CLINOTHEMS OF THE CRETACEOUS BERBICE CANYON, OFFSHORE GUYANA

by

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ABSTRACT

The Berbice Canyon of offshore Guyana evolved in the late Cretaceous in proximity to a margin that was separating from the African margin in response to the opening of the northern South Atlantic Ocean. The Berbice would be considered a shelf-incised canyon in the nomenclature of Harris and Whiteway, 2011.

This study examines the nature of the canyon morphology, fill phases and fill architecture within the Berbice Canyon using ~7000 km$^2$ of 3D seismic time and depth data, as well as chronostratigraphic data from Horseshoe-01 well drilled adjacent to the canyon fill.

The Berbice displays composite canyon development with multiple phases of cut and fill. There are six primary incisional surfaces exhibiting a maximum width of 33km, a maximum relief of 1250 m and a composite maximum relief of 2650 m when decompaction is factored.

The western side of the canyon system is primarily modified through destructional activities such as scalloping and side wall failures while the eastern side is primarily modified through constructional progradational activities.

There are clinothems deposited within the canyon between incisional surfaces I3 and I4, primarily on the eastern side. The clinothems generally have a mounded shape and are primarily sourced from the southeast. The clinoforms — based on comparison to a dataset of clinoform morphometrics compiled by Patruno et al, 2015 — are shelf-margin / shelf-prism scale clinoforms.
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1.1 Shelf Margin Canyons

In the nomenclature of Harris & Whiteway (2011), the Berbice Canyon would be considered a shelf-incising canyon. Shelf-incising canyons that are not associated with rivers occur with similar frequency on active and passive margins and make up about 28% of all large canyons occurring on continental margins. They have a mean length of 50.4km and a mean depth range of 2265m (Harris & Whiteway, 2011). River associated shelf-incising canyons occur more often on active margins and make up about 2.6% of all large canyons occurring on modern continental margins. They have a mean length of 80.9km (the longest of the canyon types) and a mean depth range of 2767m (Harris & Whiteway, 2011).

The Berbice Canyon has a length of about 89km and a depth range of about 2875m. The canyon was likely a river associated shelf incising canyon that was linked to the proto-Berbice and proto-Corantijn/Courantyne rivers (Yang & Escalona, 2011). The proto-Berbice river was the trunk stream through which Lake Maracanata transitioned to a fluvial environment flowing northeast into the Atlantic during the Late Cretaceous to the Paleogene (McConnell, as cited in Lujan & Armbruster, 2011).

In its proximal reaches, a river-associated shelf-incising canyon could bear resemblance to an incised valley and become a submarine canyon in deeper water. For example, the Congo River feeds the Congo River Estuary, and both are directly connected to the Congo submarine canyon (Babonneau et al, 2002).

An incised valley forms through significant erosion into underlying strata along with the deposition of fluvial or estuarine sediments on the overlying erosional surface (van Wagoner et
In contrast, the incision of a submarine canyon occurs in a completely submarine setting due to failure of continental margins; erosive turbidity flows originating from the river, shelf or upper slope (Shepard, 1981; Harris & Whiteway, 2011) or submarine current erosion (Prieto, 2016).

1.2 Clinoforms

A clinoform is a gently sloping depositional surface created through progradation or lateral outbuilding. Clinoforms can take on a variety of shapes and architectures — sigmoidal, oblique (tangential and parallel), complex sigmoid-oblique, shingled, and hummocky (Mitchum et al, 1977b). A clinoform may be subdivided in dip profile into a topset, foreset and bottomset (Figure 1.1). Depending on its shape, a clinoform may contain some or all of these portions, a typical sigmoidal clinoform has all three. The topset is the shallowest and low-angled portion; the foreset is the central and steepest portion and the bottomset is the basal and low-angled portion (Mitchum et al, 1977b). The clinoform head and toe points are defined as the points at which the topset and bottomset respectively become conformable with the underlying strata (Patruno et al, 2015). The rollover points are defined as the points of maximum curvature and occur landward and basinward of the clinoforms inflection points — the points of maximum slope gradient (Pirmez et al, 1998; Patruno et al, 2015) (Figure 1.1). The term clinothem refers to a sedimentary deposit comprised of clinoforms (Rich, 1951).

Clinoforms occur in different depositional environments and at different scales (Figure 1.2) (Porębski & Steel, 2003; Wolinsky & Pratson, 2007; Helland-Hansen & Hampson, 2009; Patruno et al, 2015). They can be classified into shoreline or subaerial delta clinoforms, subaqueous delta clinoforms, shelf-prism or shelf-edge delta clinoforms and continental margin clinoforms. Shoreline or subaerial delta clinoforms can be tens of meters tall and their rollover
point typically occurs on or near the shoreline break (Helland-Hansen & Hampson, 2009; Patruno et al, 2015). Subaqueous delta clinoforms are tens of meters tall and occur on the shelf at water depths up to 60m. Shelf-prism clinoforms are 100-500m tall. When shelf-prism clinoforms coincide with shoreline clinoforms they are called ‘shelf-edge deltas’. Continental margin clinoforms build continental margins and are thousands of meters tall (Patruno et al, 2015).

Clinoform foreset slopes can be related to lithology. For example, muddy subaerial delta clinoforms and subaqueous clinoforms exhibit a foreset slope range of 0.001 to 0.01 (i.e. 0.057°-0.57°). Sandy and gravelly subaerial delta clinoforms exhibit foreset slope ranges of 0.01 to 0.1(i.e. 0.57°- 5.7°) and 0.1 to 1(i.e. 5.7°- 45°) respectively. (Wolinsky & Pratson, 2007). Similarly, submarine slope clinoforms dominated by mud have lower slope angles than those dominated by sand (Adams & Schlager, 2000).

Shoreline and shelf-edge trajectories through time can be examined using clinoform rollover points. Trajectory analysis can be used to make a number of predictions, including the presence or absence of basin-floor sands (Johannessen & Steel, 2005; Helland-Hansen & Hampson, 2009; Kertznus & Kneller; 2009).

In shelf margin settings, clinothems develop through basinward progradation of sediment, followed by aggradation of the sediment to form a shallow-marine platform extending from the basin margin. Sediment is supplied to this system via deltas or strike-fed shorefaces (Steel & Olsen, 2002). These shelf margin clinoforms continue to prograde and maintain the platform as sediment is supplied. The pattern of progradation and aggradation of these clinothems over a longer time scale (several hundred thousand to several million years) is affected by changes in base level (Steel & Olsen, 2002). Base level can be affected by rate of subsidence, and changes in sediment supply and/or relative sea level (Steel & Olsen, 2002). Generally speaking, a falling
trend in base level leads to an overall progradational pattern while a rising trend in base level leads to a retrogradational pattern. A maintained base level will lead to an overall aggradational pattern (Figure 1.3).

Shelf margin deltas serve as good hydrocarbon targets because they typically have sandstone reservoirs that are further expanded early on through growth faulting (Meckel, 2003), they have laterally-extensive shale seals, and are typically linked to downdip slope and basin accumulations, thereby making those targets easier to identify (Cummings & Arnott, 2005). A lot of the largest plays in the shelf and onshore Gulf of Mexico in the past 30 years (e.g. Wilcox, Tuscaloosa, Vicksburg, etc.) have been shelf margin deltas (Meckel, 2003). Additionally, ~50% of original gas in place reserves in offshore Nova Scotia are thought to be in shelf margin delta sandstones (Cummings & Arnott, 2005).

Clinoform topsets can also serve as hydrocarbon reservoirs within coastal plain, shoreline and shallow marine environments (Milton & Bertram, 1995). However, delta clinoform surfaces can act as baffles or barriers to flow in shallow-marine hydrocarbon reservoirs when they are lined with low permeability lithologies such as mudstone (Graham et al, 2015).

