Submarine channel evolution, terrace development, and preservation of intra-channel thin-bedded turbidites: Mahin and Avon channels, offshore Nigeria

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Abstract
Terraces on the modern seafloor are defined as topographically flat areas above the active submarine channel thalweg but within the confines of the channel-belt. They have been described from many modern submarine channels, but the controls on terrace distribution, evolution and stacking patterns are not well understood. In this study, we describe the architecture of the Mahin and Avon channel-belts and their associated terraces, located offshore Nigeria towards the northwest of the Niger Delta. The studied channel sections are less than 10 km apart up-dip and converge downslope. They are on slopes with similar gradients, yet they have significantly different morphologies indicating that the interplay between sedimentary processes and channel evolution must be different.
The surfaces defining the bases of the terrace bodies have been mapped along both channels using high-resolution 3D seismic data. Spectral decomposition of the data reveals subtle variations in seismic character that highlight sedimentological detail that can otherwise not be recognized, allowing us to suggest the processes responsible for terrace formation and terrace body composition.

The contrasting evolution of the two channels is reflected in the morphology and architecture of their terraces. While the Mahin terrace bodies show a predictable pattern, typically consisting of stacked channel-fill and overbank deposits in a circular planform shape (shape controlled by cut-off channel bends), the deposits of the Avon terrace bodies up-dip of the confluence with the Mahin are dominated by overbank deposits, with the planform terrace shape heavily controlled by the topography of the underlying channel-belt deposits.

This study shows how spatially and temporally associated channels can have markedly different architectures. The evolution of the channel and the abundance and stacking patterns of compositional elements within terrace bodies are shown to be linked.

Keywords: Nigeria, channel-levee, internal levee, depositional terraces, thin-bedded turbidites, 3D seismic, channel sinuosity

1. Introduction

Submarine canyons and channels form some of the most striking features on the continental slope. They act as conduits for sediment transport from the shelf to the basin floor (e.g. Mutti & Normark, 1991) by the mechanism of sediment gravity flows (Kuenen and Migliorini, 1950; Bouma and Ravenne, 2004; Meiburg and Kneller, 2010). Submarine channel-fills are commonly associated with thin-bedded turbidites, which are deposited in channel overbank
areas, building levees and terraces. While levees have been described from numerous modern
seafloor, outcrop and subsurface datasets (Piper and Normark, 1983; Hiscott et al., 1997;
Peakall et al., 2000; Deptuck et al., 2003; Kane et al., 2007; Meiburg and Kneller, 2010; Kane
and Hodgson, 2011; Nakajima and Kneller, 2013; Morris et al., 2014) terraces have mainly
been identified in modern seafloor systems based on bathymetric and side-scan sonar data,
with little information available on the deposits below the terrace surfaces (O’Connell et al.,
1995; Hübscher et al., 1997; Torres et al., 1997; Von Rad and Tahir, 1997; Piper and Hiscott,
1999; Deptuck et al., 2003; Babonneau et al., 2004; Babonneau et al., 2010; Gamberi and
Rovere, 2011; Paull et al., 2013).

Terraces are topographically flat areas adjacent to the channel but within the channel-belt
(Babonneau et al., 2004) and are elevated above the adjacent channel base. The foundations of
these terraces can be formed by a number of different processes such as: punctuated lateral
channel migration or entrenchment within the channel-belt; continuous channel migration
within the channel-belt forming point bars; channel bend cut-offs; or by collapse of external
levee deposits into the channel-belt due to over-steepening of the inner face of the external
levee (Hansen et al., 2015). Once these terrace foundations are established, the process that
created them and which determine their composition may no longer be active. These
foundations can subsequently be subject to overspill processes from the adjacent channel,
resulting in deposition of thin-bedded turbidites. If the overspilling sediment creates a wedge
shaped deposit on top of these surfaces it is called an internal levee (Buffington, 1952;
Walker, 1975; Hiscott et al., 1997; Normark and Damuth, 1997; Skene et al., 2002; Deptuck
et al., 2003; Pirmez and Imran, 2003; Kane et al., 2007; Meiburg and Kneller, 2010; Kane and
Hodgson, 2011; Nakajima and Kneller, 2013; Morris et al., 2014) while a flat deposit is called
a depositional terrace (Hansen et al., 2015). However, these deposits most likely form a
continuum across a variety of different scales and end-members are rarely preserved (Hansen
et al., 2015). The terrace body, is defined as the sediment that comprises the thickness from
the interpreted base of the terrace (below the terrace foundation) to the seafloor, and it is really constrained by its planform geometry governed by the terrace forming process and the processes occurring after terrace formation. Both internal levee and depositional terrace deposits can include laterally extensive sand layers and can form significant hydrocarbon reservoirs (e.g. Clemenceau et al, 2000).

In this study, we use 3D seismic data to describe the architecture of mid-slope sections of the Mahin and Avon channels and their associated terraces on the seafloor, which are located on the western Nigerian continental slope (Fig. 1). The main aims of this paper are to (1) identify controls on variation in morphology between the Avon and Mahin channels, (2) identify controls on terrace distribution along the Mahin and Avon channels, and (3) understand the evolution and stacking patterns of deposits within the terrace bodies and how they are linked to the geomorphic evolution of the channels.

2. Geological setting

2.1. Western slope, offshore Nigeria

The study area is located on the continental slope offshore and northwest of the prominent Niger Delta in the Gulf of Guinea along the western margin of Africa (Fig. 1). The western offshore area of Nigeria is flanked by a 50-70 km wide shelf, with a shelf break at 150-200 m water depth (Fig. 1). The continental slope extends from the shelf break to depths of 2000-3000 m with an average slope gradient of 1.7° (Damuth, 1994).

Sediment is supplied to the offshore areas by numerous tidal channels which are present along the edge of the Niger delta and probably overlie a distributive network of incised valleys that transported sediment across the shelf to shelf-edge deltas and ultimately into deep water canyon heads during periods of low Pleistocene sea level (Deptuck et al., 2007).
Strong longshore drift currents are active along the edge of the delta, which transport sediment north up the western face of the Niger delta due to prevailing south-westerly winds (Burke, 1972) (Fig. 1). Longshore drift also transports sediment from the Volta Delta eastwards towards Mahin and along the coast of Lagos (Fig. 1) (Allen, 1965; Burke, 1972; Anthony, 2015; Dada et al., 2016). A sandy beach is present at Lagos but abruptly terminates 100 km to the east, giving way to the Mahin mud beach (Fig. 1). Longshore drift northwards of the Niger delta picks up increasing amounts of sand from successive distributaries but sand only extends as far as the Benin River, north of which the shore is muddy. Though unconfirmed, it may be that some of the sediment is directed down the numerous submarine canyons along the Niger delta even during the current sea level high-stand. However, during the late Pleistocene to early Holocene the sediment supply to these canyons was different and ample sand, from large barrier complexes, was available on the shelf edge to be transported down the canyons along the Niger delta front (Allen, 1970).

The continental margin off the Niger Delta is undergoing outward radial gravity deformation caused by rapid seaward progradation (Damuth, 1994; Wu et al., 2015). This has created an upper extensional zone of listric faults, a translational zone of mud diapirs and ridges beneath the upper slope (Hovland et al., 1997), and a lower compressional zone of imbricated thrust structures beneath the lower slope and rise (Damuth, 1994; Morley and Guerin, 1996; Corredor et al., 2005) (Fig. 1). This dataset shows that these structures have heavily influenced the deepwater depositional systems in this area.

2.2. Study area

The study area is located at water depths between 1350 and 2500 m in the mid-slope translational to compressional zone and is about 30 km downslope from the shelf-edge (Fig.
1. The seafloor in this area, particularly in the up-dip parts, exhibits a number of structural highs elevated up to 100 m above the surrounding seafloor (Fig. 2). These structural highs are underpinned by mud diapirs in the subsurface, which resulted from rapid sedimentation rates causing the mobilization of unstable mud (Burke, 1972; Doust and Omatsola, 1989; Damuth, 1994; Morley and Guerin, 1996). The topographic lows between the mud diapirs have controlled the pathway of the Mahin and Avon channels (Fig. 2). Average slope gradients vary between 0.5° and 2.5°, but are locally as high as 7° in areas adjacent to the structural highs.

