Growth of the paleo-Orinoco shelf-margin prism: Process regimes, delta evolution, and sediment budget beyond the shelf edge

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ABSTRACT

The first sedimentological characterization and correlation of onshore outcrop and offshore subsurface data (southern Columbus Basin) are presented for the paleo-Orinoco (Upper Miocene–Pliocene) shelf-margin prism, Trinidad Island, Trinidad and Tobago. The paleo–Orinoco River delta system and associated continental slope, which generated the 10-km-thick sedimentary prism, was a mixed river, tide, wave, and sediment-gravity flow system that tracked down to deep-water submarine fans. The analysis here includes: (1) an evaluation of delta-plain to deep-water turbidite sedimentary facies, which are seen in spectacular outcrops along the southwest, south, and southeast coasts of Trinidad Island; (2) well-log correlation of the same Upper Miocene–Pliocene strata across southern Trinidad and out to the southern part of the offshore Columbus Basin along an off-axis transect, because the main fairway into the most rapidly subsiding part of Columbus Basin is structurally complex, and few detailed data have been released for publication; and (3) use of published seismic data for reconstruction of clinoform morphology across the relatively undeformed segment of the margin, with quantitative sediment flux calculations and predictions.

Paleo-Orinoco shelf-margin growth was generated by repeated (≈<100 k.y. time scale) cross-shelf, regressive-transgressive transits (>100 km) of the Orinoco delta system, with internal variability in clinoform architecture and process-regime changes during shelf-margin construction. The Upper Miocene–Pliocene prism, with its linkage to the southern Columbus Basin and Columbus Channel, is composed of four progradational clastic wedges, each with a thickness up to 2 km, separated by well-known, Trinidad-wide marine flooding intervals of similar extent, followed by an aggradational wedge with decreased clinothem thickness. The studied sedimentary prism spans an ~4 m.y. period and shows an overall rising shelf-edge trajectory, despite an overall and periodic falling eustatic sea level during this global icehouse period.

The relationships among the Orinoco paleo- deltaic, shelf-edge trajectory, and clinoform height and shape are discussed for a southeastern segment of the margin that is much less deformed than the main growth-faulted Columbus Basin. However, this off-axis segment was also subject to severe tectonic subsidence, as well as high-frequency sea-level, climate, and sediment supply changes. The estimated sediment flux percentage at the shelf edge shows a similar time trend to that of the well-imaged shelf-edge trajectory. The latter shows three long-term (~0.5 m.y.) trajectory changes, whereas the estimated sediment flux percentage at the shelf edge shows three supply pulses (with shelf-edge flux varying between 40% and 91% of original sediment discharge) through the early Pliocene, with nearly 76% of the sediment on average transported beyond the shelf edge to the deep-water areas, despite a relatively wide shelf. This sediment flux calculation, and particularly the occurrence of flat segments along the shelf-edge trajectory, predicts significant sediment bypass to slope or basin-floor fans on or beyond the tosets of the paleo-Orinoco shelf margin. At short time scales, the variation in the percentage of sediment flux bypassing the shelf edge depends on a series of shelf parameters. However, at geologic time scale, the total sediment flux bypassing the shelf edge is two thirds to three quarters of the total sediment budget.

INTRODUCTION AND OBJECTIVES

The Orinoco River built one of Earth’s biggest paleodelta systems, and one of the most rapidly subsiding shelf-margin prisms since the late Miocene. Recent published work on the Trinidad Neogene sedimentary prism includes research on the chronostratigraphy and tectonostratigraphy of the Columbus Basin (Wood, 2000; Sydow et al., 2003; Alvarez, 2014); late Quaternary evolution of the Orinoco delta (Warne et al., 2002a, 2002b) as well as the late Pleistocene deep-water Orinoco fan system (Peter and Westbrook, 1976; Embley and Langseth, 1977; Belderson et al., 1984); an outline of the stratigraphy of Trinidad (Carr-Brown and Frampton, 1979; Kugler, 2001); stacked shelf-edge delta reservoirs of the Columbus Basin (Sydow et al., 2003; Dixon, 2005; Steel et al., 2007); deltaic to estuarine regime changes on the proximal paleo-Orinoco shelf represented by the Cruse, Manzanilla, and Morne L’Enfer Formations (Osman, 2006; Winter, 2006; Huggins, 2007); storm-dominated shelf-edge delta successions in the high-accommodation setting of the Mayaro Formation (Bowman and Johnson, 2014); the facies and architecture of tide-dominated delta lobes of the Morne L’Enfer Formation (Chen et al., 2014); and a high-frequency stacking pattern within a possible Mayaro Canyon (Dasgupta and Buatois, 2012, 2015).

However, there has been little attempt to integrate onshore outcrop with offshore subsurface data for the Trinidad region or to reconstruct the
large-scale paleo-Orinoco evolution since the late Miocene arrival of the delta in the Trinidad area. We used the key Trinidad outcrops and subsurface data (well penetrations and 2 two-dimensional [2-D] seismic lines from onshore to offshore) to (1) establish the paleo-Orinoco facies associations and their spatial distribution from the outcrops exposed along southern Trinidad to the offshore southern Columbus Basin; (2) reconstruct the large-scale architecture of the topsets and slope-to-basin floor clinoforms that characterize some of the Trinidad shelf-margin prism; and (3) apply a recently developed methodology (Petter et al., 2013), using clinoform height and forward growth rate, to estimate how much of the total paleo-Orinoco sediment budget has bypassed successive mappable shelf edges on the sedimentary prism.

**GEOLOGICAL AND STRUCTURAL BACKGROUND**

Trinidad, the most southeastern island in the West Indies, is located 15–20 km off the northeast coast of Venezuela (Fig. 1), separated from South America by the Columbus Channel (Winter, 2006). Structurally, Trinidad and the Columbus Basin lie at the eastern and southern limit of a belt of extensive deformation along the northern border of the South American continent (Babb and Mann, 1999). As a transpressional basin lying within the Caribbean–South American plate boundary zone (Bowman and Johnson, 2014), the Columbus Basin developed from a complex interplay of regional tectonics, extensional-growth normal faulting, high rates of sedimentation, and high-frequency sea-level changes within both foreland-basin and passive-margin settings (Wood, 2000). The faults that cross Trinidad Island include the Hinge Line, North Coast, El Pilar, Central Range, and Los Bajos fault zones (see Fig. 1), most of which are oriented northeast-southwest or east-west (Fig. 1). In terms of stratigraphy, southern Trinidad and the Columbus Basin form...
an eastern extension of the East Venezuelan Basin (Leonard, 1983) and contrast strongly with northern Trinidad, which has been much more strongly deformed by strike-slip movement and southward Caribbean compression (e.g., see El Pilar and Central Range fault zones, and the Miocene thrust belt in Figs. 1 and 2). The Southern Range fold belt progressively moved southeastward with time from early Pliocene onward. Three-dimensional (3-D) seismic data suggest that the Orinoco depocenter moved as well (R. Dixon, 2016, personal commun.). The Orinoco shelf-margin and the Columbus Basin sit on collisional plate boundaries (Carvajal et al., 2009; Alvarez, 2014). The strata, from oldest to youngest, are South American continental basement and oceanic basement, as well as Cretaceous, Paleogene, Miocene, Pliocene, and Pleistocene strata (Fig. 3).

The two primary structural elements that affected the paleo-Orinoco delivery system across Trinidad and into the Columbus Basin depocenter off eastern Trinidad were: (1) transpressional northeast-southwest–trending anticlines induced by Caribbean compression from the plate boundary in the north (Di Croce et al., 1999), and (2) northwest-southeast–oriented, down-to-the-northeast, extensional growth faults, likely driven by Orinoco sediment loading, i.e., from one of Earth’s largest rivers (Wood, 2000). Sydow et al. (2003) showed that the Orinoco River sediment supply generally exceeded the rapid subsidence of the shelf, allowing the Orinoco delta lobes to shift laterally but also to prograde steadily to the shelf edge since the late Miocene (Sydow et al., 2003). From the late Miocene onward, sedimentation across the Trinidad and Columbus Basin region was dominated by the prograding and shifting lobes of the Orinoco River delta (Díaz de Gamero, 1996), which built thickly stacked and fairly continuous delta lobes, now occurring both onshore and offshore. Growth-fault rollover structures, trending northwest-southeast, were modified by the orthogonal trend of compressional folds formed during the early Pleistocene (Sydow et al., 2003).

The high sediment supply to this segment of the paleo-Orinoco system promoted an advancing shelf margin that grew with high rates of aggradation and progradation (aggradation rate >200 m/m.y. and progradation rate = 33 km/m.y. during the late Miocene; aggradation rate >550 m/m.y. and progradation rate = 18 km/m.y. during the Pliocene; see also Di Croce et al., 1999; Carvajal et al., 2009). The Pleistocene stacking was extremely aggradational (~2500 m/m.y.), and consequent shelf-edge/upper-slope failure led to bypass of sediment to deep-water areas (Moscardelli et al., 2006; Carvajal et al., 2009).

We used shelf-edge trajectory growth patterns and a calculation of shelf-edge sediment bypass through time to characterize semicontinuous delivery of deep-water sediment during the late Miocene through Pliocene, despite very high rates of subsidence on this margin. The mapped presence of a late Pleistocene Orinoco Fan some 750 km north of Trinidad (Belderson et al., 1984) confirms this deep-water sand delivery. The use of long-range side-scan sonar data showed that the fan deposits are dominated by debris-flow deposits and braided channels up to 65 m deep that now abut against the Miocene deformation front of the Barbados Outer Ridge. Recent work (Deville et al., 2015) showed that these distant Orinoco deep-water deposits likely extend even further northward toward the Puerto Rico Trench.

We emphasize that in the linkage between onshore and offshore stratigraphy, and in the construction of the shelf-margin in general herein, we were unable to conduct correlations for the west-to-east cross section through the main Columbus Basin offshore east Trinidad. The reasons for this are that (1) the main

Figure 2. Representative cross sections showing regional structural style (Heppard et al., 1998). Cross-section A-A’ illustrates the structural style along a NNW-SSE–trending transect of the Eastern Venezuelan Basin off the east coast of Trinidad. Cross-section B-B’ illustrates a series of large normal, growth faults oriented in a NNW-SSE direction. The locations of the cross sections are also shown on Figure 1.
eastward deltaic fairway both subsided rapidly and has structurally complex growth faulting, thus making detailed correlations difficult (Figs. 2B and 3), and (2) little or no seismic or stratigraphic data from within this central part of Columbus Basin have been released for publication. As a result, we have chosen to link the onshore Trinidad stratigraphy with the offshore southern Columbus Basin, which is less structurally complex and where there is a published seismic line (Sydow et al., 2003).

