurface correlations, in the development of rock and log-based geologic models and in the building of facies-based reservoir models. The added insight into depositional facies patterns also leads to new ‘guidelines’ for the sequence stratigraphic correlation of ancient carbonate platforms from the one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) perspective during the analysis of an outcrop or a cored reservoir. Missing from these analyses, however, has been a scrutiny of the physical controls over modern platform-top deposition, which, coupled with the enhanced mapping may provide even more robust quantitative comparative sedimentology and stratigraphy guidelines and predictability for interpretation of the ancient.

Previous studies have not entirely overlooked physical controls over deposition as evidenced by two examples – water depth and antecedent topography. The combined platform-wide facies and water-depth mapping of GBB by Harris et al. (2015) created an opportunity to investigate the role of bathymetric patterns as a potential primary control over flooding history, filling (accommodation) history and the resultant depositional facies. Figure 2a shows that there is actually a poor relationship between the occurrence of the mapped facies types and water depth, in that the grainier sediment types (mud-poor packstone, grainstone and rudstone) are abundant across the full range of water depths found across GBB. Muddier sediments (mud-rich packstone, wackestone and mudstone) also span a considerable depth range, but do not extend as deeply as the grainier facies. The poor relationship between facies and water depth is not surprising and has been reported elsewhere (Dyer, Maloof, Purkis, & Harris, 2018; Gischler, Isaack, & Hudson, 2017; Purkis, Harris, & Ellis, 2012; Purkis, Riegler, & Andréfouët, 2005; Purkis, Rowlands, & Kerr, 2015; Purkis & Vlaswinkel, 2012; Rankey, 2004; Weij, Reijmer, Eberli, & Swart, 2018; Wilkinson, Diedrich, & Drummond, 1996; Wilkinson, Drummond, Diedrich, & Rothman, 1999). The fact that facies are not clearly delimited by water depth can be attributed to a combination of factors, including tidal velocities, wave energy, local topography and the depth preferences of the various grain producers, that create the local physical environment on the sea floor and control sediment characteristics.

Although islands are numerous ($n = 1,430$) on GBB, they occupy only 8%, or 8,700 km$^2$, of the platform top. Despite their small proportional occupancy of the platform, islands exert a sphere of influence over the character of sedimentation for many tens of kilometres from their coastline and play a direct role in the accumulation of muddy sediments (Purkis & Harris, 2016). Figure 2b shows a linear decrease in the probability of encountering muddy facies (potential baffle and an increasing likelihood of encountering grainy facies (potential reservoir) with increasing offset distance from islands. Figure 2c, meanwhile, shows the influence that islands exert on the filling of accommodation space. As would be expected given that island-associated mudflats, primarily the vast tidal flats welded to the western margin of Andros Island, are a dominant shallow-water motif atop GBB, the likelihood of encountering filled accommodation decreases exponentially with increasing island offset distance. The probability of encountering underfilled accommodation remains at a static 70% for the first 50 km offset, and unfilled accommodation is rarely found within 50 km of an island. Figure 2b,c emphasize two key points: (a) islands play an important role in the accumulation of muddy sediments and (b) the sphere of influence applied by islands over the character of
sedimentation extends many tens of kilometres from their coastlines.

An understanding of bottom currents and water movement atop GBB and other shallow carbonate platforms is of paramount importance towards understanding sediment production and dispersal and is the physical control over platform-top sedimentation that is principally investigated in this study. It is most unfortunate that direct current measurements are largely lacking for GBB and, therefore, can be considered an overlooked physical control, but not...
surprising considering the difficulties in acquiring such data and the vast scale and variability in the platform. Harris et al. (2015) show annually averaged OSCAR altimeter–scatterometer data for the Bahamas platforms, but shortcomings to this type of data are briefly discussed in the section immediately below. Localized and minimal current data have been acquired from only a few sites on GBB, for example, the Cat Cay ooid shoals (Cruz, 2008) and the Schooner Cays sandbody (Rankey & Reeder, 2011), but there are no data to fully evaluate the variations on current directions and velocities across the breadth of the platform. In the absence of such data, we herein explore the use of hydrodynamic modelling to simulate current data and then compare the model results to other sedimentologic observations. We fully appreciate that, as intriguing as the model results are, that they are just that – the results of a model – and they are not a replacement for gathering widespread platform-top current data in the future. In fact, we propose that the model results will point us to certain hydrodynamic–sedimentologic relationships and specific locations on the platform that might be considered as prime sites for future current data acquisition.

