Large-scale carbonate submarine mass-wasting along the northwestern slope of the Great Bahama Bank (Bahamas): Morphology, architecture, and mechanisms

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A B S T R A C T

Along the northwestern margin of the Great Bahama Bank (Bahamas), high-resolution multibeam bathymetry maps have revealed large escarpments, 80–100 m in height, and gigantic carbonate Mass Transport Complexes (MTCs), characterized by megablocks, several hundred to several thousand meters in size. The present-day configuration of this mass-wasting deposit is the result of the specific basin sedimentation of the GBB during the Neogene. Marginal sedimentation was produced by: (i) massive gravity-flow slope apron carbonates, feeding from the eastern prograding platform, including oversized MTCs; and (ii) thick, elongated, and muddier drift contourite flowing from south to north along the toe of slope. Four distinct MTCs (MTC-1 to -4) resulted from repeated slope failures in the Late Pliocene and the Pleistocene. These MTCs all glided along a common privileged décollement surface, dated Late Messinian–Early Pliocene, which coincided with a regional diagenetic key stratigraphic surface. The MTCs collapsed down from the steep mid- to upper-slope apron, partially draped the drift deposits, and flowed basinward over 10–20 km, extending over an area of approximately 400 km². With the support of good-quality seismic reflection data, a detailed analysis was produced of the stratigraphic architecture of these MTCs, highlighting the high variability of the seismic facies from tabular bounded strata to chaotic patterns. The analysis of the facies demonstrated the internal stratigraphic complexity of the MTCs as well as that of the subsequent filling of the associated headwall scar-related depressions. A depositional reconstitution of the MTCs is proposed from collapse initiation to final deposition, resulting in the present-day irregular seafloor morphology. The model accounts for the influence of the Early Pliocene drift-induced topography on the distribution and internal architecture of the successive MTCs. Most likely due to sedimentation rate increase, the contourite displayed lateral morphological variations, forming flat to mound-shaped features when upslope collapses occurred. Depending on lee-side steepness, it then acted either as secondary décollement ramp or as natural obstacle for mass-wasting deposits. Strips of sharply-bounded chaotic facies preserved within the Pliocene contourite are interpreted as far-reaching fluid escape-related facies (thixotropy), resulting from frontal impact with the contourite at the toe of the MTCs. The MTCs are not unique mass-wasting carbonate deposits, as similar features with comparable dimensions have been reported in the geological record in the Bahamas and in other carbonate basins. However, they clearly illustrate a significant volume of sediment remobilization over short distances in carbonate slope environments.

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1. Introduction

Recent technological improvements in submarine data acquisition and sub-surface mapping have revealed the broad diversity of mass-wasting morphological features on the seabeds of many continental margins (Mulder and Cochonat, 1996; Locat, 2001; Locat and Lee, 2002; Canals et al., 2004; Wilson et al., 2004; Gamberi et al., 2011). Many studies of carbonate slope architecture in both modern and ancient settings have demonstrated the common occurrence of such large-scale slope failures, which seem to play a significant role in the slope readjustment and morphological evolution of the carbonate platforms (Mullins et al., 1986, 1991; Mullins and Hine, 1989; Ross et al., 1994).

The frequency of slope failures, landslides, and gravity-flow deposits along the shelf edge and the slope is thought to be controlled either by internal or external factors, or both (e.g. tectonic to depositional slope oversteepening, seismicity, fabric and textural variation, tidal and wave water agitation, and sea level variations) (Hampton et al., 1996; Spence and Tucker, 1997). Upslope failure may trigger catastrophic gravity-flow transport and deposition along the slope to the toe of slope and basin, where it accumulates to form Mass Transport

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Complexes (MTCs) which can have run-out distances of over 100 km in a short period of time (Bull et al., 2009).

Mass-wasting deposits from outcrops have been extensively studied, revealing the great variety of stratigraphic components and facies associations (Cook et al., 1972; Ferry and Flandrin, 1979; James, 1981; Johns et al., 1981; Floquet and Hennuy, 2001b; Savary, 2003; Savary and Ferry, 2004; Courjault, 2011; Courjault et al., 2011). Although some studies have used bathymetrical data and seismic reflection to document...
large-scale mass-wasting deposits derived from the collapse of adjacent platforms along the modern carbonate platform edges (Mullins et al., 1986, 1991, 1992; Hine et al., 1992), few have produced a detailed stratigraphic architecture of these MTCs in three dimensions. Moreover, most previous works have viewed MTCs as individual occurrences, not as resulting from an accumulation of several successive events during the development of the shelf-margin.

Submarine landslides are commonly viewed as downslope translocating mass-wasting bodies forming a domain of extension (upslope) where erosional headscars prevail and a domain of compression (downslope) where landslides frontally interact with basin sediments (Farrell, 1984; Martinsen, 1989). It has also been demonstrated that they may develop two contrasting styles along a basal shear surface, prior to arrest, according to the frontal emplacement with the host sediments (Frey-Martínez et al., 2005, 2006). Both generate complex fold and thrust systems at the toe region. (1) The frontally confined landslides have toe region buttressed against undisturbed host strata. They have relatively limited displacement as they remain in situ “locked” and do not show significant topography (Trincardi and Argnami, 1990; Huvenne et al., 2002). (2) The unconfined frontally emergent landslides are free to travel considerable distances over the underformed slope position, creating positive topographic feature on the seafloor.

The GBB provides a good example of recently buried carbonate landslides that frontally interacted with massive basinal Pliocene contourite. They also show contrasting morphological styles of the frontal toe region and rapid striking architectural variation along the toe of slope.