LITHOSTRATIGRAPHY

The relatively well-established lithostratigraphy across onshore southern Trinidad is shown in Tables 1 and 2. The terminology follows the Geologic Map of Trinidad by Kugler (1959), and all of the main formations (Cruse Formation, Lower Forest Clay, Forest Formation, Moruga Formation, Mayaro Formation, Upper Forest Clay, Lower Morne L’Enfer Formation, Palmiste Formation, Lot 7 Siltstone, and Upper Morne L’Enfer Formation) are accessible at numerous
Growth of the paleo-Orinoco shelf-margin prism

Onshore and Offshore Formation Ages

It is emphasized that although there is a dearth of recent published documentation for detailed age dates of the study succession, there is general consensus that the entire succession spans latest Miocene through Pliocene in age, on the basis of micropaleontology and palynology both for Trinidad outcrops (Kugler, 1959; Carr-Brown, 1995) and for the offshore Columbus Basin (Pocknall et al., 1995; Wood, 2000; Pocknall et al., 2001; Sydow et al., 2003).

<table>
<thead>
<tr>
<th>Site</th>
<th>Formation</th>
<th>Location</th>
<th>Dominant sedimentary facies</th>
<th>Sedimentary section</th>
<th>Approx. thickness (m)</th>
<th>Sequences</th>
<th>Measured section (m)</th>
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<tbody>
<tr>
<td>A &amp; B</td>
<td>Lot 7 Silt (flooding)</td>
<td>Cedros Bay and Erin Bay</td>
<td>Tide-dominated Upper Morne L'Enfer delta complex; river-tide interaction delta lobes</td>
<td>Figure 11A</td>
<td>&gt;1000</td>
<td>&gt;10 sequences</td>
<td>808</td>
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<td></td>
<td>Lower Morne L'Enfer Fm.</td>
<td>Northeastern Moruga Bay</td>
<td>Tide-dominated Lower Morne L'Enfer delta complex; mixed wave-dominated and tide-influenced segments</td>
<td>Figure 11A; 12A</td>
<td>&gt;370</td>
<td>&gt;7 sequences</td>
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<td></td>
<td>Forest Fm.</td>
<td>Moruga Bay, SE Trinidad</td>
<td>Tide-dominated delta lobes</td>
<td>Figure 11A</td>
<td>&gt;1800</td>
<td>&gt;3 sequences</td>
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<td></td>
<td>Lower Forest Clay</td>
<td>Western Palo Seco Bay (Between Taparo Point and Anglais Point)</td>
<td>Muddy lower delta front and prodelta with basal flooding surface</td>
<td>Figure 13A; 13B</td>
<td>&gt;365</td>
<td>Multiple stacked</td>
<td>103</td>
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<td>C</td>
<td>Lower Cruse Fm.</td>
<td>Eastern Palo Seco Bay (Between Anglais Point and Chagonaray Point)</td>
<td>Deep-water slope (slope channels)</td>
<td>Figure 13D; 13E</td>
<td>&gt;1500</td>
<td>&gt;8 sequences</td>
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<td>D</td>
<td>Upper Cruse Fm.</td>
<td>East of Moruga Bay (West of Roja Point)</td>
<td>Repeated cycles of shelf-edge deltas</td>
<td>Figure 13A; 13B</td>
<td>&gt;4000</td>
<td>?</td>
<td></td>
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<td>E</td>
<td>Lower Morne L'Enfer Fm.</td>
<td>Western Morne Diablo (Between Roja Point and Siparia Point)</td>
<td>Deformed slope channels; collapsed pieces of shelf-edge deltas; mass transport blocks and associated slope deformations</td>
<td>Figure 13C</td>
<td>&gt;231</td>
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<td>F</td>
<td>Moruga Fm.</td>
<td>Moruga/Guayaguayare Bay</td>
<td>Storm wave-generated hummocky and swaley strata; muddy shelf-edge gullies</td>
<td></td>
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<td></td>
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<tr>
<td>G &amp; H</td>
<td>Palmiste Fm.</td>
<td>Moruga Bay, SE Trinidad</td>
<td>Wave-dominated shorefaces or delta fronts</td>
<td>Figure 12C</td>
<td>Multiple stacked</td>
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<td>I</td>
<td>Mayor Fm.</td>
<td>Mayaro Bay, SE Trinidad</td>
<td>Storm-wave dominated shelf-edge deltas</td>
<td>Figure 12C</td>
<td>Multiple stacked</td>
<td>103</td>
<td></td>
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</tbody>
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Note: The locations are discussed in Figure 4. Sources: Sydow et al. (2003) and Chen et al. (2014).

TABLE 2. LATE MIOCENE THROUGH PLIOCENE LITHOSTRATIGRAPHIC UNITS OF SOUTHERN TRINIDAD

<table>
<thead>
<tr>
<th>Series/Epoch</th>
<th>Formations</th>
<th>Intraformation units</th>
<th>Formations</th>
<th>Intraformation units</th>
<th>Formations</th>
<th>Intraformation units</th>
<th>Clastic wedges</th>
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<td>Pleistocene</td>
<td>Erin Fm.</td>
<td>Upper Morne L’Enfer Fm.</td>
<td>Lot 7 Silt flooding zone</td>
<td>Lower Morne L’Enfer Fm.</td>
<td>Lower Morne L’Enfer Silt, Upper Forest Clay</td>
<td>Palmiste Fm.</td>
<td>3rd wedge</td>
</tr>
<tr>
<td>Late Pliocene</td>
<td>Forest Fm.</td>
<td>Upper Forest Clay flooding zone</td>
<td>Lower Cruse Fm.</td>
<td>Lower Forest Clay flooding zone</td>
<td>Upper Cruse Fm.</td>
<td>Lower Cruse Fm.</td>
<td>1st wedge</td>
</tr>
</tbody>
</table>

Note: Sources: Kugler (1959); Carr-Brown (1995); and Vincent (2007). These formations form the four clastic wedges (Cruse; Forest/Moruga/Mayaro Formation; Lower Morne L’Enfer; and Upper Morne L’Enfer; see also Table 1) of the study succession.
Figure 4. Regional geologic map of the south coast of Trinidad. The red arrows show the direction of strata from older to younger (Kugler, 1959). Site A is on upper map in Cedros Bay. Sites B is near Erin Bay. Sites C and D are near Palo Seco Bay. Site E is near Quinam Bay. Site F is near Morne Diablo Bay (see Table 1 for more outcrop site information). Lower Cruse Formation is dark blue; Upper Cruse Formation is light blue; Forest Formation is gray/green; and Morne L’Enfer Formation is light green.
The time interval encompassed between the upper part of the Cruse Formation, when the shallow-water sands of the Orinoco Delta first came into the region, and the top of the Upper Morne L’Enfer Formation is therefore ~4 m.y. The order in which the four main clastic wedges of the Trinidad stratigraphy become superimposed on each other is clear from the onshore Trinidad outcrops, and particularly because of the Trinidad-wide occurrence of the muddy marine flooding intervals, Lower Forest Clay, Upper Forest Clay, and Lot 7 Siltstone, which separate the four sandy wedges. The expansion of the total succession from ~3 km in western Trinidad to 10–12 km in the offshore Columbus Basin certainly complicates the stratigraphy as it becomes engulfed in numerous growth faults (Wood, 2000; Sydow et al., 2003). However, mapping through the growth-fault province out to the much less structurally complex southeastern reaches of the Columbus Basin allowed Sydow et al. (2003) to erect a series of Pliocene offshore stratigraphic subdivisions (Tp10–Tp100) for this side of the Columbus Basin, and some of these subdivisions were later (Dixon, 2005) mapped into the east coast outcrops of the Mayaro Formation. In this way, the offshore horizon Tp20 was tied into the base of the onshore Lower Forest Clay, and the offshore horizon Tp38 was tied into the base of the Upper Forest Clay (Dixon, 2005, their figs. 3 and 4).

In the work herein, we therefore tried to link the conventional onshore lithostratigraphy for Trinidad with the Tp Pliocene stratigraphy established offshore by Sydow et al. (2003) and by Dixon (2005).

**Cruse Formation**

The Cruse Formation consists of both an upper shallow-marine deltaic part and a lower, deep-water turbidite slope part, and so it is the only formation on Trinidad where parts of the entire shelf-margin clinoform system, from outer shelf and shelf-edge deltas to the deep-water continental slope (Chen et al., 2016), can be observed. The total thickness of the Upper Cruse units, with sandy shelf and shelf-edge deltas, plus the Lower Cruse mudstone succession in southwestern Trinidad is some 1500–2000 m, with generally accepted ages spanning the late Miocene into earliest Pliocene (Higgins, 1959; Kugler, 1959; Leonard, 1983; Díaz de Gamero, 1996; Di Croce et al., 1999; Sydow et al., 2003; Bowman and Johnson, 2014). Outcrops of this succession extend for some 35 km in a west to east direction along the southern coast of Trinidad (sites C, D, E, and F in Fig. 4; see also Table 1). This direction is also approximately the depositional dip (shelf to basin) direction, so this distribution of the Cruse outcrops allows the approximate position of the shelf break to be identified in an area between Morne Diablo beach and Roja Point, separating a westwardly segment of in situ Upper Cruse shelf and shelf-edge deltas, with shelf-edge channels, from an eastern segment that is highly deformed, more mud rich, and contains very large (house-size) blocks of shallow-water facies that are unoriented and embedded in deformed mudstones. The Upper Cruse western segment represents the shallow-marine topsets of the shelf-margin clinoforms, whereas the collapsed and deformed eastern segment represents the underlying upper-slope deep-water deposits (for details, see Chen et al., 2016). The Morne Diablo outcrops (site F in Fig. 4; Table 1) also encapsulate the details of one of the Cruse canyons of the paleo–Columbus Channel. This contorted collapse, linked with the irregular base of the downcutting shelf-edge channels, is part of the “head” reaches of a slope canyon that cuts its way back onto the shelf. This canyon is likely to have been a feeder for bypassing sediment from the Cruse shelf to the Cruse basin-floor fans in the latest Miocene and earliest Pliocene. These deep-water fans are likely to be located within the subsurface of the present Columbus Channel (Fig. 1), some 20–40 km east of the Morne Diablo outcrop, off southern Trinidad.

The Lower Cruse Formation (sites C and D in Fig. 4; Table 1), outcropping best at western Palo Seco Bay, shows the late Miocene deep-water slope channels (site C; Vincent 2012) and related levee systems (site D; Chen et al., 2016). Although it is slightly older than the Cruse shelf edge outcrops described above, it gives direct evidence for the existence of deep-water deposits beyond the shelf margin. The thick Lower Cruse Formation is mud dominated but also contains significant sandy intervals (>91 m at Palo Seco) made up of turbidites that can often be seen to be channelized (Vincent, 2012). Lower Cruse Formation is the oldest unit and therefore deepest on the shelf-margin prism examined here. It also represents the first influx of clastic sediment attributable to the proto–Orinoco delta. For this reason (distal deposits), as well as from the description of the deposits, the Lower Cruse Formation strata are deep-water mudstones, sandy turbidites, and some associated mass transport deposits with rare bioturbation (Chen et al., 2016). The Cruse Formation may also be present in a 60–450-m-thick succession below the Lower Gros Morne sands in the Guayaguayare Bay area of southeastern Trinidad (Ablewhite and Higgins, 1965; Leonard, 1983).