The Mahin and Avon channels converge in the downslope part of the study area (Fig. 3) and the merged channel continues downslope and likely terminates in a submarine fan (Damuth 1994). Above the confluence the sinuosity and geomorphology of the two channels is markedly different, while below the confluence the Avon channel has a similar sinuosity to the Mahin channel above the confluence (Fig. 3). Within the confines of both channel-belts numerous terraces are present but their distribution and characteristics vary significantly (Fig. 3).

3. Data and methods

3.1. Seismic data

Conventional 3D seismic mapping techniques were used to interpret the 3D seismic reflectivity volumes in the study area. The 3D seismic survey covers an area of 4500 km² (45 x 100 km) with a bin size spacing of 12.5 m by 12.5 m (in-line and cross-line spacing) and a sampling interval of 4 ms. The average frequency of the full-stack data is 50 Hz, resulting in a vertical resolution of approximately 7.5 m (assuming the vertical resolution is a quarter of the wavelength (Brown, 1999) and using the velocity of seawater (1500 m s⁻¹) (Jones et al., 2010)) for the shallow section under consideration in the seismic profiles.
The data is SEG negative standard polarity where a positive reflection coefficient indicates an increase in acoustic impedance and is represented by a trough, where the data is assumed to be approximately zero phase. On the sections shown a peak is represented by red/yellow and a trough is represented by blue. These assumptions of polarity and phase are supported by the prominent seafloor event, which is represented by an approximately symmetrical trough.

The seafloor horizon was contoured in ESRI ArcGIS and the slope spatial analyst tool was used to calculate the dip of each grid cell based on the elevation of its nearest neighbours to generate a slope gradient map. Using the seafloor morphological expression each terrace within the Mahin and Avon channel-belts was constrained by a polygon. The ESRI ArcGIS aspect spatial analyst tool was used to create a map showing the spatial orientation and dip direction of each terrace surface on the seafloor. Additionally, a horizon was interpreted at the base of each terrace body within the confines of the terrace polygon (Fig. 4). This was performed manually and based on the interpretation of the base of the channel-levee system, and an understanding of the evolution of each individual terrace based on the seafloor morphological expression. The base of each terrace body is composed of the deposit that formed the terrace foundation within the channel-belt, on top of which turbidity currents may have deposited sediment due to overspill from the adjacent channel.

3.1.1. Seismic facies

Regularly spaced cross-sections through the terrace bodies allowed the identification and interpretation of six seismic facies, which helped determine the compositional elements present in each terrace body. They have been classified according to the continuity and amplitude of the reflections (Fig. 5). Due to the absence of lithological calibration from seafloor cores, the interpretation of their sedimentary environments is based on comparison
with previously published seismic and sub-bottom reflection studies (Abreu et al., 2003; Deptuck et al., 2003; Posamentier and Kolla, 2003; Gamberi and Marani, 2006; Catterall et al., 2010; Jobe et al., 2015). While not available from the present study area, seafloor cores obtained from channel-fills, internal levees and depositional terraces about 100 km to the south east have been used to calibrate seismic facies comparable to those in our study (Jobe et al., 2015), and we use these as a basis for lithological interpretation.

Facies A is characterized by high amplitude, apparently chaotic reflectors and occurs in axial channel environments or at the base of terraces (Abreu et al., 2003; Deptuck et al., 2003; Posamentier and Kolla, 2003; Jobe et al., 2015); it is interpreted as coarse grained channel-fill. Facies B is characterized by continuous straight reflectors that converge and dim away from the adjacent channels and are interpreted as the external levees that confine both the Avon and Mahin channel-belts (Hübscher et al., 1997; Deptuck et al., 2003; Nakajima and Kneller, 2013). Facies C is composed of continuous straight and parallel reflectors that can vary in amplitude and are interpreted to represent heterolithic strata that form either depositional terraces (sensu Hansen et al., 2015) or internal levees (Deptuck et al., 2003; Babonneau et al., 2004; Jobe et al., 2015). Facies D is characterized by straight continuous reflectors which are inclined towards the channel and represent heterolithic slide blocks that have slid into the channel (Deptuck et al., 2003; Babonneau et al., 2004). Facies E is composed of chaotic reflectors with varying amplitude representing slumps that may have originated from the side of the channels or from further up-dip (Deptuck et al., 2003; Posamentier and Martinsen, 2011; Ortiz-Karpf et al., 2015). Facies F is characterized by flat continuous reflectors with consistent amplitudes and represents the lobe deposit prior to incision of the Avon and palaeo-Avon channel (Posamentier, 2003; Posamentier and Kolla, 2003; Gamberi and Rovere, 2011) (Fig. 5).

3.1.2. Spectral decomposition
Spectral decomposition combined with RGB (Red Green Blue) colour blending of selected discrete frequency bands (McArdle and Ackers, 2012) is an imaging technique used to highlight subtle features and geometries in seismic data. Spectral decomposition was used to image subtle frequency variations at the base of each terrace to identify depositional elements whose scale is below the average seismic resolution of the full-stack data. Since the peak frequency response for a specific seismic interval varies with its temporal thickness (with higher frequencies imaging thinner geological features), visually blending a number of discrete frequency bands can reveal subtle changes in thickness. Therefore sedimentological features can be identified that are otherwise difficult to detect on conventional amplitude maps.

The seismic survey was decomposed into three amplitude-response volumes, each with a different average frequency: 38.33 Hz, 47.63 Hz and 68.37 Hz. The average frequencies of the decomposed volumes were selected to span the wide frequency distribution of the full-stack data, which was determined from the terrace base horizons. The selected frequencies were far spaced in order to separate and highlight geological features with a distinct frequency content. The frequency volumes were then assigned separate RGB colours (38.33 Hz = red, 47.63 Hz = green, 68.37 Hz = blue) and merged together to produce a frequency colour blend. The colour hue in the colour blend reflects the average frequency around the studied horizon and the brightness of the colour represents the amplitude of the seismic signal. Furthermore, the blended frequency volumes were calculated using different frequency filter lengths (i.e. time intervals) and therefore the visualized colour blend is a composite of three time windows centred around the chosen horizon. Typically the maps provide more detail than seismic profiles because the observed geological features are much wider than they are thick while both the vertical and horizontal resolution remains the same.

3.2. Channel and terrace measurements
In addition to seismic interpretation, the morphology of the channels and terraces at the seafloor was parameterized by taking measurements from profiles located perpendicular to the local orientation of the channels (spaced every 1 to 6 km along the channel thalweg). The zero point for channel length measurements along the thalweg is located at the easternmost (upstream) limit of the Mahin channel in the study area. The measurements in the Avon channel are referenced to the measured Mahin channel distance at the confluence and hence start at 42 km (Fig. 3b). The measurements permit comparisons to be made between two adjacent channels that cross morphologically similar slope segments, but with substantially different morphological characteristics. All measurements were taken in metres by depth converting the seafloor map using an average seawater velocity of 1500 m s\(^{-1}\) (Jones et al., 2010).

The Mahin and upper Avon channels were subdivided into three sections with the start and end points of each section determined by significant changes in channel gradient and sinuosity. The lower Avon channel was not further subdivided and is labelled as section 4. The sections allowed quantitative comparison of channel and terrace properties along the channels.

