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APPLICATION OF ENHANCED SEISMIC SEMBLANCE ATTRIBUTE TO THE CHARACTERISATION OF ELEMENTS OF DEEPWATER UPPER SLOPE CHANNELS, OFFSHORE WESTERN NIGER DELTA

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ABSTRACT

Deepwater depositional elements are the building blocks of submarine systems and represent the basic mappable elements in seismic volumes. This study utilizes good quality 3-D seismic data of 300 km^2 areal coverage in water depth of 500 m to characterise the planform morphology and distribution of channel elements in the upper slope of deepwater western, Niger Delta. The seismic interval of interest (between 500 and 1650 milliseconds two-way time (TWT), informally termed 'Channel System', was subdivided into six (6) seismic units - Intra Channels (IC) 1, 2, 3, 4, top channel system (TCS), and undeformed hemipelagites (UH). Seismic interpretation was carried out for each of the seven horizons to derive their respective subsurface TWT maps. The median surface between two successive maps were derived to capture their internal architecture within the seismic units based on reconditioning the seismic volume semblance attribute. The resulting semblance attribute maps, from the Intra Channel 1 (IC1) unit through the overlying units to the Undeformed Hemipelagites (UH) unit presented an enhanced planform morphology of various NE-SW trend channels. The IC1 is imprinted with three channels of varying sinuosity, IC2 is characterised by one non-sinuous channel and one sinuous channel, IC3 indicates three non-sinuous channel, and one sinuous channel, IC4 and the TCS' are both characterised by several sub-parallel channels and one sinuous channel, while the topmost UH unit displayed several straight slope gullies upslope with imprint of one precursor sinuous channel. The identified channel forms vary in morphology, sinuosity and distribution both spatially and across the stratigraphic succession in the upper slope. The progressive temporal disappearance of the channels is linked to the associated background hemipelagites that acted as blankets over the precursor channels.

KEYWORDS: Semblance Attribute, Slope Gullies, Sinuous Channels, Upper Slope, Niger Delta

INTRODUCTION

Channels on the continental slope and other high-relief basin margins have been recognized as important primary conduits for sediment transfer from non- and shallow marine environments to deep-water basin-floor settings (Deptuck *et al*., 2007; Hubbard *et al*., 2020) with varieties including slope gullies and canyons.

Slope gullies are straight, regularly spaced shallow channels and are an order of magnitude smaller than submarine canyons prevalent on continental slopes and steep areas of seafloor worldwide (Field *et al*., 1999; Spinelli and Fields, 2001). Their newly observed abundance is largely a result of high-resolution multibeam mapping systems (Hughes-Clarke *et al.* 1996) and 3-D seismic data (Lonergan *et al*., 2013).

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On continental slopes, they can originate at or near the shelf edge (shelf-indenting gullies) or hundreds of meters downslope of the shelf edge (headless gullies) (Shumaker *et al*., 2017). The geologic processes leading to the development of slope gullies are diverse and include erosional (Izumi, 2004; Micallef and Mountjoy, 2011) to depositional (Field *et al*., 1999; Spinelli and Field, 2001; Chiocci and Casalbore, 2011), or a combination of the two (Fedele and García, 2009; Lonergan *et al*., 2013). The role that slope gullies play in transporting sediment into the deepwater milieu have been severally analysed (Spinelli and Fields, 2001; Lonergan *et al*., 2013). Generally, sea-level fluctuations, action of sediment gravity flow, slope mass wasting have, hyperpycnal flows, internal waves, and dense shelf-water cascades (Spinelli and Field, 2001; Canals *et al*., 2006; Chiocci and Casalbore, 2011; Gales *et al*., 2012)

