Mass-transport complexes and associated processes in the offshore area of Trinidad and Venezuela

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ABSTRACT

Mass-transport complexes (MTCs) form a significant component of the stratigraphic record in ancient and modern deep-water basins worldwide. One such basin, the deep-marine margin of eastern offshore Trinidad, situated along the obliquely converging boundary of the Caribbean and South American plates and proximal to the mouth of the Orinoco River, is characterized by catastrophic shelf-margin processes, intrusive and extrusive mobile shales, active tectonics, and possible migration and sequestration of hydrocarbons. Major structural elements found in the deep-water slope regions include large transpressional fault zones (i.e., Darien Ridge, Central Range, Los Bajos), along which mobile shales extrude to form sea-floor ridges; fault-cored anticlinal structures overlain by extrusive sea-floor mud volcanoes; shallow-rooted sediment bypass grabens near the shelf break; and normal and counterregional faults. A total of 10,708 km² (4134-mi²) of merged three-dimensional (3-D) seismic surveys enable sub-sea-floor interpretation of several erosional surfaces that form the boundaries of enormous mass-transport complexes. The data show numerous episodes of MTC developments, which are characterized by chaotic, mounded seismic facies and fanlike geometry. Their extent (up to 2017 km² [778 mi²]) and thickness (up to 250 m [820 ft]) is strongly influenced by sea-floor topography. Mass-transport flows show runout distances from the source area of 60–140 km (37–86 mi). Depositional architecture identified with these units includes (1) large-magnitude lateral erosional edges, (2) linear basal scours, and (3) side-wall failures. Mud volcanoes act as barriers to cross-slope mass sediment movements and form zones of shadowing on their downslope side that protect those regions from erosion. The subsequent erosional shadow remnants (ESRs) comprise preserved regions of older levee-channel complex sediments and are considered for the first time in this study.
A current focus area of research is the interplay of tectonics, sedimentation, and hydrocarbon occurrence in Venezuela and Trinidad.

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Mass-transport complexes (MTCs) form a large stratigraphic component of many ancient and modern deep-water margins around the world. In some settings, up to 70% of the entire slope and deep-water stratigraphic column is composed of MTCs and associated deposits (Maslin et al., 2004; Newton et al., 2004). The prevalence of mass failures represents a significant threat to the security of continental slope and deep-marine engineered installations (Hoffman et al., 2004; Pirmez et al., 2004; Shipp et al., 2004). Such dangers can have a significant impact on the financial aspects of hydrocarbon exploration and development in deep-water locations. Recent interest in global warming has prompted a large number of climatologic researchers to consider the influence of catastrophic landslides in episodic release of methane into the atmosphere (Haq, 1993, 1995; Kvenvolden, 1993; Maslin et al., 1998, 2004). Paleo-marine landslides and mass failures, known to occur throughout the world’s marine margins, disrupt the pressure and temperature conditions that maintain stable frozen methane in large parts of the world’s continental margins, resulting in the release of these gases (Maslin et al., 2004). Likewise, destabilization of pressure and temperature regimes by changing water temperatures, shifting ocean currents, or lowering sea level can cause melting of frozen clathrates and initiate failures along marine margins. These episodes of catastrophic mobilization of huge amounts of slope sediments represent a risk for submarine installations, such as pipelines and communication lines (Hoffman et al., 2004), and also have the potential to generate tsunamis, a phenomenon that represents a significant hazard for coastal communities and nearshore navigation (Nisbet and Piper, 1998; Hearne et al., 2003; O’Loughlin and Lander, 2003).

Mass-transport complexes (slides, slumps, and debris flows) also pose a problem for hydrocarbon exploration and development in deep-water facies. These units typically have low porosities and permeabilities (Shipp et al., 2004), and their episodic and recurrent nature in many basins of the world means that they have the potential to constitute significant stratigraphic components of deep-water traps. Erosiveness of mass-movement processes, controlled by sea-floor irregularities, can result in deep and widely dispersed truncation and removal of underlying levee-channel deposits. Mass-transport complexes can then act as both lateral and top seals for these depositional remnants, forming effective stratigraphic traps. In this study, several of these features will be documented for the first time and defined as erosional shadow remnants (ESRs). Erosional shadow remnants are new kinds of stratigraphic traps in
deep-water deposits whose potential has to this point gone unrecognized. Brami et al. (2000) published the most comprehensive work on the deep-water stratigraphy to date in the present study area using 3000 km\(^2\) (1100 mi\(^2\)) of three-dimensional (3-D) seismic data (Figure 1A, blocks 25B and 26). The authors characterized seven depositional facies as the main architectural elements encountered in the area. These include MTCs, confined channel complexes (CCC's), levee-channel complexes (LCC's), distributary-channel complexes (DCC's) or sheet complexes, slope with minor channels, undifferentiated slope, and mud diatremes. In this study, we will present data from five separate 3-D seismic data volumes (Figure 1A, blocks 25A, 25B, 26, 27, and 4B), including the survey used by Brami et al. (2000). These data were merged into a single, contiguous volume spanning approximately 10,708 km\(^2\) (4134 mi\(^2\)). This process added 7708 km\(^2\) (2976 mi\(^2\)) of high-quality 3-D seismic coverage to the original data set that was used by Brami et al. (2000). These data provide an exceptional opportunity to document and study an entire mass-transport deposit from its staging area in the shelf break to its more distal ends.

Although Brami et al. (2000) identified MTCs as important component elements of the stratigraphic sequences in the study area, provided descriptions, and formulated observations on various aspects of these strata, a lack of updip data hampered some consideration of the controls and causes associated with these gravity-induced deposits. Likewise, Brami et al. (2000), being the first publication regarding the deep-water processes and deposits of this area, were not specifically focused on the architecture, processes, and morphology associated with MTCs. The more extensive nature of our 3-D seismic data sets allows us to better document and understand the processes that are operating in this deep-water region, placing special emphasis on mass-movement processes and deposits. The youngest MTC identified in the area (MTC_1) is the principal subject of study of this article. The exceptional quality of the data allows us to produce a detailed map of the MTC_1 event, showing its main geomorphological elements (Figure 1B) from the paleoshelf break (Block 4B) to the middle-slope area (Block 25A). This approach provided us with a comprehensive and detailed image of an entire MTC and its component elements.

MTC_1 is equivalent to the mass-transport deposit described by Brami et al. (2000) in the stratigraphic interval P10–P20. According to these authors, the interval also contains other types of depositional complexes, such as single LCC's, weak CCC's, and DCC's. However, the focus of this work will be concentrated in the description of depositional facies and processes associated with MTC_1 (Figure 1B).

Three key questions must be addressed if we are to gain an understanding of the risks that MTCs present, the function that they have in forming continental margins around the world, and the effect that they have on fluid flow and reservoir development in deep-water basins. (1) How do we recognize and map MTCs in the world's submarine margins and what function do they have in the fill of deep-water basins? (2) How do these MTCs influence underlying and overlying strata, and what factors are involved in MTC initiation, duration, and termination? (3) What function do these processes, elements, and facies have in the creation and destruction of hydrocarbon traps? It is the goal of this article to summarize our current state of knowledge regarding mass-transport deposits and, second, to use our data to map MTCs of the tectonically active Trinidad continental margin (Figure 1). These data and observations will then be used to address the three questions posed.

Previous Work in Mass-Transport Complexes

Terminology in MTC’s study remains a confusing mix of terms compiled by scientists working in subaerial and submarine environments, settings that have different fluid-flow parameters, and in modern (Masson et al., 1997, 1998; Norem et al., 1990; Gee et al., 1999, 2001) versus ancient rocks (Sohn, 2000; Wach et al., 2003; Martinez et al., 2005), where our ability to view the deposits and their details varies. The term “mass-transport complex” includes all kinds of gravity-induced or downslope deposits, with the exception of turbidites. For purposes of this discussion, turbidite deposits are grouped into a different subcategory because of their particular characteristics of turbidity currents. Remotely sensed information contained in seismic, sonar, and well and core data is commonly inadequate to identify those sedimentary structures in a deposit that defines flow parameters and conditions. Therefore, the term “gravity-induced or downslope processes” will be used when it is impossible to make a distinction between turbidites, debris flows, slides, and slumps. In this article, debris flows, slides, and slumps are considered to be constituents of MTCs, and these elements can co-occur in the same event or depositional unit.