1.3 Confined versus Unconfined Clinoform Development

Most models of clinoforming architecture deal with open shelf progradation of deltaic clinoforms and do not consider clinoforming into a highly confined space. In contrast, several examples exist in the literature on the effect of confinement on deepwater gravity flows and the resultant development of turbidite lobes, channels and submarine fan architecture (Lomas & Joseph, 2004; Pyles, 2008; McHargue et al, 2011; Marini et al, 2015). However, few have looked at the effect of confinement on clinoforms and progradational architectures.
Notably, Houseknecht (in press) documents instances of clinoforms prograding into localized topographic lows, within the Lower Cretaceous “Fish Creek Slide” of Arctic Alaska. These lows were created by a mass failure event in the lower slope that led to incision and localized collapse of the upper slope. Beyond this, few documented examples of clinoform development in confined accommodation settings exist.
Figure 1.1  Labelled diagram of a clinoform showing clinoform head and toe points, foreset, topset, bottomset, inflexion points (points of maximum slope gradient) and rollover points (points of maximum curvature). $F_I$ stands for foreset length, $F_h$ stands for foreset height, $I_h$ stands for Inflexion Point height, and $\theta$ stands for foreset slope. (Modified from Patruno et al, 2015)
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CHAPTER 2
GEOLOGIC BACKGROUND

The location of this study is the Guyana-Suriname Basin (Figure 2.1). The study target is specifically a large Cretaceous-aged canyon named the Berbice Canyon and the shelf surrounding it. In 2012, the South America and Caribbean region was ranked by the United States Geological Survey as the number one region in the world for undiscovered conventional oil resources with an estimated value of ~126 billion barrels of oil (BBO) (Schenk et al, 2012a). The Guyana-Suriname basin was estimated to be the 3rd most prospective area in the region for conventional oil resources, with an estimated mean oil resource of 13.6 BBO (Schenk et al, 2012b).

The basin is located on the continental margin of northeastern South America along the continental shelf of Guyana, Suriname and part of French Guyana. The Proterozoic Guyana Shield basement limits the basin’s landward extent, while the basin is limited to the south east and north west by the Demerara Plateau and Pomeroon Arch, respectively (Workman & Birnie, 2007; Dennison, 2017). Using Google Earth measurements, water depths on the basin’s shelf range up to around 200 m and more than 4500 m in the ultra-deep.

2.1 Guyana-Suriname Basin Formational History

The Guyana-Suriname basin’s formational history involves three phases (Figure 2.2):

2.1.1. Jurassic Central Atlantic Rifting Phase

During this phase, North and South America were separating along the Central Atlantic. The north-south rifting led to east-west extension with a component of dextral shearing. Intense syn-rift volcanism occurred along the margin at the location of the Demerara Rise (Reuber et al,
Horst and graben structures developed along the offshore, and onshore as the Takutu Graben (Yang & Escalona, 2011). These rift features established areas of high accommodation for later sediments to fill.

2.1.2. Early Cretaceous South Atlantic Rifting Phase

During this phase, rifting along the southern extension of the South Atlantic initiates separation of the southern regions of South America and Africa and initiates counter-clockwise movement of North Africa. This movement resulted in compression and the uplift of the Demerara Rise and its conjugate Guinea Rise (Yang & Escalona, 2011). The basin underwent inversion and the compressional motion led to northeast-southwest en echelon folding in the Demerara Rise. A major erosional event occurred in northern South America during this tectonic phase resulting in the regional Albian unconformity (Reuber et al, 2016).

2.1.3. Late Cretaceous Equatorial Atlantic Drift and Passive Margin Phase

During this phase, South America and Africa drift away from each other along transform faults. The drifting movement is still ongoing today, but was most active from the Albian to the Eocene (Yang & Escalona, 2011). This is a phase of significant oceanic crust development as well as collapse of the unstable shelf edge and slope (Yang & Escalona, 2011). The Berbice Canyon evolved in the late Cretaceous and was likely initiated by this extension and a portion of its sediment fill sourced from shelf and slope collapse.

2.2 Guyana-Suriname Basin Stratigraphy and Cretaceous Paleogeography

The igneous basement of the Guyana-Suriname basin is Precambrian to Jurassic in age and is associated with the Atlantic Unconformity (Figure 2.3). In the Barremian (Early Cretaceous), the predominantly basal clastic sandstone Stabroek formation was deposited and subsequently overlain with non-marine siliciclastics in the landward direction and by the Aptian-
Albian Potoco shallow water carbonates on the shelf (Workman & Birnie, 2007; Yang & Escalona, 2011; Dennison, 2017). During the South Atlantic Rifting phase, a regional erosive unconformity observable in seismic and in the Horseshoe-01 well (Figure 2.1), covered the basin at the top of the Albian. Figure 2.4A is a depiction of the basin’s Albian paleogeography by Erlich & Keens-Dumas (2007).

Following the unconformity, there was a regional flooding event that deposited the Canje formation (Yang & Escalona, 2011). The Canje is a late Albian / early Cenomanian to Turonian aged formation comprised of organic-rich shales and siltstones that serve as the primary source rock in the region (Erlich et al, 2003; Yang & Escalona, 2011; Dennison, 2017). The timing of deposition of the Canje formation coincides with a Cenomanian-Turonian global ocean anoxia event as well as a global sea level rise (Erlich et al, 2003). Figure 2.4B is a depiction of the basin’s Cenomanian-Santonian paleogeography by Erlich & Keens-Dumas (2007).

The Canje formation is overlain by the Berbice Unconformity, which forms the Berbice Canyon (Workman & Birnie, 2007; Dennison, 2017). The Berbice unconformity appears to encompass varying amounts of time, based off of missing sections in wells across the basin. In ODP wells 1258 (A, B and C) and well 1260A drilled on the Demerara Rise, Turonian-Santonian sections are truncated or missing (Figure 2.5) (Erlich & Keens-Dumas, 2007). The North-Coronie-1 well drilled about 100km northeast of the Berbice Canyon, is missing Upper Cenomanian and Turonian-Coniacian sections, which are present in the Galibi Offshore-1 well as predominantly siltstones and sandstones with some carbonates and shales (Figure 2.5) (Erlich & Keens-Dumas, 2007). In the Horseshoe-01 well closest to the canyon, middle to lower upper Cenomanian as well as Coniacian to middle/late Santonian sections are missing. Therefore, the Berbice unconformity is likely Upper Cenomanian to Santonian in age and based on its
proximity to the Horseshoe-01 well, the Berbice Canyon is likely closer to Coniacian to Santonian in age.

The Berbice unconformity is overlain by the New Amsterdam formation, which on the shelf is predominantly sand; towards the shelf margin is interbedded with clays and carbonates; and away from the margin is predominantly clay (Workman & Birnie, 2007; Dennison, 2017). Figure 2.4C is a depiction of the basin’s Campanian-Maastrichtian paleogeography by Erlich & Keens-Dumas (2007).

The end of the Cretaceous is punctuated by an unconformity, above which lies the Paleocene to Mid-Miocene Georgetown and Pomeroon formations, which are dominated by sand on the shelf, carbonates on the margin and clay distally (Workman & Birnie, 2007; Yang & Escalona, 2011).

By the mid-Miocene, carbonate sedimentation ended and siliciclastic sedimentation began to overstep the shelf edge due to an increase in clastic sediment input (Corentyne formation) to the shelf caused by the Andean uplift (Workman & Birnie, 2007; Yang & Escalona, 2011).
Figure 2.1  Outline of Guyana-Suriname Basin showing the approximate locations of the Berbice Canyon and the Horseshoe 01 well. Water depths on the basin’s shelf range up to around 200m and more than 4500m in the ultra-deep. Base map from ArcGIS. Basin outline modified from Robertson, C. G. G., 2016.
Figure 2.2  Tectonic history of Guyana-Suriname Basin (Modified from Yang & Escalona, 2011). Locus of focus in orange box. (A) Jurassic Central Atlantic Rifting Phase. North America is separating from South America. (B) Early Cretaceous Africa Rifting Phase. Africa separates from South America in a counter clockwise motion. (C) Late Cretaceous to Recent Passive Margin Phase. Ongoing phase of significant ocean crust development.
Figure 2.3  Stratigraphy of Guyana-Suriname Basin from Triassic to Recent showing the generalized lithology of the Guyana-Suriname Basin from shelf to basin as well as the positions of major unconformities. The Berbice unconformity is in orange for emphasis (Modified from Workman & Birnie, 2007).
<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>Era</th>
<th>Period</th>
<th>Stage</th>
<th>Shelf</th>
<th>Paleo-Shelf Margin</th>
<th>Basin</th>
<th>Unconformity</th>
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<td>Corentyne</td>
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<td>Pomeroon</td>
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<tr>
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<td>Tertiary</td>
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<td>Georgetown</td>
<td>Eagle</td>
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<td>Tertiary</td>
<td>Priabonian</td>
<td>New Amsterdam</td>
<td>Shelf Margin Delta</td>
<td>Berbice</td>
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<tr>
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<td>Cenomanian</td>
<td>Canje</td>
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<td>Maastrichtian</td>
<td>Potogo</td>
<td>Essequibo</td>
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<td>Aptian</td>
<td>Stabroek</td>
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<td>Demerara Plateau</td>
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<td>Basement</td>
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<td>251.0</td>
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<td></td>
<td>Continental Clastics</td>
<td></td>
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</tr>
</tbody>
</table>