Submarine canyons are common features on continental margins worldwide and have been identified to form through three processes including downward erosion in bed rock, lateral erosion leading to undercutting and slumping, and upbuilding in the form of levees (Shepard and Dill, 1966; Andrews, 1970; Andrews, *et al*., 1970; Deptuck *et al*., 2003 and 2007). In addition, Shepard (1981) have suggested that they can be of hybrid development forming over a long period. In some cases, they are formed exclusively on the upper slope, but there are also a relatively few large canyons with heads that deeply indent the shelfbreak (Popescu *et al*., 2004). Slope-confined and shelf-indenting canyons have been suggested to represent different stages of canyon evolution in which the shelf-indenting canyons may evolved directly from slope-confined canyons (Twichell and Roberts, 1982). In this process, a breach in the shelfbreak would correspond to transition from young to advance phase growth (Farre *et al*., 1983). Pratson *et al*. (1994) reported that the most active canyon development occur in the vicinity of the depocenter whereas shelf-indented canyons commonly connect with the path of a river during episodes of sea-level lowstand. In some cases, canyons may cut into the shelf deposits as far as the modern coastline and reach the river mouths as in Zaire Canyon (Babonneau *et al*., 2002) or Canyon of Capbreton (Cirac *et al*., 2001). Several shelf-indenting canyons are associated with large mud-rich deep-sea fan systems (e.g. the Amazon Fan, the Mississippi Fan, the Indus Fan or the Bengal Fan). There is general agreement that canyons acted as the main conduits for transferring river-borne sediments towards the deep sea and fed the fan system (Kolla and Coumes, 1987, Kolla and Perlmutter, 1993, Flood *et al*., 1997, Kottke *et al*., 2003; Deptuck *et al*., 2003 and 2007).

Sinuosity is a unique feature which is often display by majority of modern seafloor canyon (Babonneau *et al*., 2002; Kenyon *et al*., 1995) and subsurface maps generated from older canyons (Deptuck *et al*., 2003; Fonnesu *et al*., 2003; Kolla *et al*., 2001; Mayall and Stewart, 2000; Sikkema and Wojcik, 2000; Wonham *et al*., 2000). Sinuosity may develop in a canyon due to four causes including initial erosive base, lateral stacking, lateral accretion and sea-floor topography (Mayall *et al*., 2006) and the resulting sinuosity may vary from occasional bends in the channel to highly sinuous channels with numerous cut-off bends (Wynn *et al*., 2007)

The advent of the 3-D seismic data has aided identification and mapping of sinuous channels in the subsurface, and revealed their internal architecture and temporal evolution (Roberts and Compani, 1996; Kolla *et al*., 2001; Peakall *et al*., 2000; Abreu *et al*., 2003; Deptuck *et al*., 2003; Posamentier and Kolla, 2003)

GEOLOGICAL SETTING OF THE STUDY AREA

The Niger Delta continental margin, located in the Gulf of Guinea off the coast of southern Nigeria, is one of the world's largest deltaic systems, as documented by Doust and Omatsola (1990). It is approximately 75,000 square kilometres onshore and stretches outboard over 300 kilometres from its starting point to its mouth. Through a series of offlap cycles, the regressive delta and the adjoining margin consist of a wedge of clastic sediments with thicknesses of up to 12 kilometres, (Evamy *et al*., 1978; Doust and Omatsola 1990).

Tectonically, the Niger Delta basin began undergoing rifting during the Late Jurassic and continued into the Middle Cretaceous and subsequently, the process of rifting gradually diminished and eventually came to a halt in the Late Cretaceous (Lehner and De Ruiter, 1977). Rifting was primarily succeeded by the deformational process of gravity-induced tectonism with internal deformation of shale resulting from two contributing factors (Kulke, 1995). The first factor was the loading of under-compacted and over-pressured clays found in the prodelta and delta-slope areas of the Akata Formation by higher-density sands located in the delta-front Agbada Formation. The second factor was the onset of slope instability due to the lack of lateral and basinward support for the under-compacted Akata clays on the delta slope (Evamy *et al*. in 1978; Xiao and Suppe, 1992).

Stratigraphically, the Niger Delta is characterised by Tertiary marine and fluvial deposits, covering both oceanic crust and a portion of the African continental crust (Biloxi and Shaw, 2005).