This paper aims to illustrate the internal architecture and dynamic evolution of four distinct carbonate MTCs preserved in the Upper Cenozoic along the northwestern slope of the Great Bahama Bank (GBB). This has been achieved by incorporating newly-acquired multibeam bathymetry and high-resolution seismic data. The observations have enabled (i) the high-resolution mapping of recent carbonate MTCs on the seabed, (ii) an analysis of their internal depositional style and geometry variation along slope, (iii) a relative chronology of the stacked re-sedimented deposits and (iv) the confirmation of the influence of the morphology of massive underlying contourite drift upon the slide-induced MTC distribution along the strike.

2. Terminology

In the literature, catastrophic mass-wasting events have been broadly documented on both siliciclastic and carbonate slopes (Mountjoy et al., 1972; Mullins et al., 1986; Coleman and Prior, 1988; Hine et al., 1992; Hampton et al., 1996; Weimer and Shipp, 2004; Frey-Martínez et al., 2005; Nelson et al., 2011; Posamentier and Martinsen, 2011). Depending on the classification criteria however, this can involve deposit facies, hydrodynamics, rheology and flow behavior, types of particle support, and so forth. The terminology used to describe mass transport deposits remains ambiguous and can vary from author to author. (Nardin et al., 1979; Cook and Mullins, 1983; Mulder and Cochonat, 1996; Spence and Tucker, 1997). This section attempts to briefly clarify this terminology in order to identify and explain the appropriate terms used in this paper, thus avoiding confusion.

Mass Transport Complexes, olistostromes, and megabreccias include all re-sedimented products resulting from major gravitational instability events on the platform margin. They commonly contain lithified or semi-lithified seafloor sediment involved in sliding and/or slumping in the form of large individual coherent blocks, megablocks, or olistoliths ranging from under a meter to several hundred meters in size (Mountjoy et al., 1972) as well as organized slabs, debris-flows, and turbidites (Cook and Enos, 1977). The term, Mass Transport Complex (MTC), is broadly adopted throughout subsurface descriptions and defines a seismic facies
association consisting of “mounded, hummocky, chaotic, and subparallel reflections with poor to fair continuity and variable amplitude,” restricted to a specific stratigraphic unit (Weimer, 1989, 1990; Weimer and Shipp, 2004). It therefore includes all “seismic” features involved in mass-wasting deposits (i.e. various large-sized blocks, debris, grain-flow deposits, and turbidites) as well as large upslope collapses evidenced by kilometer-wide failure scars (Mullins et al., 1986; Pedley et al., 1992). MTCs can be considered the submarine equivalent of olistostromes, which have been defined from field studies as a lens-shaped mappable sedimentary units (Flores, 1955; Abbate et al., 1970), but which are therefore naturally limited by outcrop dimensions. Megabreccias can be defined using both seismic and outcrop data, but in the case of the former, core control is needed to allow access to the deposit lithology in order to calibrate the seismic facies. In addition, the sediment flow disaggregation suggested by the brecciated facies implies the development of secondary gravity-flows (Krause and Oldershaw, 1979; Mutti et al., 1984). Moreover, they initially excluded rock-fall, grain-flows, and turbidity currents (Spence and Tucker, 1997).

Notwithstanding the lack of information concerning the lithology of deposits, we favor the use of MTC, to describe all erosional and depositional features observed on seismic profiles related to large-scale mass-wasting deposits and involved in a single massive gravitational collapse event. Individual blocks and megablocks will be described as meter- to kilometer-sized lithified units (Mountjoy et al., 1972) preserved within an MTC.

3. Regional setting and stratigraphy

3.1. Morphology of the GBB platform

The Great Bahama Bank (GBB) is the largest shallow-water platform of the Bahamian archipelago, which forms an extensive carbonate province in the southeastern part of the North America. It is also best known as a modern example of an isolated platform that has been operating under tropical conditions as a highly productive carbonate factory since its inception in the Upper Jurassic (Masaferro and Eberli, 1999). The present-day shelf morphology of the GBB is the result of the complex tectonic and architectural evolution of the Bahamian province since the Early-Middle Jurassic rifting (Eberli and Ginsburg, 1987, 1988, 1989; Ladd and Sheridan, 1987; Denny et al., 1994; Masaferro and Eberli, 1999). The western side of the GBB currently consists of an open leeward margin, which progrades toward the west and is characterized by a gentle slope averaging 2–8° from 250 to 800 m water depth (Jo, 2013; Betzler et al., 2014) (Fig. 3).

3.2. Distribution of currents and sea-floor morphology

The western slope of the GBB is dominated by major shallow-water currents flowing in the Straits of Florida and the Santaren Channel (Fig. 1). The Florida Current is a strong shallow-water current that flows northward toward the North Atlantic realm (Mullins et al., 1987; Leaman et al., 1995; Lee et al., 1995; Wang and Mooers, 1998).
It is also supplied by a weaker shallow current issuing from the Old Bahama Channel, which connects with the output of the Santaren Channel (Atkinson et al., 1995; Leaman et al., 1995). Both main shallow currents have given rise to several drift deposits in the study area (Hine et al., 1981; Bergman, 2005). Minor, deep, counter undercurrents and semi-diurnal tidal currents flow southward on the seafloor off Florida and the Bahamas Bank (Grasmueck et al., 2007; Correa et al., 2012b; Betzler et al., 2014).

The seafloor of the northwestern slope and adjacent basin is irregular, revealing distinct morphological features such as carbonate mounds (Grasmueck et al., 2007; Correa et al., 2012a,b), sediment waves (Betzler et al., 2014), downslope erosional structures (e.g. failure scars, scars, and gullies), and large-scale mass-wasting deposits derived from the collapse of the carbonate bank slope (Mulder et al., 2012).