The measured parameters from these profiles include the channel-belt width (defined as the perpendicular width between external levee crests) (Fig. 6), channel width (defined as the perpendicular width between the channel-facing terrace edges, where terraces are present) (Fig. 6), and channel-belt depth (defined as the depth between highest external levee crest and the thalweg i.e. the deepest point in channel). The channel margin gradients were calculated from the perpendicular channel profiles by calculating the gradient along the steepest section of the channel margin. The down-dip gradient of both channels was calculated using the thalweg depths and measuring the change in depth per kilometre along the thalweg (Fig. 7a, b). A 4 km moving average of the gradient was also calculated to reduce local irregularities.
Variations of the open slope gradient adjacent to the Mahin and Avon channels were also measured in order to determine whether differences in morphology of the two channels might be related to differences in the gradient of the adjacent slope. The slopes have an average of 0.85°. The sinuosity index (formula shown in Figure 6), in which a straight feature has an index of 1, was calculated for both channels over a 6 km sliding window (Fig. 6, 7 c.1, c.2).

For each terrace, the terrace area, perimeter, cross-stream width, downstream length, circularity, and height of terrace above the thalweg was measured at the seafloor (Fig. 6). The circularity was measured using the formula shown in Figure 6 (Friel, 2000).

4. Channel geomorphology

4.1. Mahin channel geomorphology

The present day expression of the 90 km long Mahin channel section that lies within the study area is a leveed channel-belt with external levees up to a maximum of 5 km wide. It is a highly sinuous channel that has some spatial variations in its cross-sectional (relief, symmetry, width) and planform geometry (more or less sinuous) (Fig. 7). It is characterized by the presence of terraces on almost every channel bend (34 terraces in total), which locally occur in stepped pairs representing multiple generations of terraces at different heights within the channel-belt (Fig. 4b). The channel mostly has a symmetrical V-shaped cross-section with a difference in conjugate levee crest height of less than 20 m (Fig. 8a, b). The channel is most asymmetric at bend apexes due to outer channel bend erosion and deposition focused on the inner bends (Fig. 8b). Channel margins have gradients mostly between 14° and 26° but can be as low as 10° on inner channel bends (Fig. 8b).
The Mahin channel is divided into three sections. Up-dip in sections 1 and 2 the channel-levee system is almost completely confined within the structural low created by the mud diapirs and the levees are lapping onto these structural highs (Figs. 2b, 9a, b). Down-dip in section 3 the topographic effect of the mud diapirs is less, and the system is consequently less confined (Fig. 9c, d).

Section 1 is the steepest part of the Mahin channel with a channel thalweg gradient of 0.7°, and an average sinuosity of 1.57 (Table 1, Fig. 7 a.1 & c.1). In this section the channel-belt is very wide (on average 3454 m wide, see Table 1), with multiple generations of terraces. The channel thalweg gradient and channel-belt width decrease throughout section 2 and 3 to 0.36° and 2214 m respectively (Table 1). Sinuosity is highest in section 2, at 2.37, and decreases to 1.75 in section 3 (Table 1, Fig. 7 c.1). At the start (between 72.5 and 73.6 km) and end (between 88.6 and 90.7 km) of section 3 the channel gradient reverses with the channel floor rising up by several metres (Fig. 7 a.1). At the start of this section this is due to sediments that have collapsed into the channel from the inner external levee. At the end of section 3 (between 88.6 and 90.7 km) the channel thalweg rises just before it converges with the Avon channel at which point there is a 30 m drop into the Avon channel (Fig. 8c).

4.2. Upper Avon channel geomorphology

The 49 km long Avon channel also lies within a leveed channel-belt (with levees up to 3 km wide) but it is less sinuous (1.16 on average) compared to the Mahin channel (1.9 on average) (Fig. 7 c.2) and has fewer terraces (18 compared to 34 in the Mahin channel-belt). The cross-sectional form changes frequently from V-shaped to U-shaped and can be strongly asymmetrical at channel bends (Fig. 8b). The steepness of the channel margins is mostly between 18° and 26° but can be as low as 9° on inner channel bends (Fig. 8b).
The upper Avon channel is divided into three sections. Similarly to the Mahin channel, in section 1 the channel-levee system is completely confined within the structural low created between the mud diapirs with the levees lapping onto the structural highs (Fig. 9a, b). Down-dip in sections 2 and 3 the upper Avon channel becomes less confined due to the reduced topographic effects of the mud diapirs (Fig. 9c, d).

Throughout sections 1 to 3 the sinuosity is mostly consistent at around 1.1 to 1.2 (Table 1) with the exception of a moderate sinuosity increase at the transition between sections 1 to 2 where the upper Avon channel makes a sharp bend (Figs. 3a and 7 c.2). This is likely associated with a prominent topographic high obstructing the pre-bend channel direction (Fig. 3). The thalweg gradient (Table 1, Fig. 7 b.2) stays constant around 0.8° throughout section 1 and part of section 2 but increases sharply in the last part of section 2 to 1.6°, which is interpreted as a knickpoint (Fig. 7 a.2 b.2). This is associated with an abrupt increase in the channel-belt depth and width from 83 m to 184 m and 1469 m to 2484 m respectively (Table 1). The thalweg of the upper Avon channel appears to be smooth in section 1 to 3 where it is straight. However, in the lower Avon channel, after the confluence with the Mahin channel, the channel floor becomes more undulating, showing frequent bedforms, which are not seen in the Mahin channel, with up to 10 m of relief, together with an increase in sinuosity (Fig. 7 a.2).

4.3. Lower Avon channel geomorphology (after confluence)

The 39 km long section of the lower Avon channel has a similar sinuosity to the Mahin channel (1.76 in the lower Avon compared to 1.9 in the Mahin channel), which marks a distinct change between the upper and lower parts of the Avon channel (1.16 in the lower Avon vs. 1.76 in the upper Avon) (Table 1, Fig. 7c). The lower Avon channel-belt is confined by levees and is characterized by the presence of terraces along the entire channel length (19 terraces in total). It shows an overall increase in channel-belt depth (201 m on average) and
channel-belt width (3281 m on average) compared to the upper Avon (on average 102 m deep and 1978 m wide) and Mahin channels (on average 171 m deep and 2740 m wide) (Table 1). Some straighter channel sections seem to be related to a decrease in thalweg gradient (Fig. 7 b, c). The cross-sectional relief is predominantly V-shaped, but again shows asymmetry at channel bends (Fig. 8b).

5. Terrace morphometric characteristics

5.1. Mahin channel terraces

Numerous terraces are present along almost the entire length of the Mahin channel-belt (34 in total). Terraces occur both on the inside and outside bends of the channel with their area often extending across two channel bends. Some terraces occur as stepped pairs, where two adjacent terraces are at different heights above the channel. They are generally topographically flat in parts but are dominated by local topographic irregularities with different terrace sections dipping in various direction (Fig. 10). Where terraces are directly next to the channel they can be inclined towards the channel. Some terraces, in section 1, are characterized by topographic highs in their centre (Figs. 3, 4, 10). Some terraces also show a distinct topographic elevation at the channel-facing side which tapers away from the channel (Fig. 10). All terraces have a greater downstream length than width (Table 2, Fig. 11). The terrace characteristics change frequently down channel, with an overall decrease in terrace area, length and width decreasing between sections 1 and 3 (Table 2, Fig. 11). In contrast, the terrace circularity and height stay comparably more constant between section 1 and 3 (Table 2). The number of terraces is greatest in section 3 (12 terraces present in section 3) where they also have the smallest area (Table 2, Fig. 11).
5.2. Upper Avon channel terraces

The abundance of terraces along the upper Avon channel-belt is less than the Mahin channel-belt (18 compared to 34 terraces in the Mahin channel-belt) (Table 2). Terraces are more abundant on the inside of channel bends and most commonly occur as stepped pairs at different heights above the channel (Fig. 3). In sections 1 and 2, all terraces have topographic irregularities and almost all of them dip downslope by up to 5° towards the SW (Fig. 10). In section 3, which is below the knickpoint in the upper Avon channel (Figs. 3 and 7 a.2, b.2), the terraces are smoother and do not dip downslope. They are almost 100 m higher above the adjacent channel than the terraces in sections 1 and 2 of the upper Avon channel (Table 2, Fig. 11). The majority of the terraces have a long downstream length and are bigger and less circular than the Mahin terraces. Overall, the terrace area, width and length decrease downslope (Table 2, Fig. 11).

