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ABSTRACT

The relationships between the margin sedimentary regime and the platform progradation are studied using forward stratigraphic numerical simulations on the Leeward (Western) prograding margin of the Great Bahama Bank (GBB) during the Quaternary (1.7 - 0 Ma). The corresponding sedimentary regime in the slope and the platform is well known from the ODP leg 166 and Bahamas Drilling Project wells located along the “Western line” seismic transect. However the sedimentary regime on the margin is not well established: the coral reefal margin observed before between 1.7 and 0.8 Ma in the well Clino is not active anymore at present-day, and the Holocene sedimentary regime is geometrically unable to account alone for the progradation. This study is based on three 2D high-resolution forward stratigraphic numerical modeling experiments with the software DionisosFlow that include the platform, margin and slope domains on the “Western Line Section” in the same sedimentary models. The results are compared to the six sedimentary cores and to the present day bathymetry in order to identify the more realistic scenario. The three experiments test different models of carbonate sediment production and transport. Experiment 1 shows that the highstand shedding of the fine-grained uncemented platform production is unable to reproduce the progradation and the present-day profile. Experiment 2 and 3 incorporate cemented facies in the margin, with the best results obtained with the cemented marginal wedges produced in Experiment 2 during platform emersion. From these results a high-resolution interpretation of the margin seismic section is proposed. This study shows that the platform progradation can be decoupled from the highstand shedding of the fine-grained platform production. It is dependent on the accumulation in front of the steep margin of coarse or cemented material. Before 0.8 Ma this corresponds to the coral reef identified in Clino. The transition after 0.45 Ma to 100-kyr large eustatic cycles with total platform flooding created two distinct marginal regimes: (1) during platform flooding aggrading accumulation of non-skeletal sands, and (2) during platform emersion prograding cemented marginal wedges produced in-situ.

KEYWORDS

Bahamas; Forward Stratigraphic modeling; Carbonate slope; Platform Progradation; Lowstand wedges; Cemented margin

1 Introduction

1.1 High-resolution stratigraphic study of a progradational margin

Carbonate sedimentary systems are a major component of the rock record of sedimentary basins, and a major reservoir of geological resources (Schlager, 2005). The margin area is the transition domain from the shallow marine carbonate factory to the slope where sediments are re-sedimented (McIlreath & James, 1978; Mullins & Cook, 1986; Schlager, 2005; Playton et al., 2010; Reijmer et al., 2015). The sedimentary processes and physiography of the margin controls the stratigraphic evolution of the shallow platform and the sediment export mechanisms towards the slope (Eberli and Ginsburg, 1987; Playton et al., 2010). The evolution of the margin is influenced both by external factors, such as hydrodynamic conditions and tectonics, and internal ones, especially the variety of carbonate producers and the mechanical properties of the accumulated production (Playton et al., 2010).

Forward stratigraphic models such as the DionisosFlow software (Granjeon and Joseph, 1999; Granjeon, 2014) are a reliable tool to reconstruct the facies and geometry of a carbonate sedimentary system through time (Warrlich et al., 2008; Montaggioni et al., 2015; Berra et al., 2016; Lanteaume et al., 2018). This high-resolution stratigraphic model realizes a reliable process-based interpolation of the available geological data. They are used to constrain the geological parameters governing the modelled sedimentary processes (Aurell et al., 1998; Seard et al., 2013; Montaggioni et al., 2015; Kolodka et al., 2016)

This study focuses on the “Western Line” transect of the Great Bahama Bank (GBB) for the time interval 1.7 Ma to present day (Fig. 1A and 1B). Different scenarios defined by various carbonate producers and sediment properties are tested under well-constrained external controls. Different margin architectures are then generated and compared to the observations for the most recent deposits (Wilber et al., 1990; Eberli et al., 2004)and to the core sections on the slope and platform (Wilber et al., 1990; Eberli et al., 1997; Ginsburg et al., 2001; Eberli et al., 2004). These results give 1) insights on the internal and external controls of the margin geometry and evolution, and 2) their influences on the stratigraphic evolution of the whole transect. These modeling results provide conceptual insights for the sequential evolution of a leeward carbonate margin.

1.2 Bahamas case study: State of the art

The Bahamas Archipelago is one of the most studied present-day analogues for ancient tropical carbonate systems (Fig. 1A). It has yielded major contributions on the understanding of carbonate systems (Schlager and Ginsburg, 1981; Mullins and Cook, 1986; Grammer and Ginsburg, 1992; Schlager et al., 1994; Eberli et al., 2004; Betzler et al., 2014; Reijmer et al., 2015). The low-angle leeward western slope of the GBB shows a remarkable progradation of ~15 km into the Strait of Florida during the late Miocene (Eberli and Ginsburg, 1987; Eberli et al., 1997) (Fig. 1B, Fig. 2). The platform and slope architectures are well described on the 2D section known as the “Western line” defined by a continuous seismic platform-to-basin profile (Eberli and Ginsburg, 1987) (Fig. 1B). Six research wells were core-drilled on this transect during the Bahamas Drilling Project (BDP) (Ginsburg, 2001) on the platform, and during the ODP leg 166 (Eberli et al., 1997a) on the slope. The platform margin however has not been drilled for the Quaternary deposits younger than 1.7 Ma. The recent sedimentary processes on the slope and the platform have been well established (Mulder et al., 2012; Chabaud et al., 2016; Principaud et al., 2016; Harris et al., 2015; Wunsch et al., 2017; Schnyder et al., 2018). However, the margin sedimentary regime is described with good confidence only for the Holocene deposits by Wilber et al. (1990).

1.2.1 Quaternary evolution of the Western margin

The post-Cretaceous evolution of the ”Western Line” transect is well constrained by the identification of 3rd order sequences named *a* to *r* from the more recent to the oldest one (Betzler et al., 1999; Eberli et al., 2002; 2004; Principaud et al., 2016; Wunsch et al., 2018) (Fig. 2).

During sequence *d* (2.6-1.7 Ma) the non-skeletal grains become abundant on the platform with coral reefs in well Unda (Budd and Manfrino, 2001). The platform margin progrades with the deposition of a thick regressive package but it is of reduced thickness on the slope. (Eberli et al., 1997b; Kenter et al., 2001; Principaud et al., 2016).

Sequence *c* (1.7 to 0.33 Ma) corresponds to another significant progradation pulse of the platform along with a transition from a ramp-like profile to a steeper platform margin profile (Eberli et al., 1997b; Betzler et al., 1999; Principaud et al., 2016). Coevally the carbonate production along the transect becomes almost entirely non-skeletal and peloid-dominated (Eberli, 2000; Kenter et al., 2001; Manfrino and Ginsburg, 2001). These evolutions can be related to a regional pattern of coral reefs decline and extinction during the Pleistocene, culminating between 1.0 Ma and 0.8 Ma (Reijmer et al., 2002).

The interval 1.7 to 0.8 Ma is expressed by an subaerial exposure hiatus in well Unda and the progradation of a coral reefal margin in well Clino, with an evolution from reefal to reef crest and platform environment. After 0.8 Ma, the deposits in BDP wells Unda and Clino indicates mostly platform top and platform margin environments, respectively (Budd and Manfrino, 2001; Manfrino and Ginsburg, 2001) (Fig. 2, Fig. 4). On the slope, sequence *c* to *a* are dominated by the accumulation of periplatform-ooze wedges exported from the platform during the highstand flooding periods (Eberli et al., 1997a). These packages form periplatform drift wedges (Betzler, et al., 2014) under the action of the Florida Current (Principaud et al., 2016; Wunsch et al., 2018). They are separated by condensed cemented intervals related to the platform emersion during glacial lowstands (Eberli et al., 1997a; Eberli, 2000; Rendle and Reijmer, 2002) (Fig. 4).

1.2.2 Recent margin evolution and sedimentary processes

For the Holocene highstand, at the top of the Western Line sectionthe edge of the bank is gently sloping with a 3-10° slope towards a slope break at 55-60 m of water depth (Wilber et al., 1990; Ginsburg et al., 2001). The platform edge shows a 10 – 30 m thick accumulation of Holocene fine to medium non-skeletal sands (Fig. 3A). A lithified marginal escarpment marks an abrupt increase in slope reaching more than 30° down to a depth of 140-180 m. Direct sampling of lithified samples a few meters inside the “escarpment wall” have also yielded Holocene ages (G. Eberli, pers. comm.). At the bottom of the escarpment, a plunge-pool and related slope-break deposits result from the hydraulic jump of density cascading currents (Wilson and Roberts, 1992; Wilber et al., 1990; Wunsch et al., 2016; Schnyder et al., 2018). Downslope the Holocene deposits form a 10 –to 60 m thick wedge of muddy periplatform oozeIn the profiles of Wilber et al. (1990) the Holocene wedge clearly onlaps on Pleistocene surface of the plunge pool (Fig. 3A). The Holocene platform edge and thin wall deposits also appear to downlap this same surface in the lower part of the wall. Holocene sediment accretion in front of the escarpment seems severely limited by the strong activity of the downslope currents. Laterally along the GBB Western margin this profile vary with a more or less developed slope wedge (Wilber et al., 1990; Principaud et al., 2016).