2 | METHODS

Despite previous efforts, there remains a relatively poor understanding of the hydrodynamics atop isolated carbonate platforms, including the GBB. As such, a generally accepted premise is that platform-top currents are wind and/or tidally driven; hence, there is limited appreciation of how platform-top facies patterns and depositional cycles

FIGURE 2 Controls over sediment production and distribution: (a) Stacked bar graph from Harris et al. (2015) showing the distribution of facies type versus water depth as determined by a comparison between the water depth and facies maps of Figure 1a,b, respectively. (b) Probability distribution function from Purkis and Harris (2016) describing the likelihood that given facies types occur within a given distance of an island. A clear trend is seen that the likelihood of encountering grainy fabrics increases with increasing offset distance from islands. (c) Probability distribution function from Purkis and Harris (2016) describing the likelihood that a given facies type occurs within a given distance of an island for different zones of accommodation fill. The influence of islands on the occurrence of filled accommodation space is apparent – the probability of encountering an area that has ‘filled’ with sediment to within 1.5 m of present sea-level decreases exponentially with increasing offset distance from islands. Figures modified with permission
may, or may not, be influenced by ocean circulation surrounding a platform. To explore these fundamental controls, a hydrodynamic model is developed for the GBB, nearby Cay Sal Bank (CSB), and surrounding deeper waters (Figure 3; Purkis et al., 2017). Water circulation is modeled using the MIKE 3 Flow Model Hydrodynamic Module (MIKE 3 FM; http://www.mikepoweredbydhi.com).

The MIKE 3 FM is a modeling system based on a finite volume, unstructured mesh approach, developed for oceanographic, coastal and estuarine environmental applications (Danish Hydraulic Institute [DHI], 2008). The Hydrodynamic Module extracts numerical solutions from the 3D continuity, momentum, temperature, salinity and density equations. This model is based on solution of the 3D incompressible Reynolds-averaged Navier-Stokes equations using Boussinesq and hydrostatic assumptions (DHI, 2008). The experimental time period for the MIKE model is from 1 January 2012 to 1 January 2013 and a warm-up period of 1–31 December 2011 is used. A key simulation input is a digital terrain model (DTM) for both GBB (Harris et al., 2015) and CSB (Purkis et al., 2014). Bathymetry for waters <30 m deep is input into the model as a 150 m mesh. To attain this resolution for the mesh necessitated downsampling the seabed topography for areas of high-energy ooid sand production, which had originally been derived at a resolution of 30 m by Harris et al. (2011). Removing this detailed topography from the mesh was important to avoid the case whereby the distribution of flow in the model was augmented in areas of the platform where we had more detailed bathymetric knowledge. Areas in the mesh corresponding to depths >30 m are derived from the General Bathymetric Chart of the Oceans (GEBCO, http://www.gebco.net) and utilized at 300 m resolution. The DHI MIKE Zero Mesh Generator was used to produce the model domain comprising approximately 2 km

FIGURE 3 Scope of hydrodynamic model developed for the GBB, nearby Cay Sal Bank (CSB), and surrounding deeper waters. Green dashed line outlines the area for which input parameters were gathered, whereas the red dashed line highlights the scope of the simulation limited to platform tops with reliable high-resolution bathymetry. Figure modified from Purkis et al. (2017) with permission.
grid cells with a resulting mesh file consisting of 2,090 nodes and 3,703 triangular elements. An unstructured grid was used in the horizontal plane, where as a sigma-layer approach with 16 layers was used in the vertical domain. Using a 1-min time step, and considering the 2 km grid resolution, the model is capable of capturing short- and long-term perturbations at different spatial and temporal scales.