**Forest, Moruga, and Mayaro Formations**

The Forest-Moruga Formation (names given to the same lithostratigraphic unit from west to east across southern Trinidad) of early-mid-Pliocene age (Higgins, 1959; Kugler, 1959; Leonard, 1983; Díaz de Gamero, 1996; Di Croce et al., 1999; Sydow et al., 2003; Bowman and Johnson, 2014) develops a thickness of some 2000 m on southwestern and south-central Trinidad but reaches more than 4000 m on the southeast coast at Guayaguayare Bay and on Radix Point (Figs. 5 and 6; Archie, 2004). West of Moruga, the succession coarsens upward irregularly from Lower Forest Clay to Forest Sandstone (see wells F19 and V3 in Fig. 6) and is known in this region simply as Forest Formation. Outcrops in the west are poor, though some of the sandy units are known to be cross stratified. East of Moruga, the succession becomes much thicker and has been divided into three members, each characterized by a thick and irregularly coarsening-upward sedimentary succession (Leonard, 1983): (1) The Gros Morne Siltstone and Gros Morne Sandstone, well exposed on the easternmost outcrops of Radix Point, and also on Galeota Point, form the basal regressive interval (bounded at the base by Lower Forest Clay), which is dominated by storm wave–generated hummocky and swaley strata (Archie, 2004). (2) The St. Hilaire Siltstone and the overlying Trinity Hill Sandstone, exposed on the coast west of Guayaguayare Bay, and on both south and north sides of Radix Point, marking a second regressive sedimentary sequence consisting of dark-gray mudstones and siltstones passing upward into very thick, hummocky, and swaley shallow-marine sandstones (Archie, 2004). In the eastern portion of the Columbus Basin, Moruga Formation–equivalent units are also recognized, represented by thick, deep-marine shales, probably continental slope deposits, grading upward into shallow-marine sandstones (Kugler, 1959; Leonard, 1983). (3) Las Tablas Siltstone and Casa Cruz Sandstone, exposed on the coastline east of Moruga, as well as on the uppermost levels of the Radix Point succession, on both north and south coasts, form the upper succession, again irregularly changing upward from muddy siltstones up to spectacular hummocky and swaley marine sandstones (Archie, 2004). These members of the Moruga Formation all represent open-coast, wave-dominated shelf and shelf-edge deltas that prograded across the Southern Basin.
of Trinidad out toward open Atlantic coastlines of the southern Columbus Basin.

The Mayaro Formation, an outer-shelf to shelf-edge delta succession (Bowman and Johnson, 2014), is exposed as foreshore cliffs along the north-south–trending southeast coastline of Trinidad Island between two prominent headlands—Radix Point in the north and Galeota Point in the south (site I in Fig. 4; Table 1; Carr-Brown, 1971; Archie, 2004). The formation seems to be within a growth-fault compartment immediately east of Moruga Formation members and contained in the hanging wall of the northern part of the Cedar Grove fault, one of the important growth faults of the Columbus Basin (Wood, 2000; Bowman and Johnson, 2014), fairly similar to the westerly adjacent (but not obviously growth-faulted) Moruga Formation. The great total thickness of the Mayaro succession (2.5 km), as well as the thickness of the individual regressive units, is likely due to syntectonic growth against the Cedar Grove fault, one of many growth faults seen in seismic data in the nearby Columbus Basin (Sydow et al., 2003). Within a kilometer-wide segment along the Mayaro Formation coastal cliffs, and associated with some of the thickest sandstones units, there occurs a more muddy and heterolithic succession bounded by several deep erosional surfaces, with evidence of *Glossifungites* on the edge of the surface. This erosional feature has been interpreted as a small canyon cutting up into the extensive hummocky and swaley cross strata of the Mayaro Formation (Dasgupta and Buatois, 2015; Dasgupta et al., 2016a). Farther offshore into the Columbus Basin, the Mayaro Formation has been documented in well data, but with a steadily decreasing sand/shale ratio, becoming prodelta and probably continental slope mudstones out toward the East Queens Beach field (Leonard, 1983).

The process-regime change described here from the river- and tide-influenced delta lobes of the Forest Formation on the Orinoco inner shelf to the storm wave–dominated outer-shelf deltas at Moruga and Mayaro is consistent with (1) the concept that shelf-edge areas on continental margins are particularly prone to large oceanic waves (Porebski and Steel, 2006; Uroza, 2008), and (2) an increased likelihood of shorelines within growth-faulted compartments being wave reworked, because aggradational slowing of shoreline progradational rate allows more “time” for reworking (Olariu and Olariu, 2015).

**Lower Morne L’Enfer and Palmiste Formations**

The Lower Morne L’Enfer Formation, outcropping along the southwest and south coasts...
Figure 6. Tentative interpretation from onshore to offshore across southern Trinidad with spontaneous potential (SP) and gamma-ray (GR) log curves from wells H3, F6, F19, V3, A2, and C1 Southeast Galeota (SEG log is not to the vertical scale; Sydow et al., 2003; Dixon, 2005; Osman, 2006, 2007), with the flooding surfaces (blue color) showing clastic wedges boundaries (third-order sequence in Fig. 9). MRS—maximum regressive surface. The lateral distance between wells is not to scale. See section D-D' in Figure 1 for the wells and cross-section location. Deep-water deposits are not portrayed.
of Trinidad, has been generally assigned to the late Pliocene (Vincent, 2003; Chen et al., 2014) or possibly even partly earliest Pleistocene in view of the Pliocene-Pleistocene boundary having been lowered recently (Dasgupta and Buatois, 2015). The Lower Morne L’Enfer interval (including the upper part of Upper Forest Clay), some 750 m thick in the Erin Bay area, is bounded below by a major flooding surface (Upper Forest Clay flooding surface) and above by the Lot 7 Siltstone flooding surface (Fig. 7).

The outcrops of the Lower Morne L’Enfer Formation represent a single large clastic wedge that shows a continuum of change in the paleo–Orinoco River delta system, with large fluvial-tidal distributary channels and muddy interdistributary flood basins (Chen et al., 2015) on the present-day southwest coast of Trinidad interfering eastward through some seven regressive-transgressive, tide-dominated deltaic, inner- to mid-shelf sequences (Chen et al., 2014).

The Lower Morne L’Enfer succession shows vertically repeating deltaic to estuarine sequences on the inner- to mid-shelf sites on Trinidad (sites A and B in Fig. 4; Table 1), and these exhibit a spectacular array of tidal signals such as double mud drapes, spring-neap tidal rhythms, and fluid mud layers (Vincent, 2003; Chen et al., 2014). Particularly in the transgressive estuary facies, there are stacked and well-organized subtidal dunes saturated with asphalt, as mined at Stolmeyers Quarries (Wach et al., 2003; Osman, 2006). Vertical grain-size trends of individual tide-dominated deltas show an irregular coarsening-upward (40–60 m thick) delta-front succession, and these are capped by distributary channels showing an upward fining of grain size. The transgressive estuarine phases cut significantly down into the underlying deltaic part of the couplet and show thick basal estuarine fluvial-tidal channels with a large-scale, grain-size upward fining and gradually increasing marine signatures (Chen et al., 2014, 2015). Despite the tidal dominance in the inner-shelf deltaic sequences, there are also some clear storm wave–dominated segments of the system at Cedros Bay.

It is possible that the Palmiste Formation, which overlies the Mayaro Formation on the east coast of Trinidad, is partially equivalent to the Lower Morne L’Enfer Formation, and it may even be equivalent to the entire Lower plus Upper Morne L’Enfer Formations. Thus, the Palmiste Formation (Table 1) across southeastern Trinidad forms the outer part of the third wedge above the basal Palmiste Clay in the east and likely lies within a growth-fault compartment running just west of the southeastern coast of Trinidad. The correlative intervening flooding surface of the Palmiste flooding zone toward the west is the Upper Forest Clay flooding zone. The Palmiste Formation is poorly known, but it is exposed in several inland quarries and outcrops south of Mayaro Bay on southeastern Trinidad. It consists of

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**Figure 7.** Schematic lithostratigraphy of the four main late Miocene–Pliocene siliciclastic wedges along southern onshore and offshore Trinidad, separated by extensive marine flooding intervals (broken blue lines), showing the Cruse deltas, Forest/Moruga/Mayaro deltas, Lower Morne L’Enfer (LMLF) deltas/estuaries–Palmiste deltas, and Upper Morne L’Enfer (UMLF) deltas that form the Trinidad shelf-margin sedimentary prism (from Barr, 1963; Barr and Saunders, 1965; Leonard, 1983; Wood, 2000; Steel et al., 2007; Bowman and Johnson, 2014). The Tp numbers given to the boundaries of the four main clastic wedges, critical to the onshore-offshore correlation of the succession, are from Sydow et al. (2003) and from Richard Dixon (2016, personal commun.). MRS—maximum regressive surface. See the locations in Figure 4.
wave-dominated shoreface or delta-front deposits, associated with more heterolithic facies, some of which were intertidal deposits, and all of which are overlain by brackish-water and nonmarine delta-plain deposits.

**Upper Morne L’Enfer Formation**

The late Pliocene saw the development of the strongly regressive, tide-influenced Upper Morne L’Enfer Formation deltas, followed by extensive delta-plain growth across southwestern and central Trinidad (Table 1). This unit is similar in its characteristics to the Lower Morne L’Enfer Formation, but there is an important intervening flooding surface, Lot 7 Siltstone in the west. The Upper Morne L’Enfer Formation thus forms the fourth clastic wedge across Trinidad in the late Pliocene interval. This wedge is some 600 m thick in SW Trinidad and expands to >1500 m on eastern Trinidad (Table 1).

The Upper Morne L’Enfer Formation marine deltaic above the Lot 7 Siltstone flooding interval and the thick overlying accumulation of muddy flood basin deposits, distributary channels, and coal deposits have been described from Erin Bay and Cedros Bay areas by Vincent et al. (2007) and by Chen et al. (2014).

Yet more distal in the Upper Morne L’Enfer clastic wedge, in the subsurface data east of Mayaro Bay, there may be a coeval unit represented by a basal clay layer passing upward into a series of interbedded clays and fine-grained sands (Leonard, 1983). The late Pliocene was a period of major structural activity, and sedimentation was strongly affected by the north-northwest–trending growth faults and the formation of east-northeast–trending anticlines (Leonard, 1983).

**Erin Formation**

The Pleistocene Erin Formation (Table 1) is the most recent major sedimentary succession in the basin (Leonard, 1983). The environment of deposition ranged from nonmarine to marine transition in the west to shelf in the east (Leonard, 1983). This unit is not described here in detail.

