The Influence of Growth Faults on Submarine Canyons Development in the Niger Delta

ThankGod Ujowundu[1], Vincent Delhaye-Prat[1], Abimbola Aigbe[1], and Totalenergies Sr.[1]

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Abstract

This study explores geomorphology within canyons using 3D seismic imaging. It reveals crucial insights that underscore the relationship between growth faults, slope instability, and canyon development. The structural settings of canyons, often conforming to established patterns, come to light as integral components of the study. An important observation was made: the gradient, a first-order factor, exerts significant control over both canyon initiation and propagation. Furthermore, the distribution of growth faults, a major catalyst for slope instability, holds an indirect yet profound link to sediment routing within canyons and the ancient geography of the region. These findings not only enhance our understanding of canyon evolution but also play a crucial role in interpreting reservoir distribution, marking them as invaluable assets in some geological exploration and reservoir management.

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Abstract

This study explores geomorphology within canyons using 3D seismic imaging. It reveals crucial insights that underscore the relationship between growth faults, slope instability, and canyon development. The structural settings of canyons, often conforming to established patterns, come to light as integral components of the study. An important observation was made: the gradient, a first-order factor, exerts significant control over both canyon initiation and propagation. Furthermore, the distribution of growth faults, a major catalyst for slope instability, holds an indirect yet profound link to sediment routing within canyons and the ancient geography of the region. These findings not only enhance our understanding of canyon evolution but also play a crucial role in interpreting reservoir distribution, marking them as invaluable assets in geological exploration and reservoir management.

1.0: Introduction

Since the pioneering study of Dana (1863), several works have been done on continental margins to understand how submarine canyons are formed and evolve on the continental shelf and slope. Canyons, depending on where they are created are erosional pathways, on land by fluvial erosion on uplifting continental plateaus (ex. Colorado) and tectonic barriers, or down to the deep-sea across the submarine shelves and slopes on both active (endogenetic) and passive (exogenetic) continental margins (Shepard, 1981; Brothers *et al.*, 2013; Aigbe et al., 2008; Busari et al., 2008). Submarine canyons may be described as steep-walled cutting with V-shaped cross-sections that may exist down-slope to show a shallower U-shaped channel system (G. Lastras *et al.*, 2009); or as erosive conduits that incise the continental shelf and slope through retrogressive sediment failures and active erosion by gravity movements (Mascle, 1976; Li *et al.*, 2013; Soulet *et al.*, 2016). Authors have observed that submarine canyons are generated more on active margins than on passive margins; where canyons are steeper and closely spaced on active margins, sediment accumulation is higher on passive margin submarine canyons (Harris and Whiteway, 2011; Oguadinma et al., 2023). Submarine canyon systems in plain view, most times display tributary and follow a sinuous path (Lastras *et al.*, 2009; Huang *et al.*, 2014), though the values of sinuosity in average it is not seen to show a significant difference between active and passive margin canyons (Harris and Whiteway, 2011).

The processes that transport deposits and erode sediments into the underlying bedrock of submarine canyons are all reflected in the shapes of submarine canyons (Paull *et al.*, 2011). The presence of enormous sediment accumulation in deep basins from canyon heads in deep-sea turbidites and fans (Paull *et al.*, 2011) suggests that submarine canyons are priority conduits for sediment transportation from shelfal regions to the deep-sea environment (Puig, et al. 2011). The complex morphology of submarine canyons is related to interactions with ocean currents, tides, internal waves, and, erosive processes/strength acting within the extent of submarine canyons.