Mass-transport complexes can occur at any time during a margin’s history (Masson et al., 1997) but commonly develop early in cycles of shoreline fall.
Figure 1. (A) Map showing the area of study located in the area of the 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 3-D seismic data is outlined. The shelf break is shown as a heavy black dashed and dotted line along the 200–300-m (660–1000-ft) contour. The Orinoco delta system in Venezuela is the primary supplier of sediments to the eastern shelf and continental slope. (B) Seismic surveys in the study area correspond to block names, and the locations of subsequent figures is shown. Black dashed lines define lateral boundaries of the large mass-transport unit discussed in this study.
toward lowstand, when sedimentation to the shelf edge is at its peak and water overburden weight is being reduced over shelf regions (Posamentier and Kolla, 2003). Resulting deposits occupy areas on the slope and on the basin floor, commonly accumulating near the toe of slope. The volume of MTCs can vary enormously, ranging from a few meters in thickness and a few hundred square meters in area, to more than 200 m (660 ft) in thickness and tens of thousands of square kilometers in area. They commonly develop initial bathymetry that later influences sedimentation in deep-water settings (Shanmugam, 2000; Marr et al., 2001; Posamentier and Kolla, 2003; Moscardelli et al., 2004). Mass-transport complexes occur in a variety of both carbonate and siliciclastic settings; however, this study will deal with only siliciclastic debris-flow deposits and processes.

With recent advances in sea-floor imaging and visualization, relatively young, modern MTCs are being studied extensively as process and reservoir analogs for older deposits. For example, the genesis and stratigraphic features of Pleistocene-age MTCs in the north part of the Gulf of Mexico have been studied as analogs to older, Tertiary-age mass-transport deposits. A series of articles by several researchers (Beaubouef and Friedmann, 2000; Winker and Booth, 2000; Anderson et al., 2003; Armentrout, 2003; Beaubouef et al., 2003a, b; Piper and Behrens, 2003) document the latest Pleistocene in the Texas offshore area in the Brazos–Trinity slope system and in the Louisiana offshore area in the Mississippi system, where high-quality seismic data show episodic MTC development. Each MTC unit is characterized by the presence of low-amplitude, semitransparent, chaotic seismic reflections (Beaubouef and Friedmann, 2000). Several wells and continuous core taken in upper- to midslope-situated, mud-rich complexes in the Gulf of Mexico suggest that these elements (Winker, 1996) are composed of slumps, slides, and debris-flow events. These MTCs are commonly embedded in a cyclic stratigraphic succession that is composed of sandy LCCs and hemipelagic drapes (Beaubouef and Friedmann, 2000). Brami et al. (2000), documenting deep-water strata in offshore Trinidad, found that most of the fill in their study area was composed of repetitious cycles of MTCs and LCCs. The authors attributed this repetition to Pleistocene sea level change, inducing sediment-supply fluxes to the shelf edge. Similar observations and interpretations of causal mechanisms have been made in the intraslope basin system in the Gulf of Mexico (Beaubouef and Friedmann, 2000) and in the Amazon Fan (Manley and Flood, 1988), where

the vertical cyclic distribution of different depositional systems has been related to sea level fluctuations. However, other authors have suggested that tectonic events may be a major cause of slope destabilization (Moscardelli et al., 2004; Martinez et al., 2005), and gas hydrate dissolution events may also be responsible for many shelf-edge and slope failures (Knapp, 2000).

Pirmez et al. (1997), describing several sand-rich intervals in the Amazon Fan of offshore Brazil, infer these deposits to be a series of sediment gravity flows intercalated with channel-levee complexes. These deposits are interpreted by the authors to have been emplaced as slides of large coherent blocks (meters to decimeters) and relatively small amounts of deformed matrix and deformed weaker blocks (slumps). Matrix-rich deposits with small clasts at the top of some of these slides are considered true debris flows (Piper and Deptuck, 1997; Piper et al., 1997). Several authors (Damuth et al., 1988; Manley and Flood, 1988; Piper and Deptuck, 1997) have reported that MTC deposits in the Amazon Fan can reach maximum thicknesses of 200 m (660 ft) and to cover areas of more than 15,000 km² (5700 mi²). Maslin et al. (1998) attributed the genesis of these deposits to catastrophic failures in the continental margin and slope, generated by rapid drops in sea level during the Pleistocene and episodic flushing of Amazon River sediments onto the upper slope.

Actual physical characteristics of mass-transport deposits have been documented by few authors. Shipp et al. (2004), using analyses from cores, logs, and geotechnical parameters in the Amazon Fan in Brazil (Piper et al., 1997b), the Na Kika Basin debris flows in the Gulf of Mexico, and in shallow mass-transport deposits in offshore Trinidad (East Prospect, Block 25A), concluded that several physical characteristics seem to be common in these kinds of MTCs. The lithology is generally made up of muddy sediments, although in some cases, sands can be also present; log responses tend to show an increase in resistivity, compressional velocity, density, and porosity; and geotechnical measurements indicate an increase in shear strength, with a corresponding decrease in void ratio and water content (Pirmez et al., 2004; Shipp et al., 2004). All these characteristics suggest that MTCs may be considerably more consolidated shortly after deposition than other deep-water deposits, such as LCCs or hemipelagic drapes. As a consequence of this physical nature, certain factors have to be considered to prevent complications during the drilling phase (low penetration rates and problems in installation of jetted conductors) of exploration in regions of MTC development (Shipp et al., 2004).
However, the same authors pointed out that the lithology of MTCs always depends on the kind of materials composing the failure slope.

Additional consideration must be given to the distance over which these deposits might travel and impact engineering facilities. Several studies in debris flows of the Gulf of Mexico have also suggested that yield strength is inversely proportional to runout distances, whereas runout is proportional to failure volume (Gee et al., 1999; Pirmez et al., 2004). On the basis of quantitative study of several geomorphic parameters in submarine landslides located in different tectonic settings in the United States continental slope (Oregon, California, Gulf of Mexico, and New Jersey), McAdoo et al. (2000) established that (1) steepness of the slope adjacent to the failure tends to be inversely proportional to the runout length; and (2) landslides that encompass large areas occur in regions where weaker, perhaps younger, material is present and past rapid accumulations of sediment and subsequent salt or mud tectonics may combine to create high fluid overpressures and steep slopes. These observations led to the conclusion that sedimentation, erosion, and local geology are more important factors in determining landslide location and morphology than only the slope or proximity to seismic centers (McAdoo et al., 2000).

**METHODOLOGY AND DATA SETS**

The objectives of this study are to document in detail the architecture and character of a major MTC in eastern offshore Trinidad (Figure 1A) and to apply these observations toward an understanding and discussion of the processes active in deposits and the nature of mass-transport deposits. The primary tool for study of the deep-water architecture and nature of the offshore Trinidad continental margin is 3-D seismic data. Using 3-D data offers a range of visualization and attribute-analysis techniques not afforded researchers working with two-dimensional seismic or sea-floor imaging sonar. Unfortunately, few seismic surveys are large enough to encompass an entire mass-transport deposit’s stage area and depolocations. To mitigate this problem in the Trinidad study area, five separate 3-D seismic data volumes were merged into a single contiguous volume spanning approximately 10,708 km² (4134 mi²). Depths of data provided from individual surveys range from a minimum of 1500 ms (Block 4B) in the westernmost part of the area to a maximum of 5000 ms (Block 25B) of coverage over central and eastern areas (Figure 1B). These data are all late 1990s vintage, and although they were acquired by various companies working in the area, their acquisition parameters and quality are remarkably similar. Time-migrated volumes have an approximate bin spacing volume of 25 × 12.5 m (82 × 41 ft) and 4 ms vertical sampling rate. All the 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 (2.5 ft). Seismic interpretation and attribute analyses were done on seismic workstations using Landmark Seisworks, OpenVision, and GeoProbe software.