**ONSHORE CORRELATION ACROSS TRINIDAD**

Our correlation across the Southern Basin of Trinidad (the Northern Basin not included in this study) and into the Columbus Basin off eastern Trinidad utilized:

1. outcrop measured sections through the Lower and Upper Morne L’Enfer Formations at Erin and Cedros Bays (Chen et al. 2014), as well as published well data through these formations, and measured sections at Stolmeyers Quaries (Osman, 2007);
2. published measured sections through the Mayaro Formation (Bowman and Johnson, 2014);
3. observations through the various members of the Moruga Formation at Radix Point, Galeota Point, W. Guayaguayare Bay, and Moruga Bay, from data collected by the Dynamic Stratigraphy workgroup at University of Texas at Austin;
4. outcrop measured sections through the Lower and Upper Cruse Formations along southern Trinidad (Chen et al., 2016);
5. well logs through the Forest and Cruse Formations (two of these courtesy of E. Siggerud, 2016 personal commun.); and
6. a published southern Columbus Basin offshore composite well log in the Southeast Galeota (SEG) area (for location, see Figs. 1 and 5) penetrating the shelf-margin prism topset, lying above Lot 7 Silt (Tp50) and therefore equivalent to the onshore Upper Morne L’Enfer Formation (Sydow et al., 2003).

A tentative, interpreted summary correlation diagram across southern Trinidad from Cedros Bay and Erin Bay eastward to Moruga and then out to the southern Columbus Basin is shown in Figure 6 (well locations in Fig. 5). The onshore-offshore correlation goes south to the non-growth faulted area, partially because there are little or no data available for the main Columbus Basin. Although it has not been possible to correlate at the level of individual fourth-order stratigraphic sequences, and there are uncertainties related to the few wells, a correlation highlighting the stratigraphic framework of the four clastic wedges is possible. This was performed by identifying the three main flooding surfaces that bound the clastic wedges, namely, along the Lower Forest Clay flooding surface, Upper Forest Clay flooding/Palmiste flooding surface, and the Lot 7 Siltstone surface (Fig. 7). Because of scale, the sequences within the four clastic wedges are shown only schematically. The C1 log (SEG log; Fig. 6), located offshore at the SEG reservoir area, represents a composite log with some 3000 m of deposits from Tp59 to Tp95 (Sydow et al., 2003) showing some 20 stratigraphic sequences. The “Tp” nomenclature used in Sydow et al. (2003) was used in this study. The 3 km section of offshore SEG deposits is likely to be coeval with the <1500 m of Upper Morne L’Enfer Formation deposits outcropping at Erin Bay. The repeated coarsening-upward, regressive half cycles of the paleo-Orinoco delta are clear on the gamma-ray log of Cedros, Erin, and C1 on Figure 6, as are the thinner fining-upward transgressive, estuarine, or barrier-lagoon half cycles that cap many of the sequences.

**RECONSTRUCTION OF THE FOUR LATE MIocene–PlIOCENE CLASTIC WEDGES**

Based on sedimentary facies distributions and dynamic stratigraphy principles, the upper Miocene through Pliocene lithostratigraphy of southern Trinidad was used to reconstruct a four clastic wedge model with an onshore-offshore linkage from the Southern Basin of Trinidad out to the southern Columbus Basin. The clastic wedges evolve from older to younger as the sedimentary facies change laterally at the same time. Leonard’s (1983) offshore subsurface data (extending offshore from Galeota Point for 50–80 km) were used in this regional effort to revise, update, and extend our previous regional diagram (Steel et al., 2007) of the four clastic wedges (Fig. 7).

Figure 7. A tentative, interpreted summary correlation diagram across southern Trinidad from Cedros Bay and Erin Bay eastward to Moruga and then out to the southern Columbus Basin. The clastic wedge model with an onshore-offshore linkage from the Southern Basin of Trinidad extends offshore from Galeota Point for 50–80 km and may be coeval with the Lower Gros Morne sandstones of SE Trinidad. We suggest that such correlation is likely incorrect because of the proto-Columbus embayment from southwestern Trinidad, probably for some 70–80 km as far as Moruga. Within this time period, a “geological moment” in the life of the accreting shelf edge was identified, where it catastrophically collapsed around the headwall reaches of a canyon just east of Roja Point (Chen et al., 2016). The lower boundary of the Cruse wedge is placed at the base of the Lower Cruse mudstones. The upper boundary of the Cruse wedge is the extensive muddy flooding at the base of the Gros Morne Siltstone (equivalent to basal Forest Clay; Tp20 in offshore terminology of Sydow et al., 2003), despite the suggestion of Leonard (1983) that the Upper Cruse sandstones of SW Trinidad may be coeval with the Lower Gros Morne sandstones of SE Trinidad. We suggest that such correlation is highly incorrect because of Cruse shelf-edge recognition at Roja Point and the likelihood that the Cruse shelf accreted no further east than Moruga, judging from seismic data in the region (see Winter, 2006). The major cross-shelf flooding that terminated the first clastic wedge was the Lower Forest Clay (Tp20), drowning the Trinidad landscape for more than 80 km westward.
(2) The second clastic wedge was built by the tide-influenced Orinoco-Forest delta lobes in the west and, after significant cross-shelf transit, the coeval Orinoco-Moruga delta lobes, which led to a widespread mounded feature with the maximum progradation of the shelf edge at this time being just outboard of a line between Radix Point and Galeota Point on the east coast of Trinidad (Archie, 2004). From Moruga and eastward, the delta system splits up into three coarsening-upward subwedges, namely, the Gros Morne, St. Hilare–Trinity Hills, and Las Tablas–Casa Cruz units (Table 2). West of Moruga, the Forest Formation is subdivided into several unnamed coarsening-upward units, but with a total thickness much thinner than that of the east of Moruga.

The storm wave–dominated Mayaro delta lobes developed within a broadly coeval growth-fault compartment (bounded by the Cedar Gar fault) on the outermost shelf in the Mayaro fault compartment (bounded by the Cedar Gar fault). The Mayaro Formation is a separate subwedge within a growth-faulted expansion of the Forest-Moruga clastic wedge (Steel et al., 2007; Uroza, 2008). The recently suggested canyon cutting into the delta front of the Mayaro delta lobes in the coastal outcrops of southeast Trinidad (Dasgupta and Buatois, 2012; Dasgupta and Buatois, 2015) would require that the incision happened at a relatively early stage of Mayaro delta progradation, at a time when the shelf edge was still at an east coast Tp25 shelf-edge location (Fig. 7 and 8) and 25 km southwest from its late Pliocene, maximum growth location.

The lower boundary of the Forest-Moruga-Mayaro clastic wedge is taken at the Lower Forest Clay flooding surface (Tp20) in southwest Trinidad and at the basal flooding surface of the Gros Morne Silstone in southeast Trinidad. The upper boundary is at the upper Forest Clay flooding surface (Tp38) in the west and at the top Mayaro flooding surface in the southeast. The major cross-shelf flooding that terminated the second clastic wedge was the Upper Forest Clay, re-submerging much of the Trinidad landscape for more than 100 km westward.

(3) The third clastic wedge was built by the tide-dominated Orinoco–Lower Morne L’Enfer delta lobes on the inner-mid-shelf in the western reaches of southern Trinidad and by the likely coeval mixed-energy, wave-tide interaction Palmiste delta lobes in the southeast, which extended far eastward into the Columbus Basin. The base of the third clastic wedge is the Upper Forest Clay flooding surface across southwestern Trinidad and the top Mayaro flooding (Palmiste flooding) surface in the east. The upper boundary is the Lot 7 Siltstone flooding (Tp50) surface in the southwest. The latter surface reflects the most extensive Pliocene submergence of most of the Trinidad landscape, drowning the region for some 130 km westward.

(4) The fourth clastic wedge was built by the tide-dominated Orinoco–Upper Morne L’Enfer delta lobes in the southwest. The eastern coeval deltaic deposits include those seen in the SEG well above Tp50–60 (C1 on Fig. 6; Fig. 8), extending far eastward into the Columbus Basin. The base of this wedge is the Lot 7 Siltstone flooding surface, and the top is ill-defined above the deltaic units. The lack of an extensive upper flooding surface suggests that the earliest of many overlying Pleistocene wedges developed with a major subhorizontal basinward shift, analogous to that seen for the Cruse basinward shift. In contrast, the second and third wedges show significant shelf aggradation during their development.

ANATOMY OF THE INTEGRATED ONSHORE-OFFSHORE ORINOCO SEDIMENTARY PRISM

Sequence Stratigraphy of the Sediment Prism

The main stratigraphic framework discussed so far is the series of four large-scale clastic wedges, separated by major muddy, transgressive flooding intervals that are mapped and well known onshore across Trinidad (Figs. 6 and 7) and are also well imaged on the offshore seismic data (Fig. 8). Note that this main seismic line is not typical of the main Columbus Basin, but lies in the southern part of this basin, where the growth faulting that dominates the central Columbus Basin is not present (Fig. 8). The large-scale transgressive horizons are also conceptually important, because they determine the minimum shelf width within the sedimentary prism at any time. This shelf width then needs to be infilled by deltaic regression before there is any basinward migration of the shelf-slope break. This in turn affects the shelf-edge trajectory during the life of any individual clastic wedge and during the development of the entire prism.

Each of the four paleo-Orinoco clastic wedges consists of a series of smaller-scale regressive-transgressive units, most of which extend more or less to the shelf edge, and each of which has possibility of having a genetically related deep-water slope and basin-floor segment that may or may not have been deposited during sea-level lowstand. In icehouse systems like the Pliocene Orinoco system, significant sea-level falls would be expected at a sub–100 k.y. time scale (Somme et al., 2009). However, in such very high-sediment-supply systems, we know that sandy sediment can be delivered across the shelf edge onto the continental slope simply by a high sediment supply, and at literally any time in a sea-level cycle (Carvajal and Steel, 2006; Covault et al., 2007; Covault and Graham, 2010), so we prefer to term these deep-water deposits as “deep-water slope and basin-floor deposits” rather than as simply “lowstand” deposits. Individual cross-shelf, high-frequency “stratigraphic sequences” of this type, bounded by maximum flooding surfaces, were picked as follows: (1) a major coarsening-upward unit with a vertical scale of ~50 m on the inner shelf but expanding to ~200 m on the outer shelf (see Fig. 6, well C1), in keeping with the height of a shelf-transiting delta. This unit has its base on a muddy flooding surface and is identified as the regressive unit. This coarsening-upward unit is overlain vertically, and usually erosively, by (2) an irregularly developed, fining-upward transgressive unit that has the character of an estuary (up to tens of meters thick) or barrier-lagoon (few meters thick) system. In addition, there is likely to be (3) a third component of many of the sequences sited distally and consisting of slope and basin-floor deposits delivered by the regressive system as it reached the edge of the shelf and dispersed sediment to deep-water areas. For these “fundamental” stratigraphic sequences, the regressive to transgressive interval forms the flat-lying shelf topset of the clinothem, and the slope to basin-floor deposits form the basinward sloping to bottomset part of the same clinothem. There is good seismic evidence that such three-component clinothems stack laterally and vertically to form the main clastic wedges and eventually the entire paleo-Orinoco sedimentary prism. Further, the time scale of these fundamental regressive–deep-water–transgressive cycles has been estimated at <100 k.y. (Sydow et al., 2003).