Legend:
- Sandstone
- Mudstone
- Carbonates
- Shale
- Source Rock
- Continental Clastics
Figure 2.4  Cretaceous paleogeography of the Guyana-Suriname Basin. Red dots represent locations of wells whose data was used in the paleographic reconstruction. The white rectangular box represents the approximate location of the study area. (A) During the Albian, the basin had a shelf with both siliciclastics and carbonates, while shelf margin deltas transported siliciclastics basinward. A shelf margin failure — possibly associated with the separation of South America from Africa—is thought to have occurred in the late Albian, transporting material from a roughly 1000km$^2$ shelf area basinwards (Erlich & Keens-Dumas, 2007). (B) During the Cenomanian-Santonian, there was a regional flooding event that deposited the Canje formation — the source rock of the basin, while shelf margin deltas continued to supply clastic sediment basinward. (C) During the Campanian-Maastrichtian, slope feeder systems supplied clastic sediment from the shelf basinward (Modified from Erlich & Keens-Dumas, 2007).
Figure 2.5 Map showing location of wells with truncated or missing Turonian-Santonian sections. White rectangle and white circle are the approximate locations of the Berbice Canyon and Horseshoe-01 well respectively. (Modified from Erlich & Keens-Dumas, 2007)
CHAPTER 3
DATA SET AND METHODOLOGY

3.1 Dataset

The datasets used in this study include a 3D seismic reflection survey and well data.

The 3D seismic was acquired by Repsol and its partners from the Georgetown and Kanuku blocks of offshore Guyana. The seismic volume covers an area of about 7000 km$^2$ (Figure 2.1), has inline and crossline spacing of 12.5m and a sample rate of 2ms. The 3D data provided by Repsol, contains both time and depth seismic volumes. The 3D seismic volumes are pre-stack time migrated and pre-stack depth migrated respectively, as well as zero phase with American normal polarity (an increase in acoustic impedance is represented by a peak).

Well data was provided by Repsol in the form of chronostratigraphic data from the Horsehoe-01 well drilled adjacent to the Berbice Canyon by CGX Energy in 2000 (Workman & Birnie, 2007). The chronostratigraphic data was provided in the form of a table linking chronostratigraphic datums and their type (conformity or unconformity) to measured depths within the well. The table will not be shown for proprietary reasons.

3.2 Mapped Seismic Horizons

Due to the absence of well data directly through the Berbice Canyon to definitively constrain horizon ages, horizons in this study were named using a generic naming scheme.

Five key incisional horizons were mapped, from oldest to youngest: Basal Incision (BI), Incision 1 (I1), Incision 2 (I2), Incision 3 (I3), Incision 4 (I4), and Incision 5 (I5) (Figure 3.1). The basal incision defines the shape and accommodation of the basal-most canyon while
Incisions 1 through 5 are the major incisional horizons following the basal incision. Each major incisional horizon was chosen primarily due to its regionally extensive nature as well as the seismic reflection terminations along it, primarily truncation (Mitchum et al, 1977a). Each incision was first mapped on a high amplitude continuous peak (red) or trough (blue) where possible — primarily on the shelf adjacent to the incisional axis — and was these two more easily defined horizons were connected through areas of more discontinuous low amplitude reflectors.

The focus of this study is the clinoforms that appears between Incisions 3 and 4 (Figure 3.2). For this purpose, between the two incisions, clinoforming surfaces were interpreted, each encapsulating a clinothem with a shared distinctive geometry, shape, and/or trajectory.

Additionally, an approximate capping flooding surface was mapped, representing a period of relative quiescence and marking the end of the major incisional events forming the canyons. Each interpretation was verified on crosslines, inlines and random lines.

3.3 Seismic Attributes

Mapped seismic horizons were converted to surfaces which were then smoothed. Some of these smoothed surfaces were used to slice through the seismic volume and had seismic attributes run on them in order to image geomorphic architecture of the clinoforming canyon fill.

Seismic attributes utilized include root mean squared (RMS) amplitude and maximum and minimum amplitude functions run between intervals of interest.

3.4 Decompaction

In order to make more accurate measurements and calculations, the effects of post-depositional compaction on porosity need to be taken into account. Paxton et al 2002 developed an intergranular volume compaction curve using data gathered from relatively un-cemented
reservoir sandstones of varying ages, depths, and geographic locations (Figure 3.3). The 2002 study uses the assumption that at the surface, a rigid-grain sandstone’s intergranular porosity is ~40%. Between depths of 1500m and 2500m, intergranular volume gradually declines from 28% to 26%. From 2500m to 6700m, intergranular volume remains stable at 26% (Paxton et al, 2002).

The compaction curve serves as a reasonable estimate in the study area given the predominance of siliciclastics on the Late Cretaceous shelf (Figure 2.4, Figure 2.5). The Berbice canyon and its fill generally fall within depths of 2250m and below. Therefore, using Paxton et al 2002’s volume compaction curve it was estimated that at the surface, the sediment within the canyon had an intergranular volume of 40% which declined to 26% when buried. Using a best-fit power law curve through Paxton et al 2002’s data points, this resulted in the decompaction factor of ~1.3 used in this study (Sedimentary Analogs Database, 2017).

3.5 Sediment Balance

To estimate the total sediment load that bypassed the Berbice Canyon, a number of simplifying assumptions were made.

3.5.1 Total Sediment Load Discharged by River

To calculate the estimated total sediment load discharged by the proto-Berbice river, its estimated suspended sediment load discharge rate was multiplied by time.

To estimate the suspended sediment load discharge rate of the proto-Berbice river, modern analog rivers were selected from Milliman & Farnsworth’s 2013 dataset. Similar to the proto-Berbice, the Congo and Orinoco rivers are both situated on passive margins in tropical and humid to wet climates. In addition, both river systems were cross-referenced with data from Patruno et al, 2015 to determine that they are modern rivers associated with both shoreline and
shelf margin deltas. The Orinoco and Congo rivers have a total suspended sediment load rate of 150 and 43 Mt/year respectively. As a result, an average value of ~100 Mt/year was used.

An assumption was also made about total duration of suspended sediment discharge. The estimated sediment load discharge rate of the analog rivers was applied on different time estimates between the likely Coniacian to Santonian aged Berbice unconformity and the early Maastrichtian conformity observed in chronostratigraphic well data of the Horseshoe 01 well. Maximum, mean and minimum estimates of 3, 6, and 9 million years were used.

3.5.2 Total Sediment Load Entering the Berbice Canyon

The total sediment load discharged by the river would not have all made its way into the Berbice Canyon. A fraction of the sediment discharge would have been deposited en route to the canyon. To account for this sediment loss, an assumption is made that only 20% of the sediment load enters the canyon. This assumption is based on a midway value between observations made in two river associated shelf incising canyons — the Swatch of No Ground and Eel canyons. The Swatch of No Ground Canyon receives only 30% of the sediment discharged by its associated Ganges-Brahmaputra river system, while the remaining 70% is sequestered in flood plains and the subaqueous delta (Goodbred & Keuhl, 1999). The Eel canyon receives roughly 12-19% of the Eel River’s sediment discharge, the rest is sequestered on the shelf and slope (Romans et al, 2016).

3.5.3 Total Volume of Sediment Deposited in the Berbice Canyon

The total volume of sediment deposited by the river into the Berbice Canyon is estimated as the volume of sediment in its incisional axis.
3.5.4 Total Volume of Shelf Incised and Transported Basinward

The total volume of sediment incised out of the shelf and transported basinward was approximated by calculating the sum of the spatial volume between each incision surface and an arbitrarily defined straight line top from lateral horizons defined on the eastern and western margin (Figure 3.1). This method is based on the assumption that the volume that could be incised out of the shelf by the incision would be the volume within the theoretical incision “container” when it is filled to spill. Figure 3.4 shows the isopachs between each incision and its arbitrary top.