In the Niger Delta Basin (Figure 1), numerous submerged canyons of varying sizes have been found. They range from older, buried canyons in the Oligo-Miocene period, to those that are near-surface buried and active canyons (Burke et al., 1972; Petters, 1984; Damuth, 1994; Billman, 1992; Ujowundu et al., 2008; Delhaye-Prat et al., 2009). The Pleistocene canyons in the western portion of the delta,

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where turbidity currents have been recorded or inferred since the groundbreaking work of Burke et al. (1972), were investigated by Deptuck et al. (2003, 2007), Olabode and Adekoya (2007) and Oguadinma et al., (2023). The southwesterly wind's longshore drifts provide sediments to canyons that are entrenched close to the shore (such the Avon and Mahin canyons), which later develop into low density turbidites and gravity flows. In this study, we aim to asssess submarine canyon geomorphology, canyon formation dynamics and propose a model for canyon development.

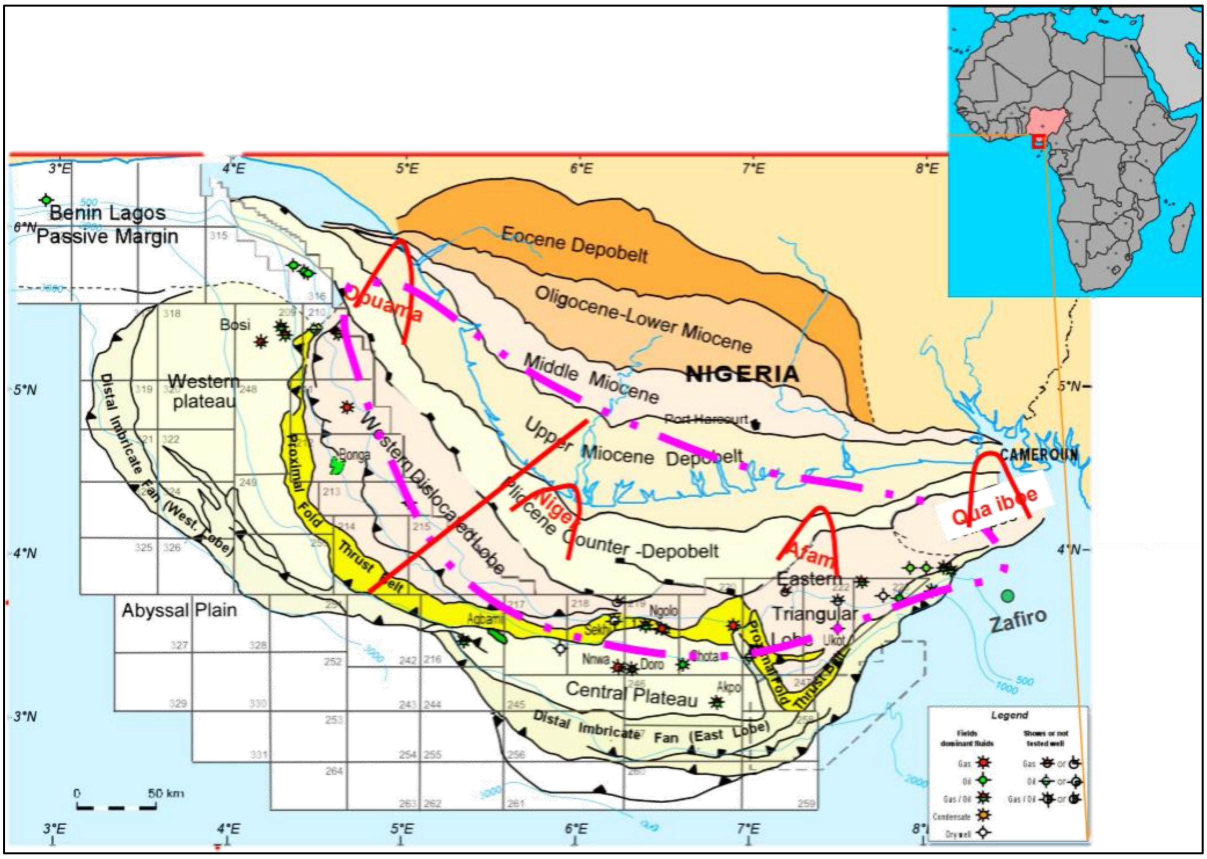

Fig. 1: Map of Africa to the upper right and map of Niger Delta below to show location of study.

