New classification system for mass transport complexes in offshore Trinidad

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ABSTRACT

This paper delineates our use of 10,708 km² of three-dimensional (3D) seismic data from the continental margin of Trinidad and Tobago West Indies to describe a series of mass transport complexes (MTCs) that were deposited during the Plio-Pleistocene. This area, situated along the obliquely converging boundary of the Caribbean/South American plates and proximal to the Orinoco Delta, is characterized by catastrophic shelf-margin processes, intrusive/extrusive mobile shales and active tectonism. Extensive mapping of different stratigraphic intervals of the 3D seismic survey reveals several MTCs that range in area from 11.3 to 2017 km². Three types of MTCs are identified: (1) shelf-attached systems that were fed by shelf-edge deltas whose sediment input is controlled by sea-level fluctuations and sedimentation rates; (2) slope-attached systems, which occur when upper-slope sediments catastrophically fail owing to gas-hydrate disruptions and/or earthquakes and (3) locally detached systems, formed when local instabilities in the seafloor trigger relatively small collapses. Such classification of the relationship between slope mass failures and sourcing regions enables a better understanding of the nature of initiation, length of development history and petrography of such MTCs. 3D seismic enables more accurate calculation of deposit volumes, improves deposit imaging, and, thus, increases the accuracy of physical and computer simulations of mass failure processes.

INTRODUCTION

Mass transport complexes (MTCs) play a large role in the stratigraphic fill of basins in offshore northeastern South America, as well as along other continental margins around the world (Table 1). An incredible variety of Pliocene- and Pleistocene-age MTCs have been documented in deep-water areas around offshore Trinidad (Moscardelli et al., 2006). These deposits provide an opportunity to examine the variety of MTCs that occur in deep-water margins, document their architecture and propose a new classification system that is based on causal mechanisms, dimensions and source areas of MTCs.

The area of this study, 10,708 km² in size, is located in water depths of 300–1500 m along the SE margin of the tectonically active Caribbean Plate Boundary Zone (Fig. 1). Earthquakes up to magnitude 7 are frequent occurrences in the area, and the region is characterized by both compressional and extensional tectonic forces. A variety of faults are found in the area, including, from south to north, extensional down-to-the-NE listric faulting, transpressional south-verging thrusts and right-lateral strike-slip faults (Heppard et al., 1998; Wood; 2000; Boettcher et al., 2003). High sediment accumulation rates, with sediment dominantly supplied by the Orinoco River and Delta, high-frequency Plio-Pleistocene sea-level fluctuations, abundant gas-hydrate deposits and tectonic instability create the right geological preconditions for mass shelf-edge failures and the subsequent deposition of gravity-induced deposits (MTCs and turbidites).

The predominance of mass-wasting processes in most continental margins around the world (Table 1) makes MTCs a potentially important element of any deep-water stratigraphic succession. In addition, their influence in the shaping of seafloor bathymetry and continental margin architecture is well documented (Norem et al., 1990; Masson et al., 1998; Gee et al., 1999, 2001, 2006; Frey-Martinez et al., 2005; Moscardelli et al., 2006). The sometimes catastrophic, erosive nature of MTC deposits represents a potential geotechnical hazard for offshore infrastructures owing to their ability to compromise the integrity of underwater equipment such as cables, communication lines and pipelines (Hoffman et al., 2004; Shipp et al., 2004). It is also well known that a sudden displacement of the seafloor through catastrophic slumping or sliding can potentially disrupt the water column above the failure and generate tsunamiogenic waves that can affect coastal areas (Pelinovsky & Poplavsky, 1996; Nisbet & Piper, 1998; Dawson et al., 2004; Fryer et al., 2004). Deep-water MTC deposits possess physical characteristics that often differ greatly from deep-water submarine-fan or slope-leveled channel systems (Shipp et al., 2004).
of these deposits in deep-water basins means that efficient oil and gas exploration and development in such settings hinge on an understanding of the nature, processes of formation, distribution and relationship that these deposits share with surrounding deep-water environments.

**Terminology and classification of MTCs**

More than four decades have elapsed since Dott (1963) pointed out that there was a considerable amount of confusion in the application of terms that were used to describe mass movement phenomena. Despite the great advances that have been made so far in areas such as facies model analysis, sequence stratigraphic studies and seismic acquisition and imaging techniques of deep-water deposits, a review of the ‘modern’ literature shows that terminology in MTC study remains a confusing mix of terms compiled by scientists working in a variety of geological environments (Nardin et al., 1979; Shanmugam, 2000, 2002). Part of the problem is that submarine mass movements are broadly defined as movement of sediment driven by gravity (gravity-induced deposits) and, therefore, a huge spectrum of deposits can fall into the category, including slides, slumps, debris flows and turbidites.

Nardin et al. (1979) reviewed the terminology and compiled a comprehensive classification system for submarine mass movement processes. The descriptive part of the classification is based on the recognition of certain
Fig. 1. (a) Map showing the area of study located in the area of northeastern South America along the Caribbean Plate Boundary Zone where the Caribbean plate (to the north) and the South American plate (to the south) meet. The area of three-dimensional seismic data is highlighted in grey. The shelf break is shown as a heavy black dash and dotted line along the 200 to 300 m (660 to 1000 ft) contour. Notice the alignment of mud-volcano ridges in the deep-marine setting, with the NE–SW-oriented anticlines located in the shelfal part of the Columbus Basin. (b) Seismic surveys in the study area correspond to block names. Shaded areas correspond to the location of MTCs within seismic unit VI.
sedimentary features of the deposits, including sorting of sediments, size distribution, stratification, grading and sedimentary fabric. On the other hand, the genetic part of the classification is based on interpretation of transport and mechanical behaviour from which characteristics of the sedimentary deposits can be inferred. This approach does not address the issues of grain-size distribution, sedimentation rate or slope gradient, which ultimately will influence boundary conditions for mechanical behaviour (Nardin et al., 1979) (Fig. 2). For purposes of this discussion, slides, slumps and debris flows will be considered constituents of MTCs and can co-occur in the same event or depositional unit (Dott, 1963).

The existing classification system (Nardin et al., 1979) is useful in recognizing MTCs from a process sedimentological perspective, but it fails to address the broader issues of causal mechanisms and pre-failure conditions of MTCs. This lack of differentiation of mechanisms from conditions is critical because it is thought that for a given set of geological conditions and environments, a variety of causal mechanisms can generate MTCs having similar geomorphological characteristics. However, previous studies in offshore Trinidad (Brami et al., 2000; Moscardelli et al., 2006) have shown that there are significant geomorphological differences between MTCs that were deposited in this region during the Plio-Pleistocene. These differences are particularly notorious in the updip (proximal) parts of the MTCs, where initial interpretations have suggested that there is a connection between the geomorphology of individual MTCs and their potential causal mechanisms (Moscardelli et al., 2006). Despite the proliferation of papers describing MTC architecture around the world (Table 1), none has categorized the geomorphological relationships that exist between the updip (proximal) and downdip (distal) parts of MTCs. We think that a detailed examination of these geomorphological relationships (updp vs. downdip), in conjunction with a comparative analysis of the scales and dimensions of MTCs, could help in deducing the causal mechanisms associated with individual MTC events.

The main aim of this paper is to propose a new classification system for MTCs in offshore Trinidad on the basis of the relationships encountered between slope mass failures, sourcing regions, dimensions and geometries of MTCs. Establishment of this new classification system seeks to enable a better understanding of the nature of initiation, length of development history and causal mechanisms of MTCs. The new classification scheme that is proposed herein is not intended to conflict with but to complement the existing classification system for gravity-induced deposits (Nardin et al., 1979). The new classification will be established by our answering the following questions: (1) What are the dimensions and geomorphological characteristics of various MTCs in the deep-marine margin of offshore Trinidad? (2) What geomorphological elements influence the distribution of gravity-induced deposits in the deep-marine margin of offshore Trinidad? (3) What geomorphological differences between MTCs have different sourcing areas? (4) Can we use the seismic geomorphology of ancient MTCs to understand the processes active at their time of deposition? (5) Does each force trigger the same process for the given critical conditions of sediment stability?