The model is forced by prevailing ocean hydrodynamics surrounding the platform, including the Florida Current, captured at a resolution of 0.08° × 0.08°, and winds and atmospheric pressure at 0.25° × 0.25°. Wind data (as pressure and two velocity components) covered the period from December 2011 to January 2013 and is given as a 1-hr average at an altitude of 10 m. These fields are derived from the Computational and Information Systems Laboratory Research Data Archive (https://rda.ucar.edu). Predicted tidal elevations were linearly interpolated to each grid at the boundaries and are based on global ocean tide model DTU10 at 0.125° × 0.125° resolution. Model runs were carried out using the following coefficients: an eddy viscosity Smagorinsky formulation of 0.28 was held constant throughout the domain (Smagorinsky, 1963), and Manning’s $n$ of 36 m$^{1/3}$/s was set to the spatially varying bed roughness specified for the bed resistance. Wind forcing was set to vary in time and domain through $u$ and $v$ wind velocity components and air pressure. The Coriolis forcing was set to vary within the domain. The scope of the model is shown in Figure 3. The area of interest within the model domain (i.e. that from which we examined the results of the simulation) covers 230,000 sq. km encompassing GBB and CSB and surrounding waters (the Little Bahama Bank is omitted because of the lack of a robust DTM), whereas the total model domain area extend to 1,000,000 sq. km, subtending the South Florida Shelf, Caicos Platform and Cuba. The total model domain is substantially larger than the examined area of interest so as to avoid hydrodynamic artefacts that occur as the model boundaries are approached.

Figure 4 shows representative time steps extracted from the MIKE model. Here, a pair of simulation outputs is interrogated relative to key examples of the sand factory (i.e. ooid sandbodies) atop GBB in Figures 5–7, and the mud factory (i.e. whittings) in Figures 8 and 9. Figure 10 is another form of model output – average annual MIKE current speed – where rate of flow is shown by contours and colours. Finally, the filling of accommodation by the sandy and muddy sediments is compared with the average annual MIKE current speeds in Figure 11.

It should be noted that the MIKE model is not the first representation of flow atop GBB. As mentioned previously, Harris et al. (2015) (their fig. 12) show annually averaged OSCAR altimeter–scatterometer data for GBB and surrounding waters. Although the off-platform flow in these satellite altimeter–scatterometer data adhere closely to those in the MIKE model, circulation on the platform top differs

![Figure 4](image-url)
substantially in some localities. For instance, the OSCAR data evidence a clockwise gyre to establish atop the Andros lobe of GBB, yet this is absent in the pair of MIKE outputs shown in Figure 4. This difference arises for at least three reasons. First, although the data are not devoid of value, OSCAR current retrievals are designed for the open (i.e. not depth limited) ocean and are poorly poised for shallow water application such as the GBB platform top (e.g. Saraceno, Strub, & Kosro, 2008). Second, the spatial resolution of MIKE (150 m) is three orders of magnitude finer than that of OSCAR. And finally, the outputs in Figure 4 are 1-min time slices and do not represent annually averaged flow, as depicted by Harris et al. (2015).

3 | RESULTS

There is an abundance of hydrodynamic information to evaluate from the model as it runs for 1 year and has very short-duration time steps. Figure 4 shows two examples (time steps) from the model to capture a common theme of episodes when platform-top currents are relatively weak (Figure 4a) and times when they are more vigorous (Figure 4b). Current direction in this figure is denoted by the orientation of the white arrows. The present study will focus on model output relative to localization of carbonate sand-producing (oolid sand factory) and mud-producing (mud factory) portions of GBB, and then briefly interrogate the model output relative to filling of platform-top accommodation space.