3.3. Stratigraphy and stratigraphic architecture

The GBB carbonate platform began a homogenous regional expansion at the end of the Paleogene (Eberli and Ginsburg, 1987), with the progressive seaward migration of the shelf edge 25 km westward into the Straits of Florida (Eberli and Ginsburg, 1988, 1989). During the Lower Neogene, the GBB appears to have experienced aggradational growth, characterized by a vertical stacking of the shelf edge associated with a ramp-like slope configuration. From the Middle Miocene, the platform appears to have developed a more prograding pattern, with a steep end-member slope and massive sedimentary aprons. The dominant east-west direction of the progradation coincides with the prevailing wind direction and is therefore thought to be the result of preferential off-bank sediment transport on the western leeward margin (Hine and Neumann, 1977).

The Neogene slope-to-basin stratal architecture is made up of two distinct re-deposited units, respectively characterized by mud- to clast-supported carbonate slope aprons and muddier drift contourite deposits. Both form distinct, thick sedimentary wedges that have coevally interfingered at the toe of slope of the GBB platform since the Serravalian (Eberli et al., 1997a; Anselmetti et al., 2000). (1) The slope apron consists of laterally stacked, sigmoidal fine- to coarse-grained carbonate sheets that gently prograde downslope into the Straits of Florida (Eberli and Ginsburg, 1987, 1989). The sheets homogeneously display west-dipping gravity-flow debrites containing shallow-water carbonate components (i.e. coral debris, gastropods, red to green algae, and bivalves) produced from the platform bank with intercalations of fine- to coarse-grained calciturbidites and slumps (Eberli et al., 1997a; Betzler et al., 1999). Favoried by regional flooding.

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**Fig. 4.** View of the main morphological features constituted by the Mass Transport Complex with a vertical exaggeration of ×10; (A) the proximal zone shows steep outer walls to the south and an ancient slide complex to the north, infilled by a sedimentary prism overlain by sediment waves; (B) zoom on the slide scar, which shows the location of the pockmarks at the top of the scar, the plunge pools vertically below the gully incisions, and the moat that follows the scar; (C) the distal area, characterized by irregular seafloor morphology due to the mass transported, which ended in large megablocks.
During the Early Pliocene, hemipelagic basinal nannofossil mud and chalk/ooze rich in planktonic and benthic foraminifers back-stepped over the slope apron, which temporally retreated eastward (Kenter et al., 2001). (2) Contourite deposits prevail in the basin and pinch-out along the strike line of the western shelf slope (Eberli et al., 1997a; Anselmetti et al., 2000). These are horizontal or east- to northeast-dipping drift deposits characterized by continuous conformable and low-amplitude internal reflections. The uppermost part of the drift was formed during the Early to Late Pliocene and shows a more mounded and lenticular morphology composed of distinct downlapping and onlapping reflections that steepen as the drift progrades upslope. The contourite deposits average 600 m in thickness, 60 km in width, and 160 km in length and belong to the Santaren Drift (Bergman, 2005). They form a typical mounded-confined drift (Faugères et al., 1999; Bergman, 2005) that thins eastward toward the moat borders. It was also during the Early to Late Pliocene that the maximum encroachment of the drift upon the base of slope occurred. Here, the drift is composed of un lithified nannofossil ooze interbedded with clay and silts (Eberli et al., 1997a; Anselmetti et al., 2000).

Carbonate production on the platform, together with the re-sedimented material flux feeding the downslope aprons, is thought to be largely controlled by third to fourth order sea-level fluctuations (Eberli et al., 1997b; Betzler et al., 1999). The sedimentation rate is considered highest during sea-level highstands, when the platform is flooded (Schlager, 1981; Mullins, 1983), while the falling stages expose the platform and restrict sediment production to the fringes (Eberli, 2000). Sediment production and off-bank transport occur along the open leeward margins of the GBB (Hine et al., 1981) and are responsible for the huge mass of re-sedimented deposits on the slope and in the basin (Wilber et al., 1990; Rendle and Reijmer, 2002).

<table>
<thead>
<tr>
<th>Acoustic facies &amp; erosional features</th>
<th>Internal configuration</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steep escarpment separating truncated continuous reflection of the slope to low-amplitude, conformable onlapping continuous reflections of the infill post mass-wasting</td>
<td>Escarpment angle ~25° Height ~100 m Slope angle ~3°</td>
<td>Scarp</td>
</tr>
<tr>
<td>Low-dip high-amplitude, continuous to discontinuous horizon separating highly chaotic facies (MTC) from medium to low amplitude continuous to discontinuous facies slope apron deposits</td>
<td>Consists of two seismic facies: 1. Highly discontinuous low-amplitude and chaotic reflections 2. Remnant folded/thrust high-amplitude reflections</td>
<td>Mass Transport Complex</td>
</tr>
<tr>
<td>Blind transparent acoustic facies, laterally limited by vertical to sub-vertical sharp boundary; Adjacent reflectors truncations</td>
<td>High-amplitude semi-continuous layered facies with sub-vertical sharp boundary; topographically overlooking surrounding seabed</td>
<td>Thixotropy</td>
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<tr>
<td>Megablock</td>
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Fig. 5. Examples of characteristics acoustic facies and erosional features defining MTCs, their internal configuration and interpretation.