Regressive sequence have been encountered in deep wells drilled in the Niger Delta and have been found to consist of three lithostratigraphic units, namely, the Akata (the oldest), Agbada, and Benin Formations (Short and Stauble, 1967). The Akata Formation is situated in a muddy continental slope and rise setting characterised by shale diapirs offshore. Typically, this shale formation is overpressured and provides detachment horizons for significant growth faults that delineate depobelts. The Akata Formation spans from the Palaeocene to the Holocene and is a marine lateral equivalent to contemporaneous delta topset strata (Doust and Omatsola, 1990). The Agbada Formation consists of neritic sandstone and mudstone, while the Benin Formation is primarily composed of non-marine sandstone. Huge submarine-fan channels go from erosional upper slope submarine canyons downslope to the continental rise, the key canyons being Lagos, Avon, and Mahin (in the west), Niger (central), Kwa-Ibo, and Calabar (in the east) (Damuth, 1994).

During episodes of declining sea levels in the early to middle Miocene, the Niger Delta's shelf and slope experienced the formation of erosional canyons. These canyons, such as the Opuama canyon in the western Niger Delta and the Afam and Kwa-Ibo canyons in the eastern Niger Delta, have since become buried and filled with clay (Doust and Omatsola, 1990).

SEMBLANCE ATTRIBUTE

The semblance attribute is a powerful transformation of seismic waveforms or traces to facilitate the measurement of the extent of similarity between post-stack seismic signals (Chopra and Marfurt, 2008) and it serves as a quantitative gauge for assessing lateral changes in amplitude (Bahorich and Farmer, 1995; Chopra and Marfurt, 2008). Obtained through a normalized cross-correlation process applied to neighbouring traces within a survey, the semblance attribute calculation eliminates variations in source-wavelet amplitude and phase to reveal the continuity of waveforms) by calculating a localized wave form or amplitude similarities in the inline and crossline directions (Bahorich and Farmer, 1995; Marfurt *et al*., 1998). It is also known as 'edge,' (Bahorich and Farmer 1995) and 'coherence,' a term used by Chopra and Marfurt (2008), along with Suarez *et al*. (2008). The calculation of the semblance attribute is particularly responsive to seismic textures and geological morphology (Chopra and Marfurt, 2008). Therefore, it is well-suited for distinguishing variations in the structure and stratigraphy.

METHODS

3-D Seismic Data and interpretation

The study was based on a high-quality 3-D seismic reflection data covering approximately 300 km^2 located in a water depth of around 500 meters in offshore of the western Niger Delta (Figure 1). It is about 30km to the littoral shoreline and represented by the slanted rectangular grid (Figure 1) which is bounded within latitudes 5º 50' 60'' and 5º 53' 43'' N and longitudes 4º 24' 4'' and 4º 30' 36'' E.

The seismic survey was acquired through vertical sampling interval of 4 milliseconds in two-w time (TWT), with inline and crossline spacing of 12.5 meters. The seismic volume was time-migrated, but migration was not carried out in the depth domain. The polarity of the data is SEG (Society of Exploration Geophysicists) format. In this convention, the blue reflection shows an increase in acoustic impedance downward, while a brown reflection indicates a decrease in acoustic impedance downward (Figure 2). The interval of interest in the seismic volume spans between 500 and 1,625 milliseconds TWT which translate to about 1,125 milliseconds thick (approximately 1,125 m). The interval was informally termed ‘interval of channel systems’ due to the occurrence of channel forms, the prominent of which is marked with a red arrow (Figure 2). This interval was subdivided into six stratigraphic units by seven key seismic horizons. These, from the interval base to its top, are ‘Intra Channel 1’ (IC1), ‘Intra Channel 2’ (IC2), ‘Intra Channel 3’ (IC3), ‘Intra Channel 4’ (IC4), ‘Top of Channel System’ (TCS), and ‘Undeformed Hemipelagites’ (UH) (youngest) (Figure 2).

Each identified seismic horizon was interpreted line by line across the entire volume of the 300km^2 3-D seismic data. The seed horizons were extrapolated through gridding to derive the smooth individual subsurface TWT maps. The median surface between two successive maps were generated to capture their internal architecture. To derive the semblance attribute that is representative of each unit, the 3-D seismic volume was re-conditioned into a semblance attribute volume and the respective semblance extracted.