If one takes a conceptual look at the architecture resulting from the repetitive stacking Highstand sediments accumulation at the margin identical to the observed Holocene package (Fig. 3A), it shows an aggrading trend for the platform margin (Fig. 3B). The construction of any prograding trend would have required additional sedimentary accumulation in front of and at the toe of the wall (Fig. 3C). So when considering the margin progradation from 0.8 Ma to the Holocene, other types of margin geometries than the observed Holocene geometry would have to come into play at some points. The well-established “highstand shedding” regime of the Western line transect (Schlager et al., 1994; Eberli, 2000; Eberli et al., 2004) is not associated with a progradational geometry for the Holocene highstand on this section.

1.3 Objectives of the paper

We present here a stratigraphic forward numerical investigation of the evolution of the Western GBB margin during the 1.7 – 0 Ma interval (Fig. 2). During this interval, the sedimentation on the margin is only known by the 1.7-0.8 Macoral reef found in Clino (Fig. 4), and the present-day regime of the Holocene margin (Fig. 3A). Our objective is to investigate the stratigraphic architecture in the uncertain domain between these two records with the following questions in mind:

1) How has the margin evolved between 1.7 and 0 Ma?
2) What is the relationship between the margin geometries and the depositional model? Which external and internal controls can be identified?
3) How does the architecture of the margin influence the progradation of the platform?

To apply a process-based modelling approach, it is necessary to use a unequivocal and consistent stratigraphic framework with time-lines that will be considered as stratigraphic markers across the whole well transect. Numerous chronostratigraphic studies have been published on this transect (Eberli et al., 1997b, McNeill et al., 2001; Eberli et al., 2002; Rendle and Reijmer, 2002; Principaud et al., 2016; Wunsch et al., 2018; see Table 1). They present some discrepancies and uncertainties: Eberli et al. (2002) estimate an average error of 0.38 Myr in their estimation of sequence *c*, *b* and *a* in the ODP wells, and on the platform wells only the 1.7 Ma and 0.8 Ma magnetostratigraphic markers can be considered as certain (McNeill et al., 2001). Choices and hypotheses made in this paper are not a new chronostratigraphic model for the “Western line” transect, but only a consistent synthesis of the published data.

The results of the numerical experiments are used in the discussion to propose a high-resolution interpretation of the seismic record at the platform margin ((Eberli and Ginsburg, 1987; Principaud et al., 2016; Wunsch et al., 2018).

2 Data and Methods

2.1 Well Data

The ODP leg 166 wells 1005, 1004, 1003 and 1007 were drilled on the slope. They were logged with a full set of wireline tools and a checkshot survey was realized for wells 1003, 1005 and 1007 (Eberli et al., 1997a).

The two wells Clino and Undawere drilled on the platform as part of the Bahamas Drilling Project (BDP) campaign (Ginsburg, 2001). Both are located on a very shallow platform (about 7 m water depth), the well Unda is located 8.5 km inward of the well Clino along the « Western Line » profile (Fig. 1A and Fig. 2. Both holes were logged with a standard suite of wireline tools and a continuous vertical seismic profile (VSP) was shot (Ginsburg et al., 2001).

2.1.1 Well Chronostratigraphy

The chronostratigraphy on the ODP leg 166 slope wellsis first based on the planktonic foraminifer and nannofossil biostratigraphic framework built for the Leg 166 initial report (Eberli et al., 1997a). Another dating approach was conducted by Rendle and Reijmer (2002) on the wells 1007, 1003 and 1005, based primarily on δ^{18}O isotopes, grain size and X-Ray Diffraction (XRD) analyses, U/Th dating and nannofossils bio-events to establish a high-resolution stratigraphy of the Quaternary deposits (Rendle et al., 2000). Wunsch et al. (2018) proposed another high-resolution stratigraphy based on the distal ODP 166 sites 1008 and 1006. They are not located in our zone of interest and record a different sedimentary regime dominated by the Florida current (Rendle and Reijmer, 2002). As these are globally undisturbed sections, compared to the slope wells these records present higher confidence for the local stratigraphy, but higher uncertainity in the correlation with sections on the slope.

For the BDP wells an age model has been established as well using foraminifera, nannofossils, strontium isotope stratigraphy and magnetostratigraphy (Mc Neill et al., 2001).

The chronostratigraphic correlation of the platform (BDP) and the slope (ODP 166 wells) has not been established and published yet. A synthesis of the available literature led us to establish a consistent age/depth correlation for all the wells, based only on geological reasoning in case of contradictory results (Table 1). We did not endeavour to re-date the cored sections. This work was guided by the premise that exposure surfaces on the platform form time-lines corresponding to condensed and lithified layers on the slope (Eberli and Ginsburg, 1987; Eberli et al., 2002: Wunsch et al., 2016). For the slope wells we considered the correlation of early lithified layers and peaks of High Magnesium Calcite (HMC) (Eberli et al., 1997a; Rendle and Reijmer, 2002).

In this synthesis we identify and correlate the seismic sequence boundaries (SSB) A, B and C defined by Eberli et al. (1997a, 1997b and 2002) (Table 1, Fig. 4).

With an age of 1.7 Ma SSB C was correlated with the Top Olduvai datum in the BDP Well Unda and Clino (Manfrino and Ginsburg, 2001). This choice is consistent with the interpretation of SSB C as a major downward shift of the regressive margin (Eberli et al.,1997b; ; Manfrino and Ginsburg, 2001; Principaud et al., 2016).

SSB B was identified on the slope wells by Rendle and Reijmer (2002) with the condensed surface of MIS (Marine Isotope Stage) 10 at 0.37 Ma (Lisiecki and Raymo, 2005).On the platform SSB B was identified as an exposure surface at the top of a thick transgressive reefal unit in BDP well Clino (40 – 28 mbsf) and the corresponding deep lagoonal unit in well Unda (38 - 27 mbsf) (Manfrino and Ginsburg, 2001). We assume it to be the backstepping record of the highly transgressive MIS 11 highstand (Lisiecki and Raymo, 2005; Miller et al., 2011).

SSB A is defined in the ODP slope wells as the base of the Holocene deposits (Eberli et al., 1997a, 2002; Rendle and Reijmer, 2002;).. The corresponding exposure surface has not been recovered in Clino and Unda, but has been identified with the bottom of the Holocene unconsolidated sediments (Manfrino and Ginsburg, 2001; McNeill et al., 2001).

Three additional stratigraphic markers have been tentatively identified in the 1.7 - 0 Ma interval in order to increase the stratigraphic constrains for the comparison of simulations with well sections.

Marker *t20,* corresponds to the top of MIS 20 (0.79 Ma) (Lisiecki and Raymo, 2005). It is identified in well 1003 by Rendle and Reijmer (2002) and is coeval with the Brunhes/Matuyama magnetostratigraphic transition,identified in Clino and Unda by Manfrino and Ginsburg, (2001). This surface was correlated in the ODP slope wells with the first notable peak of HMC composition and a remarkable positive Vp anomaly (Table 1, Fig.4).

The second stratigraphic marker, *t12,* corresponds to the top of MIS 12 (0.42 Ma), identified in ODP well 1005 and 1003 (Rendle and Reijmer, 2002). It can be correlated in wells 1004 with an abrupt decrease in Low Magnesium Calcite (LMC) concentration (Fig. 4). In the BDP wells it was correlated with the base of the transgressive reef/lagoon unit (Manfrino and Ginsburg, 2001) interpreted to correspond to MIS 11 (Table 1, Fig. 4).

The third stratigraphic marker *t6* corresponds to the top of MIS 6 (0.13 Ma)(Lisiecki and Raymo, 2005). It is identified in ODP wells 1005 and 1004 as the top of the penultimate condensed level (Fig. 4), in good agreement with ODP 166 U/Th dating (Henderson et al., 2000). It is absent in well 1003 that exhibits a major hiatus between t10 and the Holocene (Rendle and Reijmer, 2002). In BDP wells Clino and Unda, it was identified as the first transgressive lag cored (Manfrino and Ginsburg, 2001) (Table1, Fig.4).

2.1.2 Core lithofacies analysis

A synthetic lithofacies model with five facies was elaborated from the published core descriptions (Eberli et al., 1997a; Kenter et al., 2001; Manfrino and Ginsburg, 2001; Rendle and Reijmer, 2002). The lithofacies are designated by the Well Facies code (WF) A to G (Table 2). They are identified by a depositional environment, range of Dunham sedimentary fabric and dominant cementation state and mineralogical composition.