5.3. Lower Avon channel terraces (after confluence)

Below the confluence terraces are again present both on the inside and outside of channel bends and sometimes occur as stepped pairs (19 terraces in total). Some of the terraces are topographically flat but the majority have local topographic irregularities (100 to 200 m in scale) with different parts of the terrace dipping in various directions (Fig. 10). On average the terraces are bigger than the Mahin terraces, have almost the same area as the upper Avon terraces but are significantly wider than both the Mahin and upper Avon terraces (Table 2, Fig. 11). The circularity is similar to the Mahin terraces and hence greater than the upper Avon terraces. The terrace height above the thalweg is on average 26 m higher than the Mahin terraces and 93 m higher than the upper Avon terraces in section 1 and 2. They are on average almost equivalent in height to the upper Avon terraces in section 3 (Table 2). Within this section the width and area of the terraces increases downslope (Table 2, Fig. 11).
6. Terrace body compositional elements

Interpretation of seismic facies (Fig. 5) within the terrace body, together with spectral decomposition slices at the terrace base (Fig. 12) and throughout the terrace body, were used to assist in the quantification of the compositional elements that make up each terrace body along the Mahin and Avon channel-belts, and to reveal terrace forming processes.

6.1. Spectral decomposition of terrace base horizons

6.1.1. Mahin terrace bases

At the base of many of the terraces of the Mahin channel, several older channel-fills can be recognized to make up the foundation of the terrace body. Some of them show the location of older channel bends that have been cut-off. These are particularly obvious in Figure 12b where the remnant channel bend fills can be seen at the base of four terraces (process illustrated in Fig. 13c, d); on the seafloor these terraces have a distinct topographic high at their centre which is the remnant topographic high in the centre of the older channel bend. Several terrace bases show lateral accretion packages (LAPs) that may indicate progressive channel migration as channel sinuosity changed (Fig. 12b). Some areas of the spectral decomposition slices look incoherent and chaotic and are interpreted to be sediment that has slumped towards the channel (Fig. 12c).

6.1.2. Upper Avon terrace bases

Regional seismic interpretation indicates that the current upper Avon channel is underlain by older lobe and channel deposits (Fig. 13a, b). The terrace bases in channel section 1 are dominated by older channel-fills making up the foundation of the terrace body (Fig. 12d), which belong to the palaeo-Avon channel whose remnant is visible on the seafloor between the Mahin and Avon channels (Figs. 3, 9, 13, 14). In channel section 2, the chute channel remnants interpreted to have been present in the overbank areas at the initiation of the current
Avon channel are preserved at the terrace bases (Figs. 12d, 13b). In section 3, the terrace bases are dominated by older channel-fill deposited in channel bend cut-offs similar to the Mahin terraces into which the Avon channel is incising (Fig. 13c).

### 6.1.3. Lower Avon terrace bases (after confluence)

The base of the terraces in the lower Avon channel show an abundance of older channel-fills imaged by the spectral decomposition slices (Fig 12e). LAPs and multiple generations of older channel-fills can be seen, which indicates the lateral migration of this channel over time. More complex channel migration patterns can be seen in the most basinward terrace of the lower Avon channel, where several segments of channel-fill overprint one another (Fig. 12e). Some more chaotic and less coherent areas of the spectral decomposition slices suggest slumped material from the channel-belt margin that has moved towards the channel (Figs. 12e, 13d). It is unclear whether this slumped material is composed of coherent blocks or more disaggregated strata.

### 6.2. Volumetric assessment of terrace compositional elements

By using both the seismic facies and the spectral decomposition slices at the base and within the body of each terrace, it is possible to interpret the compositional elements that make up the terrace bodies along the Mahin and Avon channel-belts. Three different compositional elements were differentiated: Channel-fill, slumps and heterolithics (Fig. 14). Heterolithics are a combination of seismic facies C and D (Fig. 5), which were grouped together for the purpose of volume calculations for the terrace body because they likely underwent similar sedimentological processes during initial deposition. Facies B represents the external levees and is not present in the terrace bodies unless part of the external levee sediment slid into the channel-belt (in which case it is classified as facies D). For each terrace body, the volume of each compositional element was calculated (Fig. 14).
6.2.1. Mahin channel terraces

Almost all of the terrace bodies along the Mahin channel-belt are partially composed of remnant channel-fill facies (up to 50% with an average of 29%) (Fig. 14), which can be seen in the spectral decomposition slices from the base of each terrace (Fig. 12). The volume of heterolithics in the terrace bodies varies down dip but is commonly the largest component of each terrace body (between 36% and 83%) (Fig. 14). These heterolithics would have been deposited by overbank flow after the initial elevated surface that created the terrace foundation was established in the channel-belt. The proportion of slumps changes significantly down dip and it only occurs in three terrace bodies in sections 1 and 2 whereas it is dominant in section 3 of the Mahin channel (Fig. 14).

6.2.2. Upper Avon channel terraces

The terrace bodies of the upper Avon channel-belt consist mainly of heterolithic overbank deposits (average 93%) related to the current Avon channel. They rest directly on top of palaeo-Avon channel and lobe deposits belonging to older stratigraphic units of the Avon system. Where overbank deposits overlie lobe deposits, the terrace bases show signs of wide chute channel-like features, which are too subtle to be recognized in seismic profiles (Figs. 12c, 13b). Part of the first upper Avon terrace body is composed of slump deposits (Fig. 14).

6.2.3. Lower Avon channel terraces (after confluence)

In the lower Avon channel-belt, the percentage of channel-fill, for each terrace body is slightly higher than in the Mahin channel (average 34% compared to 29% in the Mahin channel) and slumps are still common at the start of this channel section. Three terrace bodies consist of slumps and heterolithics only (Fig. 14).
7. Discussion

7.1. Controls on morphological differences between the Mahin and Avon channels

The main morphological difference between the Mahin and Avon channels above the confluence is their sinuosity. The longitudinal evolution of the sinuosity along the Mahin channel shows a high and non-linear variability, while there is less overall variability in the upper Avon channel sinuosity as it is predominantly straight (Figs. 3, 7c). Sinuosity in submarine channels is suggested to be controlled by a number of factors such as the slope gradient, flow interaction with seafloor topography, the calibre of sediment the channel is transporting and eroding into, and channel maturity (Clark et al., 1992; Nanson and Croke, 1992; Reading and Richards, 1994; Clark and Pickering, 1996; Pirmez et al., 2000; Schumm, 2005; Peakall et al., 2007; Kane et al., 2008; Kleinhans, 2010; Straub et al., 2011; Peakall et al., 2012; Janocko et al, 2013b; Sylvester et al., 2013; Sylvester and Covault, 2016). Many factors probably affect the sinuosity of the channels in the study area but it is likely that one factor is dominant. These will be discussed below.

Variations in river channel sinuosity have been attributed to slope gradient in flume tank models of open channels (Schumm and Khan, 1972; Schumm et al., 1972) and in modern seafloor studies such as those of the Indus, Rhone, Mississippi, Monterey, and Amazon submarine channels (Clark et al., 1992; Peakall et al., 2012). However, in the study area the slope gradient measured on a line adjacent and beyond the external levees to both channels shows that the gradient is similar and has an average of 0.85°. Given the substantially different sinuosities of the two channels, slope gradient is therefore unlikely to be the controlling factor.

Flow interaction with the seafloor topography can also impact channel sinuosity. Seafloor topography can be either tectonically driven or created by the presence of other sedimentary
depositional bodies such as other channels, lobes or mass transport deposits (Reading and Richards, 1994; Pirmez et al., 2000; Babonneau et al., 2002; Adeogba et al., 2005; Straub et al., 2008; Catterall et al., 2010). In the study area the seafloor topography is largely shaped by the underlying mud diapirs, which control the location of the Mahin and Avon channels. In places diapirism has caused local increases in gradient, which has resulted in localized straightening of the channel (Fig. 2a). While mud diapirism certainly affected the channel sinuosity on a local scale, the topographic irregularities of the area occupied by the Mahin and Avon channels are similar, making it unlikely that the differing sinuosity is driven by seafloor topography.

