

The architecture of the lower parts of submarine canyons on the western Nigerian continental margin

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Abstract

Multi-beam, sub-bottom and multichannel seismic data acquired from the western Nigerian continental margin are analysed and interpreted to examine the architectural characteristics of the lower parts of the submarine canyons on the margin. The presence of four canyons: Avon, Mahin, Benin, and Escravos, are confirmed from the multi-beam data map and identified as cutting across the shelf and slope areas, with morphological features ranging from axial channels, moderate to high sinuosity indices, scarps, terraces and nickpoints which are interpreted as resulting from erosional and depositional activities within and around the canyons. The Avon Canyon, in particular, is characterised by various branches and sub-branches with complex morphologies. The canyons are mostly U-shaped in these lower parts with occasional V-shapes down their courses. Their typical orientation is NE–SW. Sedimentary processes are proposed as being a major controlling factor in these canyons. Sediments appear to have been discharged directly into the canyons by rivers during the late Quaternary low sea level which allows river mouths to extend as far as the shelf edge. The current sediment supply is still primarily sourced from these rivers in the case of the Benin and Escravos Canyons, but indirectly in the case of the Avon and Mahin Canyons where the rivers discharge sediments into the lagoons and the lagoons bring the sediments on to the continental shelf before they are dispersed into the canyon heads. Ancient canyons that have long been buried underneath the Avon Canyon are identified in the multichannel seismic profile across the head of the Avon Canyon, while a number of normal faults around the walls of the Avon and Mahin Canyons are observed in the selected sub-bottom profiles. The occurrence of these faults, especially in the irregular portions of the canyon walls, suggests that they also have some effect on the canyon architecture. The formation of the canyons is attributed to the exposure of the upper marginal area to incisions from erosion during the sea level lowstand of the glacial period. The incisions are widened and lengthened by contouric currents, turbidity currents and slope failures resulting in the canyons.

Key words: western Nigerian continental margin, submarine canyons, architecture, controlling factors, sedimentary processes, tectonic evolution

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1 Introduction

Submarine canyons are steep-sided valleys that cut into the seabed of the continental shelf, slope, and sometimes into deep ocean basins, have nearly vertical walls and occasionally have canyon wall heights of up to 5 km. They are characterised by deep erosion and meandering courses as they serve as pathways for the transport of materials from the continent and upper slope into the deep oceans. They are most often found adjacent to the mouths of major rivers, such as the Kaoping, Benito and Tugela Rivers (Liu et al., 2002; Yu et al., 2009; Jobe et al., 2011; Wiles et al., 2013), therefore serving as a media of not just sediment and

debris but also of nutrients transport which subsequently makes continental margins a hotspot for a biological production and biodiversity (Sobarzo et al., 2001; De Leo et al., 2012) as well as major petroleum reservoirs due to their base fills (Stow and Mayall, 2000; Armitage et al., 2012; He et al., 2013). These submarine canyons are influenced by turbidity (or density) currents and mass transport processes due to their proximity to high sediment sources (Shepard, 1981) and they commonly associated with steeper shelves with coarse-grained basement fill and adjacent fans created by the deposition of transported sediments (Jobe et al., 2011). The submarine canyons may serve as an archive of

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geological history due to the records of sedimentary systems embedded in them.

The Nigerian continental margin is no exception and contains the submarine canyons as well as the submarine fans and other geologic features. The structure, evolution and sedimentation of the continental shelf off Nigeria have been described by Allen and Wells (1962), Allen (1964, 1965) and Burke (1972). The margin is incised by three major canyons and numerous minor canyons. The three major canyons, i.e., Avon, Mahin and Calabar (Fig. 1), are linked to the Quaternary period and are first mentioned by Allen (1964). Their heads extend to the shallow shelf area. The minor canyons have relatively smaller sizes and their upper parts on the shelf have been filled, probably during the marine transgression that accompanied the glacial sea level fall. They are Lagos, Benin, Escravos, Ramos, Dodo, Fishtown and Niger Canyons (Deptuck et al., 2007). Olabode and Adekoya (2008) investigated the development of the Avon Canyon using seismic stratigraphic interpretations, and its V-shaped head was discovered to have undergone different stages of cuts and fills over time with four generations of the canyon (including the present day Avon Canyon) identified. Deptuck et al. (2007) employed 3-D seismic data to investigate the migration and aggradational history of a section of the Benin Canyon and discovered that the canyon was filled by a series of migrating meandering to linear U-/V-shaped channels that are flanked by overbank deposits. Armitage et al. (2012) studied the post-avulsion evolution of the channel systems off the Niger Delta intraslope minibasin and found that the channels have been aggradated through back-filling of the turbidity current deposits of sandy sediment. Other notable studies are those of Petters (1984), Deptuck et al. (2003), Awosika (2008) and Abd El-Gawad et al. (2012) among others.

In this study, using high resolution multi-beam data alongside sub-bottom profiles and a multichannel seismic line, we confirm the deeper sea extension of four canyon systems on the western Nigerian continental margin, i.e., the Avon, Mahin, Benin and Escravos Canyons, document their architectural morphologies, examine their controlling factors and propose possible

processes for their formation.

2 Geological background of the study area

The western Nigerian continental margin is located on the Gulf of Guinea in the eastern equatorial Atlantic (Fig. 1). It is underlain by the Dahomey Basin whose offshore extent runs from Ghana down to the Benin Hinge Line at the western edge of Nigeria's Niger Delta (Ihenyen, 2003; Chiaghanam et al., 2014). The margin itself is comprised of a narrow shelf that gradually widens towards its eastern end and a coastline that runs from west to east. Its marginal sea floor, similar to the Niger Delta's, has a stratigraphic succession of Late Quaternary deposits that comprises of pre-older sands of grey silts with sand and plant debris layer; a stratigraphic break marked by a major physical discontinuity; older sands that are glauconite or shelly; and younger suite of sands, silts and clays (Allen, 1964). The materials are terrigenous (Olabode and Adekoya, 2008) primarily from fluvial deposition during the Late Pleistocene sea level fall (Allen, 1964, 1965; Ihenyen, 2003). It is divided into: (1) a barrier-lagoon coast with strips of sandy barriers, comprising of the Lagos and Lekki Lagoons (Fig. 1), with shelf and slope widths that reach approximately 34 km each and a slope foot lying at a water depth of approximately 2 200 m (Allen, 1964); (2) a low lying Mahin mud beach of a muddy coast that is prone to flooding during high tides and an approximately 50 km wide shelf with an approximately 150 m shelf-break depth (Deptuck et al., 2007); and (3) the western Niger Delta with approximately 70 km shelf width and 200 m deep shelf-break (Ihenyen, 2003; Deptuck et al., 2007; Awosika and Folorunsho, 2008).

In general, the Niger Delta and the entire Nigerian continental margin constitute a classic passive marginal basin whose development was accompanied by two evolutionary stages of tension rift and post-rifting drift. The formation and development of the basin are related to the breakup of the Gondwana supercontinent and the opening of the south and equatorial Atlantic in the late Jurassic–early Cretaceous periods (Tidjani et al., 1997; Ihenyen, 2003). The basin and the margin are dissected and controlled

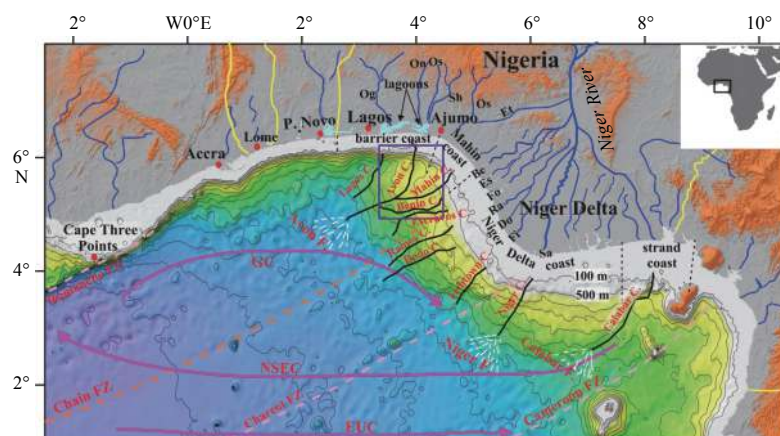


Fig. 1. Map of the Gulf of Guinea and the regional tropic equatorial Atlantic showing bathymetric contours (400 m intervals after the first 100 m); the Niger Delta and some of its estuaries (Be represents Benin River, Es Escravos River, Ra Ramos River, Br Brass River, and Bo, and Bonny River); lagoons and their sediment source rivers (Og represents Ogun River, On Ona River, Os Oshun River, Sh Shasha River, Oss Osse River, and Et Ethiopie River) (after Burke, 1972); geomorphological zones along the Nigerian coast (after Awosika et al., 2002); the distribution of the submarine canyons (after Allen, 1964; Burke, 1972; Deptuck et al., 2007) and the submarine fans (after Burke, 1972) on the Nigerian continental margin; geologic fracture zones; and the hydrology setting: Guinea Current (GC), the northern South Equatorial Current (NSEC), and the Equatorial Undercurrent (EUC) (Bourlès et al., 2002; Adegbe, 2008; Ukwé and Ibe, 2010). The study area is indicated by the purple box; the boundaries of the coastal zones are indicated by the broken black lines; the country boundaries are indicated by the yellow lines; and the coastal cities are indicated by the red dots.

by the chain, Charcot and Romanche fracture zones (Fig. 1), as an extension of the Mid-Atlantic Ridge. The upper and middle slopes of the margin are dominated by folding and faulting in response to the rapid sedimentation rates and shale remobilisation (Doust and Omatsola, 1989; Morley and Guerin, 1996). Over time, the thick stratigraphic column slowly moved downslope due to gravity gliding or sliding (Morley and Guerin, 1996), resulting in the lower slope being dominated by a series of linear toe-thrusts forming a fold-and-thrust belt.