3.5.5 Total Bypass Sediment Load

The total suspended sediment load that would have bypassed the Berbice canyon and been transported basinward is estimated by subtracting the total suspended sediment load deposited in the canyon from the sum of the load of incised shelf sediment and the total sediment load that entered the canyon. To perform this calculation, cubic kilometer volumes are converted to loads in megatons. The conversion is done assuming quartz-rich sand; ~60% sediment volume and ~40% intergranular volume (Paxton et al, 2002); and quartz particle density of 2650 kg/m$^3$.

3.6 Clinoform Morphometric Parameters

Clinoform morphometric parameters measured in this study include foreset length, foreset slope, and shape ratio.

The foreset slope was calculated as the angle between the approximated right angle-triangle defined by the height and approximate length of a given clinoform (Figure 1.1). This calculation was done by calculating the arc cosine of the quotient of foreset length and height.
In order to systematically quantify the shape of clinothems, shape ratio or normalized elevation of the inflection point was calculated. This shape ratio is calculated as the ratio of the inflection point height to the total height of the clinoform (Pirmez et al, 1998; Patruno et al, 2015) (Figure 1.1). Total clinoform height would be the height difference between horizontal topset strata and the clinoform toe. In the case of a sloping topset, the difference is calculated between the shallowest point of the river mouth and the clinoform toe point (Pirmez et al, 1998; Patruno et al, 2015). Theoretically, if the value of the shape ratio is <0.4, the clinothem is symmetric and sigmoidal. If the shape ratio is ≥0.4, the clinothem is asymmetrical and oblique (Pirmez et al, 1998; Patruno et al, 2015). The overall clinoform trajectory was determined by noting the position of rollover points of distinct clinothems in a given dipline.

For the purpose of comparison to existing datasets of clinoform morphometrics, the clinoforms were decompacted and flattened on a continuous downlap surface. Decompaction and flattening correct for the compressing effects of compaction and the exaggerated steepness caused by the slope of the canyon floor, respectively.
Figure 3.1  Example cross section through Berbice Canyon showing an un-interpreted seismic line and the same line interpreted to show sample arbitrary tops (dotted lines) assigned to incisions (solid lines) for maximum incised sediment volume calculations. Inset image uses a depth map of the basal incision within the seismic survey boundary to illustrate the location of the cross section (dashed white line). Red arrows represent truncation. Basal Incision (BI), Incision 1 (I1), Incision 2 (I2), Incision 3 (I3), Incision 4 (I4), Incision 5 (I5). [Vertical Exaggeration: 5x]
Figure 3.2  Example dip line through Berbice Canyon showing an un-interpreted line and the same line interpreted to show incision surfaces and the clinoform surfaces (black dashed lines) between incisions 3 and 4. Inset image uses a depth map of the basal incision within the seismic survey boundary to illustrate the location of the dip line (dashed white line). Basal Incision (BI), Incision 1 (I1), Incision 2 (I2), Incision 3 (I3), Incision 4 (I4), Incision 5 (I5). [Vertical Exaggeration: 5x]
Figure 3.3  Intergranular volume compaction curve for an un-cemented rigid-grain reservoir sandstone. Line of fit is for easy viewing and not a mathematical fit (Paxton et al 2002).
Figure 3.4  Isopachs between each incision surface and arbitrarily defined top (as shown in Figure 3.1) for: A) Basal Incision; B) Incision 1; C) Incision 2; D) Incision 3; E) Incision 4 and F) Incision 5. Contour Interval: 65m. Blue line shows outline of mapped canyon area.
CHAPTER 4

GEOMETRIC EVOLUTION OF BERBICE INCISIONS

Canyons and valleys are dynamic features whose geometries evolve through the interplay of erosion and deposition influenced by a variety of autogenic and allogenic forcings such as relative sea level, sediment supply, tectonics, and channel avulsion (Strong & Paola, 2008; Blum & Törnqvist, 2000). In their 2008 study, Strong and Paola distinguished between topographic and stratigraphic valleys. A topographic valley is a valley that defined surface topography at some point in time (Strong & Paola, 2008). A stratigraphic valley is a “composite valley-form erosional surface” — a surface that bears the shape or form of a valley in the stratigraphic record, but never existed in that form on the Earth’s surface (Figure 4.1). An example of a topographic valley preserved in the rock record would be one that formed in a single event and was buried without modification to its surface (Strong & Paola, 2008). The principle behind stratigraphic and topographic valleys is applicable to canyons.

The incisions of the Berbice Canyon show evidence of multiple phases of cut and fill along their margins (Figure 3.1), implying multiple phases of narrowing and widening of the incisional axis. Therefore, it is likely that the preserved incisions are time-transgressive stratigraphic surfaces and each incision is not representative of the canyon’s surface geometry at an instant in time.

By definition, all the incisions within the canyon truncate adjacent seismic reflectors, though it need not be at every point along its length. The incisional surfaces share the properties of dipping basinwards in a southwest to northeast direction. Additionally, there is a general trend of thalweg migration towards the northwest as well as a significant sharp break in slope that
occurs ~89km away from the canyon head of the basal incision. This break marks the transition for all the incisional surfaces to a depositional basin fan-like environment (Figure 4.2).

4.1 Basal Incision

The basal incision was interpreted on a seismic peak (red) and is marked by significant truncation of adjacent seismic reflectors. Underlying the basal incision are low amplitude chaotic reflectors representing mass transport deposits (Figure 4.3, Figure 4.4).

The basal incision of the Berbice canyon bifurcates into two smaller feeder canyons in its proximal reaches, both roughly trending southwest-northeast (Figure 4.2A). The western margin of the incision is cuspate in nature. Each cusp was likely the site of local mass failures and regions of other destructional processes. The eastern margin, in contrast, is relatively more constructional in nature and is marked by what appear to be gullies incising along its walls.

The basal incision has a maximum width of ~20 km and a maximum relief of 1200 m (Table 4.1).

4.2 Incision 1

Incision 1 was interpreted on a seismic trough (blue) and it truncates adjacent seismic reflectors (Figure 4.3, Figure 4.4).

Like the basal incision, Incision 1 bifurcates into two feeder canyons in its proximal reaches, both roughly trending southwest-northeast (Figure 4.2B). However, in contrast to the basal incision, Incision 1 is generally consistently wider than the basal incision and has a less markedly cuspate western margin.

Incision 1 reaches a maximum width of ~29 km and a maximum relief of ~1250 m (Table 4.1).
4.3 Incision 2

Incision 2 was interpreted on a seismic peak (red) and it truncates adjacent seismic reflectors (Figure 4.3, Figure 4.4).

Similar to the basal incision and Incision 1, Incision 2 has more than one canyon feeder at its head with both roughly trending southwest-northeast. Additionally, like Incision 1, Incision 2 is generally wider than the basal incision (Figure 4.2C). However, in contrast to both the basal incision and Incision 1, Incision 2’s canyon heads have a marked difference in width: one relatively wide (~10km) and the other relatively narrow (~3km). However, on its eastern margin and adjacent to its incisional axis, Incision 2 is cut proximally by smaller scale incisional features (1-3km wide and 5-15 km long) trending in a southeast to northwest direction (Figure 4.2C).

Incision 2 reaches a maximum width of ~27 km and a maximum relief of ~1250 m (Table 4.1).

4.4 Incision 3

Incision 3 was interpreted on a seismic trough (blue) (Figure 4.3, Figure 4.4). In addition to being incisional in its proximal reaches, Incision 3 generally serves as a downlap surface for the clinoforms that will be addressed in the next chapter.

Incision 3 begins with a southwest-northeast trending canyon head and progressively widens downdip (Figure 4.2D). The incision reaches a maximum width of ~29 km and a maximum relief of ~1140m (Table 4.1).
4.5 Incision 4

Incision 4 was interpreted on a seismic peak (red) (Figure 4.3, Figure 4.4). In addition to being incisional in its proximal reaches, Incision 4 serves as a downlap surface for clinoforms. However, its clinothems are outside the scope of this study.

Incision 4 begins incising in a roughly southwest-northeast direction. It begins this 30km further basinward than previous incisions as well as with a narrow incision (~5km across) that sharply widens in the basinward direction (Figure 4.2E).