**METHODOLOGY AND DATA SETS**

The primary data set for this study of the deep-water architecture and nature of the offshore Trinidad continental margin are three-dimensional (3D) seismic reflection data.
Seismic coverage is large enough to encompass several entire MTC staging areas and depocentres (Fig. 1). Five separate 3D seismic data volumes were available and were merged into a single continuous volume spanning 10,708 km². Imaging depths vary between individual surveys but range from a minimum of 1400 ms (milliseconds) two-way traveltime (TWTT) in the westernmost part of the area (blocks 4ab) to a maximum of 5000 ms TWTT of coverage over central and eastern areas (blocks 25b and 26) (Fig. 3a). These data are all late-1990s vintage, and their acquisition parameters and quality are similar. Bin spacing of the time-migrated volumes is 25 × 12.5 m, and they all have a 4 ms vertical sampling rate. Seismic volumes were processed to zero phase, and the average frequency content of the full-stack seismic data was 30–35 Hz. For approximate time-depth conversions at shallow depths, 1 ms is equivalent to 0.75 m.

The quality of the 3D seismic data used in this study makes it possible to correlate seismic units with a high degree of confidence. Eight regional unconformities and the seafloor were mapped and correlated across the slope into the deep-marine basin (Fig. 3a). The correlation also crossed several mud-volcano provinces (Fig. 4). The eight interpreted unconformities and the seafloor were named, from base to top, P60, P50, P40, P30, P20, P15, P10, P4 and seafloor. Mapping of these horizons was the result of a collaborative effort between different researchers working for the Quantitative Clastic Laboratory Consortium at the Bureau of Economic Geology (Sullivan et al., 2004; Garcia-caro, 2006; Moscardelli et al., 2006) (Figs 3a and 4). In each case, all surfaces were seeded using the auto-picking tool and then interpolated along key amplitude horizons; the interpolation method honoured the geometry and amplitude values of individual reflections. These surfaces were also adjusted by hand where the picking tool strayed from the horizon. The P10 unconformity defines the base of MTC1, a unit that was described extensively by Moscardelli et al. (2006). The P4 unconformity defines the top of MTC1 and the base of the youngest levee-channel complex in this region (Moscardelli et al., 2006). The latest expression of this channel complex on the modern seafloor and its main geomorphological characteristics were described by Mize et al. (2004) and Sullivan et al. (2004). Surfaces mapped were used to define the gross architecture of the basin and to assess its sedimentary fill history. Eight major seismic units (seismic units I–VIII) were defined using the mapped unconformities and the seafloor (Fig. 3a). However, the main focus of this research has been concentrated in describing and understanding MTCs that are contained in seismic units VI (MTC2, MTC2.2, MTC2.3 and MTC2.4) and VII (MTC1) (Fig. 3a). Isochron maps of the youngest seismic units (seismic units VI–VIII) (Figs 3a and 5) helped us understand the character of the continental margin fill in the last stages of basin evolution. Documentation of variations in the location and geometry of major depocentres and sedimentary conduits that connected the outer shelf/upper-slope region with the deep-marine parts of the basin was emphasized. These isopach maps were also useful in tracking changes in the areal extension and geometry of mud-volcano ridges identified in the study area (Sullivan et al., 2004). Tracking changes in the general morphology of the mud-volcano ridges was important because these features acted as palaeobathymetric barriers that helped control sediment transport and distribution in the deep-water region.

MTC architecture was imaged by using root-mean-squared (RMS) amplitude extractions. RMS is a seismic attribute that calculates the square root of the sum of time-domain energy (square of amplitude), affording high amplitudes the maximum opportunity to stand out from background contamination (Chen & Sidney, 1997). The MTCs that are described in this work were imaged by generating RMS amplitude extractions in successive 20 ms (~15 m) time windows above the P15 unconformity in blocks 25 and 26 (Fig. 6). The P15 unconformity represents the erosional surface that defines the base of the MTCs that are contained within seismic unit VI (MTC2, MTC2.1, MTC2.2, MTC2.3 and MTC2.4) (Fig. 7). The P15 unconformity was picked in blocks 25 and 26 as the ‘key horizon’ that guided the amplitude extractions within the unit of interest (seismic unit VI) because the internal architecture of MTCs is influenced greatly by the initial erosional events that generate their basal surfaces. Unfortunately, a lack of seismic coverage below 1400 ms in blocks 4ab (Fig. 3a) prevented us from mapping the equivalent of the P15 unconformity in proximal areas (updip) of the 3D megamerge (Figs 3a and 7). Owing to this data limitation, an alternative methodology had to be implemented for imaging the equivalent interval of seismic unit VI in blocks 4ab. The first step was to flatten the 3D seismic volume using the P10 unconformity (upper boundary of seismic unit VI) as the hanging horizon (Fig. 3b). The main objective of flattening the volume was to minimize stratigraphic distortion caused by post-depositional structural deformation in this area (notice the abundance of faults in blocks 4ab) (Fig. 3a). The second step was to generate an RMS amplitude extraction in a 20 ms window below the P10 unconformity. This particular time window within the upper part of seismic unit VI was chosen because it was the only one that could provide us with complete areal coverage of blocks 4ab. Finally, the amplitude extractions that were obtained for seismic unit VI in blocks 4, 25 and 26 were merged to obtain a regional picture of the stratigraphic elements that were contained in this unit (Fig. 6a). There is a vertical stratigraphic shift (200–400 ms) between the intervals that were imaged updip (blocks 4ab) vs. the ones that were imaged downdip (blocks 25 and 26) in the 3D seismic megamerge; however, the composite image of the multiple RMS amplitude extractions shows an almost perfect match of geomorphological architectures between the different blocks (Fig. 6). This match occurs because the seismic character of seismic unit VI in blocks 4ab does not present dramatic vertical variations, thus preserving a similar geomorphological expression through the entire interval.
Fig. 3. (a) Composite NE–SW–oriented regional seismic line showing a dip view across the study area. Nine key horizons, including the seafloor, were interpreted to explain the architecture of the Tertiary sedimentary infill in the region. (b) Seismic line on blocks 4ab showing flattening of the seismic on the P10MTC1 surface. In yellow – 20 ms time interval used to generate the RMS amplitude extraction shown in Fig. 6 (blocks 4ab).
Fig. 4. NW–SE-oriented regional seismic line showing a strike view across the study and location of the main mud-volcano ridges and chutes present in the region.
Fig. 5. Isochron maps between key stratigraphic surfaces. (a) Phase VI – sedimentation was constrained mainly to the NW, Darien and Haydn megachutes were delivering sediments from the outer shelf/upper slope area (main feeders of MTC_2.1). The Callicore megachute started to deliver sediments towards the NE (main feeder MTC_2). (b) Phase VII – the main axis of deposition shifted towards the SE. The Callicore and Catfish megachutes were the only active sedimentary pathways delivering extrabasinal sediments towards the deep-marine environments. During this time, MTC_1 was deposited (c) Phase VIII – last stage of basin infilling, the Callicore megachute appears to be the only active sedimentary pathway at this time. Uplifting of the northern region of the study area caused deflection of the main depositional axis towards the east. This interval was dominated by deposition of levee-channel complexes. MTCs, mass transport complexes.
Fig. 6. (a) Root-mean-squared (RMS) amplitude extraction map showing the geomorphological expression in plan view of attached (MTC2 and MTC2.1) and detached (MTC2.2, MTC2.3 and MTC2.4) MTCs in the study area. RMS amplitude extraction maps in blocks 25ab and 26 were extracted from the basal part of seismic unit VI. RMS amplitude extraction maps in blocks 4ab were extracted from within seismic unit VI (interval highlighted in Fig. 3). (b) Geomorphological interpretation of RMS amplitude extraction maps within seismic unit VI. Sedimentary sources of attached MTCs are associated with the outer shelf/upper slope area, whereas sedimentary sources for detached MTCs can be linked to the flanks of the mud-volcano ridges. MTCs, mass transport complexes.
Several exploratory wells have been drilled in the study area, but direct access to these data was not available to the authors. Several drop cores were collected in the region for geotechnical tests on near-seafloor sediments, but none was deep enough to penetrate the intervals of interest. Data from exploration drilling in the study area were used by Shipp et al. (2004) to document lithologic and physical characteristics of the north part of the shallowest MTC in the area (MTC_1 contained in seismic unit VII) (Moscardelli et al., 2006). The MTCs that are described herein are slightly older than MTC_1; however, it is thought that their lithologic and physical characteristics are similar.