The margin is characterised by a set of high energy and complex tropical zonal current bands, ranging from the Guinea Current to the northern South Equatorial Current, the subsurface South Equatorial Countercurrent and the Equatorial Undercurrent (Bourlès et al., 2002; Adegbe, 2008; Ukwe and Ibe, 2010).

Even though there is a record of the ancient canyons that have been filled and buried over geologic time (Allen, 1964, 1965; Burke, 1972; Olabode and Adekoya, 2008), at present, the western continental margin of Nigeria is incised by the major Avon and Mahin Canyons, and extensions of the Benin and Escravos Canyons whose nearshore parts are now buried (Deptuck et al., 2007; Olabode and Adekoya, 2008; Awosika, 2008; Ihenyen, 2003). In addition, the minor Lagos Canyon identified by Deptuck et al. (2007). These canyons are conduits through which sediments and other terrigenous materials move to the offshore basins in the adjacent plain.

3 Data and methods

To investigate the architectural characteristics of the deeper section of the submarine canyons in this study, we use multi-beam echo sounder (MBES) and shallow sub-bottom profile (SBP) data acquired during the China–Nigeria joint cruise of 21–29 August, 2012, onboard the R/V *Dayang Yihao* on the western Nigerian continental margin between the longitudes 2.688°E and 4.051°E, and between the latitudes 1.861°N and 6.140°N (Fig. 2, plum lines). A multichannel seismic (MCS) line off the Avon Canyon head obtained by an oil company was also used in this study.

The MBES data were acquired using a high resolution Kongsberg Maritime AS' EM120 multi-beam echo sounding system of 12 kHz. The obtained bathymetric data were processed with the Caris Hips software. The SBP data, collected by a TOPAS PS 018 sub-bottom profiler system with a wideband nonlinear differential frequency, were used for the analysis and characterisation of the shallow sediment strata beneath the seafloor of the study loc-

ation. A resolution of 30 cm was obtained with the primary and secondary frequency ranges of 12.5–17.5 kHz and 0.5–5 kHz, respectively. The SBP data were processed using Triton Imaging's SB-Interpreter™ software. The MCS line across the Avon Canyon head was analysed to show the characteristics at the head of the canyon.

4 Results

4.1 Morphological characteristics

The MBES data, spanning primarily the continental slope, cover an area of approximately 26 400 km² with a maximum depth of 3.53 km (Figs 3a and b). Along-canyon profiles were taken from the starting point to the branch or merging point for canyons with branches and from the head to the terminal for canyons with no branches. The distances covered are the measured lengths of the canyons. Across-canyon profiles were taken from several points on the canyons to examine the characteristic shapes and depths: the depths were calculated as the mathematical difference between the floor and rims of the canyons, and the deepest values were taken as the maximum depths, the shallowest values were taken as the minimum depths and their mean values were taken as the average depths. The sinuosity index was calculated as the ratio of the curvy length to the straight length between the two ends of the canyons. The gradients of the walls were calculated for several points and the average values were taken.

The shelf break to upper slope area is incised by the Avon and Mahin Canyons, and gullies of various sizes have been identified by previous studies. The structure of the study area is tectono-sedimentary with resultant deposition, i.e., it is more depositional than erosional. This structural system is evident from the area's role in the evolution of the submarine canyons and their architectural characteristics. The slope is segmented into upper, middle and lower slopes based on the abrupt gradient changes observed from the downslope profile obtained from the MBES (Fig. 3c). The upper slope is relatively steep with a gradient of 5.30°; the middle slope is gentler but still steeper than the lower slope with a gradient of 1.98°, and is characterised by the merging and branching of the canyons; and the lower slope, with gradient of 0.83°, features the canyon extensions and the merging of the Benin Canyon with the Avon Canyon. Of all the canyons in the region, it is only the head of the Avon Canyon that can be traced back to the shelf within the data limit. These

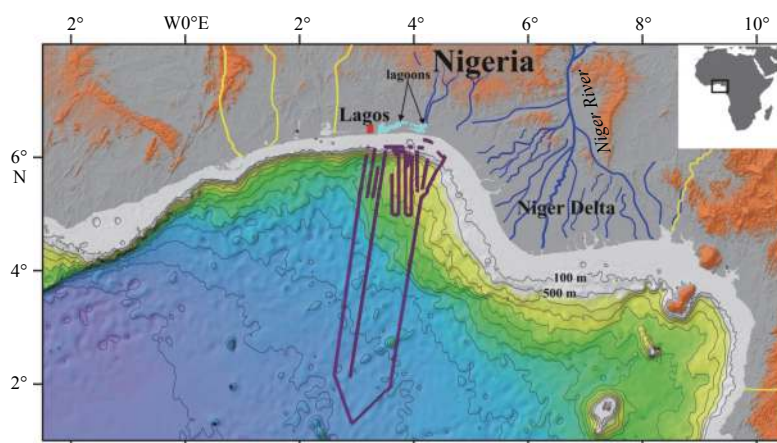


Fig. 2. Survey track lines for the MBES and SBP data used in this study.

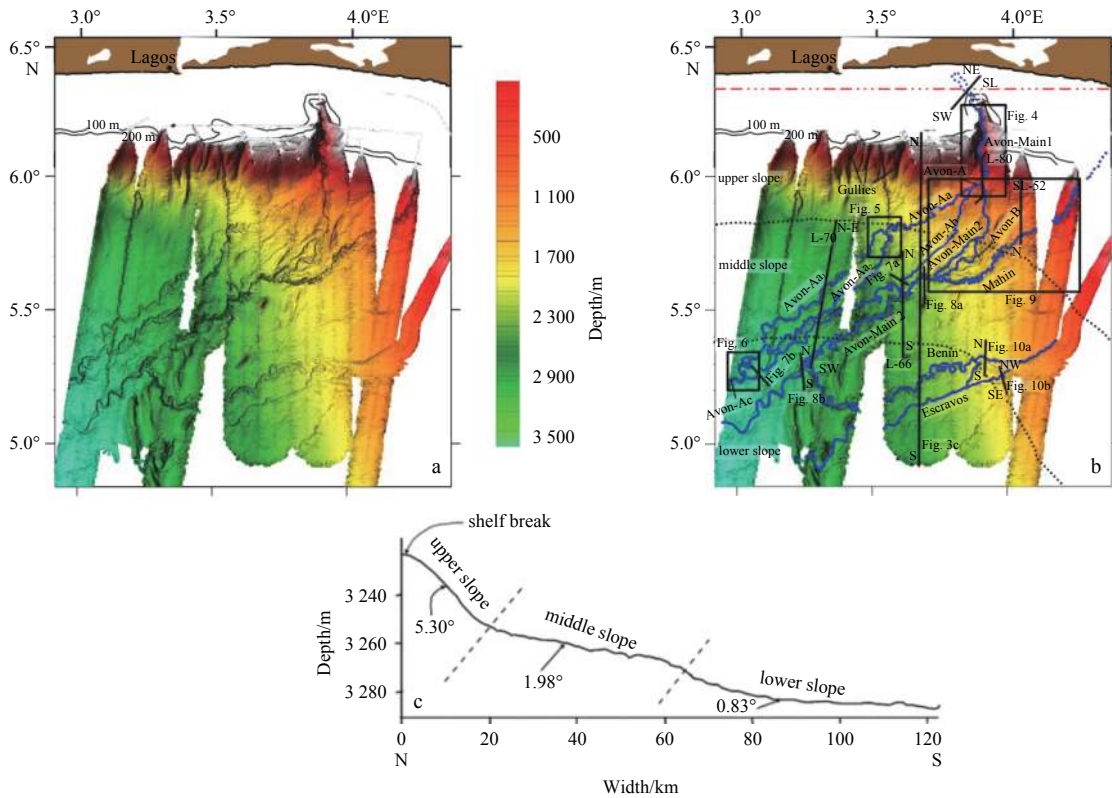


Fig. 3. Multi-beam bathymetric map (a), outline of the canyons (blue lines), displaying the locations of the figures, multichannel seismic line (SL) and sub-bottom profiles (L-52, L-80, L-66 and L-70) (b), and the location of the profile line used for the segmentation of the continental slope shown in panel (c).

canyons have varying geometries with different terraces and slope variations. The morphologic characteristics of these canyons, their branches and sub-branches are summarised in Table 1.