2.0: Geological Setting

The Gulf of Guinea, on the edge of West Africa, is home to the Cenozoic Niger Delta basin (Figure 1). According to Tuttle et al. (1999) the Niger Delta is one of the world's largest regressive and thickest deltas, while Wu and Bally (2000) identified it as a classical shale tectonic province. With a maximum thickness of 12 km, it has an approximate 140,000 km2 coverage (Allen, 1965; Evamy et al., 1978; Doust and Omatsola, 1989). The Benue Trough, which the delta is located at the southern end of, was formed when the African and South American plates split apart in the early Cretaceous (Whiteman, 1982). The onshore delta depocenter contains sediments from the Paleocene to the present day and is roughly 12 km thick.

The Niger deltaic successions are divided into three largely diachronous lithostratigraphic units. The basal up to-7km thick Akata Formation consists of prodelta to marine shales. It is overlain by the up to-3.5km thick Agbada Formation delta front siliciclastics and interbedded turbidite sands layers. The top unit consists of up to-1.5km thick continental sands of Benin Formation (Avbovbo, 1978; Doust and Omatsola, 1989). The Delta progradations encompassing those formations extended over more

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than 200km. The Niger deltaic successions are divided into three lithostratigraphic units. The marine marine prodelta shales which is up to 7 km thick Akata Formation. The layers of delta front interbedded turbidite sands and up to 3.5 km thick siliciclastics Agbada Formation. The uppermost of continental sands Benin Formation that are up to 1.5 km thick (Avbovbo, 1978; Doust and Omatsola, 1989). The formations were covered by Delta progradations that spanned over 200 km.

Three structural zones were formed in the Niger Delta Basin (Figure 2), ranging from shallow water to deep water, under the direction of gravity tectonics and continuous deposition. Normal faults in the extensional zone, which includes the current delta plain and continental shelf, cause deep-seated marine shale diapirism, with the overpressured Akata Shale Fm. typically acting as the separation level. The intra-slope basin and mobile shales predominate in the translational zone, which corresponds to the upper and intermediate slope (Doust and Omatsola, 1989; Morley and Guerin, 1996). Reverse faults and detachment folds are features of the compressional zone in the lower slope to deep basin (Damuth, 1994, Cohen and McClay, 1996; Connors et al., 1998; Morgan, 2004; Bilotti et al., 2005; Corredor et al., 2005).