The highstand carbonate sedimentation on the platform is dominantly aragonitic with a fine-grained (Silt and Clay size) and peloidal assemblage (Eberli et al., 1997a; Chabaud et al., 2016; Harris et al., 2015). It originates mostly from aragonitic green algae and seagrass production, especially *Halimeda* sp. and *Thalassia* sp., and whiting events (Eberli et al., 1997a; Manfrino and Ginsburg, 2001; Chabaud et al., 2015; Harris et al., 2015;).

WF A is the periplatform ooze slope facies corresponding to the off-bank export of the highstand platform production (Wilson and Roberts, 1992; Schlager et al., 1994; Eberli, 2000;; Wunsch et al., 2018).

WF B corresponds to the condensed deposits associated with glacial sea-level lowstands (Eberli et al., 1997 a; Eberli, 2000; Chabaud et al., 2016; Wunsch et al., 2017).. WF B is aragonite-poor due to 1) the dissolution of aragonite followed by the precipitation of an High-Magnesium Calcitic micro-sparitic cement (Schlager and James, 1978; Mullins et al., 1980; Mullins et al., 1985;; Munnecke et al., 1997; Eberli, 2000; Rendle et al., 2000; Melim et al., 2002;) and 2) a higher relative input of calcitic pelagic tests during lowstands (Eberli et al., 1997a; Eberli, 2000; Chabaud et al., 2016). WF B is clearly identifiable with 1) the marked decrease in aragonite composition in the XRD mineralogical log and 2) P-positive Wave velocity anomaly in relation with 3) early lithification state (Eberli et al., 1997a).

Several lower slope sub-facies are incorporated into WF A for synthetic considerations(Eberli et al., 1997a).

WF C corresponds to a variety of coral reef facies (Kenter et al., 2001; Manfrino and Ginsburg, 2001). WF D is interpreted by Manfrino and Ginsburg, (2001) as high-energy sandy deposits of inner platform beach and shoals. It as the last member of shallowing upward sequences (Aurell et al., 1995)

2.2 Seismic data

The seismic interpretation has been performed on a dataset composed of three different acquisitions on the “Western Line” transect (Fig. 2).

1-The original “Western Line” profile acquired in the 1980’s. Resolution in this seismic data is around 30 m in the upper part studied here It is presented in the original undersampled publication format with one trace out of seven (Eberli and Ginsburg, 1987).

2- Wunsch et al. (2018) (Fig. 9 A) have published the reprocessed version of this seismic, presented also in Eberli et al. (2004) (Fig. 16, from the platform edge and margin between well

1005 and well Clino for 0 to 700 ms TWTT). . As is clearly visible in Eberli et al. (2004) due to the very high impedance contrasts on the shallow platform, the seismic data have been cut at ~ 0.08 ms TWTT. It gives the outer platform a flat top appearance, whereas it is indeed sloping from 7.6 m water depth in Clino (Manfrino and Ginsburg, 2001) to 60 m at the platform edge (Wilber et al., 1990)(Fig. 11A).

3- Slope seismic data collected during the seismic survey of Leg 1 of the Carambar cruise (Mulder et al., 2012). have a vertical resolution of 2 m and are relevant down to approximately 1s TWTT (Principaud et al., 2016). A small displayed section in Figure 11 is part of the ODP 166 high-resolution dataset studied by Anselmetti et al. (2000).

2.2.1 Well tie

Well-tie data were published for the ODP well sites (Eberli et al., 1997a; Anselmetti et al., 2000; Eberli et al., 2002; Wunsch et al., 2018) providing with time-depth points for the SSB A, B and C (Fig. 2B). The preservation of reflector continuity for SSB B on the slope gave us a slightly shallower value at well 1005 of 80 ms TWTT versus 100 ms. Eberli et al. (2001) published also well tie data for the platform wells with the reprocessed seismic. We use these values, though for SSB A they fall above the cut at 0.08 s. The time geometry of SSB A and the seafloor was reconstructed based on these points, the reflectors visible at the platform edge and similar to the geometry of Wilber et al., 1990, and the knowledge of the sea-floor depth at the platform edge (55-60 m, Wilber et al., 1990) and at Clino and Unda (7.6 and 6.7 m respectively, Manfrino and Ginsburg, 2001) (Fig. 11B).

2.3 Stratigraphic forward modeling

2.3.1 Model outlines and strategy

The numerical forward stratigraphic DionisosFlow model (Granjeon and Joseph, 1999) was designed to investigate the 3D development of siliciclastic and carbonate sedimentary systems at the basin scale. It has been used for smaller scale clastic or carbonate systems (Rabineau et al., 2005; Csato et al., 2014; Montaggioni et al., 2015) allowing reconstruction of sedimentary architectures below the fifth order time-scale resolution. The model offers the possibility to test the impact of a conceptual depositional model on the internal stacking pattern and stratigraphic evolution of the resulting sedimentary accumulation (Warrlich et al., 2008; Montaggioni et al., 2015; Lanteaume et al., 2018). In this study the choice of the processes and the values of the parameters are based on the available geological constraints and fitted through a trial and error process. The quality of experiment is determined by the fit of the simulated stratigraphic markers position against their core interpretation and the valid geometry of the reconstructed present-day margin profile.

Three modelling experiments are tested on DionisosFlow (Fig. 5).

- Experiment 1 looks at the margin geometry associated with a progradation driven entirely by the highstand shedding of the inner platform production.
- Experiment 2 investigates the influence of bio-constructed and early cemented carbonate production at the margin.
- Experiment 3 tries to reproduce the platform evolution after 0.8 Ma under the sedimentary regime described in the Holocene (1.2.2).

The three simulations aim at evaluating the relations between highstand production and shedding and the platform progradation, and the impact of carbonate producers changes under a given eustatic history.

We used here a 42 km long 2D model, with a grid resolution of 50 m. Time is discretized into 340 time-steps of 5 kyr from 1.7 to 0 Ma BP. This pseudo 2D section represents the “Western line” transect projected in a direction orthogonal to the slope (Fig. 1B). It comprises 12 km of platform domain, and 30 km of slope domain. Due to the limited modeling of the contour current activity in a 2D section, the displayed zone of interest is limited to the slope domain and stops downward of well 1007 (Fig. 1B), with 12 km of platform domain and 9 km of slope

(21 km in total). The ODP and BDP wells were also projected under a cylindricity hypothesis on this modelled section (Betzler et al., 1999).

In DionisosFlow carbonate production is defined through time by the definition of a source function. It describes $CaCO_3$ production rate according to water depth. In this study it is tied to a type of carbonate sediment material that can be more or less easily traced back to a mix of biogenic sources. Depending on the simulated sediment, this sediment source function can integrate already a certain range of mixing, degradation and transport processes in the simulated « production » process. In that case it is would be more aptly described as an "accumulation" rate. The production rates are defined in order to fit, insofar as possible, the observed architecture. They are heavily dependent on the geometry and transport efficiency of the simulation.

The transport processes are modelled in DionisosFlow by a non-linear diffusion law approximation (Granjeon, 2014). Several diffusion coefficients are attributed to each sediment class in order to model the slope-driven transport and the wave-driven transport. The slope-driven transport expresses the sediment flux $Qs=K*S$ where S is the local slope, and K the diffusion coefficient in km^2/kyr. In the western GBB sedimentary system the major part of the transport of the fine-grained production on the platform towards the slope is due to an advection process: density-cascading of sediment-laden water from the platform (Wilson and Roberts, 1992; Eberli, 2000; Wunsch et al., 2016). This remobilization of sediment on the platform was simulated in DionisosFlow using a 1D wave model defined with a wave base action depth at 20 m (fair-weather waves). The bathymetry-dependent wave energy function allows the remobilization of the sediment according to the local wave energy. Sediment transport on the platform is actually driven by the wind and the shallow tidal currents (Harris et al., 2015). This wave-driven diffusion function is used as a diffusion boost to account for these complex shallow transport processes on the flat platform. The reworked sediment is then transported according to the local slope under the rules of gravity-driven diffusion.

2.4 Simulations parameters

2.4.1 External controls

A constant and uniform subsidence rate of 34.1 m/Myr was assumed as there is no evidence of vertical relative sediment displacement along the transect (Eberli and Ginsburg, 1987; Eberli et al., 2004; Principaud et al., 2016; Wunsch et al., 2018). This value is calibrated by the reconstitution of the correct present-day position for SSB C line and the 56 m thick accumulation observed at well Unda. The eustasy parameter was derived from the curve of Miller et al. (2011) resampled at 5 kyr resolution. In order to better constrain the real accommodation space and sedimentation rate, we also simulated the mechanical compaction.

The definition of the initial basement topography is a key assumption for the whole simulation (Montaggioni et al., 2015; Lanteaume et al., 2018). We considered the depth of the SSB C in the six wells of the section to draw a 1.7 Ma topographic profile consistent with the seismic interpretation. The initial sea-level position at 1.7 Ma was derived from the location of the first onlap in the seismic interpretation. The platform level is thus set at 40 m above sea-level at 1.7 Ma.