Clark et al. (1992) interpret the grain size of sediment transported in channels to be an important factor in determining the channel morphology, where channels with a coarser grain size range tend towards lower sinuosities than those dominated by a finer grain size range. Additionally, the cohesiveness of the substrate into which the channel is incising may impact channel sinuosity, where erosion into a muddy substrate results in more sinuous channels than erosion into more easily erodible sandy substrate, resulting in straighter channels (Nanson and Croke, 1992; Schumm, 2005; Peakall et al., 2007; Kleinhans, 2010; McHargue et al., 2011; Verhagen et al., 2013). Figure 15 shows a RMS amplitude map of the study area that illustrates the striking difference in amplitudes along the Avon and Mahin channels above the confluence. In this case the RMS amplitude has been attributed to the amount of coarse grained sediment present in the interval of amplitude extraction. The RMS amplitudes suggest that the Avon channel is fed by turbidity currents containing significantly coarser grained material than the Mahin channel. Additionally, the lobate shape of the amplitudes shows that the Avon channel is incising into older, probably sandy, palaeo-Avon lobe deposits. These observations agree with the suggestion that channels carrying and eroding into coarser grained sediments generally have lower sinuosities than those carrying and eroding into finer-grained sediments (Clark et al., 1992; Peakall et al., 2007; Peakall et al., 2012).
Evidence for the difference in the sediment supply systems to the Avon and Mahin channels can be traced back to the Late Pleistocene and earlier Holocene. In the Pleistocene (20,000 years ago) the Benin River extended across the shelf to the Mahin canyon (Burke, 1972), which may have been responsible for the initiation of the Mahin channel. The sediment that was transported in the channel then is unknown but at the maximum extend of the last transgression, around 7000 years ago, old beach ridges, also referred to as the ‘older sands’ by Allen (1964), were present at the head of the Avon canyon but these are more limited at the head of the Mahin canyon (Allen, 1964). Additionally, at the present day the coastline at the head of the Avon canyon is sandy while it is muddy at the head of the Mahin canyon, due to the dominant longshore drift patterns (forming the Mahin mud beach, refer to Fig. 1). This current apparent absence of a sand supply to the Mahin canyon may either be due to reworking and transport of sediment away from the canyon head by waves and tides due to the prevailing south-westerly wind, or due to the capture of the sand supplied by eastward longshore drift by the Avon canyon (which cuts further landward than the Mahin canyon) or by any of the numerous other canyons present along the Niger shelf edge (Allen, 1964; Burke, 1972) (Fig. 1). Hence, the Avon channel may be receiving coarse-grained sediment even during the current sea level highstand and sediment supply and cohesiveness of the substrate are interpreted to be contributing factors to the difference in sinuosity between the Avon and Mahin channels.

Channel sinuosity has also been attributed to channel maturity where younger channels are straight and become more sinuous over time (Peakall et al., 2000). This may be partly due to flows becoming smaller and muddier through time as sediment supply is reduced, ultimately causing an increase in sinuosity (Janocko et al., 2013b), or simply due to the time taken to establish an equilibrium sinuosity. Though there is no direct evidence of the relative ages of the Mahin and Avon channels, we interpret the Avon channel to be younger. Evidence for this
is the presence of the palaeo-Avon channel (Fig. 3, 9, 13, 15), which has eroded into the palaeo-Avon lobe deposit and then avulsed to form the current Avon channel. Evidence for the pre-existence of the Mahin channel is that below the confluence, the lower part of the Avon channel adopts a similar sinuosity to the Mahin channel and we speculate that the sinuosity of the lower Avon channel was created by the pre-existing Mahin channel. The 30 m drop (Fig. 8c) at the mouth of the Mahin channel suggests that the Mahin channel is no longer active, as otherwise this drop would have been eroded and smoothed by turbidity currents active in the channel. The Mahin channel inactivity may also be the reason for the abrupt brightening of the RMS amplitudes in and around the Mahin and Avon confluence. Channel confluences have been documented mainly on seafloor datasets e.g. from the Espirito Santo Basin, offshore Brazil (Gamboa et al., 2012) and the Tyrrhenian Sea, offshore Sicily (Gamberi et al., 2013). They are commonly associated with a knickpoint, which can also be seen between sections 2 and 3 of the upper Avon channel (Fig 7 a.2). This may be a result of the straight Avon channel having to navigate the previously eroded sinuosity created by the Mahin channel, which disrupted the equilibrium profile of the converging upper Avon channel. To regain the equilibrium profile the knickpoint now is migrating up the Avon channel causing increased channel erosion (and thus channel depth) below the knickpoint. Knickpoint migration has commonly been documented from deepwater channel studies (Adeogba et al., 2005; Antobreh and Krastel, 2006; Catteral et al., 2010; Gamberi and Rovere, 2011).

This suggests that, in the case of the Mahin and Avon channels, channel maturity is likely the main reason for the difference in channel sinuosity. It is important to recognize the influence of channel morphology when analysing terrace distribution and composition.
7.2. How are the terraces formed?

The spectral decomposition slices of the base of the terraces have shown sedimentological detail that allows us to interpret how terraces were initially formed, which is reflected in the composition of the terrace bodies. Four terrace forming processes can be observed in the study area (detailed description of each process is summarized in Hansen et al. 2015) but in some cases more than one of these processes has occurred. The dominant process for the formation of each terrace is shown in Figure 16.

The majority of the terraces in the Mahin channel-belt and the upper Avon channel-belt are formed by entrenchment. Entrenchment of a channel into older deposits can occur solely by vertical incision, or with a component of lateral migration by the process referred to as punctuated channel migration (Maier et al., 2012). The sediments below these elevated surfaces will be composed of whatever the channel is incising into e.g. older channel-fills, lobes, slope deposits, levee deposits. In the Mahin channel-belt, the formation of these terraces is interpreted to be mainly due to the abrupt lateral migration of the channel as the sinuosity of the channel changed over time, either as a response to local topography or due to sediment collapse into the channel resulting in a shift of the channel position. Many of the terrace bases are therefore composed of older channel-fill (Fig. 12, 13d, 14). In the upper Avon channel-belt, the terraces have been incised into previously deposited channel and lobe deposits by vertical entrenchment of the current Avon channel (Fig. 13a, b, c, 14). The incision of channels into lobes has been documented from many turbidite systems such as the Golo turbidite system, Corsica (Gervais et al., 2006) and the Karoo Basin in South Africa (Brunt et al., 2013). This may be associated with some externally imposed forcing such as a change in relative sea level and a resultant progradation of the whole deepwater depositional system (Chen and Hiscott, 1999; Hodgson et al., 2016).
Point bar accretion is a result of continuous channel bend growth, and has been convincingly demonstrated in only a few cases in turbidite systems (Abreu et al., 2003; Deptuck et al., 2007; Dykstra and Kneller, 2009; Janocko et al., 2013b). True point bar accretion is challenging to image on this seismic data and is not always distinguishable from punctuated channel migration, but can be differentiated by progressive bend widening shown by scroll bars. Figure 13d shows scenarios of how point bar accretion deposits may occur at terrace bases. Point bar accretion can be interpreted at one place in section 1 of the Mahin channel and in several places in the lower Avon channel (Fig. 16) due to the presence of scroll bars in the spectral decomposition images (referred to as LAPs in Fig. 12).

Both the Mahin channel-belt and the lower Avon channel-belt have a number of terraces with bases interpreted to have formed by channel bend cut-off (Fig. 16). Channel bend cut-offs are a common phenomenon in highly sinuous, laterally migrating channels and result from the progressive accentuation of bend curvature and eventual neck cut-off (McHargue, 1991; Cronin, 1995; O’Connell et al., 1995; Mayall and Stewart, 2000; Kolla et al., 2001; Deptuck et al., 2003; Samuel et al., 2003; Janocko et al., 2013b). Figure 13c and d show how channel bend cut-offs can create elevated areas within the channel-belt. In some cases, like the most basinward terrace in the lower Avon channel, multiple generations of channel bend cut-offs can be seen at the base of the terrace body (Fig. 12e). This indicates a complicated history of the lateral switching of the channel similar to what has been reported in McHargue et al (2011) and Hodgson et al (2011). The terrace bases created by channel bend cut-offs are the largest in area (1.5km$^2$ on average) and have on average the most circular geometry.