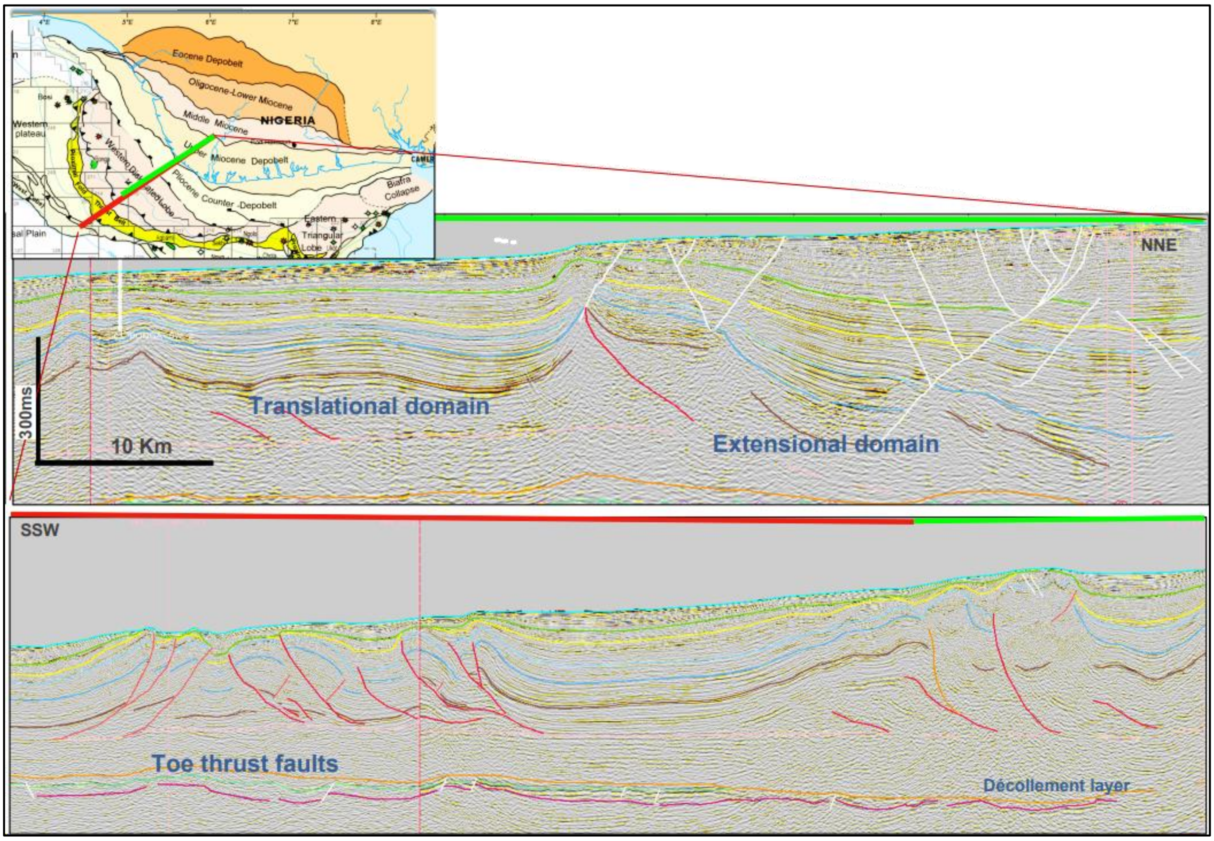

Fig. 2: Interpreted 2D line showing the general structural regimes in the Niger Delta - Adapted from Imperial College MSc project pool (Ujowundu 2007)

In the Niger Delta basin, a number of submarine canyons of various sizes have been identified, from active to near-surface buried ones (Figure 1), to older ones buried deeper in the Oligo-Miocene series (Burke et al., 1972; Petters, 1984; Damuth, 1994; Billman, 1992). Deptuck et al. (2003, 2007) and Olabode and Adekoya (2007) explored Pleistocene canyons of the western part of the delta, where turbidity currents are documented or inferred since the pioneering work of Burke et al. (1972). Longshore drifts caused by the southwesterly wind supply sediment to canyons that are entrenched close to the shoreline (e.g. Avon and Mahin canyons), then evolving to gravity flows and low density turbidites. Flow processes and the

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relationship to channel-belt aggradation were approached starting with the use of 3D reflection (Deptuck et al., 2007; Nwaezeapu et al., 2018; Oguadinma et al., 2016; Oguadinma et al., 2017; Aniwetalu et al., 2018; Ibekwe et al., 2023), while Abd-ElGawad et al. (2012) used a 3-d numerical model to simulate turbiditic current.

3.0: Data and Methods

3.1: Seismic data

A 3D high resolution seismic dataset was made available for this study. This seismic is a 3D "Pre-Stack-Time-Migration cube" with a bin spacing of 12.5 x 12.5 m. The dataset has a vertical sampling rate of 4 ms with the seismic data following the American Standard convention of zero-phased, normal polarity, where a pick (positive event = black) is associated with an increase in impedance and a trough (negative event = red) with a drop in impedance.