The Santaren Current is considered as a major external control, limiting sediment accumulation at the toe-of-slope (Betzler et al., 1999; Rendle and Reijmer, 2002; Betzler et al., 2014; Principaud et al., 2016; Wunsch et al., 2018). It was integrated in the pseudo-2D DionisosFLow with an open boundary condition on the basin section westward of well 1007. A constant northward discharge of 0.01 km^3/Myr of fine-grained sediment is applied. It prevents deposition in the basin fixes the toe of the progradation at ~10 km from the platform break.

In the model the contour current effect was activated after 0.8 Ma, though it has likely been active since the Pliocene (Rendle and Reijmer, 2002; Principaud et al., 2016; Wunsch et al., 2018). This is consistent with the sedimentary profile of the ODP well 1007, with 25 m of deposits between 1.7 Ma and 0.8 Ma, and only 12 m after.

2.4.2 Definition of carbonate producers

Three different carbonate producers are considered in our experiments for the Quaternary interval (1.7 - 0 Ma). They are simulated by different bathymetry-dependent source functions (Fig. 6), and different high-diffusion or low-diffusion gravity driven transport laws, determining respectively low or high slope angle of accumulation (Granjeon, 2014). Following the analysis of Kenter (1990) the slope of accumulation of the carbonate production is directly related to its dominant sediment fabric.

As explained in section 4.1 the value of the wave transport coefficients for the same facies can vary between different experiments in order to keep a comparable off-bank sediment flux (Table 3). The contrast in wave-driven diffusion coefficients expresses the easy mobilization of fine-grain uncemented sediment in respect to the cemented material accumulated *in situ*.

The contrast between the high-diffusion and low-diffusion facies is always preserved. Low slope-driven diffusion coefficients (Table 3) expresses the ability of cemented, bioconstructed/binded or coarse grained facies to build stable accumulations with steep slopes (Kenter, 1990; Playton et al., 2010).

The first producer, designed as “aragonite ooze”, corresponds to the fine-grained aragonite ooze produced on the platform.It has a very high gravity diffusion coefficient, constrained by the very low slope angle of periplatform ooze accumulation (Kenter, 1990; Playton et al., 2010) (Table 3). The ooze deposits cannot form any relief on the platform nor accumulate on the steep margin (Fig. 5).It is easily remobilized by the hydrodynamic currents on the platform and exported to the slope (Fig . 5). It is simulated with a high value of wave driven-diffusion coefficient (Table 3).

Two other producers were defined to account for the marginal production and accumulation. Both are cemented low-diffusion sediment accumulating in steep marginal configurations (Kenter, 1990; Grammer and Ginsburg, 2012; Betzler et al., 2016). The low diffusion value limits also their transport in the low-angle slope domains. They have a low wave-driven coefficient as they accumulate *in-situ*.

The first one is named as “reef & cemented talus” (RCT). It aims at simulating the lowstand coarse cemented wedge described by Grammer and Ginsburg (1992), supplied in particular by a fringing reef development.

The second one is named as “coarse & cemented platform edge” (CCPE). It aims at simulating the sandy and cemented accumulation described at the platform edge by Wilber et al. (1990). They are transported by shallow platform currents to this outer and deeper platform edge depocenter at water depth extending from 10 to 60 m (Wilber et al., 1990). As explained in section 4.1 the crudel model of hydrodynamism on the platform in these simulations is unable to simulate consistently this transport toward the platform edge where the sediment is accumulated and cemented. As a consequence the CCPE material is directly simulated as a cemented low-diffusion sediment, and its source function is actually an accumulation curve in the platform edge depocenter. Since it is composed of non-skeletal grains (ooids, pelletoids and grapestone) produced on the inner platform (Wilber et al., 1990; Harris et al., 2015) the CCPE producer is active in the simulation during platform flooding only.

A mechanical compaction curve was associated to each producer. For the « aragonite ooze » it was designed from experimental results of five oedometers tests on periplatform ooze samples from sediment cores of the Little Bahama Bank (LBB) northern slope, and three oedometer tests on periplatform ooze of the same slope published in Lavoie et al. (1988). The proposed curve is consistent with the porosity trend of the four ODP Leg 166 wells on the slope. For the RCM and CCPE material, the “coarse” compaction curve of Caspard et al (2004) calibrated for the platform margin of the “Western Line” section was used.

2.4.3 Production laws

The production of the “aragonite ooze” facies occurs during whitings event and with the degradation of green algae and seagrasses (*Halimeda* sp., *Thalassia* sp.) on the shallow platform (0-10 m water depth) (Schlager and Ginsburg, 1981; Manfrino and Ginsburg, 2001; Harris et al., 2015). It decreases progressively with the light intensity and stops at 50 m water depth corresponding to the base of the present-day photic zone in Bahamas (Schlager et al., 2005) (Fig. 6).

The production function for the RCT facies is defined with maximum production at 10 m water depth as observed for corals (Pomar and Hacq, 2016) (Fig. 6). This production is also restricted to the high wave energy domain above 80W/m^2 in order to prevent it reaching in the shallow platform interior. The sustained production rate between 30 and 50 m allows to account for an oligotrophic component (Betzler et al., 2016) and the gravity driven accumulation of erosional lithoclasts (Grammer and Ginsburg, 1992).

The production of the CCPE facies is defined with a similar shape but it creates slighty deeper accumulation down to the mesophotic zone (Wilber, et al., 1990) (Fig. 6).

The values of the production rate vary during the simulation (Fig. 6). These variations come mostly from the trial-and-errors calibration of the best fit for all the three experiments. They also account for the general warming that followed the end of the Mid-Pleistocene Transition and the Mid-Bruhnes event (~0.45 Ma) (Reijmer et al., 2002; Wunsch et al., 2018). The increasing trend for the “aragonite ooze” and “CCPE” facies production corresponds to the increase in the flooded surface of the platform during the highstands (Kievmann, 1998). The very high values of the “aragonite ooze” production for Experiment 2 are explained in section 4.4.

2.4.4 Definition of resulting lithofacies

The definition of five simulated lithofacies, based on the sediment composition and sedimentation rate, allows to highlight and understand the interplay between the muddy aragonitic highstand sediments in the platform and slope and the coarser or more cemented margin sediments (Table 4).

The two slope facies (below 150 m) “Periplatform ooze” and “cemented ooze” are distinguished only by a sedimentation rate threshold of 1000 m/Myr. The diagenetic signal of early cementation is simulated here (Fig. 7, Fig. 8) using the sedimentation rate as a proxy.

3 Results

3.1 Experiment 1: fine-grained uncemented margin

Experiment 1 is constructed with reefal production between 1.7 and 0.8 Ma only, leaving only the inner platform aragonite ooze production between 0.8 and the present (Fig. 6). The result shows a remarkable contrast between these two. During 1.7-1.4 Myr interval, the accumulation of mostly reefal production on the upper margin profile creates a lowstand wedge, both prograding downslope and onlapping upslope. It finally covers the whole platform domain during the 1.5-1.4 Ma transgression (Fig. 7A). During this period there is bypass on the steep margin and reduced deposition in the slope. During the following 1.4-0.8 Ma interval the prograding/aggrading evolution of the margin evolves towards a more forced prograding pattern. Vertical accretion on the platform is much reduced, but becomes dominated by aragonite ooze production (Fig. 9A). Accumulation of reefal production at the front of the margin ensures the profile progradation as the slope accumulation is much reduced.

Overall during this period the platform margin has prograded and steepened. It has created an accretionary slope profile with a constant gradient and a flat-top platform (Fig. 7A).

The profile geometry is considerably modified after 0.8 Ma until 0.42 Ma. There is almost no deposition in the system and no effective progradation of the platform (Fig. 7C). This general modification is due to both the end of low-diffusion reefal production and the change of eustatic regime with lower maximum values and two marked falls at 0.6 and 0.42 Ma (MIS 16 and 12) that reduce the available accommodation space.

With the major transgression of MIS 11 (0.42 – 0.37 Ma) the platform is flooded again allowing accumulation of aragonite mud on the platform and export downslope of a very large onlapping highstand wedge (in red on Fig.7A). The successive flooding of MIS 9 (0.34 – 0.30 Ma) and 5 (0.13 – 0.07 Ma) leaves no large accumulation on the platform, but two slope wedges that onlap progressively above the platform edge (Fig.7). This succession creates an accretionary prograding margin and a smooth slope profile with a very open platform margin (Fig.7 C). Consequently the Holocene leaves a continuous prograding tract of mud, without the onlap of a distinct slope wedge (Fig.7 A).

Experiment 1 results partially reproduce the platform accumulation in wells Clino and Unda. On the slope it captures the general increase of sedimentation rates after 0.8 Ma and the alternation of thick interglacial highstand packages with condensed lowstand surfaces.