Some of the smaller terraces along the Mahin and lower Avon channel-belts are interpreted to have formed by margin failure. Figure 13d shows how margin failure deposits may occur at terrace bases. They occur towards the end of the Mahin channel and at the start of the lower Avon channel (Fig. 14), which may be a result of the increase in channel gradient at these
locations (Fig. 7b), causing increased channel erosion and creating steep margins prone to collapse.

There is a direct link between the behaviour of the channel, which is in part controlled by the channel maturity, and the terrace forming processes. It is noticeable how many more terraces are present within the Mahin and lower Avon channel-belts than the upper Avon channel-belt. Lateral channel movement and channel bend cut-offs are terrace forming processes that are both also related to the evolution of the channel sinuosity, suggesting that terraces are more abundant next to sinuous rather than straighter channels. In addition, terraces in the Mahin channel-belt are on average 26 m lower above the thalweg than the terraces in the lower Avon channel-belt (Table 2). Hence it seems that the knickpoint migration up the Avon channel as a result of the upper Avon channel merging with the pre-existing Mahin channel has resulted in roughly 30 m more channel incision in the lower Avon channel which agrees well with the 30 m drop observed at the Mahin channel mouth (Fig. 8c). The influence of the knickpoint is most pronounced when comparing the height of the terraces above the thalweg between upstream (sections 1 and 2) and downstream of the knickpoint (sections 3 and 4) within the Avon channel-belt, which shows an almost 100 m height difference. In addition the increase in occurrence of terraces originally formed by margin failure shows that the additional channel incision due to the knickpoint migration can lead to channel margin instability. This implies that terrace forming processes can be dependent on localized channel behaviour (even as local as one channel bend), but can also be impacted by regional factors such as re-grading of the channel equilibrium profile due to channel confluences or regional tectonics (Clark and Cartwright, 2009).

7.3. **Terrace body compositional elements and stacking patterns**

By combining the spectral decomposition slices at the bases of each terrace and quantifying the seismic facies within each terrace body a model of terrace evolution can be built. Stacking
patterns identified in terrace bodies can then be compared to stacking patterns commonly
observed in other thin-bedded depositional environments, which can assist in the
identification of these deposits in outcrop and the subsurface.

The most typical stacking pattern of deposits making up terrace bodies observed in the Mahin
and Avon terraces is channel-fill at the base with heterolithics deposited on top (Fig. 17
pseudo-core A). These heterolithics may at times occur as part of external levee slide blocks
that have slid into the channel-belt. The thickness of the channel-fill deposit at the base varies
but can be up to several 10s of metres thick, especially when multiple parts of older channel-
fill are preserved (Fig. 12e). The thickness of the heterolithics above the channel-fill deposits
depends on the amount of overspill and flow stripping the terrace has experienced, which is
related to the height of the terrace above the adjacent thalweg and the height and frequency of
the turbidity currents. In the Mahin and Avon terrace bodies the thickness of the heterolithics
varies between 20 – 100 m. The heterolithics within the terrace bodies predominantly form
depositional terraces (i.e. flat deposits, Hansen et al., 2015) but some internal levees are
recognized which are described in section 7.4. This stacking pattern and deposit thickness is
similar to what is described from the C/D ridge outcrop in the Karoo Basin, South Africa
(Hodgson et al., 2011). Another common stacking pattern is channel-fill at the base followed
by slump deposit and heterolithics above (Fig. 17 pseudo-core B). This sort of stacking
pattern would have developed initially by lateral channel migration or channel bend cut-offs,
followed by margin collapse due to oversteepening of the channel margin. On top of this
elevated area thin-bedded turbidites then deposit by overspill and flow stripping from the
adjacent channel (Fig. 13d). These stacking patterns can be a vital piece of information when
trying to identify heterolithic depositional environments in outcrop and the subsurface.
7.4. Internal levees

While a clear distinction exists between internal levees (sensu Kane and Hodgson, 2011) and depositional terraces, it is likely that they form a continuum and that true internal levee and depositional terrace examples rarely occur (Hansen et al., 2015). This hypothesis is further strengthened by the varying dip directions of parts of each terrace surface seen in Figure 10, which emphasizes the complexity of these deposits. By definition, internal levees can be recognized by their wedge shape and form when the overspilling current has enough space to decelerate and deposit the majority of its sediment before it hits a confining surface. The orientation of the internal levee will depend on the dominant flow momentum of the overspilling current, which most commonly is down channel. Hence, the wedge shape of the internal levee may be orientated oblique to the channel direction. True internal levees were identified on parts of seven terraces along the Mahin and Avon channel-belts (Fig. 18) but do not occur in particularly unique locations adjacent to the channel that might imply a relationship with the geometry of the channel. The dominant influence on internal levee distribution seems to be the terrace height and width (Fig. 18). The height and width of the terraces where internal levees occur do not stand out significantly from the background trend but they are generally on the higher terraces with an average terrace width (Fig. 18). We interpret that increased height of the terrace reduces the amount of sediment that is able to overspill, and hence requires less space to decelerate and deposit most of its sediment before hitting the confinement of the channel-belt.

While there does not seem to be a specific terrace width required to form an internal levee, the terrace width impacts where on the terrace the internal levee develops. For example on terrace number 30, which does not dip downslope, only the widest part of the terrace is covered by an internal levee while on the narrower sections the deposits are either flat, dip downslope or towards the channel (see Fig. 10 insert in Fig 18). This reinforces the hypothesis that there is in fact a continuum between internal levee and depositional terrace deposits, and that the
amount of overspilling sediment and the space available adjacent to the channel determines which type of deposit is able to form (Hansen et al., 2015).

7.5. Terrace body preservation potential

This study shows that terrace bodies are composed of a number of different types of deposits including channel-fill or slumps at the base, and usually followed by heterolithics above. Terraces form significant features next to submarine channels on the seafloor and can be over 1500 m wide and up to 7 km long in a downstream direction. They have been interpreted from outcrop in the Cap Enragé Formation in Canada (Hein and Walker, 1982) as well as in numerous shallow seismic examples (Deptuck et al., 2003; Babonneau et al., 2004), suggesting that they can be preserved in the subsurface.

The channel systems studied here suggest that the preservation potential of terrace bodies is directly related to channel sinuosity and the rate of channel incision. In the Mahin and lower Avon channel-belts, the large number of terraces formed by the cut-off of sinuous channel bends seem to have been preserved by the incision of the late Mahin and lower Avon channels. Incision has been shown to inhibit lateral migration in both submarine (Janocko et al., 2013a) and fluvial (Schumm et al., 1984) channels, and typically results in laterally-stable, low aspect ratio channels, as can be seen in Mahin and lower Avon channels. Therefore, unless re-incised during future rejuvenations, these terrace bodies are likely to be preserved upon burial.

The upper Avon channel system shows a very different pattern. Its’ highly aggradational nature is responsible for frequent avulsions of the Avon channel, which reduces the terrace development time and limits long term entrenchment and increases in sinuosity. The Avon terrace bodies are therefore relatively thin and their planforms are to a large degree influenced by the morphology of the underlying deposits. Their limited thickness, along with the
frequent channel avulsions within a narrow structural confinement, suggests a lower
preservation potential in comparison to the thick Mahin and lower Avon terrace body
deposits.

8. Conclusions

The mid-slope sections of the Mahin and Avon channels, located offshore western Nigeria,
have different architectures and are both associated with a number of terraces. The main
difference between the two channels is their sinuosity up-dip of their confluence. Substrate
cohesion is interpreted to be partially responsible for the geomorphological differences
between the two channels. However, the interpreted younger age and thus channel maturity
(linked to the channel avulsion frequency) of the upper Avon channel compared to the Mahin
and lower Avon channels is interpreted to be the primary control on the difference in
sinuosity.