The incision reaches a maximum width of ~30 km and a maximum relief of ~925 m (Table 4.1).

4.6 Incision 5

Incision 5 was interpreted on a seismic peak (red) (Figure 4.3, Figure 4.4). Incision 5 begins incising 55 km further basinward than the basal incision. Similar to Incision 4, Incision 5 widens more quickly in the basinward direction than preceding incisions (Figure 4.2F).

Incision 5 reaches a maximum width of ~33 km and a maximum relief of ~800 m (Table 4.1).

4.7 Discussion

Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 place the incisional surfaces together and show their combined location and spatial relationships from proximal to distal using distinct cross sections across the study area. The cross sections underscore the proximal bifurcation, the basinward widening of the incisions, their migration towards the northwest and ultimately their transition to a basin floor fan environment as observed in cross section H-H’.
From the depth maps (Figure 4.2) we observe that the direction of downdip sediment supply is from the southwest to the northeast. This is expected because the shelf dips southwest to northeast. Notably, in the case of incisions with bifurcated heads, the isopach maps of maximum potential volume of basin-transported incised sediment (Figure 3.4A-C) highlight the dominance of the eastern incision. This dominance is shown through the greater and more sustained thickness of sediment through this feeder.

Using a number of simplifying assumptions, the estimated total suspended sediment load that bypassed the Berbice Canyon is in the range of 0.6 - 1.8 x 10^8 Mt. (Table 4.2). Therefore, sediment bypasses the canyon at a rate of 20.2 - 20.5 Mt/yr. For comparison, the Congo axial fan has a volume of 8500km^3 accumulated over the past 210,000 years (Picot et al, 2016). This translates to an accumulation rate range of 64 – 107 Mt/yr. The lower value assumes a porosity of 40% while the upper value assumes that the 8500km^3 is solely sediment volume. Additionally, the Bengal fan – the largest submarine fan in the world (Curray et al, 2002) – and its associated Swatch of No Ground Canyon have a combined accumulation rate of ~300 Mt/yr. on historical timescales (<10^2 years ago) (Goodbred & Keuhl, 1999; Romans et al, 2016).

Notably, the sediment load deposited in the Berbice canyon –5.2 x 10^6 Mt – is one to two orders of magnitude smaller than the sediment bypassing through it. This underscores the canyon’s nature as a sediment conduit to deeper water.
Figure 4.1  Figure showing the interplay between relative sea level (used as an example of a driver that can influence valley shape), and the narrowing and widening of the topographic valley surface as relative sea level falls and rises respectively. In G, the preserved stratigraphic valley depth never existed in that form on the Earth’s surface. (From Strong & Paola, 2008)
Figure 4.2  Depth maps of the major incisions in the Berbice Canyon. From oldest to youngest: BI – Basal Incision; I1- Incision 1; I2- Incision 2; I3- Incision 3; I4- Incision 4; I5-Incision 5. Lines A-A’ and B-B’ are shown in Figures 4.3 and 4.4.
Figure 4.3  Seismic cross section A-A'. Location of the line is shown in Figure 4.2. Alb. Unc. - Albian Unconformity; MTD-Mass Transport Deposit; BI – Basal Incision; I1- Incision 1; I2- Incision 2; I3-Incision 3; I4- Incision 4; I5-Incision 5; FS-Flooding Surface. Red arrows represent truncation. [Vertical Exaggeration: 5x]
Figure 4.4 Seismic cross section B-B’. Location of the line is shown in Figure 4.2. Alb. Unc. - Albian Unconformity; BI – Basal Incision; I1- Incision 1; I2- Incision 2; I3- Incision 3; I4- Incision 4; I5- Incision 5; FS- Flooding Surface. Red arrows represent truncation. Yellow arrows represent toplap. Black arrows represent onlap. [Vertical Exaggeration: 5x]
Table 4.1 Table showing for each incision: maximum cross-sectional width (in kilometers), maximum difference in height between each incision and its arbitrarily defined top (in meters), volume of incised sediment transported to the basin in erosive events (in cubic kilometers) and the total area of the shelf incised (in squared kilometers).

<table>
<thead>
<tr>
<th>Incision</th>
<th>Maximum Width (km)</th>
<th>Maximum Relief (m)</th>
<th>Volume of Incised Shelf Transported to Basin (km$^3$)</th>
<th>Incised Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal Incision</td>
<td>20</td>
<td>1200</td>
<td>710</td>
<td>1,174</td>
</tr>
<tr>
<td>Incision 1</td>
<td>29</td>
<td>1250</td>
<td>1050</td>
<td>1,482</td>
</tr>
<tr>
<td>Incision 2</td>
<td>27</td>
<td>1250</td>
<td>1040</td>
<td>1,757</td>
</tr>
<tr>
<td>Incision 3</td>
<td>29</td>
<td>1140</td>
<td>740</td>
<td>1,338</td>
</tr>
<tr>
<td>Incision 4</td>
<td>30</td>
<td>925</td>
<td>475</td>
<td>934</td>
</tr>
<tr>
<td>Incision 5</td>
<td>33</td>
<td>800</td>
<td>355</td>
<td>982</td>
</tr>
<tr>
<td>Total</td>
<td>N/A</td>
<td>N/A</td>
<td>4370</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4.2 Table showing estimated total sediment bypass load in megatons and parameters used for calculation. Sediment discharge rate was estimated using an average value between Congo and Orinoco Rivers. Cubic kilometer values were converted to megatons assuming quartz-rich sand; ~60% sediment volume (Paxton et al, 2002); and quartz particle density of 2650 kg/m$^3$.

<table>
<thead>
<tr>
<th>Time (My)</th>
<th>Total Suspended Sed. Load Rate (Mt/yr.)</th>
<th>Total Suspended Sed. Load (Mt)</th>
<th>Discount Factor</th>
<th>Total Sed. Load entering Canyon (Mt)</th>
<th>Total Sed. Volume Incised out of shelf (km$^3$)</th>
<th>Total Sed. Load Deposited in Canyon (Mt)</th>
<th>Total Sed. Load Incised out of shelf (Mt)</th>
<th>Total Sed. Load Deposited in Canyon (Mt)</th>
<th>Total Bypass Sed. Load (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>100</td>
<td>300,000,000</td>
<td>0.2</td>
<td>720,000,000</td>
<td>4370</td>
<td>3320</td>
<td>6,948,300</td>
<td>5,278,800</td>
<td>61,669,500</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>600,000,000</td>
<td>0.2</td>
<td>1,440,000,000</td>
<td>4370</td>
<td>3320</td>
<td>6,948,300</td>
<td>5,278,800</td>
<td>121,669,500</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>900,000,000</td>
<td>0.2</td>
<td>2,160,000,000</td>
<td>4370</td>
<td>3320</td>
<td>6,948,300</td>
<td>5,278,800</td>
<td>181,669,500</td>
</tr>
</tbody>
</table>
Figure 4.5  Location of cross sections A-A’, B-B’, C-C’, D-D’, E-E’, F-F’, G-G’, H-H’, and I-I’ whose incisions are shown in Figures 4.6, 4.7, and 4.8.
Figure 4.6  Sections A-A', B-B', C-C', and D-D' showing evolution of the geometry of the incisions within the Berbice Canyon from proximal to distal (Sections continued in Figure 4.7). Location of cross sections are shown in Figure 4.5. Dark purple – Basal Incision, Light Purple – I1; Dark blue- I2; Light blue – I3; Dark Green – I4; Light Green-I5; FS-Flooding Surface. Black dashed line represents an incisional surface that is not regionally extensive.
Figure 4.7  Sections E-E’, F-F’, G-G’, and H-H’ showing evolution of the geometry of the incisions within the Berbice Canyon from proximal to distal (Sections continued from Figure 4.6). Location of cross sections are shown in Figure 4.5. Dark purple – Basal Incision, Light Purple – I1; Dark blue- I2; Light blue – I3; Dark Green – I4; Light Green-I5; FS-Flooding Surface. Black dashed line represents an incisional surface that is not regionally extensive. It represents a canyon feature forming distally and below the downdip basin fan expression of the Berbice Canyon.
Figure 4.8  Section I-I’ showing geometry of Berbice canyon incisions in dipline. Location of cross sections are shown in Figure 4.5. Black – Albian Unconformity, Dark purple – Basal Incision, Light Purple – I1; Dark blue- I2; Light blue – I3; Dark Green – I4; Light Green-15; FS-Flooding Surface.
CHAPTER 5
CLINOFORMS

Between Incisions 3 and 4 are clinoforms that can be subdivided into eight clinothems by surfaces numbered C1 to C7. Figure 5.1 and Figure 5.2 are random seismic lines on the eastern and western margins respectively displaying the clinothems roughly along their dip. Evidence of these clinothems are likely focused along the canyon margins and not in its center because there is a greater preservation potential away from the axis of re-incision and reworking by later incisional events.