3.1 | Ooid sand factory

Areas of vigorous tidal exchange in the model correspond to localities where high-energy ooids and shoal systems have developed along the GBB platform margin, as indicated by the distribution of high-energy grainstones (Figure 1b). Figure 4b, meanwhile, illustrates the hydrodynamic flow intensity and direction in the areas populated by the main ooid sandbodies for a particular time step. Note that the dominant flood tide movement through the vast sandbody occupying the southern portion of the Tongue of the Ocean (TOTO) and the portion of GBB directly to the north of Andros Island (the Jouleter Cays sandbody). The Cat Cay area, directly south of Bimini Island, is impacted by enhanced flow across the platform margin. As proposed by Purkis et al. (2017), the accentuation of tidal currents in this sector of the margin might be attributed to an interaction between the Florida Current (aka the Gulf Stream) and the north-western flank of GBB. Note that

FIGURE 5  Model output highlighting tidal flow at the southern end of TOTO in relation to morphology of high-energy ooid sand (grainstone) tidal bars that form the world's largest ooid sandbody. Tidal bar morphology is extracted from the high-resolution DTM for TOTO by Harris et al. (2011), see Figure 1d. Other annotation is like that of Figure 4. T1–T4 span approximately 6 hr in the model and correspond with half a tidal cycle. Note that this portion of the platform margin is dominated by flood tides that radiate outward as they cross the margin of the cul-de-sac and sculpt the morphology of the tidal bars.
cross-margin flows are not similarly enhanced in areas where the CSB creates a lee and the influence of the Florida Current is, therefore, reduced. Also note, the model suggests that the greatest accentuation to flow in the vicinity of the Cat Cay ooid shoal is to the flood tide. The high-velocity flows confined to narrow tidal channels in the Exuma Cays are not completely resolved in the MIKE model due to its 150 m resolution, which exceeds the diameter of many of the tidal channels in this sector of the platform. This deficit in model resolution delivers offsets between the predicted rate of hydrodynamic flow and facies character. For instance, comparing Figures 1b and 10, for the area inboard of the Exumas island chain, the facies appear grainier than might be anticipated by the sluggish average annual flow <0.2 m/s. It can be assumed that, here, the flow velocity is slower than actual since the model cannot resolve the connection between the platform top and Exuma Sound.

A closer examination of the model output compared with the morphology of the ooid sandbody that surrounds the southern end of TOTO (Figure 5) reinforces the notion that model output is favourably consistent with the localization of high-energy depositional facies and many characteristics of the resulting sandbody. Four time steps from the model, spanning a 6-hr period, show current direction and velocity for half of one tidal cycle. The cul-de-sac at the southern end of TOTO is clearly a flood-dominated portion of the platform and that, along with the high current velocities predicted by the model, seem to be in concert with the tidal bar belt configuration of this high-energy sandbody, that is, long and narrow sand bars separated by wide through-going channels. Focused hydrodynamic flow across the sandbody is also likely responsible for its very extensive (>20 km) dip width, and the orientation of the sand bars as they radiate away from the crescentic platform margin of the cul-de-sac. Note that the MIKE model predicts strong currents to move through the sandbody and well to the south into the platform interior, suggesting the likelihood that any ooids transported away from the sand factory of the tidal bar crests will be onto the platform, where ooids would quickly be micritized to become peloids and incorporated into grapestone grains. The model suggests that the loss of ooids from the system in the ebb direction, into the deep topography of TOTO, is anticipated to be less important to the sediment budget of the sandbody.

A similar close examination of model output with the ooid sandbody formed along the platform margin immediately to...
the north of Andros Island – the Joulters ooid shoal (Figure 6) – is consistent with the morphology of the tidal bars and sand flats of this sandbody as described by Harris (1979). In this case, flood tides coupled with longshore currents moving to the north across this portion of the margin deliver sand bars that curve spit-like onto the platform. Note that although both of the sandbodies shown in Figures 5 and 6 are sculpted dominantly by flood-tidal currents, the lesser velocities and slightly enhanced ebb flows at Joulters have formed a sandbody that is narrower in dip width and with more irregular and less through-going tidal channels than at southern TOTO. Ooids could seemingly be transported away from the high-energy sand factory of the bars themselves to the west, south and even north into the platform interior where they would be reworked.