CHANNEL PLANFORM ANALYSIS AND DISCUSSION

Intra-Channel 1 (IC1) seismic unit

The ‘Intra Channel 1’ unit is imprinted with three (3) channels of varying sinuosity. The northern part of this unit is marked by some high chaotic semblance texture which is attached to the upslope head of a channel system of about 500 m wide and terminates downslope to the south (Figure 3a). The sinuosity of this northern channel is considered moderate. Another channel with wider width of about 2000 m and high sinuous planform developed further south. The existence of the southern channel within this seismic unit is marked by the development of multiple episodes of sinuosity which predominates in the downslope segment of the channel. In addition, in the lower part of the sinuous channel, a minor channel feature connects and split off to the north from the main sinuous channel. These two channels served as the migration pathway or sediment fairway for sediment gravity flows that have been shed off from the upslope are

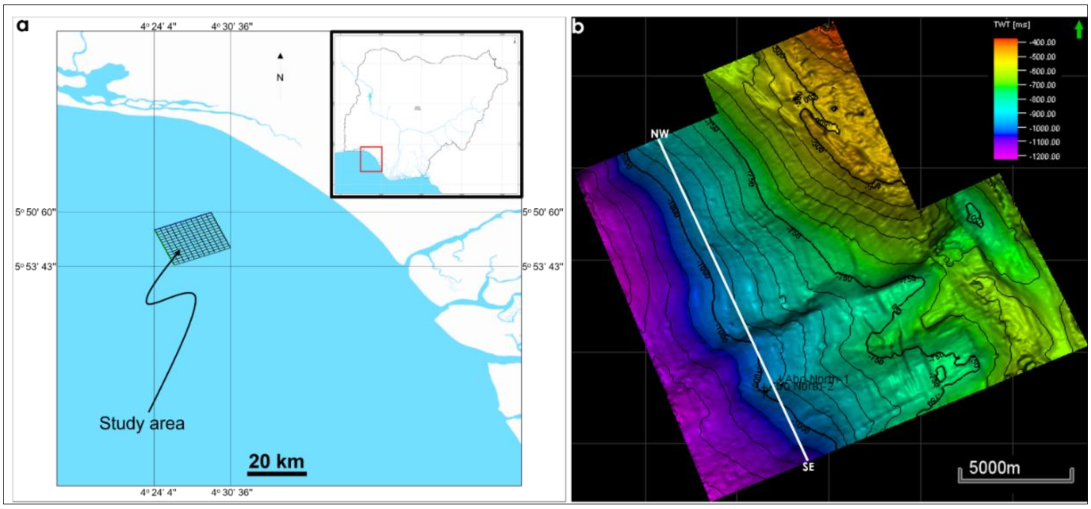

Figure 1: a. Location of study area within the western Niger Delta, Nigeria. Inset is the map of Nigeria. The slanted black rectangular grid represents the coverage of the 3-D seismic dataset used; **b.** Base map of the study area depicted by the two-way time of 'Top Channel System' horizon. The easternmost part indicated by hot colour (gold red) indicate the upslope while the warm colour (purple) to the west is the downslope part. The NW-SE trend white line is the seismic section along depositional strike of the study area.

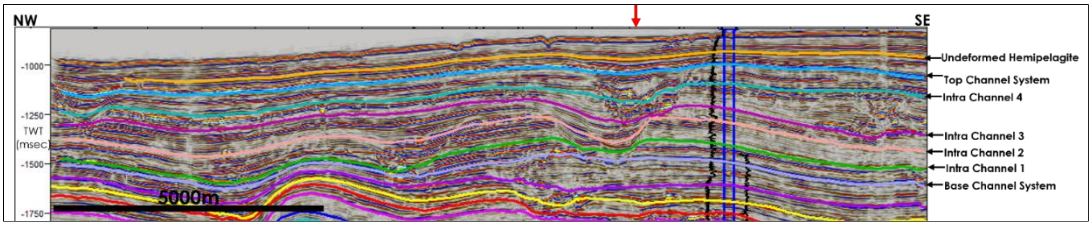

Figure 2: Strike oriented seismic section of the study interval. The succession is informally termed a 'Channel System', therefore the seven (7) identified horizons within it are referred to as Base Channel System, Intra Channel 1, Intra Channel 2, Intra Channel 3, Intra Channel 4, Top Channel System, and Undeformed Hemipelagite. The red arrow atop the section points to the large, dominant channel element within the interval.