**GEOLOGICAL SETTING**

A variety of palaeobathymetric and structural features have influenced sediment transport and distribution in the proximal and distal parts of the deep-marine margin of offshore Trinidad and Venezuela. This bathymetry affected evolution of the sedimentary succession during Pliocene and Pleistocene times (Moscardelli et al., 2006). In the outer-shelf/upper-slope area, listric normal and counternormal faults occur. Additionally, normal and inverse faults define the lateral boundaries of shelf-edge horst and graben palaeocanyons that funnel sediments from the outer-shelf/upper-slope area towards the deep-marine basin (Moscardelli et al., 2006).

In distal parts of the basin, mud volcanoes have been an important bathymetric element influencing deep-water sedimentation (Figs 4 and 5). Sullivan et al. (2004) documented 161 mobile mud-associated structures on the seafloor within the study area that vary greatly in size, shape and distribution. Some of these mud diapirs and volcanoes form visible linear clusters that are defined as mud-volcano ridges and are associated with deeper anticlinal structures (Figs 4 and 5). These mud-volcano ridges are part of the palaeobathymetric highs that bound large sediment pathways or megachutes (Fig. 5). In western parts of the study area, these ridges funnel sediments directly downslope from shelf-edge deltas and from the upper slope collapses towards basinward depocentres that are unconfined (Figs 5 and 6). Alternatively, in some areas of the basin and parts of the stratigraphic record, mud ridges
act to isolate and confine some parts of the basin from upslope sedimentation. For purposes of discussion, from the NW to the SE, the ridges associated with these mud volcanoes have been named (1) Darien Ridge (2) Haydn Ridge, (3) East Prospect Ridge, (4) Callicore Ridge, (5) Heliconius Ridge and (6) Catfish Ridge (Figs 4–6).

Summary of basin evolution

The last three stages of basin evolution (seismic units VI–VIII) are discussed briefly in this section to explain some of the elements that influenced the distribution of gravity-induced deposits in the deep-marine margin of offshore Trinidad. Isopach maps of seismic units VI–VIII show significant variations in the location, geometry and extension of the depocentres that were developed in the study area during the last stages of basin infilling (Fig. 5). Generally speaking, these depocentres have an elongated geometry and present a NE–SW orientation that parallels the axis of the mud-volcano ridges. The depocentres were connected to the outer-shelf and upper-slope region by megachutes that were responsible for sediments funneling downslope (Figs 5 and 6) (see also, Moscardelli et al., 2006). The maps also reveal an overall migration of the depocentres from NW to SE, as well as progressive thinning of the stratigraphic succession near the Darien Ridge area (Fig. 5).

The isopach map of seismic unit VI shows that the main depocentre during this phase was located in the NW corner of the study area near Darien Ridge. Darien and Haydn megachutes were most likely acting as main feeders of the NW depocentre, whereas the Callicore megachute was funneling sediments from the upper slope towards the central part of the basin (Figs 5a and 6). The MTCs that are described in this paper are contained in the NW and central parts of seismic unit VI (MTC2, MTC2.1, MTC2.2, MTC2.3 and MTC2.4) (Fig. 6).

Location and distribution of the main depocentres in seismic unit VII (Fig. 5b) greatly differ from those of the previous basin configuration (Fig. 5a). The isopach map of seismic unit VII (Fig. 5b) shows that the areal extension of the NW depocentre was significantly reduced and new depocentres were relocated to the central and SE parts of the basin. The central depocentre was located to the south of Haydn Ridge, where a 207 km² MTC (MTC1) was deposited (Moscardelli et al., 2006). The second depocentre was located in the SE corner of the data set, to the south of Heliconius Ridge, and its axis was parallel to the Catfish megachute. The isopach map of this unit also shows thinning of the stratigraphic succession towards the NW (near the Darien Ridge area), as well as an increase in areal extension of the relative highs associated with Darien, East Prospect and Haydn Ridges. During the deposition of seismic unit VII (Fig. 5b), most sedimentation started to shift from the NW (seismic unit VI) (Fig. 5a) to the central and SE parts of the study area, as revealed by the SE migration of the main depocentres.

Finally, the isopach map of seismic unit VIII shows that most sedimentation was taking place in the central part of the study area (Fig. 5c) between Haydn and Heliconius Ridges. The Callicore megachute was the main sedimentary conduit for sediments to reach the deep-marine region from outer-shelf and upper-slope regions. Development of levee-channel complexes during this time was dominant in the basin (Mize et al., 2004; Moscardelli et al., 2006). In the SE, the main depositional axis of the channelized features had an initial NE–SW orientation that was later diverted towards the east (an almost 90° shift) near East Prospect Ridge (Fig. 5c). Additional channel systems were also developed during this time to the south of Callicore and Heliconius Ridges. The modern seafloor shows the latest expression of this levee-channel complex (Mize et al., 2004). Today, hemipelagic sedimentation is dominant in the area, as well as local collapses from mud-volcano ridges and individual mud volcanoes. Occasional collapses on the shelf edge and upper-slope region could trigger deposition of gravity-induced deposits.

Boettcher et al. (2003) pointed out in a regional study that covered the SE corner of the Caribbean (including our study area), that the deep-water basin of eastern offshore Trinidad had been developed as a product of tectonic subsidence in response to emplacement of a fold-and-thrust belt associated with the Caribbean deformational front. According to this model, the origin of the NE–SW-trending mud-volcano ridges (Darien, East Prospect, Haydn, Callicore, Heliconius and Catfish Ridges) (Figs 4 and 5) can be related to successive thrust imbrications generated by the advances of the Caribbean deformational front towards the SE. In this regional context, Darien Ridge represents the eastern continuation of the Central Range onshore Trinidad and the offshore equivalent of the fold-and-thrust belt associated with the Caribbean deformational front (Fig. 1a) (Babb & Mann, 1999; Wood, 2000). The progressive advances of the Caribbean deformational front towards the SE were probably responsible for the thinning and relative uplifting that was recorded by isopach maps in the north parts of the study area (Darien Ridge region) (Fig. 5). These tectonic events were also responsible for the SE migration of the main sedimentary depocenters (Fig. 5).

From this summary, we can conclude that the morphological variations that the mud-volcano ridges experienced through time played an important role in influencing the distribution of gravity-induced deposits in the deep-marine parts of the eastern offshore Trinidad basin. These morphological variations not only controlled the location of sedimentary pathways that connected the outer-shelf/upper-slope regions with the deep-marine parts of the basin but also controlled the location and migration of the main depocentres in the region.

SEISMIC AND LITHOLOGICAL CHARACTERISTICS OF MTCs

Brami et al. (2000), using shallow 3D seismic data, characterized seven principal architectural elements in the most
recent deep-water sequence of offshore Trinidad: mass transport, confined channel, levee-channel and distribu-
tary-channel complexes; slope with minor channels un-
differentiated slopes; and mud diatremes. MTCs and levee-channel complexes seem to be the dominant facies in the basin. In cross-sectional seismic lines, MTCs are recognizable by the presence of seismic facies that show low-amplitude, semitransparent, chaotic reflections (Fig. 8c and d) (Posamentier & Kolla, 2003). However, internal to the MTC may exist regions of semi-deformed mixtures of low- and high-amplitude reflections showing thrust and embrittlement geometries (Frey-Martinez et al., 2005, 2006; Moscardelli et al., 2006) (Fig. 9b).