Figure 7 summarizes a key insight into the modelling regarding size of the ooid sandbody versus peak current speed from the model for five of the main ooid-producing areas on GBB – Cat, Joulters, Schooner and Exuma Cays and TOTO. Location of the sandbodies is shown on the map, and their morphology on a Landsat ETM+ scene, all shown at the same scale. Note that the robust relationship between increasing peak current speed from the model and increasing area of the sandbody, with the exception of the Exuma Cays, which have conspicuously high peak current speeds as they are an example where tidal currents are focused in extremely narrow channels between islands, a process which is not adequately captured at the 150 m resolution of the hydrodynamic model.

FIGURE 7 Cross plot summarizes size of the ooid sandbody versus peak current speed from the model for five of the main ooid-producing areas on GBB – Cat, Joulters, Schooner and Exuma Cays and TOTO. Location of the sandbodies is shown on the map, and their morphology on a Landsat ETM+ scene, all shown at the same scale. Note that the robust relationship between increasing peak current speed from the model and increasing area of the sandbody, with the exception of the Exuma Cays, which have conspicuously high peak current speeds as they are an example where tidal currents are focused in extremely narrow channels between islands, a process which is not adequately captured at the 150 m resolution of the hydrodynamic model.

The implication here being that even modest enhancement of hydrodynamic flow, be it through focusing of tidal currents, interactions of the platform margin with surrounding ocean currents, or a combination of these and other factors, can lead to a meaningful increase exception, however, as they have conspicuously high peak current speeds; in this area, tidal currents are focused in narrow tidal channels between islands. The relationship shown on the cross plot is super linear, such that a doubling of peak flow approximately yields a tripling in the area occupied by the sandbody. Such a relationship has implications for reconciling the large size of oolitic sand accumulations in the geologic past, which save for that accumulating in modern-day TOTO, commonly dwarf the majority of those forming atop GBB, which itself is the most prolific site of modern ooid production on Earth. Noteworthy examples from the rock record include the Mississippian of the Williston Basin (Lindsay, Anderson, Le Fever, Gerhard, & LeFever, 1988), the Permian of the Central Basin Platform (Major, Bebout, & Lucia, 1988) and the Jurassic of Saudi Arabia (Mitchell, Lehmann, Cantrell, Al-Jallal, & Al-Thagafy, 1988).
in the overall dip and strike extent of ooid accumulation. By extension, variations in hydrodynamic flow through time might be anticipated to deliver lateral and vertical heterogeneity in facies because flow-induced expansion and contraction of the sandbody will serve to interleave intervals of shoal-produced oolitic grainstones with mud-dier packstone deposits which typically accumulate inboard of an active shoal system (e.g. stabilized sand flats of the modern Joulter Cays sandbody described by Harris, 1979; the Jurassic Smackover Jay Field described by Ottmann, Keyes, & Ziegler, 1973).

3.2 Mud factory

The term ‘whiting’ has been used to describe occurrences of lime mud precipitated directly from both marine and fresh waters. As a result of the contribution of whitings to the Bahamas sedimentary record, considerable effort has been applied to understand the triggers and mechanisms of precipitation on GBB. However, the triggers remain controversial. Whitings have been claimed to originate from direct precipitation of carbonate from the water column, likely in association with cyanobacteria (Purkis et al.,...
2017; Robbins & Blackwelder, 1992; Robbins, Tao, & Evans, 1997; Shinn, Steinen, Lidz, & Swart, 1989; Smith, 1940; Swart, Oehlert, Mackenzie, Eberli, & Reijmer, 2014; Thompson, Shultze-Lam, Beveridge, & Des Marais, 1997; Yates & Robbins, 1998) as well as from the action of bottom-feeding fish—the resuspension hypothesis (Broecker, Sanyal, & Takahashi, 2000; Broecker & Takahashi, 1966; Morse, Gledhill, & Millero, 2003; Morse, Millero, Thurmond, Brown, & Ostlund, 1984). Boss and Neumann (1993) argued for a different type of resuspension origin, wherein turbulent flow lofts seabed mud. Dierssen, Zimmerman, and Burdige (2009), meanwhile, proposed wind-driven Langmuir cells as a resuspension mechanism. Some of the researchers who had previously advocated a stirred-up origin based on the absence of alkalinity changes within and outside the whitings (Morse et al., 1984, 2003) have acknowledged that there is some direct precipitation component in whitings studied on Little Bahama Bank (Bustos-Serrano, Morse, & Millero, 2009). This finding supports that of Shinn et al. (1989) and Larson and Mylroie (2014) proposition that whitings are composed of mixtures of stirred-up bottom sediments and direct aragonite precipitate.