The quality of the 3-D data makes it possible to correlate units across the slope into the deep-marine basin with a high degree of confidence. Seven regional seismic horizons have been mapped. Figure 2 (see location in Figure 1B) is a seismic line that shows a dip view across the northern part of the study area on which some regional horizons are correlated from an area proximal to the slope on the west, across a mud-diapir province, to the deep-marine environments on the east. These surfaces were mapped to define the gross architecture of the continental margin fill and three primary surfaces: the modern sea floor, the basal surface of the uppermost debris-flow event, and the basal surface of the uppermost slope LCC documenting the most recent debris-flow-levee-channel sequence, the focus of this research (Figure 3; see location in Figure 1B). In each case, all surfaces were seeded with the picking tool and then interpolated along key amplitude horizons. These surfaces were then adjusted by hand where the picking tool strayed from the horizon.

Although more than 200 drop cores exist across the study area (Sullivan et al., 2004), none penetrates the section of interest. Several exploration wells have been drilled in the area, but no direct access to these data was available to the authors. However, Shipp et al. (2004) described the lithologic and physical characteristics of these deposits using data from two exploratory wells in Block 25A. Their observations and descriptions are used in this work.

**STRUCTURAL SETTING AND FEATURES THAT INFLUENCE DEEP-MARINE SEDIMENTATION**

Extensive seismic interpretation in the offshore area of Trinidad reveals a variety of structural features that influence sediment transport and distribution in the deep-marine margin. These include mud volcanoes,
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occurring between the Caribbean plate to the north with the South American plate, the host plate for the Columbus Basin (Figure 1A). This fault system is most prevalent in the northwestern parts of the study area, where large faults break the sea-floor surface, forming a sea-floor structure called the Darien Ridge. This ridge is a narrow zone of uplift (20 km [12 mi] wide) comprising multiple complexly folded and thrusted structures. Extensional forces associated with this boundary form pull-apart grabens along the shelf edge in the north parts of the study area. In addition to graben structures (Figure 1A), several large, down-to-the-northeast normal faults affect the slope areas (Figures 1A, 4). These faults appear to be the eastwardmost occurrence of a family of northwest-southeast–oriented extensional structures that dominate the Columbus Basin shelf located to the west of the study area (Heppard et al., 1998; Wood, 2000). On the shelf, similar normal faults are Pliocene and Pleistocene in age and have throws of up to 1300 m (4265 ft). In the study area, shelf-edge normal faults appear to be relatively recent structures, expressing several meters of sea-floor relief. These normal faults are commonly coupled with landward-dipping faults, striking in the same orientation but downthrown to the west (Figure 4). These faults appear to form localized areas of accommodation for sediments in the upper slope, temporarily ponding sediments that later spill downslope in gulley channels. Deeper seismic data reveal several buried anticlinal ridges aligned northeast-southwest across the length of the study area that appear to exert a long-lived influence on sediment pathways. They show little expression on the sea floor, except for a line of sea-floor mud volcanoes parallelizing the subterranean anticlinal crest. Sediments thicken off axis in basins to the north and south of these anticlines. These anticlines continue on trend southwest through the substrata of the Columbus Basin shelf where they are buried beneath the extensive upper Tertiary overburden of the Trinidad marine shelf. The anticlinal axis of these structures appears to align with several prolific shelfal hydrocarbon fields (Wood et al., 2004). Deep regional seismic studies suggest that these anticlines are cored by transpressive faulting that is associated with regional compression along the Caribbean–South American plate boundary (Boettcher et al., 2000), the same forces responsible for the uplifting of the Darien Ridge.

**SEDIMENTARY SOURCES AND DISTRIBUTION**

The principal sediment source to the present data Columbus Basin shelf and deep-water margin is the Orinoco River and delta (Herrera et al., 1981; Meade et al., 1990; Warne et al., 2002; Aslan et al., 2003). The offshore area of Trinidad and Venezuela has been...
influenced by the Orinoco deltaic depositional systems since the late Miocene (Díaz de Gamero, 1996). Several efforts have been made to examine the marine processes on the offshore area of Trinidad and Venezuela and the influence that the Orinoco exerts on recent basin fill (Nota, 1958; Van Andel, 1967; Carr-Brown, 1972; Brami et al., 2000; Ercilla et al., 2000); however, intrarelationships between structure, tectonics, and marine processes in this offshore area are still unclear. The Amazon River is also believed to be a major contributor to the finer grained material component filling the basin. At present, sea level highstand-marine currents transport huge amounts of suspended sediment from the Amazon and Orinoco delta northwest along the northern South American coast (Warne et al., 2002). Most of the fine-grained Amazonian sediments are deposited as extensive mud capes along the Guyana and Surinam margins. However, some of the sediments and nutrients from these major river systems are carried far into the northern reaches of the Caribbean Sea before dissipating into the water column. Within the Trinidad offshore, currents strongly rework sands and silt along the eastern continental shelf during modern highstand (Wood, 2000; Sydow et al., 2003).

The Orinoco and Amazon have persisted in the geologic past as the major supplier of sediment to the basin. A strong body of evidence exists that proves that during the most recent lowstand at approximately 18 ka, sea level fell almost 125 m (410 ft) in the study area, exposing a large part of the Trinidad and Tobago shelf (Carr-Brown, 1972). Deltas prograded to the present shelf edge (Sydow et al., 2003), building lowstand wave-dominated shelf-margin deltas that, at least in the northern areas of the Columbus Basin, fed sediment almost directly into canyons that impinged upon the lowstand shelf break. Channels documented by recent seismic data (this study, Brami et al., 2000; Sullivan et al., 2004) and sonar imagery (Belderson et al., 1984; Ercilla et al., 2000; Deville et al., 2003a, b) currently transport deep-marine sediments to the northeast to sites of deposition in accretionary prism piggyback basins or, ultimately, to the modern Orinoco Fan (Belderson et al., 1984; Deville et al., 2003a, b).

STRATIGRAPHIC SEQUENCES

Two primary depositional systems, MTC and LCC, form the youngest stratigraphic fill sequences of the deep Columbus Basin (Figures 2, 3). Although data show that much of the Pleistocene basin fill is composed of these stacked elements (Figure 2), this study specifically focuses on discussion of processes and deposits in the most recent of these MTC depositional systems (MTC_1) (Figure 3).

General Description of the MTC_1

The MTC_1 in the deep Columbus Basin covers a region of approximately 2017 km² (778 mi²). However, the axial part of the complex, where deposits exceed 250 m (820 ft) in thickness, is restricted to an elongate central body that covers approximately 800 km² (308 mi²) (Figures 5, 6). The estimated volume of MTC_1 is 242 km³ (58 mi³); the thickness of this unit is variable, reaching a maximum of 250 m (820 ft) in the core area, progressively decreasing in thickness to the east (Figure 7). The MTC_1 is overlain unconformably by a thick LCC, which is, in turn, overlain by the modern sea floor (Figures 3, 8, 9). The thickness of the overlying LCC is greatest along the axial trace of the underlying mass-transport system, and it appears to have occupied space left underfilled by the mass-transport deposits (Figure 8). The LCC reaches thicknesses of approximately 150 m (500 ft). For a more detailed discussion of levee-channel systems in this area, see Mize et al. (2004).

A buried paleocanyon trending southeast-northwest and located near the seaward projection of the Darien Ridge in the slope area (Figure 5) appears to be the main feeder of the MTC_1 (Figure 6). The paleocanyon, located on the upper slope, is bounded along both margins by normal faults, forming a structural depression that is nearly 200 m (660 ft) deep. The northern border of the canyon coincides with a fault escarpment that marks the boundary between the canyon on the south and a structurally higher block on the north (horst block) (Figure 5). The paleocanyon, less than 2 km (1.2 mi) wide on its upper section (updip), widens downslope, reaching more than 10 km (6 mi) on its lower end (toe of slope). Figure 4 shows aggradational clinoforms that represent a paleo-Orinoco shelf-edge delta. The paleocanyon captures gravity-induced sediment derived from this unstable delta front and funnels them as a point source into deep-water settings.