Depth maps of each surface I3 to C7 and the thickness between each surface are shown in Figure 5.3 and Figure 5.4 respectively. Morphometric parameters for all clinothems are summarized in Table 5.1. Overall, the clinothems are oblique in shape, display maximum thicknesses in the range of 270-520 m, show mean foreset lengths in the range of 1944-7479 m, mean foreset heights in the range of 104 to 446 m, mean foreset slopes in the range of 2.92 to 4.07° (Table 5.1) and display a progradational stacking pattern (Figure 5.5). Figure 5.6 maps the location of upper and lower rollover point fronts of each clinothem and it is observed that spatially, a number of these clinothems are observed to possess a mounded shape.

This chapter addresses each clinothem sequentially, noting its seismic, morphometric and spatial characteristics as well as potential sediment supply conduits. In instances where it is difficult to conclusively distinguish a channel from a lineament on the canyon wall formed by collapse or erosion, the feature will be referred to as a feeder.
5.1 Clinothem 1

Clinothem 1 is the most proximal clinothem and is comprised of all clinoforms between surfaces I3 and C1. These are the smallest scale clinoforms (relative to Clinothems 2 to 8), with an average foreset height and foreset length of 104m and 1944m respectively. Clinothem 1 can be split into two sub-clinothems: 1A and 1B (Figure 5.7).

5.1.1 1A

1A clinoforms generally dip towards the northeast (Figure 5.6). The clinoforms are distinguishable despite their generally low amplitude and discontinuous seismic character.

A minimum amplitude extraction run between surfaces I3 and C1 shows evidence of channelization (Figure 5.8). The channels are oriented from southwest to northeast and likely supplied sediment to Sub-Clinothem 1A.

5.1.2 1B

Sub-clinothem 1B is also comprised of relatively small-scale clinoforms with an overall low amplitude character (Figure 5.7). These clinoforms dip towards the northwest (Figure 5.6). An RMS amplitude extraction — run in a window 80m below a surface C1 offset by -60m — shows a meandering channel within a small-scale side incision on the eastern margin (Figure 5.8). This incisional feature originates in surface I2 and the channelized fill of the canyon feature persists within Sub-clinothem 1B.

5.2 Clinothem 2

Clinothem 2 occurs downdip of 1A and 1B and is comprised of low to medium amplitude reflectors. Clinoforms composing Clinothem 2 exhibit average foreset length, height and slope of
3676 m, 219 m and 3.37° respectively (Table 5.1). Clinothem 2 is oriented towards the northwest (Figure 5.6).

5.3 Clinothem 3

Clinothem 3 is comprised of clinoforms occurring between surfaces C2 and C3 (Figure 5.9). These clinoforms exhibit average foreset length, height and slope of 3339 m, 171 m and 2.92°, respectively (Table 5.1). The seismic reflectors in this clinothem are relatively continuous and low to medium amplitude. Clinothem 3 occurs in a similar orientation to Clinothem 2; therefore, they likely share a sediment supply source (Figure 5.6).

5.4 Clinothem 4

Clinothem 4 is comprised of clinoforms between surfaces C3 and C4. The clinothem generally decreases in amplitude strength moving upwards from surface C3 to C4. The clinothem is made up of two adjacent sub-clinothems, A and B. Sub-clinothem 4A exhibits compensational deposition as the sediment was fed into the canyon through a localized topographic low along the eastern wall (Figure 5.3D, Figure 5.4D, Figure 5.10). Clinothem 4 appears to be supplied with a southeastern sediment source (Figure 5.11).

5.5 Clinothem 5

Clinothem 5 refers to the clinoforms that are found between surfaces C4 and C5. The seismic reflectors in this clinothem are generally high amplitude and continuous. These clinoforms exhibit average foreset length, height and slope of 6076 m, 413 m and 4.07°, respectively (Table 5.1). Sediment within this clinothem appears to be sourced from the southeast and southwest. Distinct mounded clinothem sub-bodies are observed through RMS and minimum amplitude extractions between the two surfaces (Figure 5.12).
5.6 Clinothem 6

Clinothem 6 encompasses clinoforms between surfaces C5 and C6. This clinothem is unique because, as in previous examples where clinoforms were confined to the eastern margin of the incisions, in this clinothem, there are observable clinoforms on both the eastern and the western margin (Figure 5.1, Figure 5.2). Seismic reflectors within this clinothem are generally continuous with a bright amplitude. Clinothem 6 clinoforms on the eastern margin on average have longer and taller foresets in comparison to those on the western margin (Table 5.1).

Clinothem 6 sediment on the eastern margin is likely supplied via the same source as Clinothem 5. Clinothem 6 appears to initiate above a Clinothem 5 feeder (Figure 5.12A, Figure 5.13). Sediment on the western margin was supplied from the southwest. Figure 5.14 shows evidence of feeders.

5.7 Clinothem 7

Clinothem 7 includes clinoforms between surfaces C6 and C7. The individual seismic reflectors become more discontinuous and dull as one progresses up section from C6 to C7. Clinothem 7 has a very mounded shape, observable as an isopach thick (Figure 5.4G). The reflectors within the clinothem often truncate against surface C7 (Figure 5.1). Clinoforms in this clinothem exhibit average foreset length, height and slope of 5288 m, 381 m and 4.01°, respectively (Table 5.1).

Sediment is supplied to this clinothem via southwest-northeast and southeast-northwest trending channels and feeders. These channels and feeders are observable in cross-section as well as in planform on an RMS amplitude extraction between C6 and C7. Single channels and feeders merge, delivering the canyon sediment that becomes Clinothem 7 (Figure 5.15).
5.8 **Clinothem 8**

Clinothem 8 includes clinoforms between clinoforming surface C7 and incisional surface I4. Reflectors in this clinothem are medium to high amplitude continuous reflectors. Compensational deposition is observed in this final stage of clinoforms, as sediment feeds into the canyon through the persistent localized topographic low in the canyon wall observable in surface C7 (Figure 5.3H, Figure 5.16).

5.9 **Summary of I3-I4 Clinothem Observations**

- Deposition of clinothems occurs along both the eastern and western margins of the canyon. However, deposition is overwhelmingly on the eastern side. It is important to note that evidence of these clinothems is focused along the canyon margins and not in its center likely due to a greater preservation potential away from the locus of major erosive and incisional activity.

- In the proximal reaches of Incision 3, Clinothem 1 is deposited which has the smallest scale clinoforms with an average foreset height and foreset length of 104m and 1944m respectively (Table 5.1).

- A map of upper and lower clinoform rollover point fronts of each clinothem shows that Clinothems 2 to 5 on the eastern margin predominantly migrate in a general northwest direction. Clinothems 6 and 7 migrate towards the northeast, while Clinothem 8 migrates back towards the northwest (Figure 5.6).