The upper and lower boundaries of MTCs tend to be marked by high-amplitude seismic reflections (Fig. 8c and d). The lower boundary of MTCs often shows a variety of erosive features (Figs 6 and 8). The largest of these, termed megascours by Moscardelli et al. (2006), can show scour into the substratum that can be tens of metres deep, several kilometres wide and hundreds of kilometres long (Fig. 8) (McGivney & Cook, 2003; Posamentier & Kolla, 2003; Weimer & Shipp, 2004; Moscardelli et al., 2006). These basal erosional surfaces can also contain features termed cat-claw scours (Moscardelli et al., 2006) or monkey fingers (McGivney & Cook, 2003), which are composed of a series of smaller, shallow, radiating scours, whose apex is usually close to the down-dip termination of individual megascours. Secondary scours and scratches (Moscardelli et al., 2006) or glide tracks (Nissen et al., 1999) are also common elements observed on the basal erosional surfaces of MTCs and are associated with out-runner blocks that most likely touched the scours on the seafloor. Condensed sections acting as the initial sliding surface of MTCs can also define the basal boundary of mass-wasting events (Lee et al., 2004a) (Fig. 9b). Condensed sections can sometimes be identified in 3D seismic data as continuous high-amplitude seismic reflectors (Fig. 9b). In offshore Trinidad, both ero-
sional surfaces (Fig. 8) and condensed sections (Fig. 9b) can be used to identify the basal boundaries of MTCs. However, the upper bounding surfaces of MTCs in off-
shore Trinidad commonly show erosion, which is thought to be associated with processes along the base of overlying levee-channel complexes. These channel-levee complexes appear to preferentially deposit in depo-axes controlled by alterations in bathymetry created by comp-
paction and final geometry of underlying MTC deposits (Figs 5c and 8c) (Moscardelli et al., 2006). MTCs tend to be amalgamated, and surfaces between successive, stacked MTCs can be difficult to recognize in seismic (Fig. 8) (Posamentier, 2004).

Internally, MTCs can contain thrusted blocks (Weimer & Shipp, 2004) or syn-depositional thrusts (Fig. 9b) (Frey-Martinez et al., 2005, 2006; Moscardelli et al., 2006), reflecting the ongoing deformation due to compression associated with deceleration of the flow (Marr et al., 2001). Such deceleration could occur at the terminal end of debris lobes (Fig. 9b) or anywhere the flow is constricted and slows. The presence of bathymetric barriers on the seafloor at the time of deposition, such as mud volcanoes (Figs 4–6) or salt diapirs, can contribute significantly to the reduction of the cross-sectional area in regions experiencing gravitational sedimentation (Moscardelli et al., 2006). Another distinctive internal characteristic of MTCs is the presence of internally undeformed transported blocks that lay directly on top of or partly submerged in the surrounding chaotic material (Lee et al., 2004a). These blocks can vary in size from several hundred to several thousand square metres across and 150 m thick. In contrast to these transported olistoliths, there occur intact but buried erosional remnants that are surrounded by chaotic MTC material (Moscardelli et al., 2006). In Trinidad, these features usually form in the shadow of some barrier that inhibits MTC downslope movement, causing it to flow around the obstacle, thus preserving the older strata lying downslope of the barrier. Such deposits, termed erosional shadow remnants by Moscardelli et al. (2006), are associated closely with physiographic barriers such as mud vol-
canos and salt diapirs.

The lithology of MTCs generally consists of muddy sediments showing extensive deformation, dipping beds and blocks of varying sizes (Macdonald et al., 1993; Piper et al., 1997; Shipp et al., 2004). However, it is important to point out that rheological characteristics of MTC sediments de-
pend on the nature of the original material that failed (Shipp et al., 2004; Pickering & Corregidor, 2005). The shallowest MTC in offshore Trinidad (MTC1) is composed of muddy sediments (Shipp et al., 2004) that were derived from Palaeo-Orinoco shelf-edge deltas that fed sediments into canyons that impinged upon the lowstand shelf break (Carr-Brown, 1972; Diaz de Gamero, 1996; Sydow et al., 2003). Some MTCs in offshore Trinidad were also generated by failures in the upper slope region (MTC2 and MTC21) (Moscardelli et al., 2006). These deposits are also thought to be composed of muddy sediments. Log re-
sponses of the shallowest MTC in offshore Trinidad (MTC1) show an increase in resistivity, compressional ve-
locity, density and porosity (Shipp et al., 2004). Geotechni-
cal measurements also indicate an increase in shear strength, with a corresponding decrease in void ratio and water content (Pirimze et al., 2004; Shipp et al., 2004).

GEOMORPHOLOGICAL DESCRIPTION OF MTCs IN OFFSHORE TRINIDAD

Five separate MTCs have been examined within seismic unit VI: MTC2, MTC2.1, MTC2.2, MTC2.3 and MTC2.4 (Fig. 6). As shown in Fig. 6, these five MTCs present very different geomorphological characteristics and dimensions. General descriptions of the MTCs con-
tained in seismic unit VI and a brief overview of MTC1 (seismic unit VII) (Moscardelli et al., 2006) are provided in this section.
Fig. 8. Root-mean-squared (RMS) amplitude extraction map showing geomorphological expression in plan view of attached (MTC_2 and MTC_2.1) and detached (MTC_2.2, MTC_2.3 and MTC_2.4) MTCs in the study area. The map is from the basal part of seismic unit VI. Sedimentary sources of attached MTCs are associated with the outer shelf/upper slope area, whereas sedimentary sources for detached MTCs can be linked to the flanks of mud-volcano ridges. LCCs, levee channel complexes; MTCs, mass transport complexes.
MTC_1 is the shallowest MTC in the study area (seismic unit VII). Younger than any of the MTCs described within seismic unit VI, it was described in detail by Moscardelli et al. (2006). MTC_1 was point-source fed by a single palaeocanyon graben nearly 200 m deep that was bounded along both margins by normal faults. The palaeocanyon, <2 km wide on its upper section (updip), widens downslope, reaching more than 10 km on its lower end (toe of slope) (see detailed discussion in Moscardelli et al., 2006). MTC_1 covers an approximate area of 2017 km²; its average length from the upper-slope area down to the east boundary of the seismic coverage (deep basin) is

**General description of MTC_1**

MTC_1 is the shallowest MTC in the study area (seismic unit VII). Younger than any of the MTCs described within seismic unit VI, it was described in detail by Moscardelli et al. (2006). MTC_1 was point-source fed by a single palaeocanyon graben nearly 200 m deep that was bounded along both margins by normal faults. The palaeocanyon, <2 km wide on its upper section (updip), widens downslope, reaching more than 10 km on its lower end (toe of slope) (see detailed discussion in Moscardelli et al., 2006). MTC_1 covers an approximate area of 2017 km²; its average length from the upper-slope area down to the east boundary of the seismic coverage (deep basin) is

![Diagram of MTC_1](image-url)
140 km. The estimated volume of remobilized sediments is 242 km$^3$, and the maximum thickness in its core area is 250 m. MTC1 presents a series of geomorphological features that include an erosional edge that defines its western lateral boundary, deep basal scours and pressure ridges. In addition, multiple cat-claw scours, erosional shadow remnants (ESRs), smaller scale scratch marks and imbricated thrust complexes have been reported within MTC1 (see detailed description in Moscardelli et al. 2006).

**General description and evolution MTC2**

Moscardelli et al. (2006) described the main geomorphological characteristics of MTC2 in the upper slope area near the palaeoshelf break (source area). According to this description, at least three consecutive collapse features can be seen along the palaeoshelf break that have a semicircular shape and average diameters of 4.5 km and average areas of 14 km$^2$ (their Fig. 18b; Fig. 6a this work). The collapsed sediments were transported downslope through the Callicore and Haydn megachutes as gravity-induced deposits that were finally deposited as MTC2 and MTC2.1 (Figs 1b and 6).

The core of MTC2 is located in the central part of the study area (Fig. 6). The Callicore megachute was the main feeder of MTC2 (Figs 6 and 8), feeding sediment directly and consistently from the upper-slope source into the deep-water basin. MTC2 covers an area of approximately 626 km$^2$; its average length from the upper-slope area down to the east boundary of the seismic coverage (deep basin) is 40 km. MTC2 is likely to be near its terminus at this eastern point, with evidence of significant thinning and lateral dispersion of the deposit. Its width varies from a minimum of 10 km in the proximal area, widening progressively towards the NE, until it reaches a maximum width of 25 km in the distal parts of the unit. According to seismic data, the average thickness of MTC2 is 60 m; however, it is considered to be a minimum value of the original thickness because of reductions in thickness caused by post-depositional compaction and erosion. On the basis of these values, the minimum volume of remobilized sediments calculated for MTC2 is around 35 km$^3$. The volume is a rough estimation that was calculated by multiplying the total area occupied by MTC2 and its minimum estimated thickness (60 m).