4. Data and methodology

The dataset used to carry out this study comprised a high-resolution bathymetric map and a grid of 2D high-resolution multichannel seismic reflection data (Fig. 2), both acquired during the CARAMBAR Cruise (Mulder et al., 2012). Seismic sections were shot using a mini-GI 24/24 in³ air gun, and a 96-traces/700-m-long streamer. The streamer and source positioning were derived from vessel DGPS. The seismic data was processed using SISPEED software (©Ifremer). The basic processing flow included (1) NMO correction, (2) 96-fold stacking, and (3) constant velocity gradient migration. The obtained seismic lines had a vertical resolution of 2 m.

The seafloor morphometric analysis was based on a 20 m DEM acquired with a Kongsberg EM302 multibeam echosounder. The ages of the seismic units were obtained from regional correlations performed on three southern deep ODP holes (1003-1006-1007) from Leg 166 (Fig. 1B), which provided accurate chronological constraints based on planctonic foraminiferal and nannofossil zones from the Pleistocene to...
Upper Middle Miocene (Eberli et al., 1997a). In order to improve this key operation, the seismic lines used for this drilling/seismic data correlation underwent an enhanced processing including pre-stack depth migration (Thereau, 2011).

5. Results

5.1. Seafloor morphology

The bathymetric map covers an area of approximately 1000 km² (Fig. 3) and enables the high-resolution analysis of seabed morphology from slope to basin area. The upper slope, ranging from 250 to 600 m water depth, shows a gentle mean gradient of around 3° (Fig. 3). It is incised by narrow, elongated, sub-parallel, regularly-spaced gullies with an average length of 4 km and average width of 750 m. The majority of the gullies are straight with shallow incisions not exceeding 10 m in depth. They are perpendicularly aligned to the shelf edge and extend down to 700 m water depth. To the south of the study area, at around 450 m water depth, a 40-m-high escarpment lies along the slope and extends over 40 km (Fig. 3). It forms a straight lineament edge in the middle of the slope, lies parallel to the shelf border, and clearly crosscuts the gullies.

The slope also has large-scale escarpments forming abrupt morphological cliff-like edges, characterized by a steep 25° gradient and a height of 80–100 m. Three prominent failure scars can be clearly observed, each extending over 9 km from south to north and separated by long spurs, which appear to be remnants of the original slope that has slid away (Fig. 4A). The spurs are 3.2 km long and around 400–800 m wide. The highest escarpment on the northern side is covered from slope to basin area. The upper slope, ranging from 250 to 600 m water depth, shows a gentle mean gradient of around 3° (Fig. 3). It is incised by narrow, elongated, sub-parallel, regularly-spaced gullies with an average length of 4 km and average width of 750 m. The majority of the gullies are straight with shallow incisions not exceeding 10 m in depth. They are perpendicularly aligned to the shelf edge and extend down to 700 m water depth. To the south of the study area, at around 450 m water depth, a 40-m-high escarpment lies along the slope and extends over 40 km (Fig. 3). It forms a straight lineament edge in the middle of the slope, lies parallel to the shelf border, and clearly crosscuts the gullies.

The toe-of-slope domain is characterized by a hummocky surface extending basinward over about 300 km² and a very low gradient of 0.2° (Fig. 4C). This area is also affected by strong currents as suggested by the south-north lineaments, interpreted as scours and erosional marks at the back of the debris blocks and carbonate mounds (Fig. 4C) (Mullins et al., 1984; Grasmueck et al., 2007; Correa et al., 2012a,b). The basin area, where the MTCs are located, ends at 850 m water depth with large angular megablocks, 1–2 km wide and 50 m thick. The relief between the blocks is accentuated by bottom-current erosion (Fig. 4C). The hummocks and the megablocks form topographic highs, which provide a substrate for the growth of deep-water coral communities (Grasmueck et al., 2007; Correa et al., 2012b).

6. Seismic stratigraphy

6.1. General characteristics of the MTCs

Most of these MTCs are rooted upon an asymmetrical long-wavelength concave-shaped surface which dips slightly toward the west for 10 km and then slopes backward in the basin (red reflector in Figs. 9 and 10). This surface represents an extensive high-amplitude reflector over the total study area and corresponds to a regional transgressive surface dated 5.4 Ma (Late Messinian–Early Pliocene) (Eberli et al., 1997b; Anselmetti et al., 2000; Eberli, 2000; Kenter et al., 2001) (Fig. 5). Each MTC is laterally bounded landward by vertical to sub-vertical lineaments, coinciding with elongated spur escarpments, oriented west-east. They form U-shaped erosional failure corridors, entirely filled with sediments. The filling architecture is confined within each slide scar and presents moderate- to high-amplitude well-layered seismic reflectors ranging from concordant and sub-horizontal to mound morphologies with internal thinning and truncations (Figs. 5 and 6). Outboard, the MTCs spread out beyond the spurs for 10–20 km basinward. They form elongated lobate-shaped wedges displaying a progressive thickening toward the northwestern distal area (Fig. 11). The MTCs are commonly characterized by transparent to low-amplitude chaotic facies with some packages of high-amplitude reflectors showing a greater degree of coherency. These packages are marked by highly-deformed reflectors and exhibit varying degrees of internal deformation from plane parallel to folded patterns (Figs. 5, 7, 9 and 10). They are commonly separated from the host strata by laterally and frontally sharp and nearly vertical facies boundaries.