The 3D seismic geomorphology techniques from Richardson et al. (2011) and Posamentier and Kolla (2003) were used. The 3D data has been selected for nonconformities. Hemipelagic, mass transport deposits (MTDs), and turbidite systems are some of the depositional architectures in the Niger Delta that have previously been reported. High to moderate seismic reflectivity and high root mean square (RMS) amplitudes on 3D maps are characteristics of the sandy undersea channel deposits that infill the canyons (Posamentier and Kolla, 2003; Catuneanu, 2006). Horizon and fault mapping were also carried out and converted to maps for more in-dept interpretations.

3.2: 3D seismic geomorphology

3D seismic geomorphological assessment is based on the attribute map extracted from selected seismic layers where the seismic content is averaged (Posamentier and Kolla, 2003; Hansen et al., 2017; Catuneanu, 2006). The geometry of the seismic layer can be ascertained using these maps (Chopra and Marfurt, 2007; Taner et al., 1994). In this study, the root means square (RMS), and coherency attributes were applied to the 3D seismic data using Petrel™ software. The amplitude (RMS) attribute characteristic helps to observe geometries of geobodies defined by multiphase events as channels/complexes by computing the square root of the sum of squared amplitudes across a certain geological time of interest (Catuneanu, 2006).

4.0: Result and Interpretation

4.1: Geomorphology of canyons

The morphology of submarine canyons is related to stratigraphic and structural activities (Figure 3). There has been a successful progression in the knowledge of modern submarine canyons (G Lastras *et al.*, 2009; Paull *et al.*, 2013; Oguadinma et al., 2023), explicit knowledge and understanding of the actual connection between coastal processes and the role of a submarine canyon (young strata of Niger delta basin) in the transportation of fluvial sediment from the shelf environment to the deep basin and the influence of fault in canyon development has not been addressed adequately.

The earth's landscapes, offer a diverse geological feature. In a bid to understand the internal architecture of a canyon systems, there must be adequate attention to the canyon profile showing dynamics of the ever-changing balance between erosion and deposition along a canyon.

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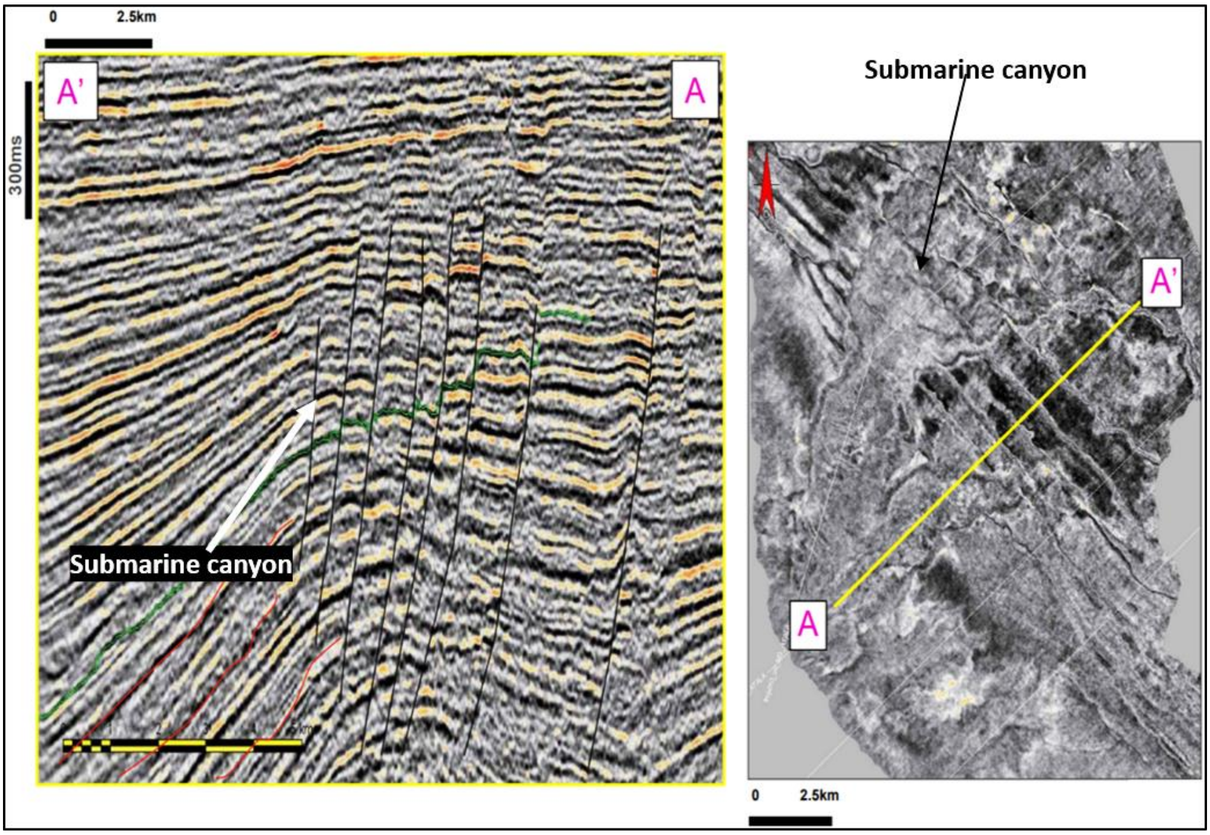