However it oversestimates the sediment thickness in the slope wells after 0.42 Ma, and underestimates it before 0.8 Ma (Fig. 9A). There is construction of a progradational margin but the progradation is not developed enough (Fig. 7C).

Most importantly, the steepening trend and the present-day profile are not reproduced (Fig. 7A). A constant smooth slope is instead realized as only one diffusive material is accumulated. Any increase in production and export would lead to larger progradation but also greater overestimation of the slope accumulation. A decrease would result in loss of progradation or even no margin deposition after 0.8 Ma, though the thickness at the slope well would be more correct. The constant slope depositional profile is unable to reproduce the steep margin and low angle slope transect evolution.

This experiment of highstand progradation of uncemented fine-grained sediment tracts is not consistent with the progradation of the observed section. Another depositional model must be considered for the Quaternary leeward slope.

3.2 Experiment 2: Cemented margin

For the 1.7-0.8 Ma period, experiments 1 and 2 are fairly identical, except for the thickness of the downslope aragonite mud deposits (Fig. 9B). This might be a consequence of the increased wave diffusion coefficient (export efficiency) in experiment 2 (Table 3).

However, after 0.8 Ma, the depositional architecture is quite different: during the 0.8-0.4 Myr interval, deposition of cemented facies occur on the margin, maintaining the steepening trend under a forced regression regime (Fig. 7A and B). Export of aragonite mud on the slope also occurs (Fig. 9B). Similarly, the MIS 11 flooding after 0.42 Ma leads to aragonite mud accumulation on the platform and the slope (Fig. 8). However the onlapping slope wedge is in a lower position and of smaller volume than in experiment 1. There is aggradation of RCT material in the margin, maintaining the steep profile. RCT material also backsteps on the platform (Fig. 7B). This can be related to the reefal accumulation observed in well Clino between 48 and 35 mbsl (Fig. 9B) and interpreted by Manfrino and Ginsburg (2001) as a reefal backstep. Accumulation is relatively reduced during MIS 9 (0.34 – 0. 3 Ma) on the platform and the onlapping slope wedge. The MIS 8-6 (0.3 - 0.13 Ma) interval shows only accumulation of cemented material on the margin, forming a lowstand prograding wedge onlapping up to the platform edge and dowlapping down to the top of the slope (Fig. 7C). MIS 5 (0.13 – 0.07 Ma) repeats the depositional pattern of MIS 11 (0.42 – 0.37 Ma) with a reduced thickness and no backstepping of the marginal cemented accumulation. The sea-level fall during MIS 2-4 (0.07-0.01 Ma) leads to the deposition of another lowstand marginal wedge of cemented material. It evolves into an aggrading margin with the Holocene transgression and the deposition of the platform and onlapping slope highstand deposits (Fig. 7C).

This experiment reconstructs fairly well the steepening trend and the present-day geometry of the profile (Fig. 7A). The well succession on the slope and platform is well reproduced, especially in terms of the different sedimentary packages and the total thickness (Fig. 9B). However the thicknesses of the highstand packages after 0.33 Ma are always moderately underestimated (Fig. 9B). The repartition of the two simulated facies is in good agreement with the information from the wells. The highstand shedding pattern of off-bank mud export into onlapping slope wedges is well reproduced in this experiment. The « Aragonite mud » is accumulated on the inner platform and on the slope, in onlapping highstand wedges separated by aragonite poor glacial layers. The cemented facies accumulates in the margin in two positions. It creates lowstand marginal wedges during the platform emersion periods, especially during the MIS 16 (0.68 – 0.62 Ma) (, MIS 12 (0.48 – 0.42 Ma), MIS 8-6 (0.3 – 0.13 Ma) and MIS 4-2 (0.07-0.01 Ma) intervals. Its ability to accumulate at steep slopes allows to fill part of the accommodation space available on the margin during these periods. The cemented facies also aggrades at the platform edge during flooding periods, maintaining a steep margin profile. However this affects the exact restitution of the platform depositional profile. Very flat-top platform morphology are created, as early as 1.5 Ma, whereas the present-day profile show a sloping geometry seaward of Clino and a more open margin (Fig. 7C). The RCT accumulation at the margin creates an inconsistently steep and shallow geometry.

The accumulation of cemented facies in lowstand marginal wedges allows for steepening of the profile . The and the progradation of the platform (Fig. 7C). The architecture obtained is that of a composite prograding margin. This experiment 2 proposes a satisfying forward reconstruction, but the exact nature and existence of the prograding cemented lowstand wedges need to be assessed.

3.3 Experiment 3: Cemented margin during highstand only

The results of experiment 3 stand in-between those of Experiment 1 and 2. Indeed it comprises a cemented facies, as Experiment 2, but the production after 0.8 Ma is nevertheless limited to the highstand periods (Fig. 8). Before 0.8 Ma the results are very similar to Experiment 1, with the same deficit of export to the slope, probably related to the relatively low value of the wave-diffusion coefficient (Fig. 9C and Table3). During the critical period between 0.8 and 0.42 Ma the production is limited to the margin area with the CCPE in a forced regression configuration (Fig. 7A and B). The reality of non-skeletal carbonate production for the CCPE accumulation during this period of very limited platform flooding is debatable. This is why reduced production values were attributed to this facies during this period (Fig. 6). After 0.42 Ma the results for the slope domain are similar to the Experiment 1, with very high sedimentation rates (Fig.8). The margin profile is however similar to Experiment 2, but with less progradation (Fig. 7C). In the absence of lowstand production the cemented margin is simply aggrading, as proposed in Figure 3B.

In this last experiment, the general architecture is well reconstructed, except in the slope (excess of sediment) and in the reduced platform progradation. In contrast with experiment 1, the simulated section in Clino is fairly correct (Fig. 9C). Indeed the platform profile is well-reproduced in this scenario, with a steep margin escarpment but still a relatively convex and open platform to margin transition (Fig. 7A). This is a good validation of the reproduction of the Holocene platform edge depocenter described by Wilber et al. (1990). The accumulation of cemented material during highstand flooding periods allows building a steep leeward margin profile, but the major drawback of this simulation is the absence of progradation even with very high rates of export and sedimentation on the slope. In a transect dominated by leeward offbank transport and highstand shedding, the presence of the lowstand marginal wedges of experiment 2 still appear critical for the progradation of the platform.

3.4 Platform-to-basin Stratigraphic evolution

The DionisosFlow simulations defines two major periods for the Quaternary interval. They are separated by a transition interval between 0.8 and 0.4 Ma that corresponds to the transition from 41-kyr eustatic cycles to the 100-kyr eustatic cycles (Fig. 7D).

After the sea-level fall at 1.7 Ma, a well-developped coral reef progrades in the upper margin (Budd and Manfrino, 2001). The progradation of the reef and lagoon unit is clearly reproduced in all the Dionisosflow experiments. It is illustrated in well Clino by the vertical succession of coral framestone, coral floatstone and lagoonal mud until 70 mbsf (Manfrino and Ginsburg, 2001) (Fig. 4 and Fig. 10). The Dionisos experiments correlate this growth episode with the 1.7–1.4 Ma time interval which corresponds to a general sea-level rise (Fig. 7D). Deposition in the slope is limited and seems to start after the more widespread flooding of the platform landward of well Unda after 1.5 Ma (Fig. 8).

After the initial build-up of this aggrading/prograding reefal wedge at the margin, the simulated stratigraphy evolves towards a regressive pattern. Important changes take place during the normal to forced regressive interval (0.8 - 0.42 Ma) (Fig. 6) with very little accumulation on the platform (Fig. 7A). In Clino, a 10-m-thick lagoonal mud interval may indicate a significant flooding possibly related to the relative sea-level highstand of MIS 17 (0.71 – 0.68 Ma) or MIS 19 (0.79 – 0.76 Ma). Otherwise the lithologic records in wells Clino and Unda for this period show reduced accumulation, with four emersion surfaces in 20 m of stacked platform deposits (WF D and E) (Fig. 4). This corresponds to the globally low sea-level values of the eustatic curve.

. This eustatic evolution between 0.8 and 0.42 Ma ensures that the sediment accumulation is limited to the margin domain (Fig. 8). The lower accumulation rates on the slope combined with the margin progradation lead a steepening of the profile.(Fig. 7A).