6.2. MTC-1 and MTC-2

MTC-1 and MTC-2 lie around 200 ms TWT below the modern seafloor (Fig. 6), and extend longitudinally over at least 10–20 km (Fig. 11). The failure scar forms a large, abrupt rectangular-shaped morphology around 100–200 ms TWT in depth and 1–2 km in width (Fig. 6). The upper termination of the buried scars coincides with a
regional stratigraphic surface, dated 3.6 Ma (Late Pliocene; blue reflector) (Eberli et al., 1997b), typified along the strike by incised V-shape canyons, 50 to 100 ms-deep, that truncate the underlying Early Pliocene succession along the slope (Fig. 6). The failure scar is filled with high-amplitude layered reflectors. Both buried failure scars and their internal filling are entirely sealed by very-high-amplitude Pleistocene wavy layered reflections (Fig. 6).

Basinward, MTC-1 and MTC-2 consist of massive units of low-amplitude and chaotic reflections with irregular upper surfaces and lateral vertical boundaries that mark a sharp contact with the low-amplitude sub-parallel layered horizons of the Early Pliocene contourite (Figs. 7 and 8). The thickness of these MTCs increases in their distal part while their width increases along the strike to subsequently decrease basinward (Figs. 7 and 8). They are overlain by concordant high-amplitude layered seismic facies (Figs. 7 and 8).

6.3. MTC-3

MTC-3 is large in comparison with MTC-1 and MTC-2 and is the most visible MTC on the present-day seafloor. The associated failure scar complex is located around 200 ms TWT below the modern seafloor and consists landward of three major sharp scars, 1.5–3 km in length and 200 ms TWT deep, separated by elongated thin spur escarpments (Fig. 6). Overall, they extend over 9 km in width and 20 km in length, presenting a lobe-shaped morphological feature (Fig. 11). The headwall region is defined by prominent spurs, made up of continuous deposits ranging from the Messinian to the Pleistocene without any major sedimentary hiatus. For each scar, the basal infilling is homogenously characterized by a thin layer of low-amplitude chaotic reflectors (Fig. 6). This unit is systematically overlain by a thick package of medium-amplitude layered reflectors, which show an asymmetrical
They dramatically thin-out toward the south and form large transversal U-shaped moats adjacent to the spur flanks (Figs. 6 and 9), which are subsequently filled by younger sub-horizontal layered reflectors. This scar significantly progrades, becomes thinner, and then passes seaward into high-disrupted seismic facies (Fig. 9).

Basinward, MTC-3 extends laterally and interfingers with MTC-1 and MTC-2, forming a large area of low-amplitude and chaotic facies (Fig. 7). This unit includes a massive package of semi-continuous, high-amplitude, highly-deformed strata reflectors, which show clear evidence of localized deformation (Fig. 7). MTC-3 is bounded in its upper part by the seafloor and laterally bounded by steep flanks cutting throughout the surrounding host strata. Toward the dip, the background strata display an undeformed thick package of low-amplitude, sub-parallel, and well-laminated layered reflectors. This unit is characterized by an elongated mounded to flat geometry and is defined as massive Early to Late Pliocene drift contourite (Bergman, 2005), which progressively fill the concave topography induced by the Late-Messinian surface (Figs. 9 and 10). The morphology of the contourites differs from the north to the south as it looks closely related to the angle of the basal surface, which appears flatter in the south (Figs. 9 and 10). In the northern part, the contourites have a mounded-shape, which dips steeply toward the eastern slope (Fig. 10) and shows several buried areas of compartmentalized chaotic facies further westward, laterally limited by sharp sub-vertical boundaries (Fig. 10).

On the present seafloor, the 1–2 km-sized megablocks are composed of continuous high-amplitude reflectors that remain entirely undeformed and well-individualized by steep outward dipping flanks. They are separated from the surrounding mass of high-amplitude, semi-continuous, and sub-parallel seismic horizons by 30–40 m deep moats (Figs. 5 and 10).

6.4. MTC-4

MTC-4 is located around 100 ms TWT below the modern seafloor (Fig. 6), and extends basinward over 10 km (Fig. 11). This event is rooted upon a Pleistocene surface, dated 0.25 Ma by Eberli et al. (1997b), which truncates the previous strata corresponding to the infill of MTC-2 (Fig. 6). Inboard, it is characterized by a V-shaped slide scar morphology, from 1.5 km in length and 100 ms TWT in depth. The lateral slide scar boundaries appear less abrupt than in the previously described MTCs. Basinward, MTC-4 shows a transparent to chaotic facies (Figs. 7 and 10), which extends over 12 km (Fig. 11) and overlays the older MTC-2 (Fig. 10). The slide scar is subsequently filled by a unit of medium-amplitude layered reflectors (Fig. 6), which laterally progrades and thins out seaward (Fig. 10).

7. Discussion

7.1. Dynamic evolution of the MTCs and dynamic mass movement model

This study has allowed for the spatial recognition of large-scale MTCs on the present-day seafloor of the northwestern slope of the GBB, which extend toward the basin for over 20 km. Furthermore, seismic
observations have revealed the presence of repeated margin collapses, which have significantly affected the stratigraphic architecture at the toe of slope and basin since the Late Pliocene. The MTCs have been clearly differentiated according to their morphology, dimensions, chronology, and the subsequent internal filling architecture of slide scars in the headwall domain, as well as their geometrical relationship with the surrounding host stratigraphy. Without direct chronological data from industrial boreholes or ODP wells in this area, it remains difficult to establish the exact timing of the collapse events. It has been possible to deduce their relative chronological succession, however, from their cross-cutting relationship with the host sediments, which has allowed them to be classified into two main diachroneous landslide groups, dating to the Late Pliocene (MTC-1 and MTC-2) and the Pleistocene (MTC-3 and MTC-4) (Fig. 6). This study aims to reconstruct the dynamic evolution of the different MTCs by highlighting the successive key building stages through time. These four MTCs display a common internal architecture, characterized by large erosional slide scars and similar depositional elements, but differ basinward in the morphological features of correlative deposits linked to the architecture of former drift deposits. In this paper, a conceptual dynamic model is proposed to explain the repeated occurrence of slope failure and the subsequent associated MTCs during the Upper Cenozoic. The influence of the pre-collapse topography generated by the former Pliocene contourite drift system from south to north upon the distribution of the MTCs is also highlighted and respectively illustrated according to two distinct scenarios: “frontally confined” versus “frontally emergent” noted A and B (Fig. 12).