The MTC_1 is bounded at its base by an extensive and irregular erosional surface (Figure 5). Internally, the MTC_1 presents multiple geometries; in the MTC core area, basal features that resemble linear grooves or scourcs can be observed (Figures 6, 9B). However, toward the east (peripheral area), the unit has a more sheetlike geometry, and grooves or incisions are absent.
(Figures 5, 6). In general, the unit tends to be relatively straight and narrow, thinning gradually toward the margins. Total runout distance of the deposit from the platform margin down to the east boundary of the seismic coverage (deep basin) is approximately 140 km (86 mi). The total runout distance was calculated considering the length of the axis of the canyon and the lengths of the western megascour and the northernmost cat-claw scour (see Figure 6). Near the slope, the unit is less than 20 km (12 mi) wide, widening progressively toward the northeast until it reaches 50 km (31 mi) in its distal part. The basal surface is irregular, presenting steep erosional edges that can reach 250 m (820 ft) in relief (Figure 10B) and elongated linear scours that are more than 30 m (100 ft) deep (Figure 9B). The slope of this surface changes along its extent, becoming steeper on the west where the walls of the feeder paleocanyon cut into the slope. Toward the northeast, slopes on the basal surface become subtler; however, sea-floor topography and mud volcanoes frequently confine the flow, reducing its cross sectional area and increasing its erosive power. Therefore, in some places, there is a steeper
Figure 6. Geomorphological interpretation of the basal erosional surface of the MTC_1. Several stratigraphic features that show significant basal incision are located in the core area (scours in pink) and indicate significant scour occurring at the base of the flow. Bathymetric features confined the flow, increasing the potential energy. The peripheral part of the mass-transport complex is shown in yellow, where the absence of deep basal incision suggests that the flow was, in large part, unconfined. However, the presence of significant erosional shadow remnants (ESRs) is evidence of the flow’s large-scale lateral erosive energy.
gradient on the basal surface. The upper boundary of the unit is represented by a prominent surface that defines the base of the overlying levee-channel system.

The western lateral boundary of the MTC is a significant erosional escarpment cut by the same processes that transported debris downslope. On the northwest side of this escarpment, strata are undisturbed and appear as conformable, continuous, high-amplitude reflectors (Figure 11). The eastern boundary of the MTC_1 is less clear (Figures 5, 6). It is seismically interpreted on
Figure 9. (A) Images of the seismic subvolume in area 2 show an oblique view looking from the south of three stratigraphic surfaces (from base to top), including an erosional surface affected by overlying MTC_1, an erosional surface defining the base of MTC_1, and the actual sea-floor bathymetry. A sculpted subvolume between surfaces b and c was generated, showing two well-defined units, numbered 1 and 2 in (A). Unit 1, interpreted as a mass-transport complex fill, is composed of reflectors that are chaotic and discontinuous. Unit 2, interpreted as a levee-channel complex, is composed of reflectors that are more continuous, with channels and levees that are easily recognizable. (B) Backstripped image showing several geomorphological elements in base of MTC_1, including the erosional edge on the west, megascours in the center of the image, and secondary scours on the east side. (C) A time slice taken 1500 ms down from the sea floor illustrates the chaotic character of reflectors that represent filling of the MTC_1. (D) Time slice taken 1300 ms down from the sea floor shows the abundant channels associated with the overlying levee-channel complex.
Figure 10. (A) Images of the seismic subvolume in area 3 show an oblique view looking from the south. The volume is sculpted between the base of MTC_1 and sea-floor surfaces. The mass-transport complex and levee-channel complex units can be easily differentiated on the basis of seismic character. Erosional edge reaches its maximum depth incision in the core area, and syndepositional thrusts were developed against the walls of the erosional edge. (B) Backstripped image shows the area of maximum incision of the erosional edge and the northern continuation of the western megascour. (C) A time slice taken 1600 ms down in the data is composited with a seismic line across the zone of syndepositional thrusts, showing that the compressional folds generated by syndepositional deformation are aligned with northeast-striking microthrusts shown on the time slice (strike in plan view). (D) A time slice taken 1500 ms down in the data is laid over the basal MTC_1 scour surface and composited with a seismic line showing the well-defined, overlying levee-channel complex. This channel system in the levee-channel complex parallels the underlying western megascour of the MTC_1.
the basis of three main observations: (1) lateral change in seismic facies character—from low-amplitude, semitransparent, chaotic reflections in the MTC unit to relatively continuous, high-amplitude reflectors in the area outside the complex; (2) an east edge defined by the change from west-east orientation to a more southwest-northeast orientation of associated flow scours and ESRs; and (3) geomorphologic and stratigraphic elements present in the southeast corner of the data set that are of a character and form completely different from those that are within the area of the MTC_1 (Figure 6). These criteria provide compelling evidence with which to define the southern boundary of MTC_1 and will be discussed in further detail.

**Seismic Facies**

Three seismic facies are distinct in the study interval of interest. Seismic facies SF1 is composed of low-amplitude, semitransparent, chaotic reflections that have been associated around the world with distinctive patterns for these MTC units (see Posamentier and Kolla, 2003) (Figure 12). Seismic facies SF2 is a mixture of low- and high-amplitude reflections, geometrically arranged as though deformed through compressive stresses. Seismic facies of this type are frequently folded and show multiple inverse fault planes and evidence of syndepositional deformation of the units (Figure 12A, B). Seismic facies SF3 is continuous, with high-amplitude reflection packages that seem to typify the overlying levee-channel system. They are also found in the undeformed unit located lateral to the MTC deposits (Figure 12C). These facies types were used to assist in interpreting the extent of the MTC_1 and its lateral, upper, and lower boundaries.

**Erosional Morphologies**

Several erosional morphologies exist in association with the MTC_1 deposit and can be used to better understand the flow behaviors that characterize the deposit. These features include an erosional escarpment, deep basal scours, multiple cat-claw basal scours, ESRs, smaller scale scratch marks, wavy ridges, and imbricated thrust complexes (Figures 5, 6). These features offer insight into the processes active in and the behavior of these deposits during their transport and deposition.

**Erosional Escarpment**

The western boundary of the northern feeder paleocanyon turns toward the northeast after 20 km (12 mi) of runout distance in the downdip direction and transitions into an erosional escarpment that defines the western boundary of the MTC_1 (Figures 5, 6). This erosional escarpment, oriented northeast-southwest, is approximately 70 km (43 mi) long. Relief along this escarpment between the base of the MTC_1 and the sea floor is variable but ranges between 65 m (213 ft) along the southernmost edge (Figure 9B) to 300 m (1000 ft) along the northern edge (Figure 10B). The depth of erosional relief in the axis of the MTC_1 is 250 m (820 ft). The erosional escarpment presents an irregular geometry in plan view (Figures 5, 6) and can easily be mistaken for a fault until examined in vertical seismic profiles. The escarpment is especially prominent where the overlying MTC_1 flow comes in contact with bathymetric barriers to its downslope path, such as areas of mud-volcanic uplift (area 3 in Figure 5). Farther downslope, the steep erosional escarpment turns eastward and gradually decreases in height more distally (Figure 13A). The sharp profile of the escarpment is interpreted to be a function of the shearing and plowing of the MTC sediments as they moved downslope.