The differing channel morphology and sinuosity greatly impact the distribution,
characteristics and stacking patterns of the deposits within terrace bodies that are adjacent to
these channels. Terrace surfaces can be formed by entrenchment, margin failure, point bar
accretion and channel bend cut-offs, which leave behind elevated areas within a channel-belt
on top of which heterolithics can be deposited by overbank flow. Terraces are much more
abundant in the channel-belts of the more sinuous Mahin and lower Avon channels compared
to the channel-belt of the upper Avon channel. Entrenchment and channel bend cut-offs are
linked to changes in channel sinuosity, resulting in greater abundance of terraces adjacent to
sinuous channels.
Many of the terrace bodies, particularly in the Mahin and lower Avon channel are composed of channel-fill at the base and overlain by heterolithics, which predominantly form deposits that lie on a continuum between flat depositional terraces and wedge-shaped internal levees. True internal levees are only found when the terrace surface is high enough above the channel that only the uppermost (more dilute) parts of the flow can overspill, and are only found in parts of the terrace that is sufficiently wide to allow the overspilling current to decelerate and deposit all its sediment before hitting the confinement.

The preservation potential of the terrace body deposits is dependent on the evolution of the channel but given the abundance of terraces on the seafloor it is likely that they occur much more commonly in outcrop and subsurface datasets than has been interpreted to date. The abundance of sand prone heterolithics and channel-fill deposits makes these deposits important to consider in hydrocarbon exploration.

9. Acknowledgements

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Figure captions

Figure 1: Regional map of Western Niger slope with the study area outlined (adapted from Burke, 1972; Deptuck et al, 2007, 2012). Note that the area shown here is outlined in the map of Africa in the top right corner. Tidal channel names are from Allen (1965) and Burke (1972): Og (Ogun), On (Ona), Os (Oshun), Sh (Shasha), Be (Benin), Es (Escravos), Fo (Forcados), Ra (Ramos), Do (Dodo), Fi (Fishtown), Sa (Sangana), Nu (Nun), Br (Brass). Dashed arrows indicate dominant longshore drift directions and dashed lines to the north indicate the presence of beach ridges (from Burke, 1972).

Figure 2: Influence of seafloor expression of mud diapirs on the pathway of the Mahin and Avon channels (indicated by the black lines). a) Time depth map of interpreted regional top of mud diapirs in the study area. Interpreted horizon indicated in pink in the seismic line in the top left corner. Pathway of Mahin and Avon channels is guided through the structural lows between the mud diapirs. b) Thickness map between the interpreted regional base of the channel system and the seafloor indicated in yellow in seismic line in top left corner. White dashed lines highlight the main structural highs in the study area. Overbank areas of the Mahin and Avon channels are onlapping onto the structural highs. (Seismic dataset owner: PGS)

Figure 3: a) Depth map of the seafloor in the study area, derived from the seafloor reflection horizon in the 3D seismic dataset. Both channels were subdivided into sections, which are indicated. b) Line drawing showing the location of key geomorphic elements such as the channel-belts, channels, abandoned channels, terraces including terrace numbers, and structural highs on the seafloor. Distance measurements along the Mahin and Avon channels are also indicated. (Seismic dataset owner: PGS)
Figure 4: Cross-sections through the Mahin channel showing the interpreted base of terrace horizons. Location of seismic lines is indicated in Fig. 3a. The high amplitude reflectors at the base of the terrace are interpreted as channel-fill deposits associated with the lateral migration of the channel over time. Depending on the evolution of the channel the base of the terrace may be stepped (in b), which indicates multiple generations of terraces. The base of the entire channel-belt is also indicated by the dashed lines. (Seismic dataset owner: PGS)

Figure 5: Seismic facies of the Mahin and Avon channel-belts

Figure 6: Descriptive geometrical parameters of a sinuous channel planform

Figure 7: Morphological characteristics of the Mahin and upper and lower Avon channels. a.1 and a.2) Thalweg depth profile of the Mahin and Avon channels with gradients indicated for each section of the channel. Note that section 4 of the channel is repeated in the Mahin and Avon channel columns as this is the section of channel below the confluence. b.1 and b.2) The gradient of the Mahin and Avon channels measured along the thalweg over a 1 km and 4 km window. The median gradient is also indicated. In b.1) the white arrow indicates increase in thalweg gradient where the Mahin channel crosses a mud diapir. c.1 and c.2) Sinuosity of the Mahin and Avon channels measured across a 6 km sliding window along the thalweg. The average sinuosity per channel section is also indicated.

Figure 8: a) Slope gradient map of the study area, with locations of cross-sections shown through both channels (indicated by the red and orange lines). b) Cross-sections through the channels indicated in a) with their orientation looking up-channel (SE to the right). Numbers indicate kilometres along channel from the zero point (which is 0 km for the Mahin channel and 42 km for the Avon channel). Note the steepness of the channel margins are indicated by the red numbers in the cross-sections. c) Confluence between the Mahin and Avon channels
showing a 30 m drop between the Mahin channel mouth and the Avon channel. Location of 
map shown in a). (Seismic dataset owner: PGS)

Figure 9: Interpretation of regional seismic lines (location indicated in Fig. 8) using seismic 
facies described in Figure 5 and showing downslope changes in the channel morphology and 
seismic facies. Note how the mud diapirs become less pronounced down-dip resulting in the 
channels being less confined. (Seismic dataset owner: PGS)

Figure 10: Orientation and dip of terrace seafloor surface divided into N, NE, E, SE, S, SW, 
W and NW. Note the irregular surfaces of all terraces. (Seismic dataset owner: PGS)

Figure 11: Characteristics of all terraces along the Mahin and Avon channels. Channel 
sections are indicated for each parameter as well as the confluence between the Mahin and 
Avon channels.

Figure 12: Spectral decomposition slices of the base of all terraces along the Mahin and Avon 
channels. Locations of b), c), d) and e) are indicated in a). LAPs = lateral accretion packages.

Figure 13: Different scenarios of terrace forming processes. Different developmental stages of 
the Mahin and Avon channel systems are indicated in the centre imitating different seismic 
horizons. These include the proto-Avon and Mahin channels, palaeo-Avon lobe, and palaeo-
Avon channel. Four different terrace forming processes are shown. a) Avon section 1 is 
dominated by the incision of the modern Avon channel into older channel-fill (CF) deposits, 
leaving behind elevated areas on top of which heterolithics (HL) aggrade. b) Avon section 2 is 
dominated by the incision of the modern Avon channel into older lobe deposits (LD) and 
overbank chute channel (OCH) deposits that formed on top of terraces created by the incision
of the modern Avon channel, leaving behind elevated areas on top of which heterolithics (HL) aggrade. c) Avon section 3 is dominated by the incision of the modern Avon channel into older channel bend channel-fill (CF) and abandonment deposits (AD), leaving behind elevated areas on top of which heterolithics (HL) aggrade. d) The Mahin and lower Avon channels are dominated by channel bend cut-offs, point bar accretion and the collapse of channel-margin sediment into the channel, forming elevated areas within the channel on top of which heterolithics (HL) aggrade.

Figure 14: Mahin and Avon channel depth profiles with histogram showing percentage of compositional elements within each terrace body. The histogram bars are located at the distance along the channel where the terraces occur and the vertical axis to the left of both graphs indicates the percentage of each compositional element. The knickpoint within the upper part of the Avon channel is also indicated.

Figure 15: RMS amplitude map extracted between 15 ms and 100 ms below the interpreted seafloor horizon. Higher RMS amplitude values suggest greater impedance contrasts and hence reflectivity within the measured interval. This may be the result either of increased impedance contrast between the lithologies present, or an increase in the frequency of reflection events due to increased interbedding of contrasting lithologies. A higher RMS value is therefore interpreted to indicate an increase in variability and interbedding of sands and muds, relative to the more homogeneous finer-grained background slope deposits. (Seismic dataset owner: PGS)
Figure 16: Quantification of terrace forming processes along the Mahin and Avon channels. Pie charts show the number of terraces formed by the processes indicated in the top left corner.