- Clinothems exhibit compensational deposition by preferentially depositing within topographic lows. This may explain why Clinothem 8 migrates in a different direction from Clinothems 6 and 7.
• Clinothems between surfaces I3 and I4 are generally mounded in shape and are oriented to the northwest or northeast. However, clinoforms within these bodies generally dip in an arc in northeast and northwest directions.
Figure 5.1  A) Dip line $X-X'$ along eastern margin showing incisional surfaces (in grey) and clinoforming surfaces C1 through C7 B) Dip line flattened on downlap surface I3. This is partly done to verify that they are indeed clinoforms. They are because they maintain a relative incline even when flattened on their downlap surface. [Vertical Exaggeration: 5x] Basemap shows location of $X-X'$. Blue outline represents boundary of basal incision surface –BI. Lilac outline represents incisional boundary of surface I3.
Figure 5.2  A) Dip line Y-Y’ along western margin showing incisional surfaces (in grey) and clinoforming surfaces C1 and C3-C6. Not all surfaces persist to the western margin. B) Dip line flattened on downlap surface I3. This is partly done to verify that sediment packages are indeed clinoforms. Clinothem 6 between surfaces C5 and C6 remains ostensibly thick and inclined. [Vertical Exaggeration: 5x] Basemap shows location of Y-Y’. Blue outline represents boundary of basal incision surface –BI. Lilac outline represents incisional boundary of surface I3.
Figure 5.3  Depth maps of surfaces: A) I3, B) C1, C) C2, D) C3, E) C4, F) C5, G) C6, and H) C7. Blue line represents boundary of basal incision surface –BI. Lilac line represents incisional boundary of surface I3. Dashed lines represent location of seismic sections shown in Figures 5.1, 5.2 and 5.7 to 5.16. Contour interval: 25m
Figure 5.4  Isopach between surfaces: A) I3 and C1, B) C1 and C2, C) C2 and C3, D) C3 and C4, E) C4 and C5, F) C5 and C6, G) C6 and C7, and H) C7 and I4. Blue line represents boundary of basal incision surface –BI. Lilac line represents incisional boundary of surface I3. Dashed lines represent location of seismic sections shown in Figures 5.1, 5.2 and 5.7 to 5.16. Contour interval: 35m.
<table>
<thead>
<tr>
<th>Clinothem</th>
<th>Maximum Clinothem Thickness (m)</th>
<th>Average Clinoform Height (m)</th>
<th>Average Foreset Height (m)</th>
<th>Average Foreset Length (m)</th>
<th>Average Foreset Slope (°)</th>
<th>Average Shape Ratio</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>119</td>
<td>104</td>
<td>1944</td>
<td>3.09</td>
<td>0.67</td>
<td>Oblique</td>
</tr>
<tr>
<td>2</td>
<td>270</td>
<td>226</td>
<td>219</td>
<td>3676</td>
<td>3.37</td>
<td>0.59</td>
<td>Oblique</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>205</td>
<td>171</td>
<td>3339</td>
<td>2.92</td>
<td>0.60</td>
<td>Oblique</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>226</td>
<td>179</td>
<td>3012</td>
<td>3.42</td>
<td>0.62</td>
<td>Oblique</td>
</tr>
<tr>
<td>5</td>
<td>420</td>
<td>503</td>
<td>413</td>
<td>6076</td>
<td>4.07</td>
<td>0.61</td>
<td>Oblique</td>
</tr>
<tr>
<td>6 (Eastern Margin)</td>
<td>490</td>
<td>502</td>
<td>446</td>
<td>7479</td>
<td>3.30</td>
<td>0.66</td>
<td>Oblique</td>
</tr>
<tr>
<td>6 (Western Margin)</td>
<td>520</td>
<td>401</td>
<td>323</td>
<td>4617</td>
<td>4.01</td>
<td>0.68</td>
<td>Oblique</td>
</tr>
<tr>
<td>7</td>
<td>310</td>
<td>432</td>
<td>381</td>
<td>5288</td>
<td>4.01</td>
<td>0.57</td>
<td>Oblique</td>
</tr>
<tr>
<td>8</td>
<td>380</td>
<td>379</td>
<td>264</td>
<td>4626</td>
<td>3.27</td>
<td>0.55</td>
<td>Oblique</td>
</tr>
<tr>
<td>Average</td>
<td>360</td>
<td>332</td>
<td>278</td>
<td>4451</td>
<td>3.50</td>
<td>0.62</td>
<td>Oblique</td>
</tr>
</tbody>
</table>

Table 5.1  Table summarizing all the morphometric parameters of the clinothems between surfaces I3 and I4. These parameters include maximum thickness, average clinoform height, foreset length, foreset height, foreset slope and shape ratio. Values are corrected for decompaction and steep shelf.
Figure 5.5  A) Section X-X’ from Figure 5.1 showing location of rollover points and clinoform trajectory of surfaces C1 to I4. Clinoforms display a progradational and downstepping stacking pattern. B) Section X-X’ flattened on clinoforms downlap surface to correct for steep shelf. Clinoforms maintain progradational stacking pattern, but no downstepping (Figure 1.3). [Vertical Exaggeration: 5x]
Figure 5.6 Upper and lower rollover point fronts of clinothem in solid and dashed lines respectively. Rollover point shows the spatial relationships between the clinothems. Blue line represents boundary of basal incision surface –BI. Lilac line represents incisional boundary of surface I3.
Figure 5.7  Seismic sections A-A’ and B-B’ showing the internal makeup of sub-Clinothems 1A and 1B, respectively, which occur between surfaces I3 and C1. Dashed line represents the downlap surface of the clinothems. Location of cross-section lines shown in basemap, Figure 5.3A and Figure 5.4A. [Vertical Exaggeration: 5x]
Figure 5.8  A) Minimum amplitude extraction between surfaces I3 and C1. Evidence of channelization. Dotted lines represent channel outlines. B) Seismic cross section C-C’. Location of cross section line shown in Figure 5.8A. Figure shows Sub-Clinithem 1A and location of a cross-cutting channel. C) RMS amplitude extraction offset 60m below surface C1 with a search window of -80m. Evidence of a sinuous channel within a side incision D) Seismic cross section D-D’. Location of cross section line shown in Figure 5.8C. Figure 5.8D shows Sub-Clinithem 1B and location of cross-cutting sinuous channel. Location of cross-section lines shown in Figure 5.7, Figure 5.3A and Figure 5.4A. [Vertical Exaggeration: 5x]
Figure 5.9  Seismic section E-E’. Location of E-E’ shown in basemap, Figure 5.3C and Figure 5.4C. Figure shows dipline through Clinothem 3 because dipline X-X’ (Figure 5.1) does not intersect the clinothem.

Figure 5.10  A) Isopach between surfaces C3 and C4 focused on clinothem and showing location of seismic line F-F’. Dashed orange line represents outline of Sub-Clinothems 4A and 4B. B) Seismic cross-section F-F’ showing Sub-Clinothems 4A and 4B. Location of cross-section line shown in Figure 5.3D and Figure 5.4D. [Vertical Exaggeration: 5x]
Figure 5.11  A) Minimum amplitude extraction between surfaces C3 and C4 showing location of section line G-G'. Sediment is supplied from the southeast to the northwest. Sediment fills in feeders on the eastern canyon wall. B) Seismic section G-G’ showing cross section of sediment feeders between surfaces C3 and C4. Location of cross-section lines shown in basemap, Figure 5.3D and Figure 5.4D. [Vertical Exaggeration: 5x]
Figure 5.12  A) RMS amplitude extraction between surfaces C4 and C5 showing location of seismic sections H-H’, I-I’ and J-J’. Figure highlights sediment feeders and mounded sub-clinotheams. B) Minimum amplitude extraction between surfaces C5 and C4 showing location of seismic sections H-H’, I-I’ and J-J’. Mounded sub-clinotheams outlined in dotted lines. C) Seismic section H-H’ shows surfaces C4 and C5 and cross section through sub-clinothem highlighted in green. D) Seismic section I-I’ is a dipline through the sub-clinothem in green. Location of cross-section lines H-H’ and I-I’ shown in basemap, Figure 5.3A and Figure 5.4A. [Vertical Exaggeration: 5x]
Figure 5.13  Seismic section J-J' showing evidence of Clinothem 6 (between surfaces C5 and C6) being sourced above feeder in Clinothem 5. Feeder outlined in dashed blue line. Location of section J-J’ shown in Figure 5.12. Location of cross-section lines shown in basemap, Figure 5.3F and Figure 5.4F. [Vertical Exaggeration: 5x]
Figure 5.14  A) Maximum amplitude extraction between surfaces C5 and C6 shows location of seismic section K-K’. Evidence of feeder on the western canyon margin. Dotted lines represent outline of a sediment feeder. Sediment was supplied from the southwest. B) Seismic cross-section K-K’ showing Clinothem 6 on the western canyon margin. Sediment feeder outlined in dotted lines. Location of cross-section lines shown in basemap, Figure 5.3F and Figure 5.4F. [Vertical Exaggeration: 5x]
Figure 5.15  A) RMS amplitude extraction between surfaces C6 and C7 showing locations of cross sections L-L’ and M-M’. White line shows outline of mounded Clinothem 7 defined in Figure 5.15B. B) Minimum amplitude extraction between surface C7 and a surface C6 that has been vertically offset by -80m. The extraction distinctly highlights the mounded nature of the clinothem, which is outlined. C) Seismic cross section L-L’ showing cross-cut feeders and channels outlined in dotted lines D) Seismic cross section M-M’ showing cross-cut channels observed in Figure 5.15A and outlined in dotted lines. The three crosscut channels merge downdip. Location of cross-section lines shown in basemap, Figure 5.3A and Figure 5.4A. [Vertical Exaggeration: 5x]
Figure 5.16  A) RMS amplitude extraction between surfaces C7 and I4 showing location of seismic sections N-N’ and O-O’. B) Seismic section N-N’ showing dipline through Clinothem 8 along sediment feeder. C) Seismic section O-O’ showing cross-section through feeder. Low amplitude channel features (as outlined in dotted line) observed within the fill. Location of cross-section lines shown in basemap, Figure 5.3H and Figure 5.4H. [Vertical Exaggeration: 5x]
CHAPTER 6
DISCUSSION AND CONCLUSIONS