After the warming phase corresponding to the Mid-Brunhes Event at ~0.45 Ma (Reijmer et al., 2002; Montaggioni et al. 2015; Wunsch et al., 2018), the very large trangression of MIS 11

(0.42 – 0.37 Ma) is the first flooding of the whole GBB platform (Aurell et al., 1995; Kievmann et al., 1998). It is well expressed in the three simulations as well as in the platform wells (Fig. 9). On the platform, a retrograding transgressive package compound of interlayered coral floastone and lagoonal mud correlates in experiment 2 with a major increase of "Aragonite ooze" sediment (Fig. 7A and Fig. 9). The coeval sediment bypass in the marginal escarpement and the thick onlapping deposit in the slope (53 m in well 1005) are well apparent in the three experiments (Fig. 7A). Flooding of the platform occurs during MIS 9 (0. 34 – 0.3 ma) and 5 (0.13 – 0.07 Ma) (Aurell et al., 1995; Kievmann, 1998; Rendle and Reijmer, 2002) (Fig. 9). MIS 7 sea-level peak is distinctively lower (Lisiecki and Raymo, 2005; Miller et al., 2011) and might not have flooded the whole platform (Fig. 7D). Concerning the platform and margin, the detailed identification in wells and seismic record of the highstand packages between SSB B and A is relatively difficult (Eberli et al., 2013). Deposition during MIS 10-6 (0.37 – 0.13 Ma) appears very limited in Clino and Unda, with mixed skeletal/non skeletal accumulation in the former (Fig. 9). MIS 5 (0.13 – 0.07 Ma) highstand is instead well-associated with platform deposits in both Unda and Clino.

A remarkable result of the Dionisos simulation is the simulation of the actual sedimentation rates on the section (Fig. 8). They can reach up to 8 m/kyr during the MIS 11 (0.42 – 0.37 Ma) transgression. Such high-values are driven by the very short duration of effective sedimentation period and are similar to those of Wilber et al. (1990) for the Holocene. For instance the Holocene slope wedge with sedimentation rates above 5 m/kyr is mostly deposited after 5 kyr B.P., when the platform flooding is effective, and not since the beginning of MIS 1 (14 kyr BP) (Lisiecki and Raymo, 2005; Montaggioni et al., 2015; Chabaud et al., 2016).

4 Discussion

4.1 Numerical experiments limitations

Several limitations exist in the DionisosFlow numerical simulations, affecting the validity of the detailed simulated architectures.They do not suppress however the consequences of the initial design of the three numerical experiments on the obtained architecture, and the subsequent conclusions.

Sub-aerial erosion is mostly limited to carbonate dissolution in Present-day systems (Schlager et al., 2015). Values of 100 m/Myr or 250 m/Myr were inferred by Kolodka et al. (2016) and Montaggioni et al. (2015). Considering an emersion period of 0.1 Myr this would lead to a destruction of 10 to 25 m of platform material, which is up to half of the record for the simulated period on the platform. This is also not in agreement with the remarkable preservation of MIS 5 deposits all around the Bahamas archipelago (Aurell et al., 1995). As a consequence a no-erosion approximation was used in our simulations. This hypothesis provides a very tight control of the subsidence rate parameter.

A more accurate integration of erosion would bring valuable refinements to the problem. Gravity, karstic and wave erosion probably occur at the steep margin wall during subaerial exposure (Grammer and Ginsburg, 1992; Rankey and Doolittle, 2012; Fauquembergue et al., 2018). The interpreted seismic surfaces also show convexe upward geometries at the platform edge that might suggest sub-aerial or wave erosion (Fig. 11B). These geometries are not very well reproduced, showing instead flatter architecture in the experiments (Fig. 11D). Improvement on the use of sub-aerial and shallow water transport model in further experiments could yield better results.

The high-resolution production and export balance on the platform is modelled without a specific model of the shallow hydrodynamic regime and transport. As a consequence, the values of the wave diffusion coefficient and the production function for the mud are not independent. They have to be set together to achieve the amount of export required for the slope section in response to a given wave energy configuration at the platform edge. The simulated wave-energy field depends on the margin geometry as it is depth controlled. As the resulting wave energy pattern becomes more favorable, the diffusion coefficient needed for a given flux of sediment decreases The volume of accommodation space is also positively affected by the off-bank export increase. As a result, both the production law and the diffusion coefficient must be jointly decreased in order to maintain the balance between platform accumulation and off-bank export. This is particularly notable for experiment 2, with the existence of a reefal shallow margin that strongly decreases the wave energy at the platform edge. The « aragonite ooze » facies is also produced on a very large platform area, more than 100 km in W-E length (Harris et al., 2015), but here only a small section of 12 km is considered. The production values must be artificially raised to account for the actual amount of mud producedon a much larger surface.

As a consequence of the no-erosion hypothesis and the very high platform production values, the accommodation space on the platform is filled very quickly. This differs from the present-day GBB platform that appears partially underfilled (Harris et al., 2015). The total produced volume simulated is directly controlled by the total accommodation space created during a flooding phase. This leads to an overestimation of the sediment accumulation on the platform during a marked transgression like MIS 11. Then the available accommodation space for the following flooding phase like MIS 9 or 5 is artificially reduced. The discrete sampling of the eustasy curve contributes to this result by missing out the maximum peaks, especially for MIS 5.

Here, the influence of contour currents is limited to an open lateral boundary condition. It controls the position of the lower slope periplatform drift in the experiments. The control of the morphology of the periplatform drift by the current action (Betzler et al., 2014; Wunsch et al., 2016) or by gravitational failures (Rendle and Reijmer, 2002; Principaud et al., 2015;

Principaud et al., 2016; Schnyder et al., 2016) are integrated into the diffusion approximation by the value of the diffusion coefficient for the “aragonite ooze”.

4.2 Mechanisms and controls of the margin progradation

4.2.1 Importance of cemented facies at the margin

All the three modeling experiments show a progradation of the platform for the interval 1.7-0.8 Ma through the construction of a reefal margin (Fig. 7B). After 0.8 Ma, only the experiments 2 and 3 show a progradation with an acceptable final profile geometry (Fig. 7C). The accumulation of early cemented material at the margin is essential in these two experiments to obtain these results. However they simulate two different marginal architectures originating from two different sedimentary systems. Experiment 2 is based on the development of marginal fringing reefs and an associated debris talus during platform emersion. This model is able to fill the accommodation space in front of the margin by accumulating material in this zone of steep topography during emersion periods. The resulting general architecture corresponds to a dominantly reefal margin with a filled lagoon. Experiment 3 model is based on the accumulation during highstand periods exclusively of coarse and cemented platform production at the platform edge and on the margin. The resulting general architecture is that of an open platform margin with a deeper prograding escarpment. These are two conceptual hypotheses that can be compared to available observations in the section and other margin depositional models.

4.2.2 Lithological and stratigraphic characteristics of the prograding margin

In the model of Grammer and Ginsburg (1992) for the slopes of Tongue of The Ocean, MIS 2-4 lowstand carbonate production is realized by fringing reefs feeding a steep (35-45°) cemented sand and debris talus. In their study on the LBB margin, Hine and Neumann (1977) observed reefal growth on the leeward margin during the Holocene transgression. After the platform flooding they are buried however by the leeward export of platform sands. Coral floatstone intervals are observed until MIS 6 (0.19 – 0.13 Ma) in well Clino (Manfrino and Ginsburg, 2001) as well as several rare occurences of coral debris in the OPD leg 166 cores for the Quaternary (Eberli et al., 1997a) (Fig. 4). All these observations indicate simply the persistence of coral production in fringing reefs (Hine and Neumann, 1977; Grammer and Ginsburg, 1992) after the regional peak of coral extinction described by Reijmer et al. (2002). This does not support the scenario of experiment 2 of a coral reefal margin constantly accumulating during flooding and emersion of the platform.

Indeed the role of coral production in the margin after 0.8 Ma appears much reduced compared to its extent in experiment 2. The margin is on the contrary dominated by the non-skeletal sand accumulation described by Hine and Neumann (1977) and Wilber et al. (1990) as modelled in experiment 3.

Interestingly the opposite trend is observed in the Pacific, with an increase in coral reef developpments after MIS 11 (0.42 – 0. 37 Ma) (Montaggioni et al., 2015). Contrasting regional environmental changes might be at play, but most probably the first cause of the relative disparition of coral reefs lies in the onset of large muddy production on the flooded platform (Hine and Neumann, 1977). However during emersion phases this inhibition is absent and coral production can be maintained in fringing reefs as proposed by Grammer and Ginsburg (1992).

Lowstand prograding marginal bodies have been described, by Grammer and Ginsburg (1992) as sandy talus sourced by a fringing reef factory. Mulder et al. (2017) identified possible coarse lowstand shelf-edge tidal deltas or gravity collapse deposits on the northern slope of the LBB . Betzler et al. (2016) also described MIS 2-1 coarse lowstand wedges on the slope of the Maldives atolls. They are dominated by rodoliths and large benthic foraminifers produced in situ. A relevant ancient analogue for lowstand wedges could be found in the Messinian

marginal reefal clinoforms described by Reolid et al. (2014) in the Cariatiz carbonate platform (Spain). Clinoforms are 80 m high and 200 m long bodies, prograding by redistribution of the coral and Halimeda marginal production and through episodes of mass-failure redeposition of very coarse debris during sea level falls. The very steep (30 -60 °) upper slope is preserved by early lithification of the corals by microbialith crusts.
In regards of these observations the hypothesis in Experiment 2 of coarse lowstand talus, with a fraction of coral component, appears conceivable. These wedges are critical in the experiments for the filling of the accommodation space in front of the margin (Cemented Lowstand Talus in Figure 10). However they do not have the development of the reefal margin observed before 0.8 Ma, during a different regime of eustatic oscillations (Manfrino and Ginsburg, 2001; Miller et al., 2011).