Fig. 3: Coherency attribute map, time structural map and seismic cross-sectional view showing identified submarine canyon, faults, canyon morphology and canyon branches.

4.2: Canyon Profile Plotted with Estimated Net Erosion and Deposition:

This study shows the canyon profile which represents a graphical depiction of the canyon system's longitudinal cross-section (Figure 4). This narrative reveals the undulating terrain created by the continuous flow of water. Yet, the canyon profile is not merely a static image; it shows the geological narrative by plotting the estimated net erosion and deposition along the canyon system. It provides a dynamic perspective, allowing the interplay of forces that shapes the landscape

In this depiction, the canyon's net erosion and deposition dynamics come to the forefront. Erosion, the relentless wearing away of geological materials, and deposition, the accumulation of sediment, are responsible for these geological features. The canyon profile (Figure 4), with its plotted data, shows the balance between these opposing forces. Studying the canyon profile, helps understand the earths dynamic processes. The subtle shifts in the profile reveal the slight interactions of erosion and deposition. They showcase the meandering paths eroded by rivers, the sediment deposited in quiet waters, and the dramatic changes in landscape over geological time scales. The estimated net erosion and deposition values within the canyon profile provide a tangible link to the past. In this study, the canyon profile serves as a highlight of geological transformation. Helping interpret the subtle changes of net erosion and deposition along canyon systems, offering a glimpse into the ever-evolving topography of the landscapes.