Robbins et al. (1997) highlighted the vast contribution of whitings to the sediment budget of GBB. Purkis et al. (2017), based on satellite observations and hydrodynamic modelling, proposed the existence of a teleconnection between platform-top circulation patterns and off-platform currents, in particular the Florida current. Modulation of platform-top currents via this connection seemingly serves to trigger whitings and control their spatial and temporal distribution (Figure 8a). A connection between platform-top hydrodynamics and the formation/suppression of whitings is evidenced in this area, which suggests a relationship between the production/deposition of platform-top lime muds (Figure 8b) and off-platform circulation patterns.

Figure 8c,d depict hydrodynamics at two contrasting points in the MIKE model for the western portion of GBB. In the first instance (Figure 8c), the Florida Current remains largely confined to the deep bathymetry of the Florida Straits and current velocity atop the GBB is correspondingly suppressed. Doldrum-like conditions stretch across the breadth of the platform lying to the west of Andros Island, save for a predominantly northerly, but low velocity (<0.2 m/s), flow regime north of Andros. By contrast, Figure 8d captures an episode of accentuated platform-top circulation triggered by an interaction between the Florida Current and cross-margin tidal exchange. At this time, the MIKE model reports current velocities >1.5 m/s as far as 15 km inboard of the portion of the western platform margin which is not sheltered by CSB. Velocities in the range of 0.3–0.4 m/s persist in the central portion of the western GBB (i.e. across the whitings zone; Figure 8a). Here, a bidirectional flow regime is established with the latitude of Williams Island marking the boundary between predominantly north and south flow (dashed line Y–Y’ in Figure 8d).

A logical extension of this linkage between the Florida Current and the frequency of whitings would lead to the conclusion that more vigorous exchange of normal marine waters with those on the platform top would increase...
numbers of whitings. However, data do not support this. Whitings are rarely observed within 15 km of the western margin of GBB and never observed in its northern reaches (Figure 9b). The MIKE model reports averaged annual current velocities >0.6 m/s in these sectors of the platform (Figure 9a), which are likely sufficiently brisk to sweep any whitings off of the platform top or, in contrast, disperse them to the point that they are no longer observable, per Boss and Neumann (1993).

Boss and Neumann (1993, their Figure 9) developed the concept of high-, medium- and low-energy regimes spanning the western platform margin, central platform and lee of Andros Island, respectively. Although developed from a completely different climatology, the MIKE model reinforces this partitioning (Figure 9b) and better defines the boundaries between the energy regimes. It is on the boundary between the high-energy regime (average annual currents >0.4 m/s) and medium-energy regime (<0.4 m/s) that the zone of peak whitings is situated (Figure 9c). Purkis et al. (2017) proposed that this zone owes its existence to a ‘Goldilocks’ combination of factors. Normal marine waters transported onto the platform are adequately supersaturated with respect to CaCO₃ to allow for whiting production. With cyanobacteria implicated in affecting the saturation state of platform-top waters, Swart et al. (2014) evoked aerosol dust from Africa, and the Fe contained within it, in particular, as a control on photosynthetic activity. Current velocity is seemingly high enough to resuspend fine sediment to serve as nucleation material for whitings and sufficient to loft the reduced product of aerosol dust to fertilize them. Meanwhile, current velocities are not so high (i.e. >0.4 m/s) as to sweep whitings off the platform.