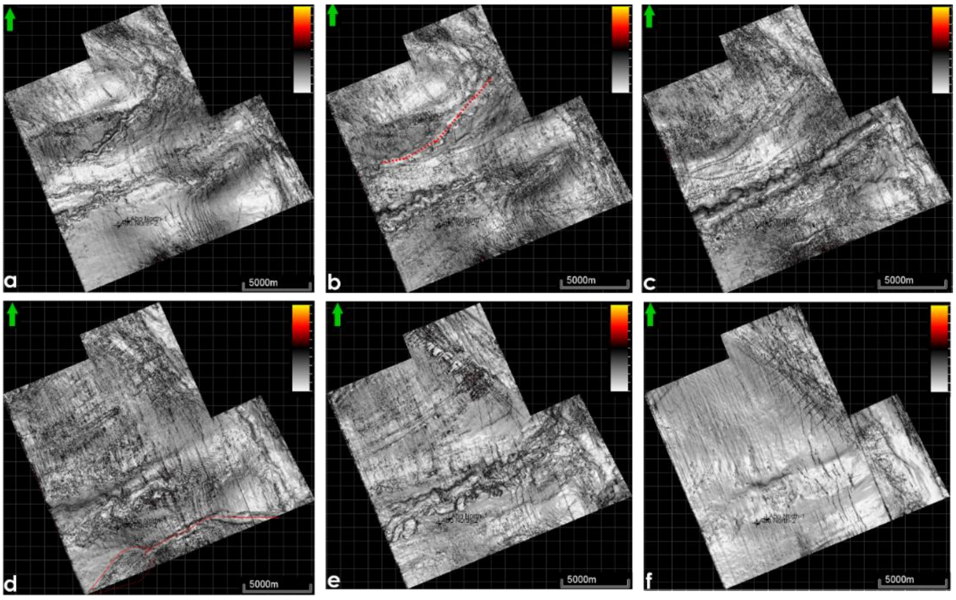

Figure 3: Semblance attribute maps across the interpreted interval in Figure 2. a. Intra-channel 1; b. Intra-channel 2; c. Intra-channel 3; d. Intra-channel 4; e. Top-channel system; and f. Undeformed hemipelagite. Note the red lines that are used to highlight some subtle features in b and d.

Intra-Channel 2 (IC2) seismic unit

Intra Channel 2 seismic unit is characterised by one non-sinuous channels and one sinuous channel. The semblance map (Figure 3b) shows a moderate semblance across the area, but channel stream is made of low semblance. The northern part of the unit is characterised by a curvy non-sinuous channel (see deduction made by red dotted line) of about 1,500 m width. The trend of the channel is generally northeast (upslope) to southwest (downslope) with a switching to westerly orientation in the terminal downslope area (Figure 3b). In the middle of the unit, a wide sinuous channel of about 1000 m and 2,500 m upslope and downslope width respectively developed.

Intra-channel 3 (IC3) seismic unit

This seismic unit is characterised by three non-sinuous channels and one sinuous channel. The semblance map (Figure 3c) shows a moderate semblance across the area. The northern part of this seismic unit shows two non-sinuous distinct curvy channels with average width of about 500 m. The channels display northeast-southwest trend from the upslope area to the downslope part. It can be observed that the lowermost of the two channels switches trend to more westerly orientation in the downslope segment. In the middle of this seismic unit, one large straight channel developed with widths of 1500 m upslope and about 2,500 m downslope. Further south, a non-sinuous channel of about 500 m developed running from the upslope environment and terminated midslope (Figure 3c).

Intra-channel 4 (IC4) seismic unit

Several sub-parallel slope gullies, one curvy channel developed and one sinuous channel in this seismic unit (Figure 3d). The semblance character of the unit can be considered high and interspersed by features of low semblance. The northernmost part is characterised by straight slope gullies trending northeast-southwest with average width of about 200 m. The centre of the unit shows impression of a sinuous channel of about 2000 m wide with its head in the midslope and runs downslope in a southwest direction. In the southernmost part, a curvy channel developed and maintains an east-southwest orientation. The downslope termination of the curvy channel is connected to a fan-like geometry made up of high semblance (red outline in Figure 3d). Near the fan, the semblance is low and indicates facies variation. The fan geometry can be considered to represent the delivery of sediment gravity flow transported downslope through the curvy channel (e.g. Type1 canyons system of Jobe *et al*., 2011).