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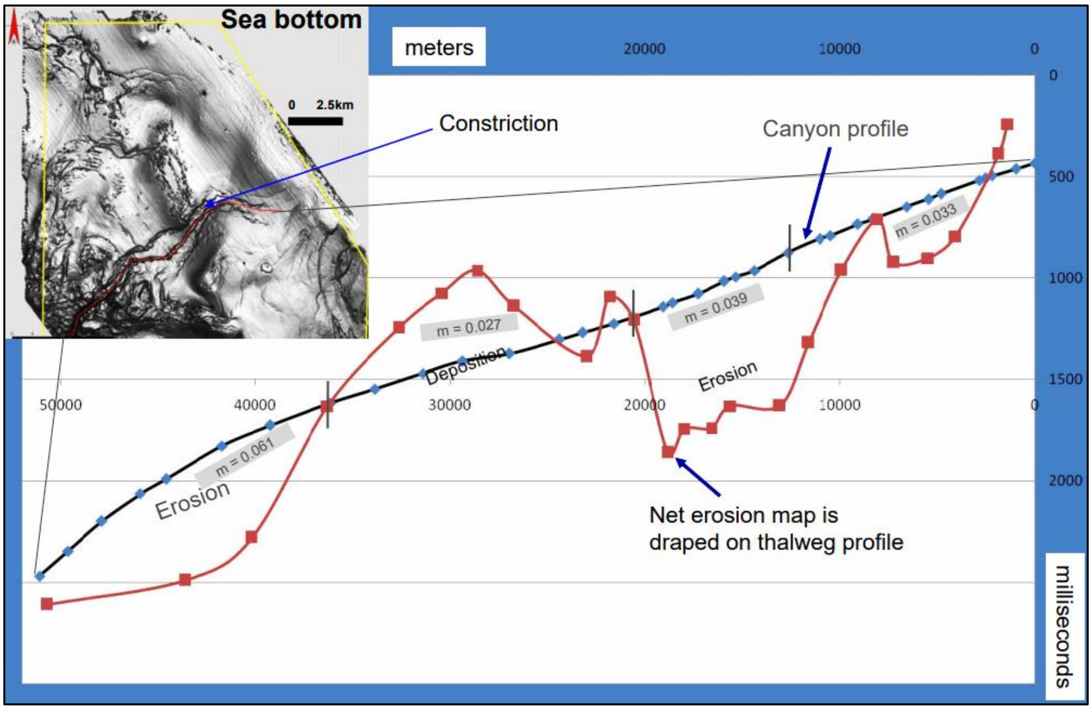

Fig. 4: Channel profile plotted with estimated net erosion and deposition along a channel system. Adapted from Imperial College MSc project pool (Ujowundu 2007)

4.3: Canyon Formation Dynamics: Role of Gradients:

The formation of canyons occurs in combination of geological forces and natural processes. One of the primary factors in this geological process is the gradient, the inclination of the earth's surface. Canyons are often associated with steep gradients, where the land plunges abruptly, creating a striking landscape. The role of gradients in canyon development is profound; they serve as the foundation upon which this geological processes unfolds (Figure 4). The steep gradient acts as a driver for the forces of erosion, setting the scene for the escavating action of rivers, glaciers, or other erosional agents. The steeper the gradient, the more erosive power these agents wield, carrying away the rock and soil, gradually shaping the canyon's features.

4.4: Canyon Develops on Steep Gradient:

A defining characteristic of many canyons is their association with steep gradients. When the earth's surface takes a sudden and sharp plunge, it paves the way for the emergence of canyons. These gradients, often created by tectonic processes, provide the ideal conditions for the inception of these geological features. The steepness of the terrain accelerates erosional forces, resulting in the excavation of deep and rugged forms that we recognize as canyons.

4.5: Influence of Fault:

While steep gradients are the norm in many canyon formations, the role of growth faults cannot be overlooked. These geological features, caused by tectonic movements, can lead to the creation of steepened gradients (Figure 5). Growth faults, by their nature, involve vertical displacements of rock layers. These movements can uplift one side of a landscape while subsiding the other, resulting in a sudden and pronounced change in elevation. It is precisely these changes that have the potential to generate steep gradients where canyons may develop. The influence of growth faults on canyon formation is an enthralling aspect of the geological narrative, shedding light on the dynamic forces at play beneath the earth's surface. This geologic feature in this study is responsible for the creation and development of submarine canyons in the study area (Figure 4).

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In this study, gradients and growth faults has proven to be important factors in canyons growth and development. The role of gradients and growth faults in canyon dynamics broadens the understanding of earth processes.