3.3 | Accommodation filling

Following the lead of Boss and Neumann (1993), the full breadth of GBB can be partitioned into zones of mean annual hydrodynamic energy on the basis of the MIKE
model (Figure 10). Moreover, this in turn can subdivide GBB into two regions: low energy (<0.2 m/s annual average speed), indicated by the grey stripped pattern in Figure 11, and higher energy elsewhere on the platform top. Accommodation filling is summarized from Purkis and Harris (2016), see Figure 1e, into regions of variably filled and unfilled accommodation. Note that low-energy portions of the platform top (<0.2 m/s annually averaged current speed) are always variably filled, in the sense described by Purkis and Harris (2016), with most occurrences being directly situated in the lee of islands. Higher energy portions of the platform top, as suggested by mean annual hydrodynamic speed of >0.2 m/s, are roughly equally split between variably filled and unfilled conditions. Areas of unfilled accommodation are skewed towards the outer platform margin and in an east-west trending ‘trough’ within the southern part of the platform.

Lacking a platform-wide isopach map of Holocene sediment thickness poses limitations to what can be achieved by a cross-comparison between the magnitude of hydrodynamic flow and the filling of accommodation space. Hence, this is an exercise in plausibility; there are no precise answers, but under the reasonable assumption that the underlying Pleistocene horizon of GBB apart from islands is basically horizontal at the scale of the entire platform, as suggested for instance by Taft, Arrington, Haimovitz, MacDonald, and Woolheater (1968) who worked on the Yellow Bank portion of GBB, Palmer (1979) who presents cores and seismic through the TOTO ooid-bar belt, and Cruz, Eberli, and Ayers (2007) and Cruz (2008) using the same methods but for the ooid deposits south of Bimini Island. Also relevant here are the digital sub-bottom profiles collected by Weij et al. (2018) on the portion of the platform west of Andros Island. These profiles uphold the
premise that the underlying Pleistocene surface is broadly horizontal, perhaps gently dipping to the south and southwest, although locally incised by channels and karst depressions. Hence, while variations in the Pleistocene topography certainly cannot be discounted, these lines of evidence suggest that current strength exerts a degree of control over sediment accumulation, but not full control. This finding is logical considering the host of other factors that serve to direct sediment accumulation, including the distribution of grain producers, the interplay of flow rate and direction, not to mention the fact that both reefal facies and high-energy sand deposits are enhanced by high rates of flow, not retarded (Harris et al., 2015; Schlager & Purkis, 2013).

4 DISCUSSION

Great Bahama Bank continues to be an important site where studies of carbonate facies and the physical forcings that dictate their accumulation can be examined. By using a hydrodynamic model like MIKE 3, the potential environmental and hydrodynamic conditions that control deposition can be evaluated and thereby an understanding of facies occurrence, patterns and distribution can be enhanced. Although the modelling results discussed here can be further evaluated, and current measurements need to be more widely acquired across the platform top, there are implications for several aspects of deposition on a platform top from the current modelling results that have significance to an understanding of modern and ancient carbonate platforms.

The production of sediment atop a platform like GBB can be directly related to localized depositional environments that produce sand-size and mud-size sediments, for example, the ooid sand factory and whitings mud factory, respectively. And both of these aspects of carbonate production are addressed by the hydrodynamic modelling. Although the modelling can provide some insight towards the positioning of other carbonate sediment-producing settings such as reefs and portions of the sea bottom that are rich in flora and fauna that create skeletal sands and muds, these settings were not the focus of the current investigation. Using the TOTO and Joulters ooid sand bodies as examples, the simulation reinforces an understanding of the seabed-current patterns along these high-energy platform margins that lead to a significant production of ooid sands and subsequent development of sandbodies with a particular size and configuration. The modelling results are consistent with characteristics of the sandbodies and support the notion that there is a predictable relationship between current speed (as reported from the MIKE model) and resultant size of the sandbody. If upheld in other localities, this relationship has profound implications for the interpretation of both outcrop and subsurface examples. For instance, one could predict where larger sandbodies might occur with rough estimations of current velocities in a regional sense or, alternatively, with some knowledge of the hydrodynamic regime including current velocities, one might predict where to look for larger sand accumulations.