**Basal Megascours**

The base of the MTC_1 is characterized by a deep, wide, erosional scour located in the midslope region that then bifurcates downslope near the toe-of-slope region into two separate megascours (Figure 9B). The midslope scour is less than 2 km (1.2 mi) wide at its upper section (updip), but it becomes wider downdip, reaching more than 7 km (4.3 mi) at its lower end. It appears to initiate in the region around the upper-slope graben paleocanyon. Once the scour bifurcates, the two megascour features, here termed the western and eastern megascours, tend to parallel the erosional escarpment previously described (Figures 9C, 10B, 13A). The western megascour is less than 2 km (1.2 mi) wide, but 60 km (37 mi) long. After about 50 km (31 mi) of runout distance, it changes orientation to run nearly east-west (Figures 5, 13A). This abrupt change in orientation is caused by the presence of a mud-diapir wall that deflected the sediments eastward. The depth of the incision in the western megascour ranges from 33 m (108 ft) in the south to less than 13 m (42 ft) in the northern region. The eastern megascour is also 2 km (1.2 mi) wide but only 20 km (12 mi) long. Its average depth of incision is 26 m (85 ft). The eastern megascour bifurcates toward the east and ends abruptly after 20 km (12 mi) of runout distance (Figures 5, 6, 9B, 13B). The bifurcation is more likely caused by the splitting of a single flow than by the action of two different flows.
Cat-Claw Scours

The north end of the western megascour defines the apex of a series of radiating small-scour features that have been termed “cat-claw scours” (Figures 5, 6, 13A). Each of these features is a single, shallow, erosional scour (10 m [33 ft] deep or less). They are fairly consistent in appearance and, as a group, radiate from the north end of the western megascour (Figure 13A). As they impinge upon an east-west–oriented mud-volcano wall, these cats-claw scours turn eastward and diverge in a radiating pattern to the east.

Secondary Scours and Scratches

Several secondary scours occur across the entire area of the MTC_1 basal surface. The most prominent of these are located next to the eastern megascour (Figure 13B).

Figure 11. Seismic line oriented north to south across the northwestern side of the erosional escarpment showing the defining western boundary of the mass-transport complex (MTC). Here, the strata appear undisturbed and are characterized by conformable, continuous, high-amplitude reflectors.

Figure 12. (A) A seismic line shows seismic facies that have been identified within MTC_1 and levee-channel complex, including SF1 = low-amplitude, semitransparent, chaotic reflections; SF2 = mixture of low- and high-amplitude reflections, geometrically arranged as though deformed through compressive stresses; and SF3 = high-amplitude and semicontinuous reflection packages. (B) A time slice (at 1608 ms) showing the morphologic character of SF1 and SF2 in plan view. On the east, SF1 shows only a chaotic, nonoriented arrangement. In contrast, to the west, SF2 shows northeast-southwest–oriented lineaments associated with similarly striking syndepositional thrusts. (C) A time slice (at 1352 ms) showing the character of SF3 in plan view. Channel patterns and their trajectories are an easily recognizable component of SF3. Seismic facies SF1 and SF2 are within the MTC_1 unit.
These smaller scale scours are less than 1 km (0.6 mi) wide, and their extent is variable, ranging in length from 10 to 20 km (6 to 12 mi). The average depth incision on these features is less than 20 m (66 ft). They parallel the eastern megascour, but their tracks diverge from one another as they progress eastward (Figures 5, 6). Several additional fields of elongated scratches that follow the orientation of these secondary scours can be seen in the regions between the mud diapirs in the northeastern part of the study area (Figures 5, 6).

Another system of similar-size scours is located 15 km (9 mi) southeast of the previous group (Figures 6). This group of small-scale scours is shorter and less incised than the ones that are located next to the eastern megascour, but they also have a distinguishable pathway that indicates transport toward the northeast (Figure 6). These features may have formed by an earlier and older flow traveling more northeastwardly.

The secondary scours documented here are similar in form and appearance to those defined by Nissen et al. (1999) in the Nigerian continental slope of west Africa as glide tracks. The authors could identify outrunner blocks that most likely tooled the scours. Here, we have identified localized high-amplitude reflections located immediately above the small scours that contrast with the surrounding low-amplitude and chaotic character of the reflections of the remaining MTC. The high amplitude of these subunits suggests that they may be composed of more consolidated material that was rafted as blocks to their present location (Figure 14).

Syndepositional Thrusts
Spectacular syndepositional-thrust imbricate fields are identified in the mass-transport core area (Figures 10, 12, 15). These regions of thrusting are localized and appear to be associated with areas of topographic confinement of the flow. As sediments moved downslope, topographic features acted as a barrier to the catastrophic downslope movement of the flow, compressing and compacting it in successive events and causing the flow to ramp up over confining walls of the erosional escarpment (Figure 10A, C). As the flow was compressed, lack of space favored the generation of a series of syndepositional imbricated thrusts (Figure 15).

The degree of shortening in this deposit was examined in two cross sections of the area of thrusting. Analyses show that the amount of shortening varies across the imbricated area. Areas of the flow proximal to mud diapirs show shortening of about 1530 m (5019 ft) (Figure 15A). Several kilometers farther downslope, where flow appears unconfined by mud diapirs, shortening in the deposits is less, only 412 m (1351 ft) (Figure 15B). When bathymetric features confine flow, thrust imbricates reflect an attempt by the flow to accommodate the decreased cross sectional area and dissipate flow energy.

Erosional Shadow Features
Several depositional remnants, here termed “erosional shadow remnants” or ESRs for their apparent association with the shadowing effect of mud volcanoes, are found preserved on the downslope side of individual mud volcanoes (Figures 13B, 16). These diapirc features acted as physiographic barriers that prevented parts of the older sea floor from being eroded by passing mass-transport flows. These preserved remnants of the older sea floor have average areas of 20 km² (7 mi²) and a maximum height of 152 m (500 ft) (Figure 16). The remnants are most likely composed of older slope or other deep-marine deposits. These remnants provide the opportunity to preserve potentially older, sandy levee-channel or sheet sand sediments trapped in accommodation moats around the mud volcanoes (see discussion above) that would have otherwise been eroded by the voracity of passing gravity-induced flows (Figure 16). These remnants are then draped by low-porosity and low-permeability mass-transport deposits, creating an effective baffle or seal. The mud volcanoes, commonly fault-cored active fluid-migration pathways in the basin, can hydrocarbon charge these erosional remnants, which may have reservoir volumes of greater than $3 \times 10^8$ m³ ($1.05 \times 10^8$ ft³). This study is the first to document the presence of such a stratigraphic trapping mechanism in deep-water settings.

The main axes of these erosional shadow features (Figure 17) align in a radial pattern that converges to a specific area upslope. This point of convergence marks the location where the mass-transport sediments started to become unconfined and can be extrapolated updip.

Pressure Ridges
A field of pressure sea-floor ridges occurs in the area between prominent erosional shadow features. These features were previously described by Brami et al. (2000) (Figures 5, 6, 17). Pressure ridges are a relatively shallow sea-floor phenomenon, and their specific occurrence is most likely associated with debris-flow confinement between sea-floor mud volcanoes. The features are similar to those identified in experimental debris-flow studies of Marr et al. (2001). Similar features have also been documented by Posamentier and Kolla (2003) in the Green Canyon area of the Gulf of Mexico.
Figure 13. (A) Images of the seismic subvolume in area 4 show the cat-claw scours, erosional edge, and western megascour. The western megascour bifurcates into several small and shallow erosional branches in a dispersive radiating pattern as the surfaces progress to the northeast. To the north, a highly populated area of mud volcanoes defines a mud diapir wall that inhibited flows from breaching farther to the north. (B) Images of the seismic subvolume in area 5 show the eastern megascour and secondary scours along the basal surface. The seismic line shows the chaotic fill of the MTC_1 deposits overlain by the more continuous reflectors of the levee-channel complex. Several mud diapiric uplifts in the area favor development of erosional shadow remnants (ESRs).