These fundamental stratigraphic sequences, however, tend to group together into larger-scale, longer-time-scale sequences that are mappable seismically, before reaching the level of the clastic wedges described earlier. This means there is a stratigraphic hierarchy (Fig. 9; Table 3), with four levels within this very thick succession.

(1) Fourth-order sequences: The basic or fundamental stratigraphic sequence is the shelf-transit, regressive–deep-water–transgressive (R-T) clinothem; each fundamental clinothem is composed of one R-T cycle in the topset plus an additional deep-water component (<100 k.y.; Fig. 10B). There are up to 100 of these fundamental clinothems within the Pliocene and upper Miocene study succession, formed during a
Figure 8. (A) Two-dimensional (2-D) seismic profile extending into southern Columbus Basin with clinoform set boundaries (clinoform sets in Fig. 9). The Southeast Galeota (SEG) interval is from Tp59 to Tp95 (onshore thickness >700 m; SEG equivalent thickness is 3 km). For location, see Figures 1 and 15. (B) 2-D clinoform sets (clinoform sets in Fig. 9) interpreted by Dixon (2005). Blue/green colors on shelf represent clastic wedge flooding surface boundaries. Reddish/yellow colors represent likely times of shelf-edge collapse and major sediment bypass following steep rise of the shelf-edge trajectory, and possible evidence of slope readjustment after strong shelf aggradation. Lower Forest Clay flooding occurs below Tp25, so that the Cruse clastic wedge lies farther west.
third-order sequences can be mapped onshore to offshore with seismic data, and there are 11 Pliocene clinothem sets imaged on the seismic line in Figure 8A, suggesting a duration of some 200–250 k.y. for these sequence sets.

(3) Third-order sequences: Clastic wedges contain numerous stacked sets of clinothems and are defined by the intervals between the major onshore to offshore mappable flooding surfaces already discussed, i.e., the clastic wedge boundaries. The time duration of clastic wedges is estimated to some 800–1000 k.y., i.e., the classic third-order sequences of sequence stratigraphy. The Lot 7 Silt flooding surface defined a very important boundary at about Tp50 (estimated at 3.3 m.y.) and is broadly coeval with the start of the late Pliocene cooling stage (Miller et al., 2005). This boundary possibly separates higher-frequency Tp cycles and higher-amplitude sea-level changes above Tp50 (Fig. 9) compared to those below Tp50. The Mayaro Formation was interpreted to occur approximately between 4.2 and 3.6 Ma, as the Gros Morne Formation is believed to have an age of 5.0–4.2 Ma, based on seismic and well-log data (Dixon, 2005; Winter, 2006; Bowman, 2016). The megasequences of Wood (2000) range between 3000 and 4000 m in thickness and were each deposited over a period of 300 k.y. to 500 k.y., possibly corresponding to the third-order sequences of this study.

(4) The entire study succession represents ~2.75 m.y. for the Pliocene plus ~0.97 m.y. into the Miocene, and an additional approximately 0.28 m.y. into the early Pleistocene. This gives a maximum of 4 m.y. for the four clastic wedges in the study succession (1 m.y. each, though the Cruse Formation likely has a somewhat longer time duration, whereas the Lower Morne L’Enfer was likely shorter).

Two examples of stacked, fundamental stratigraphic sequences with the dimensions and time scale mentioned here are shown in Figure 10, both from the shelf setting only, and therefore with only regressive and transgressive components, and no deep-water deposits. One example (Fig. 10A) is from the Upper Morne
Growth of the paleo-Orinoco shelf-margin prism

<table>
<thead>
<tr>
<th>Sequences</th>
<th>Time duration</th>
<th>Strata thickness (onshore part)</th>
<th>Strata thickness (offshore part)</th>
</tr>
</thead>
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<tr>
<td>Fourth-order sequence</td>
<td>~35–40 k.y.</td>
<td>~50 m</td>
<td>~200 m</td>
</tr>
<tr>
<td>Clinothem set</td>
<td>~200–250 k.y.</td>
<td>&gt;100 m</td>
<td>&gt;500–750 m</td>
</tr>
<tr>
<td>Third-order sequence</td>
<td>~0.5–1 m.y.</td>
<td>&gt;300–500 m</td>
<td>~1.5–4 km</td>
</tr>
<tr>
<td>The entire Pliocene plus</td>
<td>~4 m.y.</td>
<td>&gt;2 km</td>
<td>~9.5 km</td>
</tr>
<tr>
<td>Latest Miocene succession</td>
<td></td>
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</tbody>
</table>

Note: Fourth-order sequences: shelf-transit regressive–deep-water–transgressive clinothems; third-order sequences: clinothem sets (containing a group of regressive–deep-water–transgressive clinothems) imaged well on the seismic data; third-order sequences: clastic wedges containing stacked sets of clinothems; entire Pliocene plus latest Miocene succession ~4 m.y. Stratal thickness expands seaward across the prism topset from onshore to offshore areas, e.g., 50 m sequence in western Trinidad commonly expands up to 200 m at shelf edge.

L’Enfer succession outcropping at Cedros Bay, and it represents some eight cross-shelf, paleo-Orinoco River delta transits, recorded here in an inner-shelf location; the other (Fig. 10B), from a well some 110 km farther east at an outer-shelf location, is from the same Upper Morne L’Enfer stratigraphic unit, also representing the transits made by the paleo-Orinoco River delta. The outer-shelf succession contains more R-T cycles (17 cycles with average thickness of 200 m) than the inner-shelf succession (8 R-T cycles with average thickness of 40 m). The likely reason for the different number of sequences is that the paleodelta not only moved proximal to distal across the shelf during a transit cycle, but it also spread out laterally over a broad area of the shelf to maintain uniform aggradation. This lateral spreading means that the thicker and better-preserved cycles of the outer shelf likely amalgamated more easily in proximal areas, and therefore they may be discounted on the inner shelf.

Deltas and Estuaries on the Shelf: Deep-Water Channels and Levees on the Slope

Reference has been made herein to deltas, estuaries, and deep-water channels or levees as the main environments that developed on the Orinoco shelf and deep-water slope at any point in time. We now wish to place these environments more firmly into the sequence stratigraphic context of the regressive, transgressive, and deep-water parts of stratigraphic sequences. The paleo-Orinoco delta, in any part of the topset stratigraphy, formed a progradational succession with more proximal deposits (including distributary channels) overlying delta front, prodelta, and shelf deposits. In addition, the prograding delta front is likely to have been dominated by tidal processes in some places, and by storm-wave processes in other places, either developed along strike from each other or developed in different reaches of the same cross-shelf transit (Olariu et al., 2012; Chen et al., 2014). In contrast, the estuary systems developed during retrogradation of the system; i.e., they formed transgressive system tracts, where brackish and marine deposits overlie fluvial channels or channelized tidal bar systems (Dalrymple and Choi, 2007). In the overall fining-upward transgressive interval, the stacking of the fining-upward packages may be punctuated by short intervals of delta-front progradation, forming a so-called punctuated transgressive backstepping pattern.

Summary diagrams of these three stratigraphic components (regressive, transgressive, and deep-water parts) within any clinothem are exhibited on a sequence extraction from the seismic line in Figure 8. These are shown in Figures 11, 12, and 13 as typical Orinoco transit stages based on the outcrop examples on south Trinidad. Compensatory “stacking” of individual sequences from 3-D seismic data suggests that delta lobes switched frequently during the evolution of the sediment prism, indicating that the regressive and transgressive parts could have existed at the same time laterally, just as they do in their modern analog on the Orinoco delta.

In some tide-dominated stratigraphic sequences, a series of changes can be seen in the evolution of the delta-estuary system, as follows (Fig. 11): (1) In the early stage of development in a tide-dominated delta, there is transgressive backfilling of the previous delta distributary channels by fluvial and then estuarine deposits, and these are eventually covered by a transgressive marine mud (Chen et al., 2015). (2) By stage 2, the channels and bars in the transition zone change seaward from a solitary tidal-fluvial channel to multiple distributary channels and islands on the tide-dominated delta front. The channels subdivide into several branches by transient elongate bars that can become vegetated before being eroded (Dalrymple et al., 2003); the axial zone, with tidal bars and channels, is sand-rich and dominated by subaqueous dunes and compound dunes. (3) In stage 3, the funnel-shape morphology of the tide-dominated delta has become infilled and is in the process of converting from funnel-shape tidal delta with branch channels to multiple delta lobes with distributary channels, and it is finally replaced by tide-dominated delta lobes during progradation of the system (Dalrymple and Choi, 2007). Examples of measured sedimentological logs up through estuarine and deltaic facies for tide-dominated cases are shown in Figure 11. The sequence stages are developed from flooding surface to flooding surface, i.e., flooding−regressive delta−transgressive estuary−flooding surface.

In some wave-dominated stratigraphic sequences, the stages of evolution can be seen as in Figure 12: (1) During the transgressive stage, the wave-dominated system becomes a wave-dominated estuary with an inland bayhead delta, muddy central basin or lagoon system, and inlet channel cutting through the barrier. (2) During the regressive and progradational stage, the wave-dominated delta forms coast-parallel “lobes” of beach ridges related to output from a single distributary channel, or a highly skewed series of beach ridges if wave approach to the coast is oblique (Bhattacharya and Giosan, 2003).

Especially in river-dominated or falling sea-level stratigraphic sequences, delta-front lobes that reach the shelf edge and are wave reworked by longshore drift can eventually collapse down onto the upper deep-water slope. In addition, channelized turbidity currents form in slope channels, deep-water channels, and adjacent levee systems (Fig. 13). Outcrops of Neogene deep-water slope deposits are scarce in the study stratigraphy, except for the Cruse Formation along the south coast of Trinidad, where turbidite-filled, deep-water slope channels and levee deposits have been identified. Examples of outcrop sedimentological logs through these deposits are illustrated in Figure 13 (logs C, D, and E). Almost all of the paleo-Orinoco shelf sequences also have deep-water equivalent deposits on the continental slope and basin floor beyond, and although we cannot illustrate the complete deep-water segment of a clinoform with log data, the coeval accumulation of sediment on the deep-water continental slope is clear from the seismic line illustrated in Figure 8. In general, the deep-water slope deposits are mud-prone and become sandy only when deep-water channels or canyons are occasionally encountered.