4.2 Avon Canyon

The Avon Canyon is a relatively large, generally U-shaped valley and is a meandering system with a head incising the continental shelf off the Barrier-Lagoon coastline (Fig. 1). It is 276 km long within the limit of the study area and is characterised by branches and sub-branches that later merge down the slope. For convenience, we divided the Avon Canyon into two sections: a section from the starting point around the head on the shelf to a

point where the canyon sharply bends and changes direction on the end of the upper slope, herein named Avon-Main1; and the rest of the course, herein named Avon-Main2 (Figs 3 and 4).

4.2.1 Avon-Main1

Avon-Main1 lies between the shelf and upper slope and is oriented in the N-S direction, with an estimated length of 51.6 km and a sinuosity value of 1.50: local sinuosity is as high as 2.48 in some sections. At its widest point, the canyon is more than 16 km wide, primarily due to the gully it runs through. Avon-Main1 has the largest depth of 718 m at a water depth of 967 m (Fig. 4). Its geometric V-shaped axis in the nearshore part gradually changes towards a U-shape with noticeable axial incisions (Fig. 4b), while

Table 1. Summary of the morphometric characteristics of the canyons and their branches derived from the multi-beam data

Canyon and branch	Length/km	Depth/m			Shape	Sinuosity index	Average gradient/(°)
		Max	Min	Average			
Avon-Main1	51.60	718.0	60.0	337.0	V/U	1.50	7.1
Avon-A	9.13	30.6	#	#	V	1.24	18.4
Avon-Aa	64.20	94.0	#	#	U	1.74	8.3
Avon-Aa1	92.40	80.0	15.5	36.8	U	1.35	16.7
Avon-Aa2	90.00	102.4	42.0	73.5	U	1.47	14.9
Avon-Ab	130.00	66.4	7.6	21.8	U	1.52	10.4
Avon-Ac	34.00	125.1	71.4	98.0	U	1.95	11.9
Avon-Main 2	224.00	134.0	17.3	46.6	U	1.84	16.3
Avon-B	31.20	70.0	20.2	41.4	U	1.91	12.6
Mahin	110.40	115.8	83.7	110.7	V/U	1.84	20.3
Benin/Escravos	#	83.0/72.0	15.4/13.0	60.0/56.0	U	#	9.2/10.1

Note: # represents length before splitting/merging.

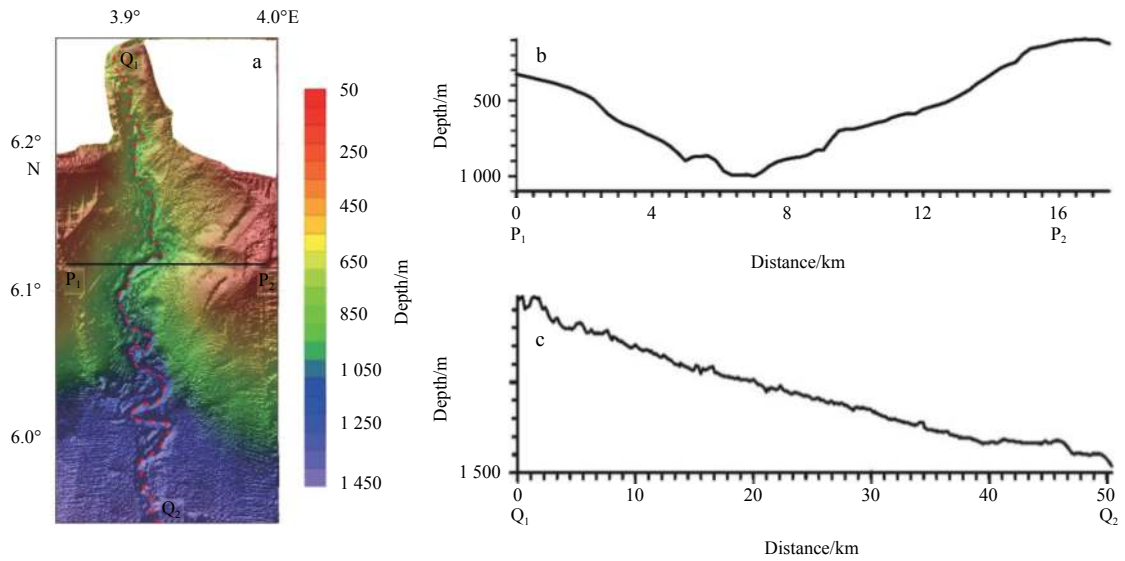


Fig. 4. Bathymetric map of the Avon-Main1 Canyon (a), profile across the canyon (location shown in Fig. 4a running from P₁ to P₂) (b), and profile along the canyon floor (the red dotted line in panel Fig. 4a from Q₁ to Q₂) (c).

its walls are characterised by terraces and sidewall scarps, having an average gradient of 7.1°. The floor shows undulations, which are signs of erosion and deposition along the course (Fig. 4c). On the western wall of the Avon-Main1 on its upper slope is the first branch, herein named Avon-A (Fig. 3).

4.2.2 Avon-A

Avon-A trends in the ENE–WSW direction and runs 9.13 km before splitting into two branches. It has a winding sinuosity with a value of 1.24, a symmetric V-shaped double thalweg morphology that is characterised by sidewall scarps, terraces and nick-points on the northern wall, a smoothly steepened southern wall and a depth that reaches 30.6 m from the rims to the axis. Avon-A

splits into two channels (sub-branches of the Avon Canyon) that, within this work, are called Avon-Aa and Avon-Ab (Figs 3 and 5a).

4.2.3 Avon-Aa

The northern section of the split Avon-A, herein called Avon-Aa, lies on the upper slope with a length of 64 km (the data gap area is measured on a straight path) and has an ENE–WSW directional trend and a meandering sinuosity of 1.74. Most of its upper and middle sections are very shallow while its lower section is relatively deep. The two across-canyon profiles (Figs 5b and c) taken in the lower section of Avon-Aa show a smooth U-shaped wall on top with a depth of approximately 60 m and a rough

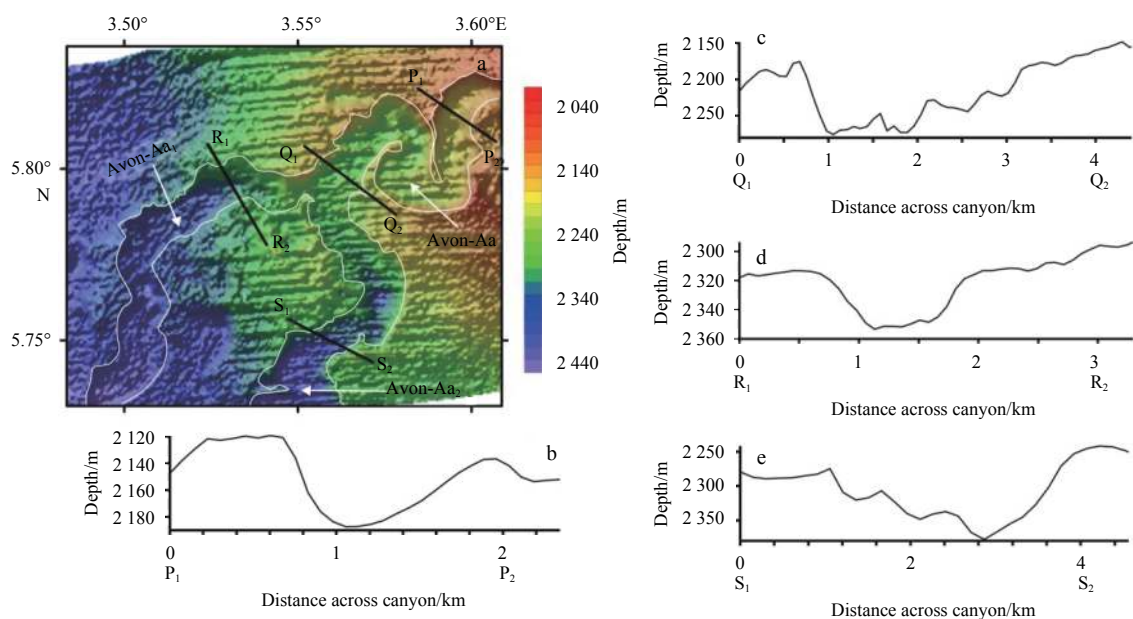


Fig. 5. Bathymetric map showing the lower section of Avon-Aa and the heads of Avon-Aa₁ and Avon-Aa₂ (a), profile across Avon-Aa (location shown in Fig. 5a running from P₁ to P₂) (b), profile across Avon-Aa₁ (location shown in Fig. 5a running from Q₁ to Q₂) (c), profile across Avon-Aa₂ (location shown in Fig. 5a running from R₁ to R₂) (d), and profile across Avon-Aa₂ (location shown in Fig. 5a running from S₁ to S₂) (e).

structure on the bottom close to the mouth where the depth increases to approximately 94 m. The rough structure of the bottom shows the presence of sidewall scarps of different sizes and a series of terraces on the walls with double thalwegs. Avon-Aa further splits into two, named Avon-Aa₁ in the north and Avon-Aa₂ in the south (Figs 2 and 5a).