Top of channel system seismic unit

This unit shows several occurrences of straight slope gullies and one sinuous channel (Figure 3e). The unit is generally characterised by low semblance with some distinct features of high semblance. The northern part of the unit is imprinted by slope gullies that are near-straight with average width of 200 m. These northern gullies have spacings between 200 m and 1,500 m and are orientated northeast (upslope) to southwest (downslope) reflecting a variable gully density along the slope (e.g. Spinelli and Fields, 2001). Although the head of the gullies connect to the upslope environment (similar to Lonergan *et al*., 2013) without much distortion, however, the two southernmost gullies have indications of high semblance chaotic features which can interpreted to represent zones of localized slope instability leading to the generation debris flows. To the south of the seismic unit, a high sinuosity channel developed with a width of about 4,000 m (Figure 3e). This channel cuts through the entire unit from upslope to the down slope in a northeast-southwest orientation. Within this sinuous channel, shingled bodies are formed which indicate that multiple episodes of channelisation occurred within the large channel framework (Posamentier and Walker, 2006; Straub and Mohrig, 2008; Straub and Mohrig, 2009; Straub *et al.,* 2008; Quan *et al*., 2017).

Undeformed hemipelagites (UH) seismic unit

The undeformed hemipelagite unit is predominantly characterised by low semblance across the entire area. Channel forms comprised of straight slope gullies and impress of a large channel (Figure 3f). The slope gullies are restricted to the northern part of the area. They have widths that range between 100 m to 150 m and have spacings between 1,000 and 1,500 m and trend northeast (upslope) to southwest (downslope). Their lengths are short which averages 4,000 m, so they terminated before the midslope (Figure 3f). In the south, wider channel forms, approximately, 4,000 m developed in a northeast-southwest trend. It is nearly straight and devoid of sinuosity.

DICUSSION

Variations in channel planform and morphology exist both across the spatial and the temporal evolution of the analysed seismic successions of IC 1, IC 2, IC 3, IC 4, TCS, and UH units. In all the units, going from the old (IC 1) to the young (TCS), the development of less sinuous channel, curvy and straight slope gullies are concentrated in the north. Conversely, advanced sinuous channels developed within the identified canyon in the south of IC 1, IC 2, IC 3, IC 4, and TCS units. This observation is consistent with the variation in channel evolution documented in Deptuck *et al*. (2003; 2007) where highly sinuous channel developed to the east and to the west it is straight. Thus, indicating that the temporal evolution of the channels in the north are different from the evolution of the channels in the south, perhaps due to deep-seated intra-basinal controls attributable to the changing grade of the seafloor where the deeper channel forms can be considered to have developed on above grade profile and the shallower channel forms on a more graded profile.

The slope gullies evolution was initiated on IC 3 unit and their distribution increases upward across the younger units (compare Figures 3c, d, e, and f).

In the results of seismic interpretation contained herein, the density or distribution of the gullies decreases downslope, although there are examples where the density of slope gullies increases downslope (Lonergan *et al*., 2013). For the identified slope gullies in IC 3, IC 4, TCS, and UH units, it can be suggested that subsequent deposition is significantly rich in background sediments which settles to form hemipelagic blanket over the precursor slope gullies.

The persistence of the sinuous canyon (Figure 3a, b, c, d, and e) which is still evident on the younger seafloor represented by the 'Undeformed Hemipelagite' unit (Figure 3f) shows that this area has remained the site of canyon development since the formation of the Intra Channel 1 unit (Figure 4), In addition, the morphology of the canyon has considerably modified from rough to smooth and aggradational with consequent loss of sinuosity. Although the canyon head can be observed at different upslope positions on all the units along the northeast-southwest trend, with the most upslope head in IC 3 (Figure 3), it is rather challenging to determine if this is a slope-confined or shelf-indenting canyons that have been recognized by Shepard (1981), Twichell and Roberts (1982), (Popescu *et al*., 2004), Farre *et al*. (1983), Pratson *et al*. (1994), Babonneau *et al*. (2002), Capbreton (Cirac *et al*., 2001) and Jobe *et al*. (2011). However, given the presence of slope fan apron attached to the downslope limit of the southernmost channel (Figure 3d), it can be deduced that this is a shelf-indenting Type I canyon described in Jobe *et al*. (2011).