In the central and distal parts of the data set, the base of MTC2 is defined by an erosional surface that contains a series of distinctive megastratigraphic features that are typical of regional MTCs (Fig. 7). These features include erosional edges, megascours and multiple levels of terracing. Steep erosional edges that can reach 60 m in relief define the west and east lateral boundaries of MTC2 (Figs 7 and 8c). Various terrace levels, located in the south part of the western erosional edge, suggest that several episodes of incision took place during the emplacement of MTC2 (Figs 7 and 8c). Elongated megascours that are more than 50 m deep and 4 km long surround individual mud volcanoes in the east part of the unit (Figs 6–8). These megascours were formed when passing debris flows were confined by individual mud volcanoes, causing a reduction in the flow’s cross-sectional area and a short-term increase in the erosive power of the flow (Marr et al., 2001; Moscardelli et al., 2006). Similar features have been described in several MTCs around the world (Lee et al., 2004a; McGilvery et al., 2004; Posamentier, 2004).

RMS amplitude extractions that were taken from different stratigraphic levels within MTC2 (Fig. 8) reveal two main phases of this unit’s evolution. Phase 1 (Fig. 8a) is associated with initial erosional processes that generated the basal surface of MTC2. During this phase vertical and lateral erosion was the dominant process, several megascours were generated around individual mud volcanoes (Fig. 8a), and successive episodes of incision were responsible for generation of different levels of terraces on the SW margin of the Callicore megachute (Fig. 8a and c). Sediments were transported from the SW to the NE, parallel to the main axis of Haydn and Callicore Ridges. Most sediments were deposited between these two major mud-volcano ridges (Figs 6 and 8). However, during Phase 1 part of the sediments were diverted towards the NW through a relative low that was located between Haydn and East Prospect Ridges that allowed a ‘tongue’ of sediment to spread through this opening (Fig. 8a). This elongate flow of sediments is 15 km long and extends from the west margin of the main body of MTC2 to its terminal end to the NW (Fig. 8a). Near the main body of MTC2, the tongue of sediments widens from 1 km towards the NW to a width of 4 km. In the NW termination of the tongue of sediments, a series of pressure ridges can be observed on the RMS amplitude extraction map, which are typical in terminal lobes of debris flows (Fig. 8a). Similar pressure ridges have been described at the terminal ends of MTCs in offshore Morocco (Lee et al., 2004a), offshore Brunei (McGilvery & Cook, 2003), offshore Israel (Frey-Martinez et al., 2006) and in the Nigerien continental slope (Nissen et al., 1999).

Phase 2 represents the final stages of evolution of MTC2. RMS amplitude extractions were taken through the top part of MTC2 (Fig. 8b) and show an increase in the areal extent occupied by the amplitude anomalies that have been associated with MTC seismostacies. The RMS amplitude extraction map of this interval (Fig. 8b) shows high-amplitude lineations that diverge from one another as one follows them towards the north and NE. Such patterns are interpreted as indicating lateral spreading of the sediments in the north parts of Callicore Ridge. The ‘gateway’ that allowed the ‘tongue’ of sediments to move towards the NW during Phase 1 (Fig. 8a) has become inactive at this time. The interruption of sediment supply towards the NW through the ‘sediment gateway’ could have been triggered by a series of factors, including (1) reactivation of Haydn Ridge and subsequent uplifting of its northeastern termination, resulting in a closing of the gateway and/or (2) obstruction of the gateway entrance between Haydn and East Prospect Ridges by the sediment excess deposited
during Phase 1. Of these two hypotheses, reactivation and relative uplifting of Haydn Ridge because of migration of the Caribbean deformational front towards the SE (Babb & Mann, 1999; Boettcher et al., 2003) is most likely the cause of this interruption of sediment supply towards the NW (Fig. 8b). Therefore, during Phase 2 an important part of the active sedimentation that had occurred in this area shifted towards the NE, where these sediments started to fill up the region located to the north of Callicore Ridge (Fig. 8b). Internally, additional megascours formed between the west erosional edge and individual mud volcanoes in the central part of MTC2. Similar to the megascours that were described in Phase 1, these features were generated as a result of the reduction in cross-sectional area between the erosional edge and the individual mud volcanoes. This reduction caused an increase of the frictional forces that were affecting the basal parts of the flow, prompting vertical incision and development of drag marks from the movement of huge chunks of lithified rock in the base of the flow (Moscardelli et al., 2006) (Fig. 8c and d).

**General description and evolution of MTC2.1**

MTC2.1 is located in the NW corner of the study area, between Darien and Haydn Ridges (Figs 6, 9 and 10a). Similar to MTC2, sediments from the upper-slope area were transported from the SW to the NE through the Haydn megachute into deep-marine settings (Fig. 1b). The main geomorphological difference between this system (MTC2.1) and MTC2 is that the former presents a more elongated morphology in plan view (Figs 6 and 9). The elongate geometry of MTC2.1 suggests a major degree of lateral confinement during deposition. The area covered by MTC2.1 varies from 60 to 100 km², its average length from the upper-slope area down to the NE boundary of seismic data coverage is 29 km, and it is more than 60 m thick. Basal and upper parts of MTC2.1 are separated by a seismically prominent reflector that is well preserved in the downslope parts of the basin but abruptly onlaps Haydn Ridge and disappears in upslope (Fig. 9b). This reflector is interpreted to be the seismic expression of a condensed section, similar to that described by Lee et al. (2004a) in the Tejas A MTC in offshore Morocco. The presence of the condensed section means that a significant time break occurred between deposition of the basal and upper parts of MTC2.1. According to Lee et al. (2004a), these condensed sections have the capacity to provide the initial surfaces across which mass failure destabilizes and slides. The surfaces are often destroyed by the initial erosional processes associated with MTC development, but preservation of the basal condensed sections indicates the predominance of laminar flow in the basal parts of the MTCs.

RMS amplitude extractions taken from different seismic time intervals within the MTC2.1 unit reveal two main stages of development. An amplitude extraction taken over the basal part of MTC2.1 (Phase 1) (Fig. 9a) revealed the geomorphology of MTC2.1 during its first stages of development. Figure 9a shows MTC2.1 during this phase as a NE–SW–elongated body that internally presents a series of closely spaced pressure ridges. During this phase the unit was approximately 20 km long and 3 km wide and covered an approximate area of 60 km².

An amplitude extraction near the top of MTC2.1 (Phase 2) (Fig. 10a) shows that this interval has a slightly different geomorphology. The upper deposits are more aerially extensive than the lower deposits, and although its elongated geometry is preserved in the proximal (SW) parts of the deposit, this unit shows a more lobate shape in the distal (NE) terminal locations (Fig. 10a). The length of the upper unit (phase 2) is 38 km, showing an increase of 18 km compared with the length of the underlying lower unit (phase 1) (Fig. 9). The width of the upper deposit is 3.5 km in proximal areas and 10 km in distal areas (Fig. 10a). Once again, the deposit is widening in its late stages (upper unit, NE locations). The total area covered by the upper unit is approximately 100 km², and the total remobilized volume of sediments was calculated to be 7 km³.

The first stages of infilling for MTC2.1 were influenced greatly by the presence of the mud-volcano-cored Haydn Ridge. This ridge acted as a strong physiographic barrier that constrained gravity flows to the NW, within the Haydn megachute (Fig. 9a). However, during Phase 2 the flow reached the NE terminus of this relatively confined minibasin, where more accommodation space was available, thus allowing the lateral spreading of sediments (Fig. 10).

**General description and evolution of MTC2.2/MTC2.3/MTC2.4**

These localized MTCs (MTC2.2, MTC2.3 and MTC2.4) cover significantly smaller areas than the previous MTCs (MTC1, MTC2 and MTC2.1) (Table 3), and they are fed by localized source areas that do not have a continuous influx of shelf- or slope-derived, extrabasinal sediments (Table 2). MTC2.2 is located along the south flank of Darien Ridge in the NW corner of the study area (Figs 9 and 10). MTC2.3 and MTC2.4 are both located along the north flank of Heliconius Ridge (Figs 6 and 11a) in the SE corner of the study area. Given its closely spaced amplitude extractions (Fig. 8), MTC2.3 appears to be slightly older than MTC. 2.4, with MTC2.3 appearing along the flanks of Heliconius Ridge earlier than MTC2.4. The areas covered by these smaller MTCs range from 11 to 22 km², and their thicknesses range from 98 to 150 m. Estimated volume of remobilized sediments that collapsed from the flanks of mud-volcano ridges is between 1.3 and 3 km³ (Table 3).