4.2.4 *Avon-Aa₁*

Avon-Aa₁ lies entirely on the middle slope between the water depths of 2 280 m and 3 180 m. It is 92.4 km long (the data gap area is measured on a straight path) with a NE-SW trend and a sinuosity index of 1.35. It has an average depth of 15.5 m even though its depth reaches 80 m towards its terminal point where it merges with Avon-Aa₂, an indication that its depth increases down the slope. The across-canyon profile (Fig. 5d) taken in its upper part indicates a U-shape morphology and shows a nearly smooth wall and incision of the axis.

4.2.5 *Avon-Aa₂*

Avon-Aa₂, conversely, has over 80% of its estimated 90 km length on the middle slope and the rest on the lower slope. It runs parallel to Avon-Aa₁, approximately 8 km away, and eventually merges with it at a water depth of 3 180 m. It is a little deeper than Avon-A₁ (73.5 m on average and 102.4 m at its deepest point) and has a higher sinuosity index value (1.47). Its across-canyon profile (Fig. 5e) shows a nearly smooth SE wall but a rough NW wall that is characterised by terraces, escarpments, scarps and nickpoints. The merging of the two canyons produces a single channel, herein named Avon-Ac (Fig. 6).

4.2.6 *Avon-Ac*

Within our study area, Avon-Ac is 34 km long with a sinuosity

index of 1.95 and a local sinuosity index of 11.2. Figure 6a shows a bathymetric map of the Avon-Ac Canyon while Figs 6b, c and d are profiles across and along its course respectively. The along-canyon profile shows a series of erosional and depositional undulations while the two selected across-canyon profiles show a U-shaped morphology with an incised axis in the lower section of the canyon. Terraces and sidewall scarps are also obvious from the profiles. The depth ranges between a maximum of 125.1 m and a minimum of 71.4 m with an average of 98 m as the canyon courses down.

4.2.7 *Avon-Ab*

Avon-Ab is the southern section of the split the Avon-A Canyon (Section 4.1.1 for Avon-A) and lies between the upper and lower slopes, covering a length of 130 km. Its trend is complex, starting at approximately N60E from Avon-Aa and having series of bends along its course (Fig. 3) with a total sinuosity value of 1.52 before changing to a direction parallel to Avon-Aa₁ and Avon-Aa₂, and eventually merging with Avon-Ac from its eastern wall (Figs 3 and 6a). The across-canyon profiles taken in the NW-SE direction from its middle and lower segments (Figs 7a and b, locations shown in Fig. 3b) and the along-canyon profile (Fig. 7c) taken in the NE-SW direction along the floor indicate an average depth of 7.6 m and a maximum depth of 66.4 m. The walls are nearly regular in the upper to middle areas of the canyon but become irregular with sidewall scarps, levees and terraces as the canyon goes down its course. It is generally U-shaped with axial incisions around its lower segment.

4.2.8 *Avon-Main2*

Avon-Main2 is the second section of the Avon Canyon from the end of Avon-Main1 (Section 4.1.1 for Avon-Main1) to the ter-

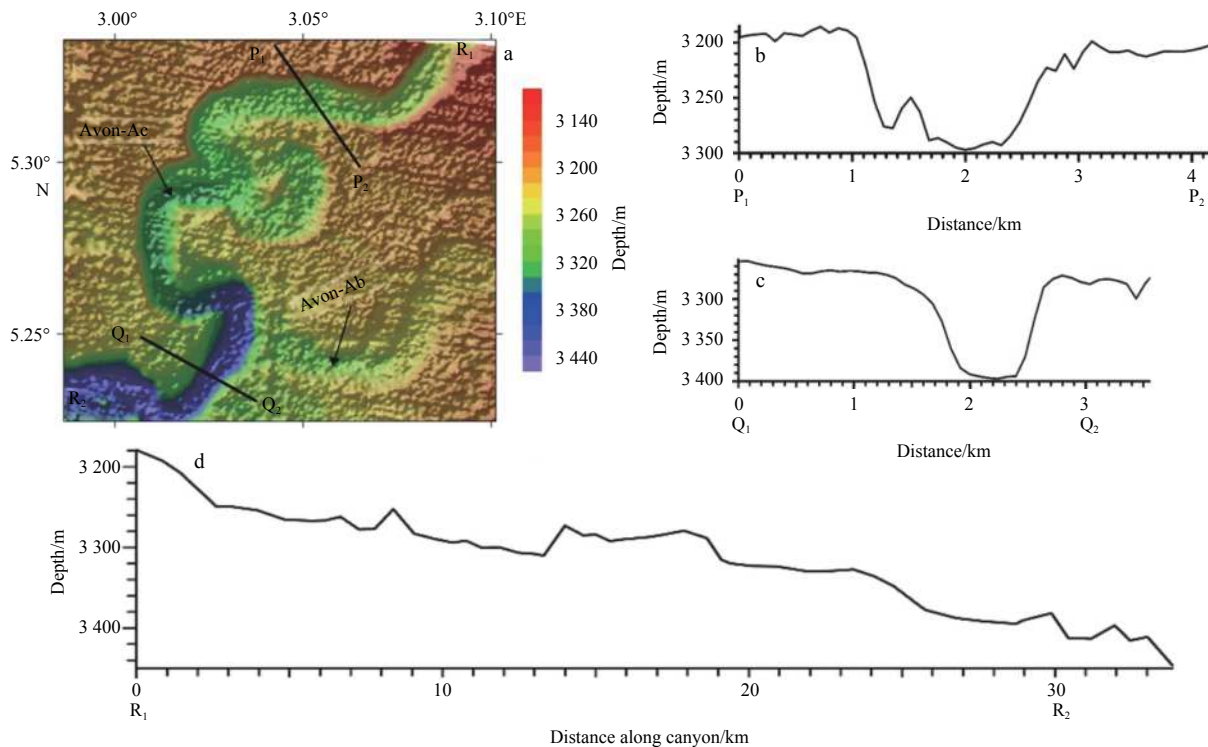


Fig. 6. Bathymetric map of Avon-Ac (a), profiles across Avon-Ac on (B1) its upper segment (location shown in Fig. 6a running from P₁ to P₂) (b), its lower segment (location shown in Fig. 6a running from Q₁ to Q₂) (c), and profile along the canyon floor (the red dotted line in Fig. 6a running from R₁ to R₂) (d). Note the merging of Avon-Ab to Avon-Ac in Fig. 6a.

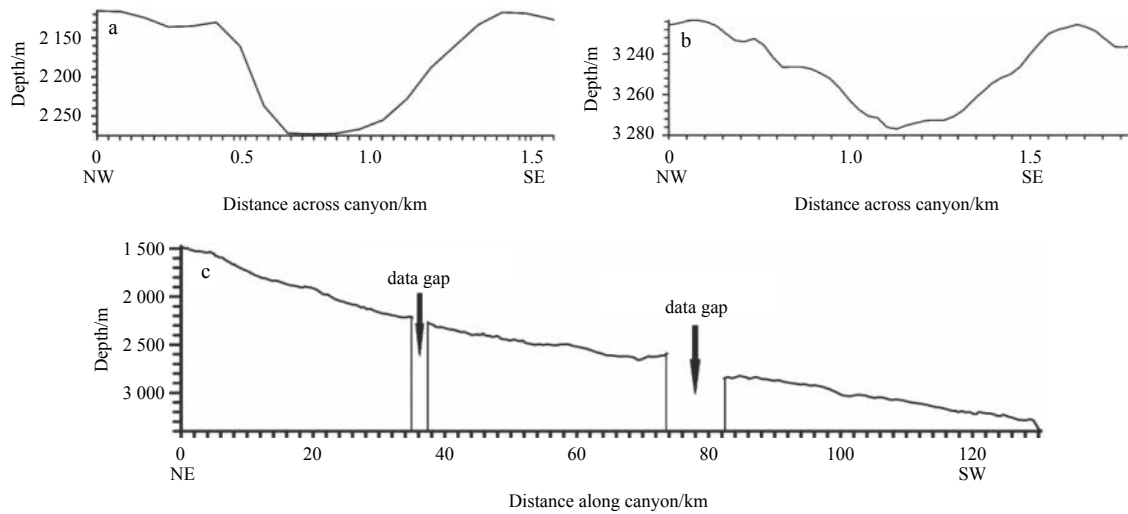


Fig. 7. Profiles of the Avon-Ab Canyon: across the middle segment (location shown in Fig. 3, profile runs from NW to SE) (a), across the lower segments (location shown in Fig. 3, profile runs from NW to SE) (b) and along the canyon floor (locations shown in Fig. 3, profile runs from NE to SW) (c).