The results of the hydrodynamic modelling have also caused a re-evaluation of where and when whitings occur on GBB and thereby added new insight into mud production on modern and ancient carbonate platforms. Purkis et al. (2017) utilized the MIKE hydrodynamic model and proposed a plausible link between off-platform and on-platform currents in the production of whitings. Their analysis suggested that the interaction between the Florida Current and the GBB platform margin might be a precondition for whitings because these events serve to nourish the platform top with normal marine water, which is substantially more supersaturated with respect to CaCO3 than waters that have stagnated atop the platform. Purkis et al. (2017), however, do not discount additional factors that might promote whitings, such as evaporation of bank-top waters leading to altered water chemistry (e.g. Morse et al., 1984). However, the manifestation of the hydrodynamic link made by Purkis et al. (2017) is the drastic decrease in frequency of whitings in the portion of GBB sheltered from the Florida Current by CSB, as compared to the portion that interacts more strongly with this current. Their modelling results suggest that alongside conducive water chemistry, a rather specific configuration of platform-top hydrodynamics is also needed to form whitings. This observation is relevant to the production of carbonate muds in ancient platforms, as whitings might not have been as widespread in the geological record as previously assumed.

The modelling results also have a direct bearing on the positioning of the ooid sand and mud factories on GBB, and by analogy, ancient platform equivalents. In this study, an initial effort was made to address the combined effect of these sediment factories on producing sediment in sufficient quantities to fill accommodation space to various degrees. Although the results should be considered preliminary in nature, an initial comparison between mean annual current speeds from the model and accommodation filling shows that lower energy and proximity (leeward) to islands leads to a high probability of accommodation filling, whereas higher energy conditions alone are not a direct indicator of substantial filling. Other controls over deposition must be considered, in addition to the higher energy aspects, to drive deposition to the point that substantial and prolonged deposition takes place.

The modelling presented in the present study, along with the supportive facies studies, emphasizes how surrounding ocean circulation patterns have the potential to exert indirect control on shallow-water hydrodynamics and
therefore influence the type and distribution of sediments accumulating on the platform top, their thickness and lateral heterogeneity — including the distribution of extensive hialtal surfaces (sites of non-deposition). A broader understanding of platform-top currents and their diverse controls can aid interpretation of the rock record, including identification of locations on a platform which have the potential to host the most complete depositional cycles and therefore a key to the sequence stratigraphic reconstruction of the system.

5 | CONCLUSIONS

The paper presents a new hydrodynamic model for the full breadth of GBB and emphasizes how this simulation might refine the understanding of the platform-top ooid sand and whitings mud factories, which in turn, direct the filling of accommodation space. By pairing the model with satellite observation of the size and geometry of carbonate sandbodies, a mathematical relationship is defined which relates their size to the magnitude of current velocity. For the mud factory, a plausible link is demonstrated between platform-top hydrodynamics and the formation/suppression of whitings mud factories, which in turn, direct the filling of accommodation space. By pairing the model with satellite whitings mud factories, which in turn, direct the filling of accommodation space. By pairing the model with satellite observation of the size and geometry of carbonate sandbodies, a mathematical relationship is defined which relates their size to the magnitude of current velocity. For the mud factory, a plausible link is demonstrated between platform-top hydrodynamics and the formation/suppression of whitings, as evidenced west of Andros, suggesting a relationship between the production/deposition of platform whitings, as evidenced west of Andros, suggesting a relationship between the production/deposition of platform whitings and potential relationship to wind-driven Langmuir circulation. Biogeosciences, 6, 487–500. https://doi.org/10.5194/bg-6-487-2009

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