RMS amplitude extractions guided by the P15 horizon (Fig. 7) in the basal parts of seismic unit VI revealed that MTC2.2 is lunate in plan view (Fig. 9), whereas MTC2.3 and MTC2.4 have a more elongate geometry (Fig. 11). These units also have a series of common geomorphological characteristics. Seismic lines parallel the depositional
strike axis of these localized MTCs (Figs 10 and 11) and show vertical incision and erosion affecting their basal surfaces. An RMS amplitude extraction map of the top part of MTC_2.3 (Fig. 11a) also shows a series of concentric amplitude anomalies located at the NE termination of the MTC_2.3 lobe. These concentric anomalies are the plan view expression of terminal syndepositional thrusts (Fig. 11b). The seismic lines also show that the proximal part of MTC_2.3 is composed of a series of slumps (Fig. 11b). Similar syndepositional thrusts and slumps have been interpreted in updip and downdip parts of MTC_2.2 and MTC_2.4 (Figs 10b and 11d).

Sediments that form these localized MTCs are collapsed sediments derived from the flanks of mud-volcano ridges. Extensional forces associated with gravitational instabilities that affected the upper parts of the flanks of the mud-volcano ridges caused the initial slumping that triggered formation of these units. The collapse materials moved downslope and reached a transitional state where flow transformations started to occur. Decrease in slope angle, loss of cohesiveness and lack of space to accommodate the incoming volume of sediments eventually caused deceleration of flow and formation of syndepositional thrusts that compensate for lack of space in the distal ends.

Fig. 10. (a) Root-mean-squared (RMS) amplitude extraction map near the top of the MTC_2.1. The upper part of MTC_2.1 is more aerially extensive than its lower part. The elongated geometry of MTC_2.1 is preserved in the proximal part of the deposit, but it shows a more lobate shape in its distal termination. (b) NW–SE seismic line parallel to the depositional dip of MTC_2.2. The line shows slumped material that failed downslope—the top half of the unit is composed of low-amplitude, chaotic reflectors, but the internal character of the lower half of the unit shows small fragments of continuous high-amplitude reflectors that appear to be downsloping onto the P15MT2 basal surface. This seismic character and geometry is typical of slumps. MTCs, mass transport complexes.
of these MTCs (Farrell, 1984; Farrell & Eaton, 1988; Martel, 2004). The flow direction followed by the collapsed sediments that form these localized MTCs was controlled mainly by the geometry and changes in slope gradients that occurred in the flanks of the mud-volcano ridges.

**NEW CLASSIFICATION SYSTEM FOR MTCs**

**Defining the classification system**

The new classification system that is used herein takes into account a series of factors, including (1) geomorphological and morphometric dimensions of the MTCs, (2) causal mechanisms, (3) location of their source area and (4) relationship of the MTCs to their source area. This classification system defines two categories: attached MTCs and detached MTCs. Attached MTCs have also been subdivided into two subcategories: shelf attached and slope attached (Tables 2 and 3).

In terms of scales and dimensions, regionally extensive attached MTCs can occupy hundreds to thousands of square kilometres in area and tens of kilometres in width and length. Detached MTCs are smaller; these deposits are less than tens of square kilometres in area and only a few kilometres in width and length (Tables 2 and 3). In this paper, length is a measurement based on the total area that has been affected by the mass wasting event, and it represents a possible maximum value for run-out distance (given their areal extension and complexity, different parts of the flow within a single MTC event can present different run-out distances) (Fig. 12). The thickness of MTCs is not a useful parameter for differentiating between attached and detached systems because our data show that both types of MTCs can reach thicknesses in excess of 100 m (Table 3). However, the sediment volume associated with detached MTCs does not seem to exceed 10 km$^3$ (Table 3). The length/width ($L/W$) ratio of these deposits can also be used to differentiate attached from detached MTCs. According to our data, $L/W$ ratios $>4$ are characteristic of attached MTCs, and $L/W$ ratios $<4$ indicate detached MTCs (Tables 2 and 3).

Attached MTCs are triggered by regional events that have the capacity to destabilize outer-shelf/upper-slope areas, causing massive collapses that are responsible for...

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### Table 2. Classification, causal mechanisms, and source areas of MTCs

<table>
<thead>
<tr>
<th>Classification</th>
<th>Causal mechanisms</th>
<th>Source area</th>
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<tbody>
<tr>
<td>Attached MTCs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area = 100s to 1000s km$^2$</td>
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<td></td>
</tr>
<tr>
<td>Width and Length = 10s km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shelf-attached MTC</td>
<td>Relative sea-level fluctuations</td>
<td>Palaeoshelf edge deltas</td>
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<tr>
<td>MTC1</td>
<td>High sedimentation rates</td>
<td></td>
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<tr>
<td>Slope-attached MTC</td>
<td>Tectonism (earthquakes)</td>
<td>Upper-slope collapses (mega-cookie bites)</td>
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<tr>
<td>MTC2</td>
<td>Volcanism</td>
<td></td>
</tr>
<tr>
<td>MTC2.1</td>
<td>Gas hydrate dissociation</td>
<td></td>
</tr>
<tr>
<td>MTC2.2</td>
<td>Longshore currents</td>
<td></td>
</tr>
<tr>
<td>MTC2.3</td>
<td>storms and hurricanes</td>
<td></td>
</tr>
<tr>
<td>Detached MTCs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area = 10s km$^2$</td>
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<td></td>
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<td>Width and length = few km</td>
<td></td>
<td></td>
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<tr>
<td>MTC2.4</td>
<td>Gravitational instabilities on the flanks of mud-volcano ridges/salt masses and levee-channel complexes:</td>
<td>Flanks mud-volcano ridges/salt diapirs/leves</td>
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### Table 3. Classification and morphometry of MTCs in offshore Trinidad

<table>
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<tr>
<th>Classification</th>
<th>MTC</th>
<th>Area (km$^2$)</th>
<th>Length (km)</th>
<th>Width (km)</th>
<th>Thickness (m)</th>
<th>Volume (km$^3$)</th>
<th>Length/width</th>
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</thead>
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<td>Attached MTCs</td>
<td>MTC1</td>
<td>2017</td>
<td>140</td>
<td>25</td>
<td>&lt;250</td>
<td>~242</td>
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<td></td>
<td>MTC2</td>
<td>626</td>
<td>40</td>
<td>10–25</td>
<td>&gt;60</td>
<td>&gt;35</td>
<td>4–1.6</td>
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<tr>
<td></td>
<td>MTC2.1</td>
<td>60–100</td>
<td>20–38</td>
<td>3–10</td>
<td>&gt;60</td>
<td>&gt;7</td>
<td>6.6–3.8</td>
</tr>
<tr>
<td>Detached MTCs</td>
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<td>22</td>
<td>5.6</td>
<td>5.5</td>
<td>150</td>
<td>3.3</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>MTC2.3</td>
<td>21.4</td>
<td>8.7</td>
<td>3</td>
<td>136</td>
<td>3</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>MTC2.4</td>
<td>11.3</td>
<td>5.4</td>
<td>2.5</td>
<td>98</td>
<td>1</td>
<td>2.16</td>
</tr>
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</table>

*Estimated.

MTC, mass transport complexes.
Fig. 11. (a) Root-mean-squared (RMS) amplitude extraction map near the top of MTC2.3 and MTC2.4. Both detached MTCs are derived from the north flank of the Heliconius Ridge. (b) NE–SW seismic line parallel to the depositional dip of MTC2.3. Notice the slumps on the SW part of the MTC and the syndepositional thrusts on its NE termination. (c) NW–SE seismic line parallel to the depositional strike of MTC2.3. (d) NW–SE seismic line parallel to the depositional dip of MTC2.4. Syndepositional thrusts can be interpreted on its NW termination. (e) NW–SE seismic line parallel to the depositional strike of MTC2.4. MTCs, mass transport complexes.
the initiation of mass-wasting processes (Table 2). Geomorphologically speaking, shelf-attached and slope-attached MTCs are quite similar in distal area (downslope part of the deposits). However, their geomorphological differences greatly in the staging area near the palaeoshelf break (upslope part of the deposits). Geomorphological elements common in the proximal part of shelf-attached MTCs include palaeocanyons that funneled sediments downslope, as well as aggradational or progradational cliniforms near the palaeoshelf break that are recognizable in 3D seismic lines. On the other hand, regionally extensive scarps that are tens of kilometres long and hundreds of metres deep define the updip boundaries of slope-attached MTCs in the shelf-break/upper-slope region. Seismic reflections associated with the collapsed materials that are contained in the updip parts of slope-attached MTCs tend to be discontinuous and chaotic.