minial within the data limit (Fig. 3). It is approximately 224 km long within the study area, orientating in the N-S direction as the continuation of the Avon-Main1 Canyon for approximately 21 km before sharply bending and changing direction to a NE-SW trend. It meanders with a sinuosity index of 1.84 and a very strong local sinuosity index of 10.6 at a section near the middle. The canyon's depth varies from 17 m at its upper segment to 134 m at its middle segment. The across-canyon profiles (Figs 8a and b) taken in the N-S direction at its middle and lower segments, respectively, show a wide near-flat bottom that transforms to a U-shape as the canyon extends down its course. The walls are relatively smooth with the absence of terraces, scarps and scours as shown by the profiles; however, their presence cannot be completely ruled out. There is a trace of an axial incision around its lower segment (Fig. 8b). The thalweg is characterised by undulations (Fig. 8c). Avon-Main2 receives a tributary of the merged Avon-B and Mahin Canyons on the middle slope and the Benin Canyon on the lower slope, both on its eastern wall (Fig. 3).

4.2.9 Avon-B

The second branch of the Avon Canyon is called Avon-B and starts near the section of the major bend in Avon-Main1 approximately 21.2 km before the start of Avon-Main2 (Fig. 3). It is 31.2 km long with an orientation of nearly NE-SW, notwithstanding, a series of bends along its course. It has a sinuosity index of 1.4 estimated along its entire length. It has a rough along-canyon floor but relatively smooth U-shaped across-canyon morphology with depths ranging from 20.2 to 70 m and an average gradient of 12.6°. It terminates when it joins the Mahin Canyon on its northern wall on the middle slope.

4.3 Mahin Canyon

The Mahin Canyon (Figs 3 and 9) is smaller than the Avon Canyon in terms of its size and morphology. Its starting point on the shelf is not covered by our data because it first appears at the edge of the shelf-slope area off the Mahin mud coastal zone; however, Allen (1964, 1965) placed it at around a longitude 4.5°E

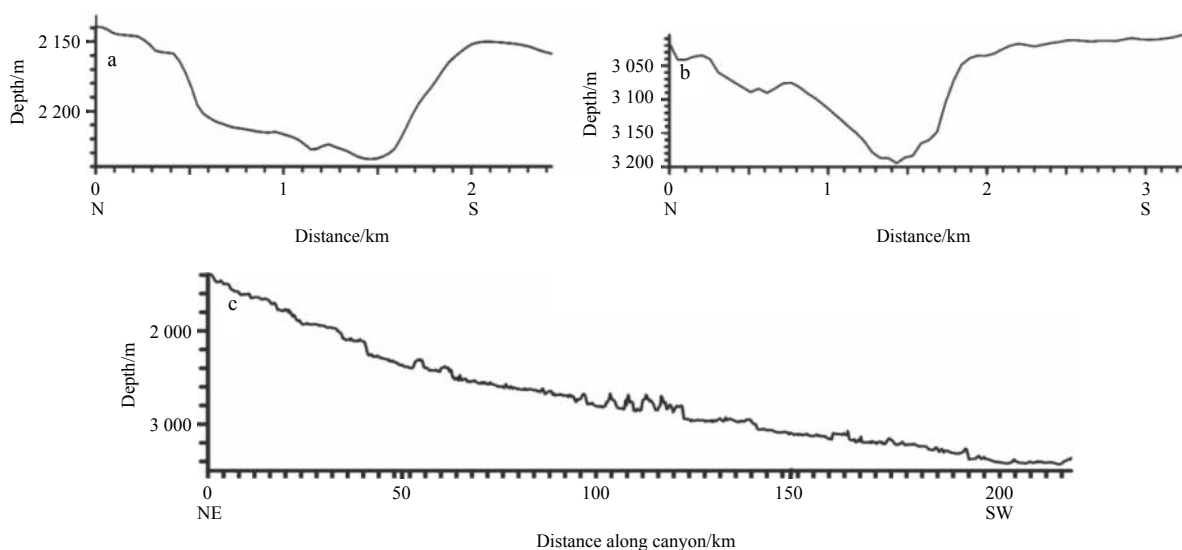


Fig. 8. Profiles of the Avon-Main2 Canyon across the upper segment (location shown in Fig. 3, profile runs from N to S) (a), across the lower segments (location shown in Fig. 3, profile runs from N to S) (b), and along the canyon floor (profile runs from NE to SW) (c).

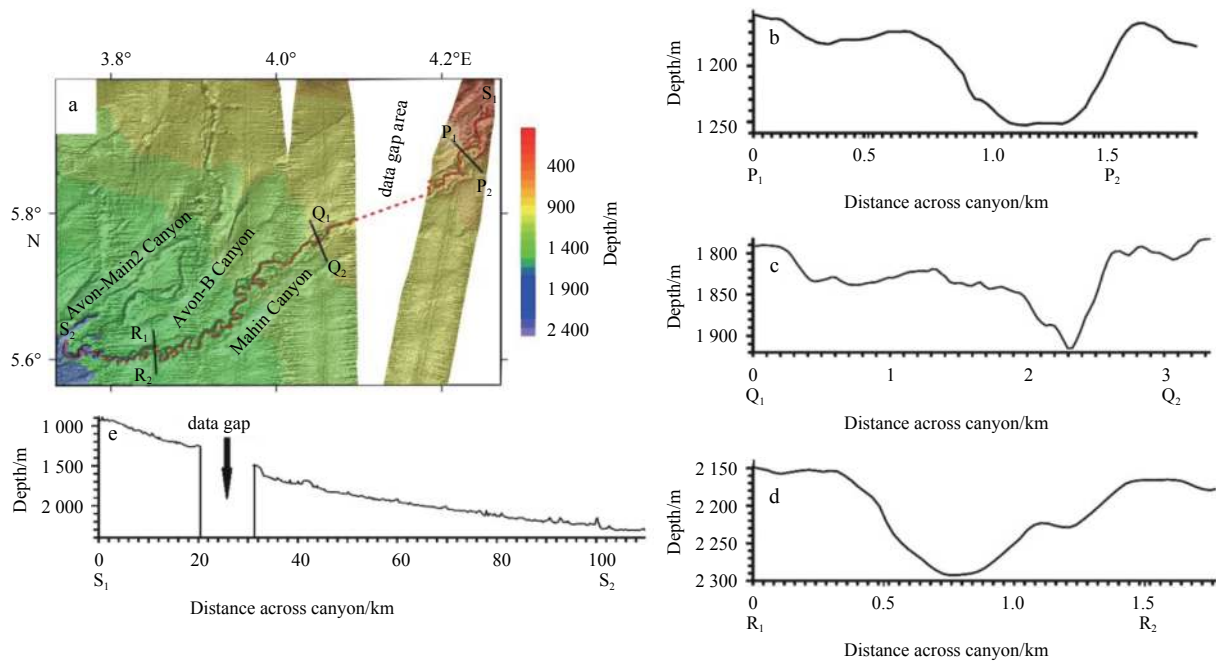


Fig. 9. Bathymetric map of the Mahin Canyon (a), profiles across the upper segment (location shown in Fig. 9a running from P_1 to P_2) (b), middle segment (location shown in Fig. 9a running runs from Q_1 to Q_2) (c), and lower segment (location shown in Fig. 9a running from R_1 to R_2) (d), and profile along the canyon floor (the red dotted line in Fig. 9a from S_1 to S_2) (e). Note the merging of the Avon-B to the Mahin Canyon in Fig. 9a.

and a latitude 6°N , some 20 km coastward from the start of our data. It covers a length of 110.4 km within our data limit, and receives Avon-B as a tributary on its northern wall before merging with the Avon Canyon through Avon-Main2 on its eastern wall near a water depth of 2 300 m, generally trending in the NE–SW direction in the process. It meanders with a sinuosity index value of 1.84 as it dissects the margin at an average depth of 110 m, having a maximum depth of 115 m towards its end and a minimum depth of 84 m around its middle segment. The Mahin Canyon's shape alternates between U- and V-shapes along its course (Figs 9b, c and d, locations shown in Fig. 9a), likely due to deposition in some regions and erosion in other. The along-canyon profile (Fig. 9e) shows a relatively smooth floor at its upper segment, a slightly rough floor at its middle segment and a very rough floor with a series of undulations, small valleys and axial incisions at its lower segment.