Source-to-Sink Trends

Within Individual Stratigraphic Sequences

From source to sink, during the period of development of a typical, fundamental paleo-Orinoco stratigraphic sequence, envisaged here (and argued by Sydow et al., 2003) as having a duration of <100 k.y., we see a basinward change from Orinoco River deposits to...
the development of multiple fluvial-tidal Orinoco distributary channels on the extensive and muddy Orinoco delta plain (mud flood basins separating sandy channels). The sediment remaining and bypassing through the distributary channels, after a percentage of the budget was extracted and stored in the flood basins, reached the coastline to feed the prograding delta lobes. During this regressive phase of sequence building, the delta lobes would have shifted, spread, and been reworked by wave and tidal processes across a coastline length of up to 200 km, such as we see on the modern Orinoco Delta. The distance of overall marine-shoreline progradation for a single sequence, from the first proximal development of delta-front facies out to the terminal delta-front development at the preexisting shelf edge, averaged 80–120 km for the 80 or so Pliocene sequences. Upon reaching the outer-shelf and shelf-edge area, the Orinoco delta would have had the potential to deliver sediments onto the continental slope by turbidity currents and other mass transport processes (see Sydow et al., 2003, their fig. 9). This is likely to have happened only at specific exit points along the shelf edge, because the storm-wave energy fence along much of the shelf edge would have prevented direct downslope sediment delivery in many areas. Instead, the storm waves would have stored and swept the sediment alongshore in sand belts on the outer shelf (such as we see in Mayaro Formation) until a canyon or slope channel or other topographic break in the shelf edge.

Figure 10. A comparison of proximal inner-shelf sequences (A) with outer-shelf sequences (B) of about the same age in Southeast Galeota (SEG) offshore well. Note difference in scales. SB—sequence boundary. (A) 0–302 m Upper Morne L’Enfer Formation from Cedros Bay showing ~8 repeated regressive-transgressive (R-T) sequences (fourth-order sequences in Fig. 9). The average thickness of each R-T cycle is ~40 m (Chen et al., 2014). (B) SEG composite well log from Tp59 to Tp95 (17 R-T units), which is broadly coeval to onshore Lot 7 Silt up to top of Upper Morne L’Enfer Formation, with ~20 sequences in SEG area, where the average thickness of each R-T cycle is ~175 m (Sydow et al., 2003). These R-T units are full sequences with consistently thin but significant transgressive parts. The boundaries of fourth-order sequences in SEG well correspond with maximum flooding surfaces (MFSs), i.e., the highest gamma-ray readings on log.
Growth of the paleo-Orinoco shelf-margin prism

Figure 11. A paleo-Orinoco inner-shelf (Lower Morne L’Enfer Formation) snapshot showing tide-dominated delta morphologies (e.g., Erin Bay and Cedros Bay; see also Boyd et al., 1992; Dalrymple et al., 1992). Stage 1: estuarine system of channels and channel bars developed during transgression. Stage 2: tide-dominated delta front. Stage 3: tide-dominated delta distributaries. TD—tide dominated. Measured vertical succession (composite section from measurement at Erin Bay site) illustrates the deposits of stages 1–3 (Chen et al., 2014, 2015). MFS—maximum flooding surface; SB—sequence boundary. Grain size: Mu—mud; Si—silt; Vf—very fine sand; F—fine sand; M—medium sand; C—coarse sand.
Figure 12. A paleo-Orinoco offshore/outer-shelf snapshot (Mayaro Formation), showing wave-dominated deltas at the shelf edge (Heward, 1981; Boyd et al., 1992; Dalrymple et al., 1992). Stage 1: Wave-dominated barrier-bar shoreface (e.g., Cedros Bay) with inlet, which is the only marine sediment source in the embayed lagoon system (Boyd et al., 1992), and bayhead delta deposits developed on the inner reaches of adjacent estuary. Stage 2: Storm-wave–dominated delta front (e.g., Mayaro Bay), with only a single distributary channel, and the delta front is dominated by shore-parallel beach ridges that are skewed in the direction of wave approach. WD—wave dominated (Panin, 1989; Bhattacharya and Giosan, 2003; Uroza, 2008; Uroza and Steel, 2008; Bowman and Johnson, 2014; Chen et al., 2014). Grain size: Mu—mud; Si—silt; Vf—very fine sand; F—fine sand; M—medium sand; C—coarse sand; Fl—lower fine sand; Fu—upper fine sand; M—medium sand.
Figure 13. A paleo-Orinoco outer-shelf/shelf-edge Cruse Formation snapshot with wave-river deltas, shelf-edge collapse, and deep-water slope channels and levees. RD—river dominated. (A) Shelf-edge delta front (e.g., Quinam Bay) with deformed slope mudstones. (B) Shelf-edge channels (e.g., Quinam Bay). (C) Distorted and slumped slope channels and shelf-edge collapse (e.g., Morne Diablo). Facies A, B, and C are stacked together within the shelf-edge to deep-water transit systems. (D) Deep-water channels (e.g., Palo Seco Bay). (E) Levees (e.g., Palo Seco Bay). Grain size: Mu—mud; Si—silt; Vf—very fine sand; Fl—lower fine sand; Fu—upper fine sand; M—medium sand.
allowed capture of sediments onto the slope. The portion of the <100 k.y. interval taken by this regressive and deep-water sediment delivery phase is unknown, but it is estimated to more than three quarters of the total cycle time. The expression of the regressive phase out to near the shelf edge is well illustrated by the irregular but upward coarsening of grain size seen in the individual sequences of the SEG well log (C1; Fig. 10B). An additional feature of significance in a source-to-sink context, shown by the same log, is the general thinning and increasing sand/shale ratio of the regressive units up through the logged succession, reflecting decreasing accommodation landward across the shelf, as well as decreasing preserved mud volume in the same direction.

During subsequent rising relative sea level, decreased supply of sediments, or simply autogenetic retreat (Muto and Steel, 1997; Muto and Steel, 2004; Kim and Muto, 2007; Olariu, 2014), the delta system would have stepped landward, much like the 150 km retreat of the modern delta in the last 20,000 yr (Sydow et al., 2003). During this landward retreat, a range of transgressive estuary and barrier-lagoon coastal segments would have developed, also punctuated by short-lived phases of regressive delta or shoreface construction. Again, the SEG Pliocene log data, from an outer-shelf setting, clearly show that the backstepping transgressive intervals of sequences commonly reached thicknesses of 10–20 m (Fig. 10B).

Within Clastic Wedges

Source-to-sink trends for the clastic wedges, of some 600–1000 k.y. duration, are similar to that described for sequences. Individual wedges began after a major landward shift of facies with regional transgressive drowning. Series of sequences prograded the delta system intermittently basinward by several tent of kilometers. There is clear evidence of storm-wave dominance on the deltas of the outer shelf and shelf-edge reaches, whereas there is likely to be more mixed tide and wave influence along strike and particularly on the delta lobes on inner-shelf locations. The progradation at the wedge scale tended to happen in a series of rise-to-flat style movements of the long-term shelf-edge trajectory that are described in the following section (Fongngern et al., 2016). Each of the clastic wedges, as well as the entire sedimentary prism, shows a marked increase in thickness from onshore Trinidad topset deposits to deep-water continental slope deposits, reflecting both water deepening and the severe and rapid subsidence across this shelf margin (Fig. 6).

ORINOCO PALEOFLUX ESTIMATION

Methods

The late Miocene–Pliocene architecture of the clinoformed shelf margin of Trinidad provides data not only about the position of the shelf edge and changes in margin accretion style through time, but it also records detail on vertical stratal thickness along the length of individual clinothems and forward migration distance of the shelf edge between successive clinothems. This, if combined with data on the duration of clinothem growth, provides an estimate of sediment flux across the clinoform and, eventually, a prediction for the presence or absence of deep-water deposits (Dixon et al., 2012).

The paleo-Orinoco’s large sediment supply resulted in high aggradation (A) and progradation (P) rates for the stacked clinothem stratigraphy of A = 200 m/m.y. and P = 33 km/m.y. during the late Miocene, and A = 550 m/m.y. and P = 18 km/m.y. during the Pliocene (Di Croce et al., 1999; Carvajal et al., 2009). The velocity of the clinoforms depends on the width used for the time-depth conversion of the seismic data; different velocities would result in different clinoform patterns. The time domain (Fig. 8A) sections are shown here to illustrate clinoform patterns. The seismic velocity is likely to have varied from 1.75 to 5.33 km/s (14,000 ft/s) at different depths from Cretaceous to present (Higgins, 1959), with seismic velocity of 2.38–2.5 km/s within the upper Miocene to Pliocene (Higgins, 1959). For clinothems 4–13 in Figure 8A (seismic line E-E’), the estimated velocity used is 2.38 km/s (Higgins, 1959).

An approach using the fundamental clinothems is not possible for the estimation of paleo-flux. The paleoflux calculation requires that most of the clinoform is imaged, and this means that it can only be accomplished using seismic data. At the scale of seismic data, the basic clinothems (<100 k.y. duration) are too thin to be imaged, and so for the purposes of paleoflux calculation, a “set” of clinothems, containing 2–15 of the fundamental clinothems, was used (Fig. 9) for this part of the analysis of the shelf-margin sedimentary prism. Clinothen set thicken from ~100–300 m on the inner shelf to some 300–500 m on the outer shelf and expand probably up closer to 600–1000 m on the deep-water slope (Fig. 6 and 8B). In the case of the paleo-Orinoco shelf margin, there are no well data available on the basin floor, so that the clinothem boundaries had to be picked and interpreted from the upper slope to the basin floor based on seismic data (Fig. 8), as has been done by Dixon (2005).

For estimation of sediment flux across the clinothems, the method of Petter et al. (2013) was used on the seismic data (Sydow et al., 2003; Dixon, 2005; Steel et al., 2008), though, as noted already, we applied the method to clinothem sets. Details of the method are given in Figure 14 and Table 4. The main parameters included the height of the clinoform (η), as well as the progradation and aggradation rates of that clinoform (P and A in Fig. 14). Using the kinematic wave equation in Figure 14 (Eq. 1), where η is the concentration of sediment in the bed (i.e., 1 – porosity; Petter et al. 2013) and integrating Equation 2 with respect to x, we can calculate the sediment flux at any point x along the clinoform elevation profile with a total length L by Equation 3. The sediment flux at any point x can be solved by Equation 5, where A is individual time duration. According to the clinothem thickness (T) trends in Equation 6, where a is the initial coefficient, and b is the decay constant, the distal pinchout distance (X′) can be solved by Equation 7, and the elevation of the pinchout position (η) can be calculated by Equation 8. The distance/elevation framework (X′, X′) between clinothem pinchout (X′, X′) and shelf-edge (X′, X′) positions and corresponding coordinates can be calculated by Equations 9 and 10. The estimated sediment flux q (units of L/T) at the shelf edge (q, X′) on the seismic line can be solved by Equation 5. Similarly, the distance/elevation framework (X′, X′) relative to the clinothem’s landward pinchout (X′, X′) and shelf-edge (X′, X′) position and adjusted coordinates can be calculated by Equations 11 and 12 (Petter et al., 2013).

One of the uncertainties in calculating sediment flux across the clinoform margin is caused by the tectonic context. Growth faulting as well as slight thrusting and postdepositional tectonic movements have occurred off eastern Trinidad. The seismic line being used (Fig. 8, line E-E’), however, presents an “off-axis” transect compared to a line through the growth-faulted main Columbus Basin fairway. Other potential biases of the calculation may be caused by the trend line estimation of the clinothem pinchout position, and also limitations coming from the lack of 3-D seismic data and only one 2-D seismic line being used for the calculation.