According to Frey-Martínez et al. (2005, 2006), a “frontally confined” versus “frontally emergent” (i.e. unconfined) submarine landslide derives from the mode of emplacement of the compressive domain, i.e. whether the frontal toe region is buttressed (frontally confined) or freely ramps out over the pre-landslide downslope seabed (frontally unconfined), leading to the dislocation of the toe region into irregular blocks (“emergent or out runner blocks”) by kinematic release. As Frey-Martínez et al. (2006) also quoted, the difference of MTC styles along the GBB slope may represent successive stages in the dynamic evolution of a NW migrating mass-wasting in which the southern frontally confined MTC could be attributed to the early stage and the northern frontally emergent MTC to the mature and final stage.

The initial phase represents the Miocene to Pliocene stratigraphic configuration of the northwestern slope of the GBB prior to the first MTC collapse (Fig. 12, A1 and B1). The depositional system and its associated topography involve a complex geometric configuration, including the downslope accumulation of prograding slope-apron deposits, which interfinger seaward with massive contourite deposits, as observed southward (Eberli et al., 1997a; Betzler et al., 1999; Anselmetti et al., 2000). The contourite drift body is characterized by a rapid morphological change along the strike, from a flat to mounded shape, which is mostly conditioned by the pre-existing concave up-shaped Late-Messinian surface along the dip profiles (Figs. 9 and 10).

To the south, the Pliocene contourite drift displays a relatively flat topography, which passively onlaps the toe of slope (Fig. 12, A1), while to the north, its convex up-shaped morphology presents a more steeply dipping slope (>1°) (Fig. 11, B1).

The second stage accounts for the slide failure initiation of both MTC-1 and MTC-2, which simultaneously occurred during the Late Pliocene (Fig. 12, A2 and B2). Massive sediment collapses began on the middle of the slope and propagated basinward, gliding northwesward upon the inclined Late-Messinian slide plane surface. These concomitant failures created two distinct large, deep scars. Masses of sediments,
up to 100 m thick, probably composed of coherent discrete landslide blocks, embedded in a muddy matrix, rapidly spread out over at least 10–20 km at the toe of the slope and hit the frontal part of the previously formed contourite drift. Sediment disturbances causing the apparent chaotic seismic facies were probably triggered by the frontal impact between the mass-wasting deposits and the drift. Such an impact is likely to have also been responsible for instantaneous water escape and combined sediment liquefaction (thixotropy) in the distal part of the drift.

From the Late Pliocene to the Pleistocene, slope deposition prevailed again and was characterized by the complete infilling of the former erosional failure scars (Fig. 12, A3 and B3). Basinward, the contourite drift deposits continued to aggrade and migrate toward the eastern base of the slope where they interfingered with the slope deposits.

During the Pleistocene, a new MTC was triggered on the upper slope, forming the three adjacent scars, which are separated by long, thin spurs. A sediment mass flowing downslope was at the origin of the massive MTC-3 in the basin (Fig. 12, A4 and B4). Its detachment took place along the deep Late-Messinian surface, as observed for the previous MTCs-1 and 2. MTC-3 greatly expanded over 10–20 km until it came abruptly into contact with the face of the Late Pliocene drift contourite in the basin. Some remnants of Early Pliocene contourite are embedded in the chaotic facies of the MTC, indicating a significant reworking of drift sediments in the vicinity of the frontal impact area. The morphology of the contourite clearly played a significant role in the distribution of the subsequent MTC-3 prior to slope failure. To the south, (Fig. 12, A4) MTC-3 was abruptly stopped by the flat contourite drift and remained confined to the toe of slope, while it clearly pulled-up along the

Fig. 12. Time series of 2D-sketches showing the reconstruction of the dynamic evolution of distinct and repeated slope-failures development and their associated MTCs over time. Note that the pre-collapse topography linked to the Mio-Pliocene contourite drift system caused two distinct models, noted A and B.
mounded contour to the north (Fig. 12, B4). In the latter case, MTC-3 locally reached the seafloor surface and formed a positive topographic relief above the original seabed (Frey-Martínez et al., 2006). Schnellmann et al. (2005) have demonstrated that when a massive avalanche of upper slope material hits a basin plain, subsequent deformation features form within the pre-existing underlying base of slope sediments. It is clear that the vertical mass-wasting of MTC-3 to the north was controlled by the steep lee sides of the contourite drift, which inherently acted as a secondary décollement surface in the basin, allowing MTC-3 to dramatically change its direction of flow motion. When the MTC reached the seafloor, its kinetic energy dissipated, and the emergent slab broke into kilometer-sized angular megablocks, forming the present-day irregular seafloor topography in the distal domain. MTC-3 appears to have glided and expanded over the contourite-induced topography rather than having laterally migrated where topographic lows where made by the contourite moat. Paleogeographic confinement may have occurred at the toe of slope when the sedimentation rate of Early Pliocene contourite drift was high enough to form a steep, thick asymmetrical wedge, creating a topographic obstacle facing down-flowing slope apron carbonates. This implies that the velocity of collapse-related sediments was high enough when reaching the base of the contourite to flow upwards.