4.4 Benin and Escravos Canyons

In the lower section of the study area between the middle and lower slopes are extensions of the Benin and Escravos Canyons (Fig. 3). Their heads were likely linked to the Benin and Escravos river estuaries of the Niger River but have been filled over time. Within our data limit, they appear on the middle slope near a water depth of 1 400 m and are oriented at approximately 240° from the northern direction. The Benin Canyon splits into two branches, with one branch going southward to merge with the Escravos Canyon and the other one mostly maintaining the orientation of the mother Benin Canyon. A short distance later, they start moving in the same direction, parallel to each other, for nearly 70 km before drastically changing direction near a water depth of 2 700 m on the lower slope where they start drifting apart. The Benin Canyon moves northward in the SSE–NNW direction, eventually merging with the Avon Canyon on the southern wall of Avon-Main2 while the Escravos Canyon moves in the

NNE–SSW direction (Fig. 3). Figure 10 displays the morphological features across the upper segment of the Benin and Escravos Canyons. They are characterised by incisions on the floor, side-wall scarps, terraces and occasional levees. They are primarily U-shaped with symmetric rims.

4.5 Seismic interpretation

The internal structure of the canyons and their surrounding strata were examined using an MCS profile and four selected SBPs that cut across the Avon and Mahin Canyons (SL and L-52, L-80, L-66 and L-70 in Fig. 3b).

4.5.1 Multichannel seismic stratigraphy

The location of the MCS section is across the head of the Avon Canyon (SL in Fig. 3b), up on the shelf. The section shows the canyon paleo-channel which consists of channel-fill, levee/overbank deposits, and areas of mass transport complex. Channel-fill deposits are characterised by high-amplitude sub-parallel reflections having poor to good continuity. The levee/overbank deposits are characterised by low-moderate amplitude and parallel to sub-parallel reflections with good continuity. The walls are relatively smooth, except for a small erosional scarp on the western wall of the V-shaped section (Fig. 11). Two large and one small (possibly a remnant) paleo-channels, herein named LPC1, LPC2 and SPC, that have undergone series of erosions and depositions over time were identified beneath the Avon Canyon: the erosional and depositional features include stepwise characteristic of the canyon walls that show the presence of terraces, nickpoints, and sidewall escarpments as well as deep and wide axial incisions. The surrounding ocean floor is non-deformed. The seismic features of the older large paleo-channel (LPC1) include a relatively high-amplitude discontinuous reflection that is moderately chaotic, and a low frequency on average, which is relatively consistent with the SPC. The characteristics of the younger large pa-

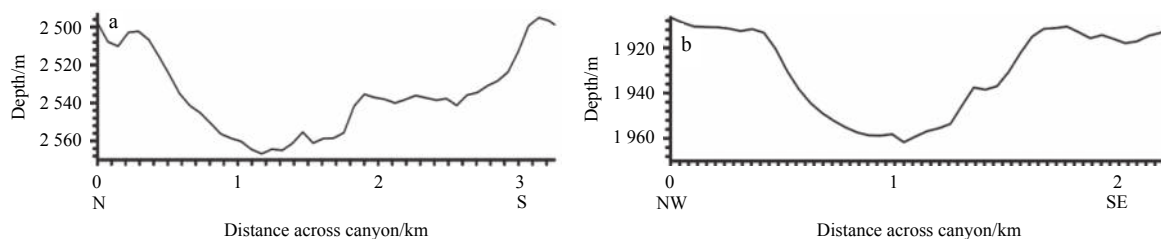


Fig. 10. Profiles across the upper segment of the Benin Canyon (location shown in Fig. 3, profile runs from N to S) (a), and the Escravos Canyon (location shown in Fig. 3, profile runs from NW to SE) (b).

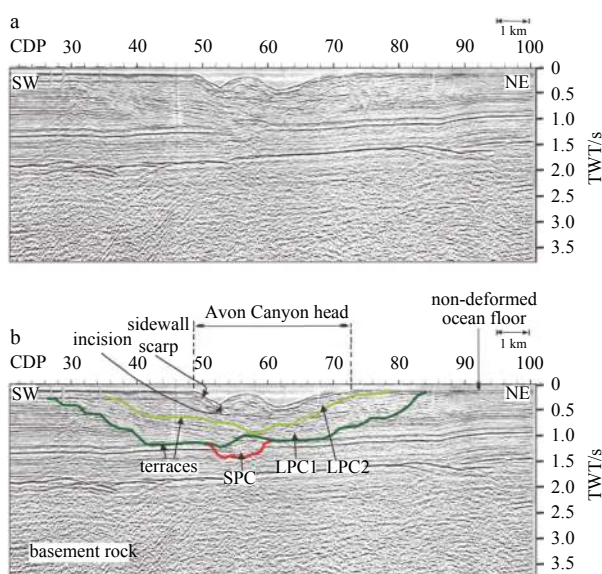


Fig. 11. Multichannel seismic section across the Avon Canyon head (Avon-Main1): uninterpreted (a) and interpreted (b).

leo-channel (LPC2) conversely, include continuous and fairly chaotic reflection features with high amplitudes (but relatively lower amplitude compared to that of the older channel) and frequency.

4.5.2 Sub-bottom profiles

The SPBs L-80, L-70 and L-66 (locations shown in Fig. 3b) were selected to interpret the Avon Canyon through Avon-Main1, Avon-Aa₁ and Avon-Main2, respectively. Profile L-52 was selected for Mahin Canyon (location in Fig. 3b). Profile L-80 crossed the Avon Canyon at Avon-Main1 twice as the canyon meanders along its course, thereby displaying two thalwegs with V-shaped morphology (Fig. 12a). The profile shows continuous shallow reflective horizons indicating parallel sub-bottom strata. A number of eastward-dipping normal faults are found on the western flank of the Avon Canyon, which obviously affected the structure of the wall, herein called faulted wall, and that of the canyon itself as indicated by the broad down-cutting terrace and smooth wall. On the eastern flank, a levee is recognised whose small size could indicate that it is either recently formed or has been reduced to its present size due to erosion. Profile L-70 (Fig. 12b) cuts across Avon-Aa₁ on the middle slope from north (right flank) to south (left flank). The relatively symmetrical rims indicate the flatness of the sea floor as a result of rapid erosional activity in the vicinity. The profile is characterised by a high reflection amplitude and continuous facies, showing parallel bed layers. The southern flank is more fault dominant than the northern flank. The sea

floor on the southern flank is a little deformed and sagged which can be linked to the dominating faulting activity. L-66 runs from south northward, cutting across Avon-Main2 and Avon-Ab (Fig. 12c). This profile is characterised by parallel, high-amplitude reflective horizons with a transparent sediment sequence. A normal fault on each of the sides of Avon-Main2 is recognised while three others are seen on the northern wall of Avon-Ab. The sea floor to the south is non-deformed, probably because the canyon is receiving most of the sediment coming down the slope. The axes of both canyons are filled with sediment deposits as indicated by the chaotic facies.

Profile L-52 (Fig. 12d) cuts across the Mahin Canyon at the middle segment. Several normal faults are recognised at both ends of the canyon, and the irregularities characterising the structure of the canyon can be attributed to these faults. The levee on the southern rim is still preserved while that on the northern rim has gradually been eroded. The higher number of faults on the northern flank where much of the erosional activity takes place can indicate that the faults are the controlling factor on the canyon. This is obvious from the weakness and instability of the flank is attributable to the presence of the faults, which consequently cause slumping and mass-wasting of the walls. The original axis of the canyon is being filled with sediments from the eroded walls and the new floor shows incision due to erosion.

5 Discussion

5.1 Sedimentary processes

The highly steepened shelf-slope transition area of the western Nigerian continental margin is characterised by various gullies (Fig. 3), especially in the region off Lagos. With steep and slightly smooth walls, the gullies range in depth from a few tens of meters to approximately 700 m. Their formation is associated with the turbidity currents resulting from sediments supplied by river drainages that deeply entrenched the marginal area prior to the marine transgression in the late Pleistocene-early Holocene (Allen, 1964).