Paleoflux Results

The sediment flux values (estimated from cross-sectional area on seismic data) at the shelf edge (q, X′) for a clinothem set in seismic line E-E’ are estimated to have varied from 15 to 90 m²/yr, whereas the sediment flux from the most landward position on the same clinoform set is estimated to have been ~18–100 m²/yr (Table 5). The calculated difference shows that
Growth of the paleo-Orinoco shelf-margin prism

Figure 14. (A) Clinothem thickness along its length, illustrating the spatial patterns of clinothem depocenters with an exponential decay of clinothem thickness basinward of the maximum thickness at the shelf edge. (B) Schematic elevation profiles illustrating the exponential decay of clinoform patterns at the shelf edge and estimation parameters (Petter et al., 2013). (C) Equations. 

Table 4. Calculation Parameters and Descriptions

<table>
<thead>
<tr>
<th>Calculation parameters</th>
<th>Units</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>meter</td>
<td>Height of clinoforms</td>
</tr>
<tr>
<td>( P )</td>
<td>km/m/y.</td>
<td>Progradation rates</td>
</tr>
<tr>
<td>( A )</td>
<td>km/m/y.</td>
<td>Aggradation rates</td>
</tr>
<tr>
<td>( c_{sed} )</td>
<td>coefficient (e.g. 0.8)</td>
<td>Concentration of sediment in the bed (i.e., 1 - porosity)</td>
</tr>
<tr>
<td>( X )</td>
<td>meter</td>
<td>Any point along the clinoform elevation profile</td>
</tr>
<tr>
<td>( L )</td>
<td>meter</td>
<td>Total length of the clinoform elevation profile</td>
</tr>
<tr>
<td>( q(x) )</td>
<td>( L^2/t )</td>
<td>Sediment flux at any point x (units of ( L^2/T ))</td>
</tr>
<tr>
<td>( t )</td>
<td>year</td>
<td>Individual time duration</td>
</tr>
<tr>
<td>( T )</td>
<td>meter</td>
<td>Clinothem thickness</td>
</tr>
<tr>
<td>( a )</td>
<td>coefficient</td>
<td>Initial coefficient</td>
</tr>
<tr>
<td>( b )</td>
<td>coefficient</td>
<td>Decay constant</td>
</tr>
<tr>
<td>( X_d )</td>
<td>meter</td>
<td>Distal pinchout distance</td>
</tr>
<tr>
<td>( X_{adjSE}, \eta_{adjSE} )</td>
<td>meter</td>
<td>Distance/elevation framework between clinothem pinchout and shelf-edge positions</td>
</tr>
<tr>
<td>( X_{adjLW}, \eta_{adjLW} )</td>
<td>meter</td>
<td>Distance/elevation framework relative to the clinothem’s landward pinchout positions</td>
</tr>
<tr>
<td>( X_{SE}, \eta_{SE} )</td>
<td>meter</td>
<td>Elevation of the pinchout position</td>
</tr>
<tr>
<td>( X_{adjSE}, \eta_{adjSE} )</td>
<td>meter</td>
<td>Distance/elevation framework between clinothem pinchout and shelf-edge positions</td>
</tr>
<tr>
<td>( X_{adjLW}, \eta_{adjLW} )</td>
<td>meter</td>
<td>Distance/elevation framework relative to the clinothem’s landward pinchout positions</td>
</tr>
</tbody>
</table>

Note: Sources: Petter et al. (2013).

an average of \( \sim 76\% \) of the discharged sediments passed beyond the shelf edge. Note that each of the clinothem sets was built within a relatively short time period \(< 0.5\) m.y.; Sydow et al., 2003). Note also that the \( 76\% \) average shelf-edge sediment flux (Table 5) varied from a low of \( \sim 40\%–52\% \) for clinothems 5 and 11 to \( \sim 77\%–91\% \) during clinothems 4, 6–10, and 12–13 (see the location of seismic line E’E’ in Figure 15 and clinothem numbers in Fig. 16). The average sediment flux entering each of the 10 clinothem sets 4–13 was \( 42.6 \) m²/yr. If the paleo-Orinoco delta was \( 100 \) km in width, with assumed sediment density of \( 2.65 \) g/cm³, and considering removal of porosity due to compaction (Burgess and Gayer, 2000; Petter et al., 2013; because the averaged dry density of sediments in the Yangtze River Delta is \( 1.6 \) g/cm³ [Liu et al., 2007], and an assumed landslide deposit density of \( 1.9 \) g/cm³ has been used in New Zealand with sediment yielding \( 7 \times 10^4 \) ton/km² yr\(^{-1} \) [Korup et al., 2004; Scherler et al., 2016] and an assumed compacted density of \( 1.8–2 \) g/cm³ [Burgess and Gayer, 2000; Burgess et al., 2014]), the Pliocene sediment discharge is estimated to have been \( \sim 1.13 \times 10^6 \) ton/yr. These results provide an additional interesting quantitative estimate that about two thirds to three quarters of the total paleo-Orinoco sediment budget was bypassing the shelf edge into deep-water areas during the Pliocene.

SHELF-MARGIN PRISM

Basinward Growth of the Prism

The northwest-southeast trend of successive paleo-Orinoco shelf edges (Dixon, 2005) illustrates the broad strike extension of the studied sedimentary prism, whereas the basinward extent of growth is shown by the migration of the shelf-slope break from the embayed Columbus Channel along offshore Trinidad to its present position some \( 150 \) km off the modern Orinoco River delta (Fig. 15; Di Croce et al., 1999; Wood, 2000; Sydow et al., 2003; Dixon, 2005). From southern Trinidad and northward, the sedimentary prism became severely deformed by the southward-moving thrust belts, especially from late Pliocene onward (Di Croce et al., 1999; Wood, 2000).

Aggradational Evolution of the Sedimentary Prism

Shelf-margin aggradation and the repeated cross-shelf, regressive-transgressive transits of the paleo-Orinoco delta system are evidenced by the basic “tramline” character of the topset seismic reflectors and the rising shelf-edge...
TABLE 5. ESTIMATED TOTAL INITIAL SEDIMENT FLUX ENTERING EACH OF 10 CLINOFORM SETS (QS-TOTAL), THE SEDIMENT FLUX REACHING AND PASSING THE SHELF EDGE (QS-SHELF EDGE), AND THEREFORE THE PERCENTAGE OF THE SEDIMENT DISCHARGE PASSING ONTO THE CONTINENTAL SLOPE AND BASIN FLOOR FOR SEISMIC LINE E-E′

<table>
<thead>
<tr>
<th>Clinothem</th>
<th>Qs-total (m²/yr)</th>
<th>Qs-shelf edge (m²/yr)</th>
<th>Qs percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>99.96</td>
<td>30.60</td>
<td>0.91</td>
</tr>
<tr>
<td>12</td>
<td>38.95</td>
<td>30.61</td>
<td>0.97</td>
</tr>
<tr>
<td>11</td>
<td>39.98</td>
<td>16.06</td>
<td>0.40</td>
</tr>
<tr>
<td>10</td>
<td>31.12</td>
<td>27.48</td>
<td>0.88</td>
</tr>
<tr>
<td>9</td>
<td>45.21</td>
<td>40.48</td>
<td>0.90</td>
</tr>
<tr>
<td>8</td>
<td>18.48</td>
<td>15.55</td>
<td>0.84</td>
</tr>
<tr>
<td>7</td>
<td>52.32</td>
<td>40.27</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>38.47</td>
<td>30.95</td>
<td>0.80</td>
</tr>
<tr>
<td>5</td>
<td>42.72</td>
<td>22.36</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>19.07</td>
<td>16.18</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*Note: See section profile in Figure 16.*

Figure 15. Estimated paleo-Orinoco shelf-edge positions and trends (late Miocene through Pliocene; from Sydow et al., 2003; Dixon, 2005; Alvarez, 2014). Dixon’s (2005) seismically mapped westward re-entrants on the Cruse (Tp20) shelf edge suggest a series of superimposed slope canyons, consistent with canyon head outcrop evidence documented by Chen et al. (2016). Line E-E′ shows the location of the seismic section E-E′ in Figures 8 and 16, and the shelf-edge locations for clinoform sets are marked. NR—Northern Range, DR—Darien Ridge, GR—Galeota Ridge.

Trajectory (Fig. 8). However, the internal architecture of the sedimentary prism is more complex than this. There are two more levels of stratigraphic organization caused by grouping of these fundamental, high-frequency clinothems:

1. The Pliocene to lower Pleistocene succession has been divided into 13 clinothem sets, based on their recognition in the depositional-dip-oriented seismic data (Fig. 8). The average clinothem set thickness on the outer shelf is 300 m, as read from the seismic reflection data (120 ms interval; Fig. 16) and also from outcrop measurements from the onshore formations (Chen et al., 2014).

2. A final prominent organization of the late Miocene–Pliocene succession is into four

...
large-scale, coarsening-upward sedimentary wedges, separated by three prominent mudstone flooding intervals, well known from Trinidad onshore stratigraphy. Each clastic wedge contains multiple seismic clinothem sets. The four clastic wedges are not simply stacked evenly upward through the sedimentary prism; they are stacked in a punctuated manner. There is a prominent and abrupt, basinward progradation shift at clinothem sets 1 (10 km), 5–6 (10.05 km), 8–9 (5.96 km), and 12–13 (12.8 km) (Fig. 16). In contrast, there is a marked aggradational stacking of clinothem sets 2–5, 6–8, and 9–12 (Fig. 16). This punctuated growth style is well seen by tracing the shelf-edge trajectory upwards through the 13 clinothem sets, and it is discussed further in the following.

**Shelf-Edge Trajectory Changes**

Each of the four shelf-margin growth stages (the clastic wedges) noted here is highlighted by shelf-edge trajectory changes. The most marked trajectory changes are the basinward shifts at clinothem sets 1, 6, 9, and 13, with aggradational rises between them (Fig. 17). This repeated rise-flat architecture likely reflects forced regression
and maximum sediment bypass from the Orinoco paleodelta, where the shelf-edge trajectory is flat, and aggradational growth with increased storage of sediment on the shelf when the trajectory is rising. The most important implication of these trajectory changes is that basin-floor turbidite fans are most likely to have been optimally constructed when the flat shelf-edge trajectory allowed maximum bypass of sediments. According to our sediment flux calculations, however, fan construction also likely occurred when the trajectory was rising because of the very high sediment supply, but these fans are likely to be of smaller volume.

**Clinothem Thickness and Shape**

Shelf-margin clinoforms of Trinidad are sigmoidal forms consisting of a topset, foreset, and bottomset (Steel and Olsen, 2002; Petter et al., 2013), and they can be divided into three different types according to their shape (Fig. 18).

1. The first type (type O) is thickly stacked on the shelf, but it is thinner on the slope and basin floor. This implies relatively high shelf-aggradation rates and relatively little delivery of deep-water sediment. Examples are the clinothem sets 3, 7, and 15 in Figure 18.