A massive prograding wedge composed of slope sediment finally filled the downslope depression induced by MTC-3 in the headwall domain (Fig. 12, A5 and B5). A final event (MTC-4) occurred in the north, above MTC-2, as a subsequent erosional event. It entirely sealed the underlying MTC-3 with the deposition of large sheets of debris that extended basinward over 10 km. Present-day slope deposits prograde and completely fill the initial erosional escarpment.

7.2. Significance of the basal décollement surface

The MTCs seem to have detached from the same stratigraphic key surface, dated Late-Messinian (Eberli et al., 1997a; Anselmetti et al., 2000; Eberli, 2000). Based on studies made on the ODP well located 50 km southward (Fig. 1), this surface presents the following characteristics: (1) It is interpreted as a regional transgressive surface, marking the transition between the end of the Late-Messinian eustatic sequence and Early Pliocene marine flooding (Eberli et al., 1997b; McKenzie et al., 1999). It coincides with a texture contrast as the Early Pliocene nanofossil ooze/chalk is unconformably overlain by Late-Messinian bioclastic wackestones to packstones (Eberli, 2000; Kenter et al., 2001). (2) Condensed sections, such as hardgrounds, are also observed just above the surface in the lower slope domain (ODP Site 1007) (Eberli et al., 1997a; Bätzler et al., 1999). (3) It is located along a prominent high-gradient depositional slope apron (Eberli and Ginsburg, 1988, 1989). (4) The uppermost part of the Late-Messinian limestones present high dolomitic and low Mg-calcite-rich cements resulting from hydrological and diagenetic transformations due to a major regional drop in sea-level (Melim et al., 1995; Eberli et al., 2002). (5) Martinsen (1994) also suggested that the position of basal shear surface is mainly determined by the pressure gradient in the sediment. It is not surprising to see that the depth of the detachment surface coincides downslope with the top of the Pliocene drift because muddy contouritic deposits could be easily prone to overpressuring with the overburden and hence specifically act as a décollement surface.

The MTCs commonly deform along an over-steepened zone, characterized by weak mechanical properties (Spence and Tucker, 1997). Previous descriptions imply that several factors may have favored the detachment of these MTCs along this particular key surface. (1) Aquifer horizons could have been trapped during lowstand conditions in the Late-Messinian succession. Interstitial inter-granular pores of coarse-grained limestone could therefore have been saturated, generating hydraulic pore-water overpressure and shear strength decrease (Spence and Tucker, 1997). (2) Condensed sections also appear to have constituted weak geotechnical units, possibly due to diagenetic fabrics with burrows in the foraminiferal oozes (Weimer and Shipp, 2004). (3) The surface is located at the steepest part of the slope apron, which would have greatly facilitated down-slope mass-wasting (Kenter, 1990; Ross et al., 1994). (4) The resulting textural and density contrast between the dolomitic and low-Mg calcite (or aragonite) cements preserved in the Late-Messinian carbonates and overlaying the Early Pliocene mud-prone nanofossil chalk may also have contributed to low shear strength (Melim et al., 1995; Spence and Tucker, 1997). Similar mineralogical fractioning between hightstand and subsequent transgressive units has been clearly observed in the Late Quaternary of the North West Shelf in Western Australia (Dix et al., 2005).

The MTCs observed in the GBB operate on a décollement surface, without disturbance from the underlying strata. As previously described by Mulder and Cochonat (1996), several nested failures can slide along the same failure plane following the down-dip stratification.

7.3. Significance of the chaotic facies

A compartmentalized distribution of chaotic seismic facies has been observed in the study area, but their significance varies. A first type of chaotic facies entirely typifies the MTCs and accounts for re-sedimented gravity-flow deposits induced by the destabilization of the slope. Lithified sediments along the slope collapse down, generating gravity-spreading avalanches involving different block sizes and discrete rock-fall and debris-flow along the slope and the base of slope (Mulder and Cochonat, 1996). The resulting seismic facies are sharp-bounded, unorganized, and highly disturbed (Fig. 5). These seismic characteristics and the presence of reflectors packets in the landslide mass identical to those observed in the undisturbed surrounding strata, suggest a direct correlation between stratigraphic units. Such a correlation would imply that the continuous reflections within the chaotic facies correspond to portions of indurated sediments that have detached from the carbonate slope and been transported in the landside but that have still preserved their primary stratification.

A second type of seismic facies is only found within the contourite drifts far into the basin. The compartmentalized chaotic seismic facies strips sharply crosscut the previously deposited, thinly-laminated contourite (Fig. 5). The shock inherently produced when the MTC hit the basal contourite did not generate deformation structures within the contourite, as shown by the lack of significant compressive folds and thrust and/or faults, but it did induce fluid-escape structures (thixotropy). It has been suggested that liquefaction is associated with an increase in pore-fluid pressure and that it can be initiated by the disturbance of loosely-packed sediment by seismic shaking (Owen, 1987; Owen and Moretti, 2011). The sub-vertical frontal suture between the contourite and the MTC is explained by the thick, stable nature of the contourite drift, which acted as a massive undeformable structure. The deformation thus appears to have propagated and dissipated both retrogressively within the MTC and basinward within the contourite. Indeed, numerous thick sharp-bounded zones of chaotic facies have been locally observed within the contourite. These strips of chaotic facies are interpreted here as local fluid-escape structures, most likely generated by the “shaking” of water-saturated sediments by small waves that propagated along the flat-layered contourites just after the shock with the MTC.

7.4. Do the Mass Transport Complexes in the northwestern GBB constitute a common re-sedimented feature upon platform slopes?