Figure 14. Close-up of the seismic line showing the bright-amplitude, discontinuous, stacked reflectors (yellow arrow) in the base of the MTC_1 deposit that are interpreted to represent more consolidated, rafted blocks above the basal incision.
Figure 15. (A) Seismic line cross section, accompanying line drawing, and map view of the confined regions of the mass-transport deposit. In these regions where MTCs flow, the cross sectional area was confined by diapiric uplift shortening of the flow by thrust faulting, which can reach 1530 m (5019 ft). (B) Seismic line cross section, accompanying line drawing and map view of the more nonconfined regions of the mass-transport deposit. In these regions where MTCs flow, the cross sectional area was less confined by diapiric uplift shortening of the flow by thrust faulting, which decreases to less than 412 m (1351 ft).
Mass-Transport Complexes in Offshore Trinidad and Venezuela

![Diagram of Mass-Transport Complexes](image)

- **A** Mud Volcano
- **B** Pressure Ridges
- **C** Levee-Channel Complex
- **D** Mass-Transport Complex
- **E** Erosional Shadow Remnant (ESR)

Legend:
- **1** Mass-Transport Complex
- **2** Levee-Channel Complex
- **3** Erosional Shadow Remnant (ESR)
CHARACTER VARIABILITY OF AXIAL AND PERIPHERAL PARTS OF THE COMPLEX

The axial part of the complex is less than 250 m (820 ft) thick, and it has an area of 800 km² (308 mi²) (Figure 6). It covers an elongated central area, where several mega-stratigraphic architectures show significant amounts of basal incision (erosional escarpment, megascours, and cat-claw scours). Syndepositional structures that show considerable amounts of compressional strength are also present in the core area (Figures 10, 12, 15). We assume that a certain degree of confinement on the flow that affected this area was necessary in order for the incision created by the erosional morphologies (erosional escarpment, megascours, and cat-claws scours) to be generated, and the compression appreciated in some internal depositional morphologies (syndepositional thrusts).

In contrast, the peripheral part of the complex is less than 100 m (330 ft) thick and 864 km² (333 mi²) in extent (Figure 6). The unit in this area has a more sheetlike geometry, and deep basal grooves or incisions are absent. The flow that affected this area was under partly unconfined conditions because it is characterized by signs of lateral or frontal erosion. The presence of ESRs (Figure 16) is evidence of the flow’s large-scale erosive energy; however, neither deep basal scours nor bounding erosional escarpments exist in this area.

Basal-Flow Processes

Origin of Megascour Features
McGilvery and Cook (2003) identified elongate grooves in offshore Brunei that are similar to the megascours that we have identified in the offshore area of Trinidad. According to these authors, the features suggest some component of gouging during the transport of sediments. Posamentier and Kolla (2003) also pointed out that these types of large scour features are distinctive attributes of debris-flow deposits and commonly characterize the basal surface upon which the debris flows are deposited; they documented some features in offshore eastern Borneo (Indonesia) that are similar to the megascours that we have described in offshore Trinidad (Figure 9). These authors reported divergence seaward similar to the divergence that we see when the eastern and western scours bifurcate near the lower end.
of the western feeder canyon (Figure 9B). According to their findings, the common divergence of grooves down-system suggests divergent flow vectors in an unconfined setting. We agree with the idea of divergence of flow, but we think that the megascours were generated during a transitional state in which the flow was under partly confined conditions (Figure 6). Clearly, in the offshore eastern Trinidad setting of uplifted sea-floor ridges and mud-volcano highs, confined flow is a typical state of many of these deposits. In our interpretation, at least some sort of confinement was probably necessary to sustain the energy needed to generate the extreme basal scour. At the same time, note that the western megascour is at least 60 km (37 mi) long. Some sort of confinement was likely necessary to preserve the effectiveness of the flow over long distances (Figures 5, 6).

The eastern megascour is shorter than the western megascour, and it bifurcates toward the east, abruptly ending after 20 km (12 mi) of runout distance (Figures 9B, 13B). This abrupt end is related either to a lack of flow competence, preventing further erosion from occurring on the basal surface, or to the initiation of flow and drag-block hydroplaning as it moved downslope (Figure 17). The presence of several secondary scours immediately north of the eastern megascour and in apparent geometrical continuation suggests that the theory of hydroplaning is the more appropriate one to explain the abrupt termination of the eastern megascour (Figures 6, 17). Moreover, several additional fields of elongated scratches that seem to represent the northeastern continuation of the secondary scours can be seen between the mud diapirs in the northeastern part of the study area (Figures 6, 17). We think that the north end of the eastern megascour defines the boundary or the transitional area where the flow started to pass from partly confined to partly unconfined conditions.

Defining when the flow is frictionally attached to the substrate and when it has the capacity to hydroplane is important because these attributes are closely related to the physical properties of debris-flow mixtures and can be used indirectly to infer their gross lithologic composition. Sohn (2000) pointed out that the style of flow transformation may change depending on clast size, viscosity of interstitial fluid, and permeability. According to the same author and the study of Miocene fan deltas in South Korea, a debris flow rich in coarse gravel clasts may become longitudinally segregated, developing a frontal concentration on a large scale. Such a debris flow is not likely to hydroplane. However, a debris flow composed of small gravel clasts and a muddy matrix may hydroplane, involving various flow-transformation processes. The predominance of fine-grained sediments in the offshore area of Trinidad and Venezuela and evidence associated with the abrupt termination of the eastern megascour suggest that a significant part of the studied MTC in this area behaves like a hydroplaning debris flow composed mainly of small gravel clasts and a muddy matrix.

**Origin of Cat-Claw Scouring**

The north end of the western megascour defines the apex of a series of small radiating scour features that have been termed “cat-claw scours” (Figure 13A). Similar features, referred to by McGilvery and Cook (2003) as “monkey fingers,” have been described in the deep-marine environments in offshore Brunei. McGilvery and Cook (2003) pointed out that these features diverge downstream and exhibit squared-off ends at their terminal extent, suggesting an origin related to basal gouging, followed by lift-off from the sea-floor bottom of the gouging tool. These authors also suggested that the geometry and orientation of this divergence provide information regarding relative distance and direction of transport. Additionally, using side-scan sonar, Klaucke et al. (2004) identified similar finger-shaped features in the Monterey channel-mouth lobe in the offshore area of California that they interpreted as small erosional depressions whose formation is associated with massive sand deposits.

In offshore Trinidad, the cat-claw scouring is interpreted to represent a response to an abrupt change in deposit-flow conditions (Figure 6). At some point during formation of the gravity-induced deposit, a mixed mass of sediments and water coming from the southwest (following the partly confined pathway) encountered a mud-volcano wall located on the northeastern corner of the region (Figures 5, 6, 13A). This wall acted as a physiographic barrier that prevented the flow from continuing on its natural trajectory northward, effectually redirecting it to the east (Figures 5, 6). As a consequence, the flow was locally spread out from the apex (north end of the western megascour) (Figure 13A). However, the associated flow energy remained high enough and the flow competent enough to incise and erode the substratum. This high-energy, competent expansion of the flow’s cross sectional area resulted in the formation of radially distributed cat-claw scours and a broadening of the overlying debris-flow deposit.

**Origin of Syndepositional Thrusting**

Syndepositional thrusts have been described as one of the internal depositional morphologies located in the core area of the axial part of the unit (Figure 6). The
maximum incision here is 250 m (820 ft) (Figure 10B); the area is constrained by irregularities of the erosional escarpment and several mud diapirs. Marr et al. (2001) were able to document the presence of imbricate slices in laboratory gravity transport experiments. In these experiments, geometry associated with previously detached bodies of static sediment allowed the flow to ramp up over these bodies, creating different slides that are in contact with sharp surfaces. Shanmugam et al. (1988) also documented similar, but much smaller scale duplexlike features in an outcrop of the Jackfork Formation (lower Pennsylvanian) of the Ouachita Mountains in Arkansas. They described soft deformation features associated with the Ouachita flysch succession exposed at the DeGray Dam spillway in the Upper Jackfork Formation. This unit was deposited in a deep-water, submarine-fan complex and is composed of pebbly and massive sandstones, with beds showing thinning-upward trends (Morris, 1971; Moiola and Shanmugam, 1984). Deformation of un lithified turbidites into duplexlike structures in the succession has been attributed to the action of high-energy sediment gravity flows. Similar duplex features were described in the Jurassic–lower Tertiary pelagic carbonates in the Umbria–Marches Apennines of northern Italy, where synsedimentary submarine slide deposits are common (Alvarez et al., 1985). McGilvery and Cook (2003) also described contractional imbricate toe thrusts in the distal part of a cohesive slump complex in a stepped slope profile offshore Brunei. Posamentier and Kolla (2003) mentioned the presence of pressure ridges, indicative of thrust faults commonly present near the boundaries of debris flows; they documented these features in the Green Canyon area of the Gulf of Mexico. Nissen et al. (1999) also studied pressure ridges in the continental Nigerian slope in Africa, defining them as regularly spaced undulations caused by compression in the main body of the debris flow. For the syndepositional thrusts that we documented, the process was not related directly to slumps or to the terminal part of the debris flow; imbrications were generated when the material contained within the partly confined flow area encountered lateral barriers (irregularities in the geometry of the erosional escarpment and individual mud diapirs) (Figure 6) that caused them to overthrust because of a lack of space for accommodation. These syndepositional thrusts are very similar to the compressional features described as ridgelike structures in slump complexes from the continental margin of Israel (Martínez et al., 2005). This process was generated while sediments were still unconsolidated and sedimentation was still actively moving downslope.