2. The second type (type S) is relatively thin on the shelf, with a thicker slope, and thin again on the basin floor (for S-type thickness, see solid lines in Fig. 19). Examples are clinothem sets 3, 4, 6, 7, 9, 10, 12, and 13 in Figure 18, some of which have thin S-type forms with average thickness of 100–300 m (Fig. 19B), and others of which have thick S-type forms (up to 500 m; in Fig. 19A). The clinothem thickness shows a peak value on the upper slope. The clinothem thickness changes from thin to fairly thick from inner-shelf to outer-shelf sites, and especially across the shelf edge, where the thickness increases spectacularly; i.e., the aggradation rate to progradational rate ratio A/P is relatively low (Carvajal et al., 2009). The clinothem thickness decreases to the basin floor after stacking thickest on shelf edge and slope areas (P3 in Fig. 20).

In this case, sedimentation rates reached a maximum value on the upper slope as the near-bed shear-stress field decreased and shallow-marine transport gave way to sediment-gravity flow transport (Ross et al., 1994; Petter et al., 2013). This resulted in an apron of sediment on the upper slope. Sedimentation diminished downslope because sediment flux became depleted by deposition. The upper-slope apron may have been partially redistributed or further bypassed by gravity flows, which have the potential to move sediment out onto the lower slope and basin floor (Petter et al., 2013). Each of the third-order clastic wedges of the shelf-margin prism begins with an S-shaped clinothem (clinothem sets 3, 6, 9, 13).

3. The third type (type F) is thin on the shelf and thin on the slope but relatively thick on the basin floor (with basin-floor fans), for example, clinothem sets 5, 8, 11, 14, 15, and 16 in Figure 18. The clinothem generally thickens from shelf to basin floor for the F-type thickness, see dashed lines in Fig. 19C). Most of the clinothem sets in the sedimentary prism tend to end with an F-shaped clinothem, which is a muddy flooding interval, probably composed of mud-prone basin-floor deposits. Possible explanations for this case are: (1) significant volumes of sediment were transported onto the basin floor, indicating a highly progradational clinoform, or (2) the thin slope was eroded by an overlying highly progradational clinothem.

In summary, there is a tendency for clinothem sets to change from thick S-type (clinothem sets 3, 6, 9, 13) to thin S-type (e.g., clinothem sets 4 and 10), and then to F-type (clinothem sets 5, 8, 11, and 14) forms (Fig. 18). This type of change is apparent from the intervals younger than Moruga Formation. Assuming the sediment supply was constant, when the trajectory changed from rising to flat, the basinward shift of clinothem P3 in Figure 20 led to an increase of shelf-edge flux with a high P/A ratio (Fig. 20).

**FACTORS IMPACTING ORINOCO DELTA PROCESS REGIME AND EVOLUTION**

The interaction between the paleo-Orinoco River delta process regimes and the larger control factors is important in shelf-margin evolution. The growth of the shelf prism is the integrated product of sediment supply, tectonics (subsidence and growth fault activities), eustatic sea-level changes, and basin processes (Steel et al., 2000, 2007).

**Tectonic Subsidence and Growth Faults**

Tectonic subsidence and eustatic sea-level movements particularly affected Orinoco accommodation space. Some initial deformation of upper Miocene to lower Pliocene strata resulted in local folding and minor thrust faults, and small depocenters formed during shortening and subsequent normal faulting (Bowman and Johnson, 2014; Garcia-Caro et al., 2011). With high shelf-margin subsidence rates (up to 1000 m/m.y.; Wood, 2000), the sediments were more likely to be stored on the shelf instead of being bypassed into the deep-water areas. With uplift movements (and base-level fall), more sediment would have been partitioned into deep water. Factors possibly influenced by uplift and tectonic subsidence include steep slope gradients, rapid sediment mobilization, elevated water turbulence, and lowered salinity due to hypopycnal gravity flows (Dasgupta and Buatois, 2012, 2015; Dasgupta et al., 2016a, 2016b).

Abundant syndepositional growth faults in the offshore Columbus Basin also locally controlled the accommodation of sediments and could act as either space providers or transit zones for deposits (Bhattacharya and Davies, 2001; Carvajal et al., 2009; Oliveira et al., 2011; Olariu et al., 2013). The shelf-edge deltas were expanded by growth faulting and stacked because of the extremely rapid subsidence in the Columbus Basin growth fault province (Wood, 2000; Sydow et al., 2003).

**Sea-Level Change Icehouse**

As our best documented icehouse period, there is no doubt that eustatic sea level rose and fell on the Orinoco shelf margin during the late Miocene and Pliocene by up to 80 m at a frequency of less than 100 k.y. (Miller et al., 2005). Rising of relative sea level would have caused more deposits to be stored on the shelf, whereas falling relative sea level would have effectively driven sediments beyond the shelf margin. The fluctuations of relative sea level in the Columbus Basin were due to combined eustasy and tectonism. Despite very rapid tectonic subsidence rates that would have caused a relative increase of accommodation, eustatic falls of sea level would have outpaced this accommodation increase to drive Orinoco regressions frequently to the shelf edge, as seen in the SEG well (Fig. 10).

The entire late Miocene and Pliocene succession is composed of four large clastic wedges with Trinidad-wide flooding zones between. Each clastic wedge is further composed of multiple, high-frequency regressive-transgressive sequences, most of which were evidently well able to reach the shelf edge. It is very likely that it was the <100 k.y. eustatic sea-level falls that primarily drove the cross-shelf deltaic regressions of the same time scale, though high sediment supply would have aided in this, and high subsidence rate would have had a contrary modulating influence. These sea-level–driven, high-frequency cross-shelf delta transits had four stages: (1) During sea-level highstand, the delta system would have prograded and aggraded with delta lobes shifting and sediment spreading on the inner to mid-reaches of the preexisting shelf; (2) during sea-level falling stage, the delta system would have continued to prograde and spread out to the mid- to outer shelf and shelf-edge reaches, with a slightly downstepping shoreline trajectory; (3) during
Growth of the paleo-Orinoco shelf-margin prism

Figure 18. Clinothem set shape patterns from seismic line E-E’. S—S-type clinothems; F—F-type clinothems.
Figure 19. Clinothem thickness from seismic line E-E'.
Growth of the paleo-Orinoco shelf-margin prism

Figure 20. Schematic basinward shift and increased accommodation of S-type clinothem with the assumption that the sediment supply is constant. $A$—aggradation rate; $P$—progradation rate; $Q_s$—total sediment supply; $Q_{se}$—sediment beyond shelf edge.

Sea-level lowstand, sediment would have bypassed the shelf edge and would have accreted on the slope and built the basin-floor fans. For those high-frequency sequences where the sediment flux was continuously high (i.e., little abated by rising sea level), it is likely that bypass of sediment to the deep-water slope and basin floor would have persisted for a longer period from highstand through lowstand, creating fans at all sea-level stands, as reported by Carvajal and Steel (2006) and by Covault and Graham (2010). In addition to the control exerted on deep-water sediment delivery by supply and eustatic sea level, it has also been noted that the process regime at the shelf edge is critical, and that sediment bypass to deep water is greatly aided by river-tide-dominated reaches of the shelf-edge deltaic coast (Carvajal and Steel, 2012; Dixon et al., 2012, 2013) and hindered or dampened by storm-wave-dominated shelf-edge reaches (Carvajal and Steel, 2009).

(4) During rising sea level and the development of a shoreline transgressive stage on the shelf, the delta would have backstepped, commonly becoming an estuary or barrier-lagoon system and causing embayed or funnel-shaped shorelines. These latter shorelines represent the farthest landward movement of marine and brackish water back into the sediment prism, though transgression was often punctuated by short-term regression.

Sediment Supply

Very high sediment supply and high-energy river-channel erosion may have caused sediments to bypass the shelf edge at any time during the $<100$ k.y. R-T shelf transits, as noted previously herein. If the sediment supply was not strong enough to drive the sediments to the shelf edge, the sediments became aggradationally stacked on the shelf instead of bypassing the shelf edge. The same negative effect could have been attained by a large oceanic wave regime at the shelf edge that drifted the sandy sediments along the shelf edge instead of bypassing it onto the slope (Carvajal et al., 2009).

CONCLUSIONS

(1) The outcrops of late Miocene through Pliocene strata exposed on the southern coasts of Trinidad Island display a series of facies associations, which include the deposits of: tide-dominated delta lobes and estuarine channels with associated delta plains and tidal flats; wave-dominated delta front or shoreface; shelf-edge delta front; shelf-edge channel; large-scale shelf-edge collapse; deep-water slope channel; and levee systems.

(2) The facies associations, although from different formations from the late Miocene through Pliocene, represent a predictable facies linkage from delta plain to shoreline and shelf edge, and then to deep-water slope and basin-floor sink.

(3) The entire late Miocene through Pliocene shelf-margin sedimentary prism can be subdivided into (a) fundamental fourth-order clinothems (topset, deep-water slope and basin floor) of $<100$ k.y. duration, which are the basic regressive-transgressive deltaic to deep-water building blocks of the succession, (b) clinoform sets of a $200–250$ k.y. duration that are relatively well imaged on the 2-D seismic data and can therefore be used to estimate paleoflux partitioning across the clinoforms, and (c) four clastic wedges of $<1$ m.y. duration that are bounded by three very extensive muddy marine transgressions that are well known from onshore units in Trinidad.

(4) A first attempt at correlating the southern Trinidad onshore and southern Columbus Basin offshore successions was made, but only at the level of the four clastic wedges. Most of the onshore Trinidad formations occupy the topsets (delta plain, shoreline, and shelf) of the clinoform succession, but the Cruse Formation, representing the continental slope, contains good examples of shelf-edge collapse and mass transport deposits, as well as deep-water turbidites filling slope channels and levee systems.

(5) Three types of clinothem set shapes can be distinguished. O-type clinothems are thickly developed on the shelf topset but are thin on slope and basin floor and indicate shelf storage and aggradation. The S-type clinothems show maximum thickness at the upper slope or slope, and indicates significant shelf-edge progradation, and sediment bypass. F-type clinothems show their maximum thickness developed the basin floor or the clinothem toe area, indicating thick basin-floor deposits, or erosive shelf and slope conditions. The F-type clinothem is likely associated with mud-prone basin-floor deposits.

(7) During the late Miocene through Pliocene, more than two thirds of the total sediment discharge in most clinothems was transported beyond the shelf edge to the deep-water areas, predicting a significant presence of basin-floor fans in the high-sediment-supply paleo-Orinoco system. The sediment flux at the shelf edge varied from 40% to 91% of the total sediment budget, based on the available seismic profiles.

(8) Short-time-scale (tens to hundreds of thousands of years) changes in sea level, tectonics, climate, and sediment supply caused short-term variations in sediment partitioning across the shelf edge and to deep-water areas. However, there was also variation in the shelf-edge trajectory over longer time scales ($>1$ m.y.) whereby shelf-margin growth maintained an equilibrium, allowing at least two thirds of the total sediment budget to bypass the shelf edge.

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