According to experiment 3, the escarpment is the site of accumulation of sandy platform material. This is compatible with the present-day observations on the GBB leeward margin (Wilber et al., 1990). The accumulation at the steep margin by cementation of the platform production would be comparable in geometry to the deep boundstone factory described by Playton et al. (2010). However in this case the progradation of the planar clinoforms of the margin is realized by the accumulation of debris apron resulting from frequent autogenic collapse.Such wedges of marginal progradation are lacking in experiment 3. As this non-skeletal sands observed in the Holocene corresponds only to flooding periods, we propose a conceptual model combining lowstand talus during emersion periods and aggrading platform edge sand bodies during flooding periods (Fig. 10).

As a conclusion the sedimentary accumulation at the margin has changed between 1.7 Ma and the Present-day. It has evolved from a reef-dominated margin to the Present-day cemented sand accumulation. The progradation of the platform before 0.8 Ma has been mostly realized by a coral reef barrier. After 0.8 Ma the geometry obtained with experiment 2 is the more consistent with the observed Present-day geometry. It supports a conceptual model of lowstand cemented talus wedges alimented by an undefined carbonate source, possibly reefal in part. It is distinct from the cemented non-skeletal sand accumulation deposited only during platform flooding periods in an aggrading pattern. The progradation of the margin after 0.8 Ma is realized by the succession of these two sandy and early cemented accumulations during emersion and flooding phases (Fig. 10).

4.2.3 Extrinsic and intrinsic controls

From the simulations results the interaction between extrinsic and intrinsic factors and the evolution of the margin architecture can be discussed.

The situation before 0.8 Ma of a partial flooding of the platform (Kievmann, 1998) appears more favorable to the progradation than later when the platform is completely flooded during every highstands. The change in the eustatic regime between 0.8 and 0.42 Ma with a net increase of accommodation space is influential in this change of sedimentary regime with the increase of non-skeletal production. After a regressive phase of accumulation on the margin, the sediment deposition is now concentrated on the platform and slope. The second period (0.42-0 Ma) corresponds to an overall increase in accommodation space, with higher amplitude sea-level rises and falls than during the first period and the abrupt transition from a sloping reefal margin to a steep cemented margin. The resulting comprehensive flooding of the GBB platform inhibits coral growth at the margin, and leads instead to the aggrading accumulation of non-skeletal sands at the margin (Fig. 10). This promotes a steepening of the margin profile, accentuating in turn the contrast between total emersion phases, with the development of a steep cemented talus *in front* of the margin, and the aggradation *on* the margin during flooding of the whole platform.

The very pronounced series of sea-level falls starting at 0.6 Myr also enhance the development of a steep marginal escarpment (Wilber et al., 1990; Eberli et al., 2004; Rankey and Doolittle, 2012; Mulder et al., 2017) (Fig. 7).

Chabaud et al. (2016) observed a similar major change in sedimentary regime at MIS 11 (0.43 – 0.37 Ma) for the northern slope of the LBB, corresponding to the flooding of the whole bank. Remarkably the higher sea-level has led to increased production and export of sediment to the slope (highstand shedding), but only to minor platform progradation (Fig. 6 and Fig. 7A). This modification of the sedimentary regime corresponds to the change of the margin geometry. In turns, it seems to be controlled by the type and mechanical properties of the carbonate production as well as by the eustatic regime. The progradation regime is not controlled primarily by the ratio of production rate and accommodation rate, but by the properties of the carbonate production. As the dominant muddy production cannot accumulate on the steep slopes inherited from the reefal progradation, it is built by early cementation of the coarse accumulations. The reduced volume and the geometry of this sandy platform edge depocenter favour an aggradational stacking pattern as observed in experiment 3 (Fig. 7C).

The activity of the Santaren Current is undoubtedly a major control parameter of the sediment accumulation on the slope and basin, especially of the geometry of slope wedges (Rendle and Reijmer, 2002; Betzler et al., 2014; Principaud et al., 2016; Wunsch et al., 2017; Wunsch et al., 2018). By preventing the sediment accumulation at the toe of slope, it enhances the steepening of the transect indifferently of the progradation or aggradation of the platform edge. It seems actually to have no direct influence on the margin geometry: in Wilber et al. (1990) the geometry of the platform-edge depocenter is very stable for all the transect, whereas the varying slope geometry further down is indeed related to spatial variations in the current activity.The active off-bank density currents (Wilson and Roberts, 1992; Betzler et al., 2014; Wunsch et al., 2016; Schnyder et al., 2018) are probably one of the main controls of the aggrading geometry of the platform-edge depocenter. They create erosive plunge-pools at the base of the margin wall (Wilber et al., 1990; Schnyder et al., 2018), and probably limit sedimentary accumulation along the steep wall.

4.3 Interpretation of the stratigraphic architecture in the seismic

The high-resolution geometries and stacking patterns simulated with DionisosFlow offer a consistent template of the margin evolution (Fig. 7). The interpretation of the seismic geometries at the margin *per se* is difficult, as the cored wells do not really constrain the physiography of the margin domain. Moreover the reflectors can be difficult to pick in this area of high-frequency impedance contrasts and variations (Eberli et al., 2004). It is however possible to propose an interpretation of different genetic bodies using the results of the forward stratigraphic modeling (Fig. 11).

The seismic section of the margin was analyzed in terms of reflectors terminations: downlap, toplap and onlap distinguishing between coastal onlap due to deposition at the base-level on the platform or the margin and marine onlap due to deposition in the slope underwater. Reflectors with good amplitude and continuity and significant terminations relationships were highlighted. The variations in amplitude of the reflectors in the margin were also used by interpreting the very bright reflectors as indicative of early cementation.

SSB C is downlapped by a well-organized prograding unit on the flatter upper margin, with moderate amplitude and low continuity reflectors (Fig. 11B). Deposition is further reduced below 270 ms TWTT, on the steepest part of SSB C profile, down to a lower slope marine onlap at 400 ms TWTT.

More continuous but lower amplitude reflectors underline a forced regressive architecture, carrying the platform edge down to a remarkable downlapping/onlapping suspended body at 200 ms TWTT. Accumulation is still reduced on the lower margin and the slope (Fig. 11B). As a consequence the steepening of the margin profile increases. This phase seems to end with a general retrogradation of the system highlighted by the development of a cemented surface at the very edge of the platform. Deposition occurs then on the slope, with new marine onlap, and is also backstepping on the relatively flat platform up to the very bright reflector identified as SSB B (Fig. 11B).

This evolution is very consistent with the results of the numerical experiments. The forced regressive evolution between 0.8 and 0.42 Ma (Fig. 6) as well as the final retrogradation during MIS 11 (0.42 – 0. 37 Ma) are well observed in all the experiments. The new profile of SSB B is more similar to the present-day profile than SSB C (Fig. 11C). .

Above 180 ms TWTT the geometries appear quite different on the margin (Fig. 11B). Platform-edge bodies, delimited by bright sub-horizontal reflectors and with internal downlaps can be identified with the platform edge depocenters described in Wilber et al. (1990) (Fig. 10). They are onlapped by steep margin wedges with very bright reflectors indicating probably cemented material. In the slope bodies with moderate amplitude and very continuous reflections are onlapping the steep margin (Fig. 11C). Downlapping cemented marginal wedges are observed in the seismic (Fig. 11B) similar to the cemented marginal wedges of experiment 2 (Fig. 7C). Coastal onlaps that indicate an accumulation during platform emersion especially MIS 6-8 and MIS 2-4 (Fig. 11B).

The interpretation of the margin stacking pattern in the seismic yields an architecture consistent with the numerical results. The early geometries show the progradation of a reefal margin. The progradation/aggradation after 0.42 Ma appears to involve platform edge bodies and prograding marginal cemented wedges. The observed geometry of the present-day Holocene mud wedge stands out from the earlier MIS 5 or 11 slope periplatform wedge, but it might not correspond to the preserved highstand geometry (Fig. 11C).

5 Conclusions

The use of numerical forward stratigraphic modelling allowed us to investigate the high-resolution evolution of the Quaternary leeward margin of the GBB. Maximum information has been extracted from the quality data of the platform and slope wells, as well as the reprocessed seismic of Wunsch et al. (2018) by comparison with the results of several conceptual models.

This study has shown that the evolution of the margin during the Quaternary interval of interest (1.7 – 0 Ma) can be divided in two different phases, with a transition period between 0.8 and 0.42 Ma. The first period (1.7–0.8 Ma) corresponds to a period of partial flooding of the platform and progradation of dominantly coral reef and lagoon system. The second period (0.8-0.42 Ma) corresponds to a period of short and discrete flooding episodes of the whole platform triggering massive muddy offbank transport, and lowstand periods of margin accumulation and progradation.