**INTERPRETED CAUSES AND CONTROLS FOR MTC GENERATION**

Mass-transport complexes can be generated as the result of a series of processes, most of them associated with slope failures. Gravitational instabilities in the upper slope can be triggered by a variety of factors, including high sedimentation rates, gas-hydrate dissolution, sea level fluctuations, and/or tectonic activity. Brami et al. (2000) have compared the apparently cyclic repetition of seismic facies (Figure 2) in the studied area as similar to those observed in the passive margins of the Gulf of Mexico and offshore Brazil (Amazon Fan). They interpreted this apparent cyclicity as primarily driven by Pleistocene high-frequency sea level changes. However, the complexity of the geology in the area (close proximity to an active tectonic margin and the high sedimentation rates associated to the Orinoco delta system) suggests, in our opinion, a higher frequency mechanism at work than sea level fluctuations alone.

To pinpoint individual causes for each MTC event in the complex geologic environment of the study area is difficult because several mechanisms could be acting at the same time and overlapping their signatures. However, data covering the paleoshelf break and slope areas (Figure 1, Block 4B) reveal interesting clues regarding the origin of these MTC deposits. Figure 18A shows a time slice at 492 ms in the shelf edge and upper slope regions where the southeast-northwest–trending paleocanyon that is the main feeder of MTC_1 can be found. Figure 18B shows a deeper flattened horizontal coherence slice at 1126 ms taken over the same area but stratigraphically located below the erosional surface that defines the base of MTC_1 (see Figure 4 for reference). This deeper coherency image shows the updip parts of an older MTC (MTC_2) failure event. In this deeper interval (Figure 18B), several geomorphological features are revealing the presence of gravitational collapses that are located in the upper slope area near the paleoshelf edge (Figure 18B). At least three major collapses can be seen updip. Two of these collapses are located on the northwestern corner of the area presenting a distinctive semicircular shape (cookie bite shape) with average diameters of 4.5 km (2.8 mi). The average length of the perimeter around individual heads of the collapses is 6 km (3.7 mi), and both cookie bite features cover an approximate area of 28 km² (10.8 mi²) in the upper slope (Figure 18B). These collapses have a concave-upward appearance, and they are cutting the upslope strata. This area represents the depletion zone of the older MTC_2. In addition, abundant gullies that are...
Figure 18. (A) Seismic amplitude time slice taken 492 ms down in the data and an accompanying seismic geomorphologic interpretation shows the continental shelf edge and upper-slope regions (Block 4B) where the southeast-northwest–trending paleocanyon that is the main feeder of MTC_1 is located. (B) Seismic coherence time slice taken over the exact area as (A) 1126 ms down in a volume flattened from the modern sea floor. This images the older shelf edge and shows significantly large cookie bite failures associated with older mass slumping events along the margin.
perpendicular to the collapse can be observed through the margin, and multiple minor headscars are interpreted (Figure 18B). It is quite apparent from the geomorphological evidence that the formation mechanisms of these two MTC events were different. As previously noted, the source for MTC_1 does not appear to be failure of the upper slope, but instead, a direct point source from shelf-edge deltas. The distinct differences in the origin of two similarly massive shelf and slope failures, so close in geologic time, suggest a variety of mechanisms destabilizing the continental margin in this region. In the following sections, we will further discuss the possible causes generating these mass failure phenomena in this region of the world.

Sea Level Fluctuations, High Sedimentation Rates, and MTCs

Establishing recognition criteria to differentiate causal mechanisms of MTCs is a crucial step to better understand these deposits. In this study, two causal mechanisms have been identified: (1) gravity-induced deposits that are generated by variations in relative sea level fluctuations and high sedimentation rates (MTC_1) and (2) catastrophic failures of upper-slope sediments caused by gas-hydrate disruption and/or earthquakes (MTC_2). These differentiations have a huge impact on reservoir characterization issues and risk assessment for coastal communities.

Sydow et al. (2003) suggested the most recent shelf-edge event to have occurred at the last glacial lowstand was at approximately 18 ka. At that time, sea level was thought to be nearly 100 m (330 ft) lower than at present. Such a drop would have exposed the present-day Columbus Basin shelf and brought the shoreline to approximately the location of the present-day shelf slope break (Carr-Brown, 1972; Sydow et al., 2003). Butenko and Barbot (1980), conducting a geotechnical study in the shelf break and upper slope of the Orinoco delta system, identified a major buried erosional surface with paleochannel development, which they interpreted to have formed during a sea level drop at the end of the Pleistocene. The same authors identified a large area of irregular sea-floor topography in the continental margin, an active area of rotational slumping where northwest-southeast—trending sea-floor scarps with a maximum throw of 45 m (147 ft) were reported. Sydow et al. (2003) presented four northeast-southwest seismic lines located in the outer-shelf and upper-slope areas of the Columbus Basin. One of these lines (seismic line D; see relative location of the Sydow line in Figure 1A) is adjacent to the southwestern corner of Block 4B, where the paleocanyon of MTC_1 is identified. The northeastern part of seismic line D clearly shows sigmoid clinoforms that are interpreted by the authors to be composed of unstable delta-front facies. Based on available well data, the authors identified this unit as the 18,000-yr shelf-edge delta; debris flows and slump deposits have been identified as the dominant constituents of these facies (Sydow et al., 2003).

MTC_1 appears to have been point source fed by a single paleocanyon (Figures 4–6) that captured sediments directly from aggradational clinoforms. Figure 4, a northwest-to-southeast, depositional dip-oriented seismic line across the main axis of the paleocanyon located proximal to MTC_1, shows a series of aggradational clinoforms that are prograding to the southeast. These prograding clinoforms are located in the updip parts of the paleocanyon, confirming the connection between the shelf-edge systems and the upper-slope area. The paleocanyon geometry and orientation is structurally controlled by faults associated with transtensional plate margin structural forces. The underlying structural graben generates sea-floor irregularities, indicating ongoing transtensional deformation that defines a preferential northwest-southeast sedimentary pathway. The aggradational clinoforms located in the upper parts of the paleocanyon are interpreted as a paleo-Orinoco shelf-edge delta whose delta-front facies were increasingly unstable, affected by gravitational tectonics and slumping. The aggradational character of the clinoforms (Figure 4) is interpreted to reflect the response of the shelf-edge delta to a rising shoreline following lowstand conditions. This increasing accommodation prompted the accumulation of sediments in the unstable shelf break, oversteepening of the clinoforms, and eventually, gravitational collapses that fed the downslope systems.

Stratigraphic relationships inferred from the seismic lines published by Sydow et al. (2003) indicated that the clinoform unit associated with the 18,000-yr shelf-edge delta (lowstand systems tract) may be slightly younger than the aggradational clinoform unit described in this study. Notice that clinoforms reported by Sydow et al. (2003) are prograding toward the northeast, and the aggradational clinoforms reported in this article and associated with the MTC_1 event are prograding toward the southeast, indicating a different origin. Moreover, the aggradational character of the clinoforms associated with MTC_1 and their relative stratigraphic position and orientation suggests that this unit was generated during times of prevalent stillstand conditions or during
the early stages of relative sea level rise. This interpretation of deposition of MTC_1 during late lowstand and early transgression is a different interpretation from that presented by Brami et al. (2000). Although the previous authors believed the MTC_1 deposits to have been deposited during maximum shoreline lowstand, we are placing the timing of the genesis of the unit in the rising limb of a cycle. The high sedimentation rates associated with the paleo-Orinoco delta system are believed to be a key factor for the formation of the shelf-edge delta that fed MTC_1. Although frozen gas hydrates have been reported as a causal mechanism for other slope failures around the world, it is believed that the staging area for the MTC_1 was in water too shallow for generating or destabilizing hydrates.