Figure 17: Schematic of a channel-levee system with terrace body deposits within the channel-belt. Stacking patterns of deposits in pseudo cores going through terrace body deposits. Stacking patterns can vary considerably. Channel is eroding into pre-existing lobe deposit as observed in the upper Avon channel. (modified from Hansen et al., 2015)

Figure 18: Slope gradient map of the study area highlighting the terraces in red where internal levee deposits are present. The graph in the top left corner shows a cross-plot of the terrace width vs terrace height with the terraces that have internal levees indicated in red and labelled with terrace numbers. The map in the bottom right corner is an insert from Figure 10 showing dip direction of the terrace surface on the seafloor. Note the irregularly dipping surface with part of it forming an internal levee as shown in cross-section A-A’ (Seismic dataset owner: PGS)

**Table captions**

Table 1: Average geomorphological properties for the Mahin and Avon channels.

Table 2: Characteristics for all Mahin and Avon terraces.
Figure 2

Local increase in channel gradient and straightening of channel. Mud diapir active after channel incision.

Local decrease in channel gradient as channel cuts through structural high.
Figure 4

(a) and (b) illustrate the geological features of the study area, including external levees, terraces, channels, and the base of the terraces. The diagrams show the seafloor and the base of the channel belt, with depth scales in meters. The northwestern (NW) and southeastern (SE) directions are indicated, with distance scales of 1000 meters.
<table>
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<th>Architectural element</th>
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<td>High amplitude apparently chaotic reflectors</td>
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<td>Channel-fill</td>
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<tr>
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<td>Continuous straight reflectors that converge and dim away from channel</td>
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<td><img src="image" alt="Schematic F" /></td>
<td>Lobe deposit</td>
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Figure 6

L = Channel thalweg length
\( \delta \) = Average channel course (straight path)
\( \Delta \) = Bend amplitude
\( \lambda \) = Bend length

Terrace circularity = \( \frac{4\pi \times A}{P^2} \)

Channel sinuosity = \( \frac{L}{\delta} \)
Figure 7

Mahin channel

a.1) Channel depth profile


Confluence

Section 4 Section 3 Section 2 Section 1

0.5° 8.7 m/km
0.36° 8.5 m/km
0.44° 9.7 m/km
0.7° 12.9 m/km

b.1) Gradient

Median gradient
Thalweg gradient (1 km window)
Thalweg gradient (4 km window)

Gradiente (°)

1.5
0.5
0

0.5
1
2
3
4

Average sinuosity

0
1
2
3
4

c.1) Sinuosity

Avang sinuosity

Less sinuous

More sinuous

Avon channel

a.2) Channel depth profile


Confluence

Knickpoint

Section 4 S. 3 Section 2 Section 1

0.5° 8.7 m/km
0.8° 14.1 m/km
0.9° 17.3 m/km
0.8° 14.1 m/km

b.2) Gradient

Median gradient
Thalweg gradient (1 km window)
Thalweg gradient (4 km window)

Gradiente (°/m/km)

30
20
10
0

0
0.5
1
2
3
4

c.2) Sinuosity

Average sinuosity

Less sinuous

More sinuous
Figure 8

(a) Upper Avon channel

(b) Mahin channel

Legend

[Map details with various channels and sections labeled]

Figure 9a, 9b, 9c, 9d, 9e

(c) Confluence

Distance (m)

Water depth (m)
Figure 10
Figure 11

**Mahin channel**

Terrace height above thalweg (m):

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Terrace circularity:

| Confluence |

Terrace downstream length (m):

| Confluence |

Terrace width (m):

| Confluence |

Terrace area (km²):

Along channel distance (km)

**Avon channel**

Terrace height above thalweg (m):

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Terrace circularity:

| Confluence |

Terrace downstream length (m):

| Confluence |

Terrace width (m):

| Confluence |

Terrace area (km²):

Along channel distance (km)
Figure 12: Map showing the distribution of Palaeo-Mahin and Palaeo-Avon channel fills. (a) Main map with knickpoint and meander bends indicated. (b) Close-up of channel bend with LAPs and Palaeo-Mahin channel-fill. (c) Detailed view of Palaeo-Mahin channel-fill and meander bend cut-offs. (d) Overbank chute channel-fills. (e) Multiple generations of channel-fill in several meander bend cut-offs.
Figure 13

b) Avon Section 2

1) Development of Proto-Avon lobe
2) Inception of modern Avon channel (an incised channel with wide, chute-dominated overbank areas)
3) Aggradation of heterolithics & maintenance of a bypass-dominated channel

C) Inception of Palaeo-Avon channel system & development of Mahin channel

D) Abandonment of Mahin channel & development of modern Avon channel

3) Rejuvenation of Proto-Avon channel-belt by incision of modern Avon, aggradation of heterolithics in abandoned meander
2) Abandonment & partial burial of Proto-Avon
1) Development of Proto-Avon (an incised meander-belt)

a) Avon Section 1

1) Development of Palaeo-Avon channel (an incised channel-belt consisting of small, low-sinuosity channels)
2) Abandonment of Palaeo-Avon & inception of modern Avon channel
3) Incision of Avon thalweg & aggradation of heterolithics

Architectural elements
- Channel fill
- Lobe deposits
- Overbank deposits
- Channel margin failure deposits
- Background deposits
- Channel-belt deposits, undifferentiated

1) Incision of Mahin channel meander-belt, point bar deposition on inner channel bend
2) Abandonment of meanders by neck & chute cut-off, collapse of channel-belt margins
3) Incision of thalweg, aggradation of heterolithics, restriction of lateral channel migration

c) Avon Section 3

1) Development of Proto-Avon (an incised meander-belt)
2) Abandonment & partial burial of Proto-Avon
3) Rejuvenation of Proto-Avon channel-belt by incision of modern Avon, aggradation of heterolithics in abandoned meander

d) Mahin & Lower Avon
Figure 14

Mahin channel

Avon channel

Confluence

Knickpoint

Along channel distance (km)

Along channel distance (km)
Figure 16

Terrace forming processes:
- **Entrenchment**
- **Channel bend cut-off**
- **Point bar accretion**
- **Margin failure**

Upper Avon channel: 100%

Lower Avon channel:
- Entrenchment: 55%
- Channel bend cut-off: 20%
- Point bar accretion: 15%
- Margin failure: 10%

Mahin channel:
- Entrenchment: 35%
- Channel bend cut-off: 52%
- Point bar accretion: 10%
- Margin failure: 3%
Figure 17

Core A:
- Depositional terrace deposit
- External levee slide block
- Channel fill

Core B:
- Internal levee deposit
- Depositional terrace deposit
- Slump
- Channel fill

Legend:
- DT = Depositional terrace (flat deposit)
- ET = Entrenchment terrace (flat surface)
- MFT = Margin failure terrace (flat surface)
- EL = External levee (wedge shape deposit)
- IL = Internal levee (wedge shape deposit)
- CF = Channel fill
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## Table 2

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**Average** 1.0 628.3 2180.3 0.5 61.9

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### Lower Avon channel (after confluence)

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**Average** 1.1 836.2 1547.2 0.6 134.5

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### Mahin channel (before confluence)

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<td>164.6</td>
</tr>
<tr>
<td>21</td>
<td>0.3</td>
<td>372.0</td>
<td>1122.0</td>
<td>0.6</td>
<td>110.0</td>
</tr>
<tr>
<td>22</td>
<td>0.5</td>
<td>1263.5</td>
<td>1179.8</td>
<td>0.3</td>
<td>178.0</td>
</tr>
</tbody>
</table>

**Average** 0.7 711.6 1260.2 0.6 109.8

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### Section 1

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### Section 2

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### Section 3

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### Section 4