The depth, width and morphological characteristics of the canyons in the study margin vary along the canyon courses; this variation points primarily to the sedimentary processes of erosion and deposition within and around the canyons. The canyons are generally U-shaped in the deeper sections with widths that are often greater than 1 km (Figs 4–10). The shallower sections on the shelf, however, have been observed to be V-shaped by previous authors (e.g., Allen, 1964, 1965; Burke, 1972; Petters, 1984; Olabode and Adekoya, 2008). This might imply more drastic erosion along the V-shaped canyon walls and deposition along the U-shaped canyon walls. The axial incisions displayed in the U-shape geometry indicate that the erosion and deposition processes are cyclical. Smooth U-shape profiles with no axial incisions can indicate that the deposition phase is re-

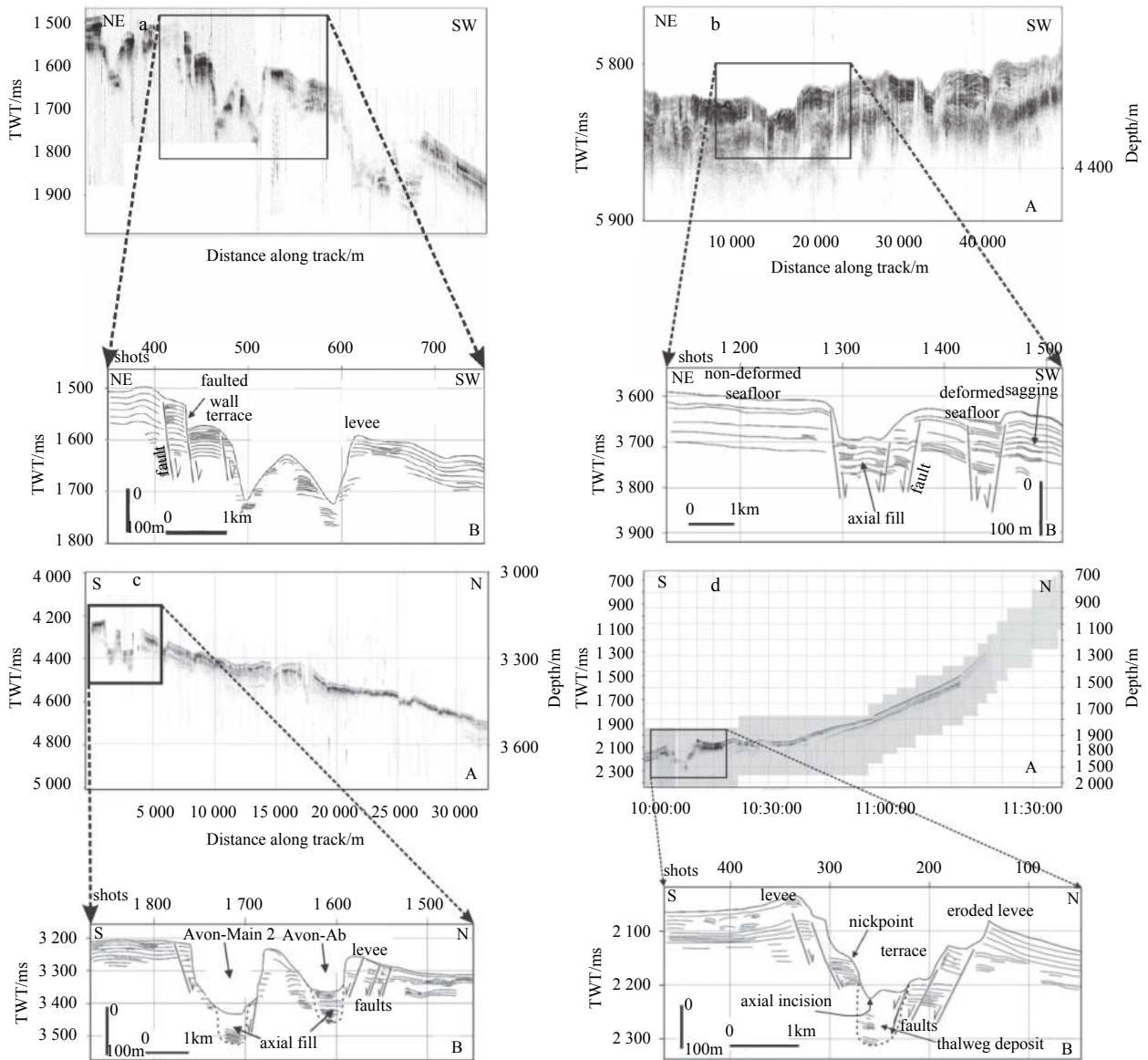


Fig. 12. Sub-bottom profile L-80 across Avon-Main1 (a), L-70 across Avon-Aa₁ (b), L-66 across Avon-Main 2 (c) and L-52 across the Mahin Canyon (d). A: uninterpreted and B: interpreted.

cent, or simply that the surfaces are composed of hard cemented bedding planes that provide resistance to erosion (Oiwane et al., 2011). The U-shape could also emanate from the combined effect of erosion and deposition when sliding and failure of the steepened walls provide material that spread across the floor and results in a flat-U-shaped system.

All the canyons have very high sloping gradients (Table 1), with the Mahin Canyon in particular reaching as much as 20.33° in the middle section. These gradients are reasonably attributed to erosion which reshaped the gentle walls into steep ones. Piper and Normark (2009) suggested that gradient greater than 0.38° were a sign of turbidity current evolution, and our canyons have far higher gradient values. It is, therefore, safe to conclude that the gradients in this study area are influenced by turbidity flows. This hypothesis is supported by the abundance of levees observed on the Benin Canyon by Deptuck et al. (2007). The terraces, sidewall scarps and nickpoints characterising the canyon architectural geometries likewise resulted from sedimentary processes, primarily erosion. The terraces are mostly gently sloped,

indicating erosion, but are flat in some places (e.g., Fig. 8a), indicating deposition.

The head of the Avon Canyon on Avon-Main1 also shows evidence of deposition as two paleo-channels have been identified as being buried underneath the canyon on the shelf area (Fig. 11) after their axes were filled by sediment, an indication of the long-term depositional process in the area. From the seismic section (Fig. 11), the paleo-channels are characterized by the stepwise walls and wide and deep axial incisions with the older channel underneath being much more incised. The width and depth of these channels are surprisingly large, a possible indication that their heads were far landward and that the coastline was farther inland than its present location.

The meandering of the canyons also provides evidence of sedimentary influences on the canyon architecture. This characteristic is the consequence of the erosion of one flank and the deposition of the material on the other, thereby forcing the canyon path to shift towards the depositional side (He et al., 2013). The canyons on the western Nigerian continental margin have high

sinuosity indices, with the Avon Canyon having a value reaching 1.95 along the Avon-Ac (Table 1). The lowest value recorded is 1.24 for the Avon Canyon at Avon-A.

The effect of sedimentary processes on the morphology construction has also been reported for the Argentine continental margin canyons (Lastras et al., 2011), the Goto Submarine Canyon off the Huanghe River (Oiwane et al., 2011) and the Tugela Canyon in the Natal Valley off South Africa (Wiles et al., 2013).

The origin of the sediments in the canyons is the continent. The sediment around the Avon Canyon is terrigenous (Olubode and Adekoya, 2008), the source of which was linked to the Ogun, Ona, Oshun and Shasha Rivers which appear to have fed the canyons during the low sea level of the Würm-Wisconsinan glaciation (Burke, 1972) when the sea level dropped to approximately 130 m (Oiwane et al., 2011). At that same period, the Mahin Canyon was fed by the Ethiopie and Osse Rivers (Burke, 1972); therefore, the sediment there could be terrigenous as well. The present day supply of such terrigenous sediment into the Avon Canyon is still sourced from those rivers as they empty into the Lagos and Lekki Lagoons before being transported to the continental shelf via the Commodore Channel and then discharged into the canyon head by the longshore drifts that result from the southwesterly winds (Allen, 1964; Burke, 1972). The Ethiopie and Osse Rivers, conversely, empty their sediments into the Benin River which then discharges the sediments to the shelf where they are distributed along the shelf by longshore drift and across the slope by turbidity and contour currents. The sediments that reach the heads of the canyons are transported to the deep sea through the canyons. Considering their relative off shelf positions, the sedimentary materials in the Benin and Escravos Canyons are most likely from the Benin and Escravos Rivers because of the rivers discharge on to the shelf, even though distant materials from distant could also be brought to the river mouths through drifting. However, sediments may also be sourced from the walls of the canyons themselves when the walls collapse due to excessive steepening of the walls as a result of lateral erosion.

5.2 Fault effect

The underlying geologic structures of a margin can influence the formation and maintenance of submarine canyon systems because they play important roles in the sedimentary processes of the continental margins (Dantec et al., 2010; Ding et al., 2013; He et al., 2013). Such structures include faults and fracture zones, and there are several reports of such structures controlling canyon locations, migration, orientation and architectures, e. g., the Gaoping Submarine Canyon in southwestern Taiwan, China (Yu et al., 2009), the submarine canyon offshore La Jolla in southern California (Dantec et al., 2010), The Central Submarine Canyon in the Qiongdongnan Basin in the South China Sea (Gong et al., 2011), submarine canyons along the continental margin of Equatorial Guinea (Jobe et al., 2011), and the Zhujiang River Canyon system in the South China Sea (Ding et al., 2013). The Nigerian continental margin is a passive one with no profound tectonic or faulting activity taking place at the present. However, several passive faults of various types, including normal (Fig. 13), strike-slip and thrust faults, are dominant on the margin, especially in the Niger Delta (Corredor et al., 2005; Deptuck et al., 2007; Leduc et al., 2012). Some of these faults were formed during the period of active tectonic events when the margin was created, while others were formed by sedimentary activity, i.e., sediment-mass movement as the weight of the accumulated sediment deposition caused stress, strain and break in the

continuity of the mass. Several normal faults representing places of strata discontinuity on the SBPs are seen to lie near the walls of our submarine canyons (Figs 12a–d). Faults are defined to be zones of structural weakness (Ding et al., 2013) and it is believed that continued motion along faults can enhance active deformation which, in turn, can define the nature of the canyon walls (Restrepo-Correa and Ojeda, 2010). The extent of the terrace on the northern wall of the Avon Canyon (in Avon-Main1) is marked by a normal fault that dips down along the wall (Fig. 12a), and the presence of terraces, scarps and nickpoints are marked by faults on both walls of the Mahin Canyon (Fig. 12d). These morphological features may then be attributed to these faults.