The question of whether these enormous carbonate mass-wasting complexes constitute common features among similar MTCs known in the geological record is important as it may significantly contribute to the evaluation of the volume of re-sedimented materials during the development of carbonate platform slopes. Such an assessment requires a comparison of the parameters characterizing the MTCs of the GBB,
such as width, length, and thickness, with equivalent features described in the literature.

As previously mentioned, the different MTCs on the northwestern slope of the GBB occurred as massive carbonate slabs, and all sediments involved in the gliding strictly belonged to the upper part of the slope apron, as no detachment of the upper platform was observed. The MTCs of the GBB are 20–200 m in thickness, widening basinward, and range from 10 to 22 km in length and 5 to 8 km in width. The volume of re-sedimented carbonate averages 2–20 km³. Megablocks in the extremity of the MTC indicate average dimensions of 0.5–2 km in length, 0.3–1.5 km in width, and 50 m in thickness.

Widespread carbonate MTCs occurred during the Upper Cenozoic in the south of the GBB (Mullins et al., 1991, 1992; Jo, 2013), in the West of Florida (Mullins et al., 1986), and the western Caribbean Sea (Hine et al., 1992). They are described as fan-shaped mass-wasting deposits, tens of kilometers long, containing individual blocks and megablocks that respectively average 100–600 m in width and 20–110 m in height. These gigantic re-sedimented deposits are usually linked to platform bank margin collapses, causing amphitheater-shaped failure scars up to 10 km wide and 10–100 km long (Mullins and Hine, 1989).

In the Phanerozoic record, the carbonate MTCs were reported as smaller features with materials transported over 10–15 km across the basin and individual megablocks reaching around 200 m in length and 10–50 m in width (Cook et al., 1972; Carrasco, 1977; Playford, 1980; Johns et al., 1981; Floquet and Hennuy, 2001a, 2003). In contrast, the Turonian–Coniacian Ayabacas Formation in the southern Peru probably represents an over-sized complex, as more than 10,000 km³ of re-sedimented carbonate has been mapped out, with long folded slabs, rafts, and megablocks ranging from several meters to several kilometers in length and spread out over hundreds of kilometers along the slope (Callot et al., 2008a,b).

The MTCs observed on the GBB slope and its architectural components do not therefore constitute unique mass-wasting carbonate deposits as similar features with comparable dimensions have been reported in the geological record. However, among the examples cited here, they clearly illustrate a significant volume of sediment remobilization over short distances in known carbonate slope environments.

In all the examples cited above, submarine MTCs are widely considered as resulting from a variety of triggering mechanisms, such as local slope oversteepening linked to rapid sediment accumulation, seismic shocks, and relative changes in sea level (Cook et al., 1972; Carrasco, 1977; Playford, 1980; Johns et al., 1981; Mullins et al., 1986, 1991, 1992; Hine et al., 1992; Floquet and Hennuy, 2001a, 2003; Callot et al., 2008b; Jo, 2013). On the basis of all MTC case studies in the Bahamas dating from the Upper Cenozoic, seismic shocks induced by earthquakes are the most frequently invoked mechanism, linked to the proximity of the Caribbean–American collision (Mullins et al., 1991, 1992; Jo, 2013).

8. Conclusions

A high-quality geophysical dataset, involving EM302 multibeam bathymetry and seismic reflection data collected along the northwestern slope of the Great Bahama Bank, has allowed a detailed description to be produced of the surface morphology and internal architecture of repeated submarine carbonate Mass Transport Complexes resulting from middle-slope collapse failure.

Bottom roughness on the present-day seafloor indicates partially-buried debris and blocks overlain by carbonate mounds. The largest individual megablocks measure hundreds of meters in width, 1–2 km in length, and 50 m in thickness, forming an unusual and irregular morphology.

A total deep, and far-reaching deformation of at least 400 km², extending from the slope to the basin was induced by four successive MTCs during the Late Pliocene (MTCs 1 and 2) and the Pleistocene (MTCs 3 and 4).

The individual MTCs are characterized at the headwall domain by large U-shaped escarpments, 80–100 m high, separated by thinner elongated spurs. Basinward, they form massive low-amplitude tabular and chaotic facies, 50–200 m thick, which present sharp, sub-vertical boundaries with the surrounding host contourite drift deposits. They expand in the basin over distances of 10–20 km. All the MTCs are rooted upon a deep, regional, highly-cemented dolomitic surface dated Late Messinian–Early Pliocene, which acts as a preferential basal décollement surface.

The host strata and décollement surface morphology significantly influences the dynamic evolution of the massive carbonate MTCs. The topography of the basal sedimentation area is inherited from a slope and contourite drift morphology that greatly varies along the strike and directly influences the spatial extension and confinement of the subsequent mass-wasting deposits. Two generic models have been proposed to depict “frontally confined” versus “frontally emergent” MTCs, with regard to the former toe of slope and contourite-induced topographic variations. In the south, the MTC is locked downslope and frontally face the Pliocene contourite, while in the north MTC develops upon a longer distances, moving along and at the top of the Pliocene contourite to finally emerge at seafloor.

Fluid-escape zones probably resulted from the “shaking” of water-saturated sediments, generating thixotropic basinward into poorly-consolidated contourite deposits, responsible for widespread sharp-bounded chaotic facies.

These catastrophic events are not unique mass-wasting carbonate deposits, as similar features with comparable dimensions have been reported in the geological record in the Bahamas and other carbonate basins. However, they clearly illustrate a significant volume of sediment remobilization over short distances in carbonate slope environments.

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