**Tectonism, Gas Hydrates, Free Gas, and MTCs**

Figure 18B presents a completely different scenario for deep-marine debris-flow development than that documented for the younger MTC_1 deposits (Figure 18A). The kilometer-diameter-scale cookie-bite collapses can be found in several locations along the margin. This geomorphology provides a more line source, upper-slope source of material for MTC_2 deposit. Although not described here in detail, the MTC_2 deposits appear to be generated by failures in numerous locations. Such broadly distributed, isolated pods of source material imply a broadly active process for slope failure. Although a relative drop in sea level might destabilize hydrates, it is still unlikely that significant amounts of hydrate occur in the upper slope where the cookie-bite scars are found. A second destabilizing process may have been large storms or tropical depressions and hurricanes.

A more likely scenario is that a tectonic event, such as a major earthquake, caused the destabilization of a broad area of the upper slope and subsequent failure. In contrast to the point-source, clinoform fed deposits of MTC_1, the materials that failed and comprise the MTC_2 deposits would be mainly composed by shaly slope sediments. Martinez et al. (2005) documented similar tectonically driven collapse features in the continental margin of Israel; the authors pointed out that the high occurrence of slumping processes in this area was possible because of a combination of seismic activity, presence of free gas in the sediments, and slope oversteepening. All these influences are present in the Trinidad offshore. In the study area, significant and frequent earthquakes occur because of the interaction between the Caribbean and South America plates, abundant free gas associated with the inner and outer shelf regions, slope oversteepening associated to shelf-edge deltas, and the presence of abundant gas hydrates.

Submarine landslides triggered by earthquakes have also been documented in the upper-slope area of the eastern Aleutian Islands (south coast of Alaska) caused by a significant earthquake in 1946 (Fryer et al., 2004), and by a 1929 earthquake, which triggered a landslide and subsequent 30-m (100-ft)-high tsunami in the Grand Banks area in the offshore area of Newfoundland (Canada) (Nisbet and Piper, 1998; Dawson et al., 2004). We believe that the mechanisms that triggered MTC_2 in the offshore area of Trinidad are similar to those that generated these submarine landslides in Alaska (1946) and in offshore Newfoundland (1929).

**MASS-TRANSPORT COMPLEX RESERVOIR ELEMENTS**

Few authors have reported quantitative information on the lithology, petrophysics, and general character of mass-transport deposits in the subsurface. The ability for mass-transport deposits to act as subsurface fluid reservoirs or barriers is, at present, a poorly understood phenomenon. Shanmugam et al. (1995) noted that plastic flows, believed to characterize some debris flows, generate laterally discontinuous and disconnected sand bodies that are harder to predict in terms of their spatial distribution and geometries. In contrast, turbidity currents produce some high-reservoir-quality deposits that are laterally continuous, making them more attractive exploration and development targets. This difference in the nature of sediments deposited from plastic flows (debris flows) versus turbidity currents (turbidites) makes it all the more important to distinguish between these two processes active in continental margins. Such ability will enable accurate prediction of reservoir geometries and aid in defining reservoir uncertainty and quality.

Mass-transport deposits may constitute a critical factor in modeling fluid flow because they have been reported to have poor porosity and permeability values with respect to turbidite sands (Pirmez et al., 2004; Shipp et al., 2004). In contrast, some researches (Shanmugam et al., 1995; Shanmugam, 2000, 2001) have shown that slumps and debris flows can contain thick, amalgamated sands bodies with high porosity (27–32%) and permeability (900–4000-md) values. The Frigg Formation in the North Sea has been pointed out as one of such units. Similarly, Jennette et al. (2000) interpreted four different sequences in the evolution of
the Tay and Forties and Sele basin-floor fans in the central part of the North Sea, with the sandstone bodies of the upper sequences being interpreted as sandy debris flows. Based on well data, Jennette et al. (2000) recognized that these phases of debris-flow fan building lead to high-quality reservoir sands that have strongly mounded, cross-sectional geometries. However, limited lateral continuity of these deposits and the ability to predict their occurrence may still be major issues to overcome before the deposits are viable reservoir targets (Shanmugam et al., 1995; Jennette et al., 2000; Shanmugam, 2000, 2001).

Finally, although the deposits themselves may not prove viable reservoirs, many of the erosive processes and subsequent stratigraphic relationships surrounding debris-flow development provide the opportunity to create stratigraphic trapping opportunities. It is shown in this research and reviewed in other studies (Shipp et al., 2004) that MTC_1 is a Pleistocene fine-grained, low-porosity and low-permeability, gravity-induced deposit that does not appear to have any reservoir potential. However, the recognition of ESRs (Figure 16) associated with mud volcanoes has raised the relevance of processes associated with MTC_1 for forming stratigraphic traps in deep-water margins. Erosional shadow remnants, formed by lateral erosion of passing debris flows, can be quite large and comprise older turbidites and gravity deposits. They are common in the study area (see sections above).

CONCLUSIONS

Enormous MTCs characterize the margin of northeastern South America. Such mass-transport processes and deposits are prevalent in margins around the world. It is clear from the evidence presented here that laminar and turbulent flow can occur simultaneously within these gravity deposits, producing a variety of sedimentary structures. Likewise, a flow can transition as it moves downslope from laminar to turbulent and from confined to unconfined through its interaction with the substrate and surrounding sea-floor bathymetry.

The primary mass-transport deposit, MTC_1, is characterized by active slump processes in the upper-slope area, enormous scour at its base, and cannibalization of the underlying sea-floor and older, deep-marine deposits. Basal scours as much as 2 km (1.2 mi) wide and 30 m (100 ft) deep attest to the erosive power of the flow. However, the distinct changes in basal-scour types (e.g., megascours to cat-claw radial scours) can be used as evidence of flow transition from confined to unconfined. Sharp termination of scour marks can occur with the transition from nonhydroplaning to hydroplaning flow and the plucking of scour tools from the basal surface of the flow.

Large stratigraphic traps, termed here erosional shadow remnants (ESRs), are formed in this setting by the erosive power of the debris flows. In this setting, older, possibly sand-rich levee-channel deposits are preserved on the downslope side of diapirs. These strata are then blanketed by low-permeability and low-porosity deposits of the overlying debris flow. Direct contact of these strata with hydrocarbon-migration pathways provided by the mud volcanoes themselves produces a low-uncertainty scenario and high-probability success for traps of this type.

Consistency of mass-transport development processes in this offshore region suggests a higher frequency mechanism at work than sea level fluctuations alone. High sedimentation rates, gas-hydrate dissolution, high-frequency sea level fluctuations, and a high occurrence of earthquakes have been identified as the main factors that have generated instabilities in the outer-shelf and upper-slope area. They have caused episodic gravitational collapses of huge amounts of sediments that have been funneled toward deep-marine environments. As a result, multiple stacked MTCs have been generated, and these units can cover as much as 2017 km² (778 mi²) in area, reach more than 250 m (820 ft) in thickness, and include several internal sub-units, such as rotational slumps in the upper-slope area, syndepositional thrust in the downslope confined areas, and hydroplaning debris flows in the distal complex.

Little agreement exists in the geologic community regarding the recognition criteria to differentiate between and the terminology to describe debris flows and turbidites (Shanmugam et al., 1995; Hiscott et al., 1997; Shanmugam, 2000, 2001). This lack of agreement has a relevant impact in deep-water reservoir characterization because many deposits originally identified as turbidites have been renamed debris flows (Shanmugam et al., 1995; Shanmugam, 2000, 2001) and vice versa (Hiscott et al., 1997). This creates a lack of continuity in the research of these types of phenomena. Only through additional characterization studies, such as the one presented herein, can the pertinent observations be made to resolve many of the disagreements regarding the processes that dominate these complex deposits and the function that they have in the development and fill of continental margin basins.
REFERENCES CITED


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