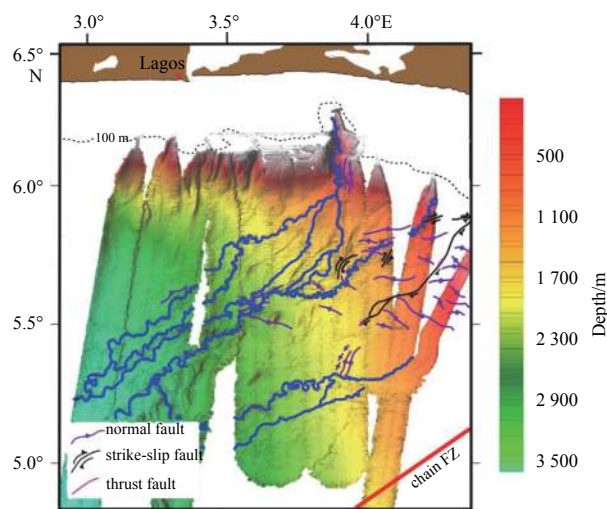


Fig. 13. Distribution of faults within the study area. Modified after Leduc et al. (2012) with additional normal fault locations from our SBPs and Deptuck et al. (2007).

Abrupt lateral displacement resulting from faults along their margins can also influence the bends and meanders of canyons (Mountjoy et al., 2009), and if this theory is applied to our canyons, we can assume the presence of faults to be responsible for the bends and meanders of our canyons. The asymmetry of the canyon flanks observed in some of the canyons could likewise have been affected by faults. Restrepo-Correa and Ojeda (2010) observed similar asymmetric walls in the La Aguja Submarine Canyon offshore Santa Marta which were attributed to faults.

The major controlling factor of the submarine canyons on the western Nigerian continental margin is sedimentary processes; however, considering the observations made above and the supporting references, we believe that the effects of faults, no matter how small, are likely to also control the canyon systems, especially the Avon and Mahin Canyons. This same assumption has been mentioned for transfer faults controlling the position of submarine channels in the western Niger Delta by Morgan (2004).

5.3 Canyon formation

The initiation of the submarine canyons off the western coast of Nigeria can be attributed to the fluvial systems cutting through the continental shelf during the marine regression of the Würm-Wisconsinan glacial maximum that resulted in a drop in the sea level (Allen, 1964; Burke, 1972; Olubode and Adekoya, 2008). The

formation of the vast ice sheets during the glacial period resulted in a dramatic sea level lowstand of over 100 m (Oiwane et al., 2011) which subsided and exposed the shelf and shallow part of the slope to the river courses whose hyperpycnal and sediment laden currents flowed at high velocities and incised and eroded the exposed underlying marginal area (Ding et al., 2013), creating flowing paths or channels in the process. The greater the amount of sediments supplied by the rivers, the deeper and wider the incisions and erosion, gradually enlarging the created channels. Therefore, the Benin and Escravos Canyons are products of initiations by the Benin and Escravos Rivers respectively. This is evident in the proximal locations of the canyons and the rivers, even though their nearshore portions have filled over time (Allen, 1964; Burke, 1972). The Avon and Mahin Canyons, on the other hand, have no direct link to any river mouth at present; however, Burke's (1972) reconstruction of river courses crossing the shelf during the marine transgression via the projection of recent rivers, based on an analogous comparison of the Nigerian continental margin's Gulf of Guinea to the Mississippi Delta's Gulf of Mexico of Allen (1964) suggested that the inland Ogun, Ona, Oshun and Shasha Rivers draining into the lagoons in Lagos initiated and fed the Avon Canyon, while the Osse and Ethiopie Rivers initiated and fed the Mahin Canyon (Fig. 1). By the time of the transgression that succeeded the glaciation as a result of ice sheet melting, the incisions and channels had been flooded and submerged beneath the ocean, resulting in the present form the canyons. Several other processes of the sedimentary system combined to shape, expand, evolve and maintain the canyons. For example, sediments were also sourced from slope failures and undersea landslides, as well as from the slumping of the walls of the canyons due to over-steepening. The transportation of these sediments through high velocity turbidity flows aided in deepening and widening the canyons as well as elongating them as the flows further eroded the floor down the slope. These processes have been reported to have influenced several canyons, especially the canyons on the Argentine continental margin (Lastras et al., 2011), the Hikurangi margin off New Zealand (Mountjoy et al., 2009), the Equatorial Guinea continental margin (Jobe et al., 2011) as well as the Zhujiang River Canyon in the South China Sea (Ding et al., 2013) and the Avon Canyon off Nigeria (Olabode and Adekoya, 2008).

At present, however, while the Benin and Escravos Rivers can directly supply sediment into their respective canyons, the rivers of the Avon Canyon only discharge into the lagoons which then transport the sediment to the shelf through the opening at the Commodore Channel and distribute them across the shelf via longshore drifts before emptying into the canyons. The Osse and Ethiopie Rivers attributed to the Mahin Canyon in the glacial period are now emptying into the Benin River before being transported to the sea. The final destination of these sediments is the Avon submarine fan at the foot of the continental rise (Fig. 1).

Another possible mechanism for the initiation and formation of the submarine canyons in this study area is the scours that characterise the canyon walls. Scours are also believed to be present on the sea floor around the study area (Deptuck et al., 2003). Similar features have been identified on the sea floor and canyon interiors off Argentina by Lastras et al. (2011). Prior to the glacial period when the sea level was high, several such erosive bedform features resulting from bottom currents may have littered the shelf-slope area. The continuous flow of the bottom currents may have merged the scours together and making them grows larger over time. During the sea level lowstand of the glacial period, the shelf-slope area were exposed and terrigenous

sediments were able to be transported across the shelf-slope area and may have further eroded and enlarged the incisions resulting from the scours. At the subsequent sea level rise, the incisions would had been submerged and the turbidity current flows would have helped in the extension of the incisions up and down the shelf-slope, creating sinuous and meandering patterns as the flows cut through less resistive seabed. This hypothesis requires further investigation and such scours need to be examined.

6 Conclusions

The western Nigerian continental margin is characterised by four major submarine canyons of different morphological architectures, namely: Avon, Mahin, Benin and Escravos Canyons. This study examines the architectural characteristics of these canyons in the deeper section, mostly in the slope and deep ocean basin area. The Avon Canyon, in particular, located off the Barrier-lagoon, incised the shelf down to 718 m in its head area with a width as wide as 16 km, primarily due to the large gully through which it passes. It has undergone a series of cuts and fills over time, as identified by Olabode and Adekoya (2008). Conversely, the Mahin Canyon, located off the mud coast, has incised the bed up to approximately 116 m. Developments of all four of these canyons are associated with river entrenchment and submerging during the Quaternary regression and transgression. The Avon Canyon has two visible branches, one on the upper slope and another on the middle slope, two sub_branches on the upper slope, and two further sub_branches on the edge of the upper-middle slope transition area. The Mahin Canyon merges with the middle-slope branch of the Avon Canyon before the two eventually merged with the main course of the Avon Canyon. The Benin and Escravos Canyons are relatively smaller than the Avon Canyons. The positions of their heads on the shelf are not covered by our data; however, they both appeared to be interconnected around the upper-middle slope area when they surfaced in our study area and later diverge from each other around resistive hills, with the upper Benin Canyon going NNW to merge with the Avon Canyon and the lower Escravos Canyon moving SSW towards the deep ocean. Their nearshore sections are believed to have been filled over geologic time. All these canyons exhibit both erosional and depositional architectures in terms of the sidewall scars, terraces, axial incisions, nickpoints, heavy meanders, high wall gradients and occasional scours on the floor. They are mostly U-shaped in the deeper studied sections while the Avon Canyon's shallower section is mostly V-shaped.

A number of normal faults were found in the SBPs around the Avon and Mahin Canyon walls while other types of faults have been reported in the same vicinity by Deptuck et al. (2007) and Leduc et al. (2012). These faults, together with sedimentary processes, are believed to be the controlling factors of the morphology of the canyons.

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