Previously described geomorphological differences between shelf-attached and slope-attached MTCs reflect the different causal mechanisms that can trigger each system, as well as the variety of source areas that can be associated with them. Sedimentary sources of shelf-attached MTCs are usually associated with shelf-edge deltas that are controlled by sea-level fluctuations and high sedimentation rates. Oversteepening in the distal parts of shelf-edge deltas can trigger gravitational instabilities in the outer-shelf region that can generate debris flows, slides and slumps. Seasonal increments in sediment and water discharge affecting the fluvo-deltaic systems associated with shelf-edge deltas can also prompt the development of mass-wasting events in the delta front. In contrast, sedimentary sources of slope-attached MTCs are associated with catastrophic and extensive collapses of the upper continental slope that are usually triggered by earthquakes, long-shore currents, hydrate dissociation, or strong storms and/or hurricanes. Accelerated rates of sea-level fall can also trigger slope-attached MTCs by destabilizing gas-hydrate reservoirs on the continental slope, causing subsequent failure of the upper-slope region (Maslin et al., 2004, 2005).

Alternatively, triggering mechanisms of localized detached MTCs depend more on local gravitational instabilities that occur on the flanks of mud or salt masses, along the flanks of levees in levee-channel complexes, or on the flanks of mid-oceanic ridges. Detached MTCs are defined in this paper as deposits that are formed when instabilities that affect localized bathymetric highs trigger partial collapse of their flanks, generating cascading debris flows or slumps. Most of the sediments of detached MTCs are derived locally within the minibasin of deposition (Table 2).

**Classification of MTCs in offshore Trinidad and worldwide analogues**

According to the MTC classification scheme proposed herein, MTC1 (Moscardelli et al., 2006) is classified as a shelf-attached system, MTC2 and MTC2.1 (this paper) are classified as slope-attached systems and MTC2.2, MTC2.3 and MTC2.4 (this paper) are classified as detached systems (Fig. 13) (Tables 2 and 3).

MTC1, MTC2 and MTC2.1 all occupy regional extensive areas (from 100 to 2017 km²) (Table 3), which is a characteristic of attached MTCs. In addition, previous studies suggest that MTC1 was fed by aggradational cliniforms associated with a Palaeo-Orinoco shelf-edge delta, whose delta-front facies had become increasingly unstable and affected by gravitational tectonics and slumping during still-stand conditions (Carr-Brown, 1972; Sydow et al., 2003; Moscardelli et al., 2006). According to Moscardelli et al. (2006), high sedimentation rates associated with the Palaeo-Orinoco delta are a key factor in the formation of the shelf-edge delta that fed MTC1. Previous observations...
support the classification of MTC1 as a shelf-attached system whose triggering mechanisms are associated with relative sea-level fluctuations and high sedimentation rates (Fig. 13a). In contrast, the areally extensive nature of scarps observed in the updip parts of MTC2 and MTC2.1 near the palaeoshelf break suggests that earthquakes, caused by ongoing tectonic activity along the Caribbean plate boundary, most likely triggered multiple failure events (Moscardelli et al., 2006). Because MTC2 and MTC2.1 were probably triggered by an earthquake, these MTCs have been classified as slope-attached systems (Fig. 13b).

MTC2.2, MTC2.3 and MTC2.4 are areally constrained to the flanks of the mud-volcano ridges in offshore Trinidad, and their areas do not exceed more than 22 km². Their formation is clearly tied to gravitational instabilities affecting the flanks of the mud-volcano ridges that are present in the area. The localized nature of these MTCs (MTC2.2, MTC2.3 and MTC2.4) and their disconnection from source areas located in the shelf or upper-slope region were considered relevant factors that allowed us to classify these deposits as detached MTCs (Fig. 13c). Validation of this new classification system depends on its applicability to similar deposits around the world, as well as to the use of different types of data sets (e.g. outcrop studies) for class identification. The eastern and western debris flows in offshore Brazil (Maslin et al., 2005) are good examples of shelf-attached systems. These MTCs are thousands of square kilometres in area and hundreds of metres thick. Both MTCs were generated during relative sea-level rise or still-stand conditions. Increase in the sediment discharge of the palaeo-Amazon River probably boosted sedimentation rates in the palaeo-Amazon shelf-edge delta (Maslin et al., 2005). This increase in water and sediment discharge could have been caused by deglaciation of the Andes during greenhouse times (Thompson et al., 1995; Maslin et al., 2005). The extensive areal coverage of eastern and western debris flows in offshore Brazil (~10 000 km²) and their connection with the palaeo-Amazon shelf-edge delta as their primary sedimentary source suggest that these systems can be classified as shelf-attached MTCs (Fig. 13a).

The Deep Earth MTD and Unit R MTD also located in offshore Brazil (Maslin et al., 2005) are thousands of square kilometres in area and were deposited during icehouse periods of rapidly falling sea level that occurred between 35 and 37 ka and between 41 and 45 ka, respectively (Shackleton, 1987; Flood et al., 1995). However, the triggering mechanisms associated with these mass-wasting events were not directly related to relative fall in sea level. Instead, removal of water over the shelf and subsequent reduction of hydrostatic pressure during this time caused destabilization of the gas-hydrate reservoirs on the continental slope, triggering the subsequent failure of the North Brazilian margin (Maslin et al., 2004, 2005). Identification of gas-hydrate dissociation as the main causal mechanism that finally triggered deposition of the Deep Earth MTD and Unit R MTD in offshore Brazil was the key criterion that we used to classify both units as slope-attached systems. This particular case study highlights the difficulties that interpreters can encounter when trying to pinpoint specific causal mechanisms for individual MTC events. These complications increase when several mechanisms act in a short time before the occurrence of the mass-wasting event. However, it is critical to make the differentiation between shelf-attached MTCs and slope-attached MTCs because the former can be generated in successive events (e.g. multiple clinoform collapses over a period of time), but the latter generate as the result of a catastrophic event (e.g. earthquake).

This new classification system for MTCs shown herein can also be applied to MTCs that have been identified in outcrop studies. It is difficult to appreciate the real spatial dimensions of MTCs in outcrops because their thicknesses often are in excess of the dimensions of the outcrop (Kleverlaan, 1987). Moreover, compaction and erosion are also factors that need to be considered when trying to compare outcrop thicknesses of MTCs using ‘equivalent’ measurements collected in modern continental margins using 3D seismic reflection data. Despite all these ‘scale’ complications, it is more accurate to identify sediment provenance (source area) of MTCs if outcrop studies can be integrated with seismic observations.

Pickering & Corregidor (2005) documented an MTC in an outcrop of the Ainsa Basin in the Spanish Pyrenees that, according to the classification system defined herein, fits into the shelf-attached category. This particular unit was described as a multiphase granular flow associated with extraformational material derived from the shelf and from fluvo-deltaic input. This unit contains well-rounded pebbles, shallow-marine shells and abundant reworked nummulites. The thickness of the Ainsa MTC ranges from a few metres to tens of metres and may show cumulative basal erosion of up to tens of metres. The basal part of these multiphase granular flows is defined by regional erosional surfaces that contain flutes and grooves (Pickering & Corregidor, 2005). This MTC exhibits in the outcrop some of the characteristics described in the basal parts of MTCs that have been identified in offshore Trinidad, offshore Brunei and offshore Indonesia using 3D seismic reflection data (McGilvery & Cook, 2003; Posamentier & Kolla, 2003; Moscardelli et al., 2006). Identification of fluvo-deltaic input in the Ainsa MTC and geomorphological elements described in the basal part of the unit allowed us to classify the multiphase Ainsa MTC (Pickering & Corregidor, 2005) as a shelf-attached system.