6.1 Gradient of Incised Substrate

Within the study area, the Berbice Canyon incises into a substrate that has an average gradient of roughly 1.7°. This value exceeds the typical gradient of a passive margin shelf, which is ~0.1° as observed on the current Guyana margin. Therefore, it is possible that the Berbice Canyon may have formed on a steeper than normal shelf or incised the shelf only near its shelf break and is predominantly situated on the slope. However, there is evidence to suggest the potentially greater likelihood of the former.

Regional structural and free-air gravity maps of the Guyana-Suriname basin suggest evidence of a shelf-located depocenter in the Cretaceous that roughly coincides with the study area location (Figure 6.1). This Cretaceous depocenter is located on a structural low observed in the Jurassic acoustic basement, suggesting that the Cretaceous depocenter is above a Jurassic Graben (Yang & Escalona, 2011).

A structural high can be observed in the proximal region of the study area that is truncated by the Albian Unconformity (Figure 4.4). There is also evidence of significant normal faulting. The study of the basement structure was out of the scope of this study, but could be explored in the future to dispute or confirm the notion of a steeper shelf caused by underlying structure.
6.2 Sediment Supply

The river feeding sediment to the Berbice canyon is thought to likely have been from the proto-Berbice and proto-Corantijn/Courantyne rivers (Yang & Escalona, 2011). The present day Berbice and Corantijn Rivers are minor rivers with total suspended sediment loads of 0.2 and 1.1 Mt/year respectively (Milliman & Farnsworth, 2013). Therefore, in order to have supplied sediment to the Berbice Canyon, their predecessors would have been more significant rivers.

Headcutting by the Branco River (Figure 6.2) — a tributary of the Amazon River — is thought to have progressively minimized the influence of the proto-Berbice river to its relative modern insignificance (De Souza et al, 2012; Lujan & Armbruster, 2011).

Studies of evolutionary patterns of Neotropical fishes are used to determine late Cenozoic to Mesozoic drainage patterns in South America (Lundberg et al, 1998; Lujan & Armbruster, 2011). The proto-Berbice river basin is thought to have been one of the largest drainage systems of the central Guiana shield during the Cenozoic (Figure 6.2). The river is thought to have originated from Lake Maracanata which was a lake 75 to 100 m deep which occupied the Takutu Graben (Crawford et al, 1984) (Figure 2.2). In the Early Cretaceous, the lake transitioned to a fluvial environment flowing through its trunk river – Proto Berbice – and its tributaries into the Atlantic (McConnell, as cited in Lujan & Armbruster, 2011).

However, in the seismic volume there is little clear evidence of persistent through-going channelization observed in the interval of clinothems between surfaces I3 and I4. Channel deposits were likely eroded away with subsequent incisional and re-working events.

Additional sediment may have been supplied to the Berbice canyon from sources such as longshore drift currents or through the action of storms. Although, the influence of storms on sedimentation would be restricted by the wave base which typically lies within water depths of
tens of meters (Plint, 2010), super greenhouse climate conditions in the Cretaceous may have
deepened wave base along many of the paleo-continental margins by as much as hundreds of
meters (Arora and Wood, in review). Using clinoform height as an approximation of paleo-water
depth (Pekar & Kominz, 2001), at any given time the clinothems of the Berbice Canyon could
have been in water depths of ~113 - 1300 m (decompacted and un-flattened values), potentially
placing it in the range of storm-supplied sediment.

6.3 Canyon Morphology

The Berbice canyon exhibits a western margin dominated by destructional and failure
processes (Figure 4.2) while its eastern margin exhibits a dominance of clinothem deposition as
observed between surfaces I3 and I4 (Figure 5.1). This difference in margin activities could
potentially be linked to the action of a vector of southeast to northwest oriented longshore drift.

The action of a vector of southeast to northwest oriented longshore drift could be
responsible (Figure 5.6) for sediment supply concentrated on the eastern margin. In addition, the
persistence of these currents interacting with the western canyon margin could create structural
weaknesses that result in failures.

6.4 Clinoform Classification

Patruno et al (2015) analyzed a large dataset of clinoforms which led to the
characterization of different scales of clinoforms based on quantitative parameters. Comparing
the clinoform morphometric parameters of Clinothems 1-8 to the results of that analysis, the
clinoforms appear to be shelf-prism or shelf-margin scale clinoforms (Table 6.1).

The overall downstepping stacking pattern and falling trajectory of the Clinothems 1-8 on
the shelf would normally suggest the movement of large proportions of sediment basinwards
(Johannessen & Steel, 2005). However, the steepness of the substrate likely results in an exaggerated falling clinoform trajectory and when flattened on their downlap surface, the clinoforms maintain only their progradational stacking pattern, but lose their downstepping nature (Figure 5.5). Therefore, they cannot be described as downstepping for purposes of comparison to other clinoform systems.
Figure 6.1   A) Depth map of top of acoustic basement B) Free-air gravity map labelled to show location of Cretaceous depocenter thought to be associated with the topographic low of the basement surface (Sandwell & Smith, 2009 as cited in Yang & Escalona, 2011) White rectangle represents our study area. Figures modified from Yang & Escalona, 2011.
Figure 6.2  Major modern rivers and drainage basins of the Guyana shield. The outline of the proto-Berbice River basin is shown in yellow. The Branco and Essequibo Rivers are numbered 10 and 20, respectively (From Lujan & Armbruster, 2011).
Table 6.1  Quantitative comparison of Clinothems 1 to 8 to data taken from Patruno et al, 2015 on continental-margin and shelf-prism scale clinoforms. Clinothems 1-8 are generally within the range of shelf margin clinoforms.

<table>
<thead>
<tr>
<th>Quantitative Parameter</th>
<th>Continental-margin scale Clinoforms</th>
<th>Shelf-prism Clinoforms</th>
<th>Clinothems 1-8 (Average)</th>
<th>Clinothems 1 – 8 (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreset Height (m)</td>
<td>1120 - 2570</td>
<td>97 - 300</td>
<td>278</td>
<td>104 – 446</td>
</tr>
<tr>
<td>Foreset Slope (°)</td>
<td>1.1 – 12.5</td>
<td>0.6 – 4.7</td>
<td>3.5</td>
<td>2.92 – 4.07</td>
</tr>
<tr>
<td>Total Clinoform Height (m)</td>
<td>670 - 3050</td>
<td>140 - 460</td>
<td>332</td>
<td>119 – 503</td>
</tr>
<tr>
<td>Shape Ratio</td>
<td>0.38 – 0.76</td>
<td>0.33 - 0.69</td>
<td>0.62</td>
<td>0.55 – 0.68</td>
</tr>
</tbody>
</table>

Table 6.1  Quantitative comparison of Clinothems 1 to 8 to data taken from Patruno et al, 2015 on continental-margin and shelf-prism scale clinoforms. Clinothems 1-8 are generally within the range of shelf margin clinoforms.
REFERENCES


Arora, K. and L. Wood, Hummocky cross-stratification as an indicator of mega-storm processes in the middle Cretaceous. Submitted to Journal of Sedimentary Research


Dennison, N.M. Guyana Oil and Gas Association Inc (2017, March) A Brief Account of Features Typical of the Offshore Guyana & Takutu Basins. Oil and Gas Conference, Georgetown, Guyana.