The evolution of the transect architecture during this period cannot be explained only by the offbank transport of the fine-grained platform production. The Present-day sedimentary architecture and profile is actually only indicative of the recent Holocene platform-flooding highstand conditions. It has been shown that different sedimentary regimes have probably existed during the Quaternary not only before MIS 11 transgression (0.42-0.37 Ma) but also after during the long-duration emersion periods.

The numerical investigation shed some light on the controls of the margin architecture and the progradation of the platform. The margin profile as interpreted in the seismic and observed at present day seems always due to the marginal accumulation of a cemented or bio-constructed material, different from the fine-grained inner platform-production exported off-bank. This marginal material is well known before 0.8 Myr as a coral reef drilled in Clino. The numerical experiments do not give an unequivocal identification of the undrilled material after this date.

It shows nevertheless that the Present-day platform edge accumulation of platform sands is not sufficient to explain the architecture of the observed Present-day margin.

The experiments demonstrated the role of lowstand marginal accumulation in the progradation of a leeward carbonate margin. A carbonate factory has to be producing and accumulating at the steep margin area during platform emersion. Its characteristics differ from the fine-grained Present-day platform production to be able to accumulate there, meaning coarser grain sizes, cementation or bio-construction. Such a lowstand component is not visible in studies of the slope area, as shown in our experiments, and can be overlooked in the model based primarily on geophysical and sedimentary data from the slope (Principaud et al., 2016b; Wunsch et al., 2016; Wunsch et al., 2018). However coarse and cemented lowstands prisms have been described in recent systems, notably in the Maldives by Betzler et al. (2016) and in the Bahamas by Grammer and Ginsburg (1992). In that latter case the carbonate source proposed was lowstand fringing coral reefs, but other carbonate sources like red algae or large benthic foraminifera could be considered as well (Betzler et al., 2016).

The evolution of the architecture of the platform-to basin transect during the Quaternary appeared controlled by the eustasy as well as the characteristics of the carbon production. Eustasy produces a strong control on the timing of the evolution but the geometry is controlled by the carbonate production. The diffusive DionisosFlow model highlights the critical role of the stability domain of carbonate grains and early cementation (Kenter, 1990; Playton, 2010) to build the steep margin/low angle slope accretionary profile of the GBB leeward slope.

The change in carbonate production after 0.42 cannot be disconnected from the evolution of the eustatic regime toward high transgression of 100-kyr cycles. The resulting comprehensive flooding of the platform and large leeward off-bank transport of sediments was probably an important factor in the demise of large coral reefs. The diminishing importance of the coral production is coeval with a reduction of the progradation rate of the system.

This high-resolution forward modeling approach could be implemented in on a wider extent on the well mapped Leeward GBB Bahamas slope (Principaud et al., 2016; Wunsch et al., 2018), or other slopes. A 3D approach could fully integrate the effect of the contour currents. This approach could be conducted further for “source-to-sink” estimations of production, transport and deposition balances of sediments in the whole carbonate system. The inputs of the data from the Bahamas Drilling Project wells Clino and Unda (Ginsburg et al., 2001) were invaluable in this study. New subsurface drilling investigations of present-day carbonate margin can bring major insights in the dynamic and controls of carbonate platforms.

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TABLE CAPTIONS

Table 1: Age, Depth and time position of this study stratigraphic markers in the six wells, compared with the previous publications on this transect.

Table 2: The five lithofacies identified in the six wells of the study, with their lithology, depositional environment and, mineralogic and diagenetic fabric.

Table 3: Values of transport coefficients for the DionisosFlow simulation.

Table 4 : Definition of the simulated lithofacies from the output of the DionisosFlow simulations.

FIGURE CAPTIONS

Figure 1. A: General location of the Great Bahama Bank (GBB) and the leeward western slope. In orange, the area surveyed by the Carambar Leg 1 mission (Mulder et al., 2012), with, in red,

the interpreted transect. B: Multibeam bathymetry of the western GBB slope (Principaud et al., 2016) with the position of the “Western line“ Seismic transect (Eberli and Ginsburg, 1987), the ODP 166 Wells (Eberli et al., 1997a) and the BDP Platform wells (Ginsburg et al., 2001).

Figure 2. « Western Line » platform to basin seismic transect and the six reference wells. A: Original seismic data. B: Sedimentary sequences interpreted on the Western line, following Eberli et al., 1997a nomenclature. The six post-Miocene seismic sequences interpreted by Eberli et al., 1997b are displayed. The “Quaternary” (1.7 – 0 Myr) refers here to the specific interval studied here. The seismic data come, from left to right, from the Carambar 1 HR data published in Principaud et al., 2016; in the box, the reprocessing of the “Western line” original acquisition published by Wunsch et al., 2018, superimposed on the original ” Western Line ” data as published by Eberli and Ginsburg, 1987.

Figure 3. Present-day geometry of the leeward GBB margin, after Wilber et al. (1990), and geometrical implications for the stacking pattern. A: Observed Schematic section of the depositional geometry for the Holocene and the previous interglacial stage, after the drawing of Eberli et al. (2004; Figure 17 C) and the section of Wilber et al. (1990; Fig. 3). B: Conceptual scheme of the aggrading stacking pattern resulting from the accumulation of the Holocene deposits of A) minimizing the supplementary material needed. C: Conceptual prograding stacking pattern resulting from the accumulation of the Holocene deposits of A) plus supplementary material in the marginal zone.

Fig. 4. Well correlation for the ODP wells 1003 to 1005 and the two BDP wells Clino and Unda showing the lithofacies interpretation corresponding to table see Table 2) and the identified stratigraphic markers (described in section 2.1). Left-top corner: Wells positions in the “Western Line” (see Fig. 1B and Fig. 2).

For the BDP wells Clino and Unda, from left to right, we present the interpreted lithofacies and the detailed lithological description of Manfrino and Ginsburg (2001). For the ODP 166 wells, from left to right, the interpreted lithofacies and the lithological description of Eberli et al.

(1997), for well 1005 the ODP Vp seismic velocity (core (red) and log (black) data of Eberli et al. (1997a)), and the XRD mineralogical composition modified from Eberli et al. (1997a).In the middle the time evolution of the accommodation on platform calculated from the eustatic curve of Miller et al. (2011) with our hypothesis of constant subsidence rate of 34.1 m/Myr.

Figure 5. Schematic of the three experimental designs for the DionisosFlows simulations after 0.8 Myr. Befor this date they are all similar to Experiment 2.

Figure 6. DionisosFlow production laws. Left: the normalized production profiles for the three producers. Right: time evolution of the maximum production value for the three producers, with the difference between Exp.2 and Exp 1&3 for the aragonite ooze production. The production of the CCPE facies (in Exp. 3) is discontinuous with time.

Figure 7. Simulated sections at 0 Myr. A: Age results for the three experiments, following the color chart presented in D). B: Lithofacies results for the three experiments, according to table 3.The black line indicates the observed present-day profile. C: Detail view of the age results of the experiments for the margin and slope. D: Eustatic Sea-level variations for the simulated interval, after Miller et al. (2011) in black line, and selected data points for the DionisosFlow simulation (in red). The color indicates different time periods, corresponding after 0.8 Myr to MIS 19 to 1.

Figure 8. Wheeler diagram for the three experiments results, expressing the sedimentation rate. The position of the wells is indicated. On the right the eustatic sea-level variations for the simulated interval, after Miller et al. (2011) in black line, and selected data points for the DionisosFlow simulation (in red). The color indicates different time periods, corresponding after 0.8 Myr to MIS 19 to 1.

Figure 9. Basin to platform well correlation showing side by side the interpreted well and modelled deposits at the well location (right and left, respectively). The interpreted lithofacies log is represented on the right. On the left the simulated lithofacies column is shown, with the

« aragonite ooze » facies composition log (solid line) in opposition to the sedimentation rate log (in dashed black line).

Figure 10. Conceptual model of margin and slope architecture for the GBB leeward slope during the 100-kyr large sea-level oscillation period (0.45 - 0 Myr)

Figure 11. High-resolution seismic interpretation for the GBB leeward margin on the data from Wunsch et al. (2018) and Eberli and Ginsburg (1987). From top to bottom: A) original seismic data, B) High-resolution interpretation, with the downlap (red), toplap (blue), marine onlap (light blue) and coastal onlap (light green). The colored line corresponds to the seismic surfaces identified by Eberli et al. (1997a), the black line to the additional time-line reflectors identified in this study. C) The interpreted margin section, with the stratigraphic stages colored as in Fig.7. D) Simulated margin section from Experiment 2, with the same time-color code from fig. 7. This section is a projection of the seismic line orthogonal to the slope, therefor the bathymetric profile is steeper and the horizontal scales are not matched.

TABLES & FIGURES