In offshore Trinidad, detached MTCs are derived from the flanks of mud-volcano ridges (MTC2.2, MTC2.3 and MTC2.4), although according to the new classification scheme, detached MTCs can be originated from any palaeobathymetric high in the seafloor (Fig. 13). In the offshore region of the Gulf of Mexico, detached MTCs can originate from the flanks of salt masses and from the relative bathymetric highs that define the boundaries of distal minibasins (Fig. 13c and d) (Posamentier, 2004;
Fig. 13. Schematic depiction of the different kinds of MTCs and the processes associated with their genesis. (a) Slope-attached mass transport complex – sediments are derived from the catastrophic collapse of the upper slope area. (b) Shelf-attached mass transport complex sediments are provided by shelf-edge deltas and are dumped into the deep-marine basin. (c) Detached mass transport complex whose genesis is associated with the collapsing flank of a mud-volcano ridge. (d) Detached mass transport complex whose genesis is associated with oversteepening of one of the margins of a deep-water minibasin. (e) Detached mass transport complex whose genesis is associated with a levee-channel complex. MTCs, mass transport complexes.
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DISCUSSION

According to Posamentier & Kolla (2003), the occurrence of MTCs has been traditionally associated with lowstand conditions, when sedimentation on the shelf edge is supposed to be at its peak and water overburden weight is being reduced over shelf regions. These same authors presented a schematic depiction of traditional relationships that have been defined between relative sea level and dominant mass flow processes. According to this scheme, a typical deep-water stratigraphic succession comprises (1) debris flow deposits at the base corresponding to the initial period of relative sea-level fall (traditional MTCs associated with lowstand), (2) frontal–splay-dominated sections and then (3) leveed-channel–dominated sections that correspond to the subsequent period of late lowstand and early relative sea-level rise, respectively. However, this scheme has an addition in which the succession is ultimately capped by deposition of debris flow and condensed section deposits, corresponding to periods of rapid sea-level rise and highstand. This relatively new conceptual model suggests that MTCs can be deposited at any time during a margin’s history (Masson et al., 1997; Posamentier & Kolla, 2003). Observations made by a series of researchers in different continental margins seem to support this idea (Wynn et al., 2000; McMurtry et al., 2004; Maslin et al., 2005; Moscardelli et al., 2006; Sutter, 2006; Twitchell et al., 2006; Wynn, 2006; Gao, 2006).

The existing MTC classification system (Nardin et al., 1979) was designed mainly from a process sedimentological perspective (Fig. 2) and cannot answer questions associated with potential triggering mechanisms or the overall geological conditions that were predominant at the time of MTC deposition. The new classification system that is proposed in this work provides an alternative classification approach that goes beyond the traditional subdivision of MTCs into slides, slumps and debris flows. This new MTC classification system de-emphasizes the role of relative sea-level fluctuations as the dominant control in MTC generation and in so doing explicitly expands the range of geological conditions that can be interpreted as potential causal mechanisms of these deposits. It instead emphasizes the relationship between mass failures and the geomorphology of their source areas. Despite the variety of triggering mechanisms that can create MTCs, the new classification scheme avoids introduction of further complications by narrowing classification criteria into three main aspects: (1) sourcing regions of MTCs, (2) geomorphological expression of MTCs on their updip part (source area) and (3) dimensions and geometries of MTCs (Table 2).

The new classification system provides a simple scheme that can be used to qualitatively determine pre-failure geological conditions and triggering mechanisms for MTCs (Fig. 13). These conditions in turn have implications for the material that comprises the mass failure deposit. Such understanding is critical to assess the impact these deposits may have as fluid reservoir or seal elements in a basin’s fill.

From the oil and gas exploration perspective, shelf-attached MTCs are more likely to preserve parts of stratified sediments in the updip parts of the system, where potential reservoirs could be encapsulated within slides. However, preservation of reservoir quality intervals in the updip parts of slope-attached MTCs, where most of the sediments are catastrophically evacuated and where internal stratigraphic architectures are completely lost, would be very unlikely. Detached MTCs are also unlikely to contain viable reservoirs because the original material that fails is composed mainly of mud (e.g. mud-volcano flanks in offshore Trinidad) or by poor reservoir quality rocks (e.g. detached MTCs derived from the Mid-Atlantic Ridge). Although both attached and detached MTCs may not prove to be top-quality reservoirs, the erosive processes and subsequent stratigraphic relationships surrounding MTC development provide the opportunity for stratigraphic trapping to occur (Moscardelli et al., 2006).

Additionally, determination of MTC triggering mechanisms and pre-failure conditions is a valuable tool that can be used to assess the tsunamigenic and geotechnical hazards that are associated with MTC occurrences. Modelling has shown an apparent relationship between depth at which failure occurs, the volume of material that fails, the speed at which the original slide moves and the height of the tsunamigenic waves that are generated by the mass failure event (Pelinovsky & Poplavsky, 1996; Bryant, 2001). This classification scheme allows us to predict water depth of origin. When combined with the apparent deposited volume of the MTCs, prediction of palaeo–tsunamigenic hazards is possible.

Classification of MTCs as shelf-attached, slope-attached or detached systems allows geoscientists to define the geological context in which the deposits originate, as well as to analyse the implications associated with their causal mechanisms, dimensions, geomorphology and physiographic location. Success in the application of this classification system resides in the availability of data to complete detailed geomorphological descriptions of the MTCs, as well as the capacity to determine where the sourcing areas of MTCs are located.

CONCLUSIONS

Three different types of MTCs have been identified in the study area of offshore Trinidad and mapped using an

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extensive 3D seismic data volume. These three types include (1) shelf-attached MTCs (MTC1) (Moscardelli et al., 2006), (2) slope-attached MTCs (MTC2 and MTC2.1) and (3) detached MTCs (MTC2.2, MTC2.3 and MTC2.4). Attached MTCs are more likely to be regional units that can reach thousands of square kilometres in area and hundreds of metres in thickness; their source areas are usually associated with extrabasinal systems such as shelf-edge deltas and zones of collapse in the upper-slope region. Causal mechanisms associated with regional attached MTCs include large-scale earthquakes, relative sea-level fluctuations, gas-hydrate dissociation, high sedimentation rates, storms and hurricanes and longshore currents. All these elements can potentially destabilize the upper-slope area and trigger mass-wasting processes. Regional attached MTCs have been subdivided into shelf-attached and slope-attached systems. This classification was made on the basis of differences associated with sourcing areas, geomorphology and morphometric parameters that characterize each system.

Detached MTCs are smaller; they can occupy tens of square kilometres in area and their source areas are usually constrained within the margins of minibasins or from localized bathymetric highs. Collapsed flanks of mud-volcano ridges, unstable margins of deep-water mini basins, collapsed flanks of midocanoidic ridges and oversteepened levees in levee-channel complexes are common sources of sediments for detached MTCs. These systems are triggered by local gravitational instabilities that can be associated with seismicity, oversteepening of slope or diapir/volcano reactivation.

The length/width ratio (L/W) of MTCs is an important morphometric parameter that can be used to determine the level of confinement of these deposits. L/W ratios that are >4 indicate regional attached MTCs, whereas L/W ratios that are <4 are characteristic of confined detached MTCs.

Within the study area, large, buckle-fold ridges represent a major control in the definition of sedimentary pathways that are responsible for funneling sediments from the outer-shell/upper-slope area to the deep-marine basin. These ridges often show mobile muds associated with their core and display significant mud-volcano trains along their crests. In the study area, six mud-volcano ridges have been identified as the main palaeobathymetric features that controlled sedimentation pathways in this region during the Tertiary: (1) Darien Ridge, (2) Haydn Ridge, (3) Callicore Ridge, (4) Heliconius Ridge, (5) Catfish Ridge and (6) East Prospect Ridge. Four major sedimentary pathways associated with these ridges have been identified as main conduits of extrabasinal sediments to the deep-marine basin: (1) Darien, (2) Haydn, (3) Callicore and (4) Catfish megachutes. Such ridges and intervening chutes are important components in deep-marine transport systems, affecting the nature of MTC run-out pathways, thickness of deposits and their links to shelf-sediment sources.

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