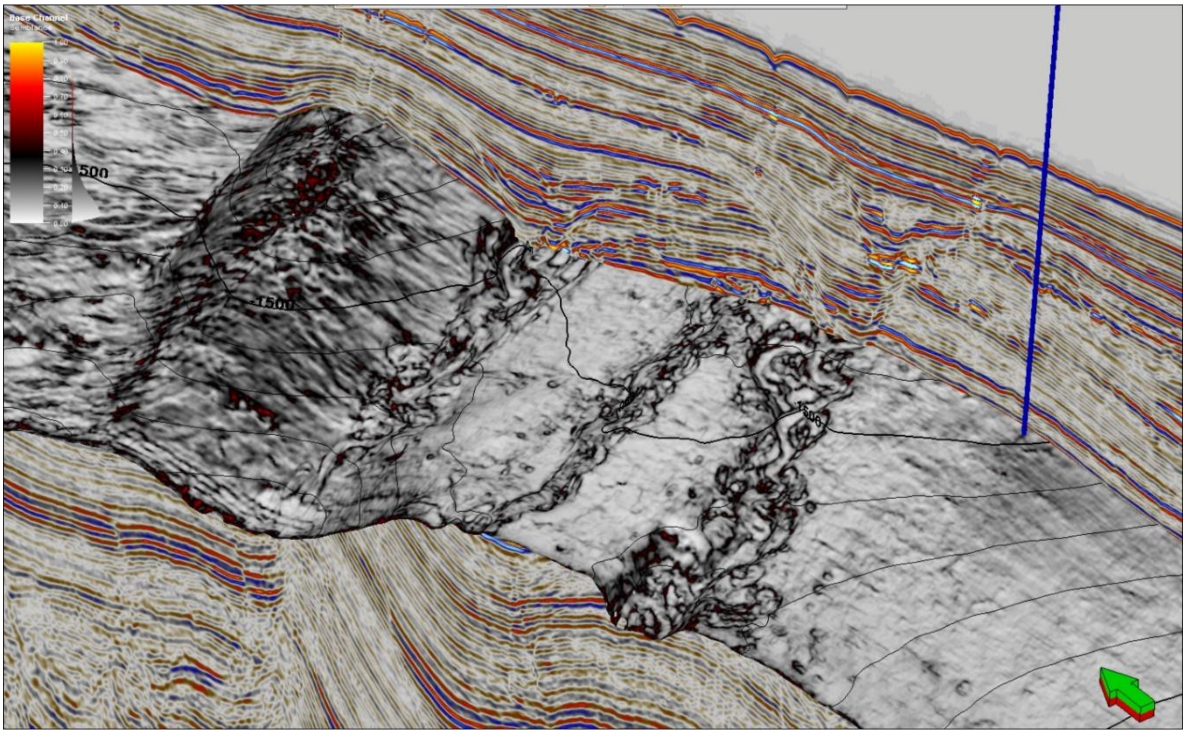

Figure 4: Strike-oriented 3-D visualization of regional seismic section with intersection of the Base Channel System horizon. These canyon features indicate the gradual fill of the ancestral canyon topography which has remained the sites of canyon occupation since the initiation of the channelisation.

CONCLUSION

1. Seismic semblance attribute has immense capability to capture and present high resolution image of subsurface channel forms and their associated features in deepwater upper slope milieu.
2. The analysed area within the deepwater western Niger Delta is characterised by various occurrences of northeast and southwest oriented channel forms including slope gullies and sinuous channels within a large submarine canyon which acted as conduit for the transfer of sediment gravity flows from the upslope environment to the downslope environment in the upper slope.
3. Channel forms vary in morphology, sinuosity and distribution along any given surface and across the stratigraphic succession in the upper slope.
4. Subsequent deposition of background sediments which are associated with sediment gravity flows acted as blankets of hemipelagites over the previous or ancestral channels thereby reducing the distribution of the channel forms across the seismic-stratigraphic succession.

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