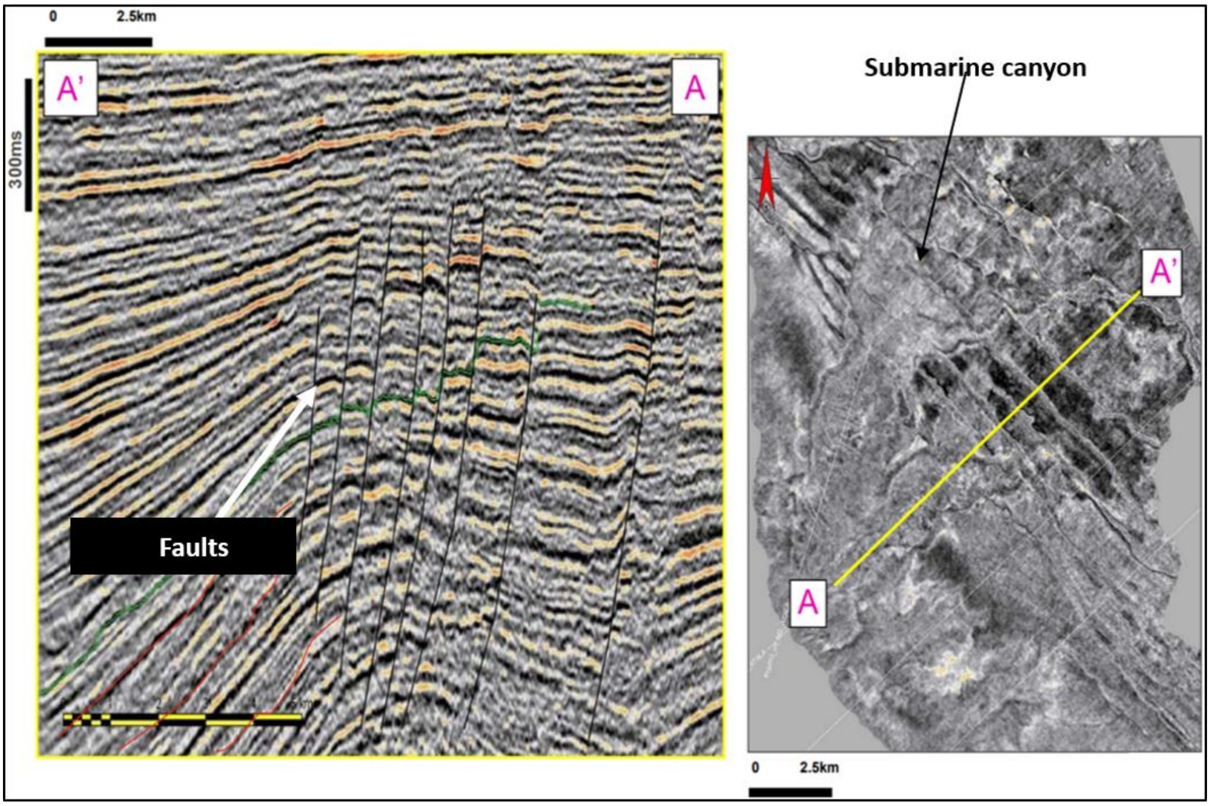

Fig. 5: Seismic cross-sectional view on the left and RMS amplitude map to the right showing the location of the canyon, identified and interpreted faults (Ujowundu 2007)

4.6: Canyon formation dynamics – Role of growth fault

Study into canyons, uncovers the linearity and parallelism that unfolds at high slope gradients, an intricate relationship between sinuosity and gradient reduction, and the unmistakable role of gradients in shaping these geological features.

4.7: Canyon Branches Linear and Parallel at High Slope Gradients:

At high slope gradients, canyons reveal a distinctive characteristic; their branches stretch linearly and align themselves in a parallel fashion. This geometry showcases the influence of gradients on canyon development. The steepness of the terrain encourages canyons to erode their path with precision, creating a network of linear branches that weave their way through the landscape. The result is a visual evidence where canyons shows that its origin comes from forces of nature.

4.8: Sinuosity and Branching Increases with Reducing Slope Gradient:

As gradients reduces and their steepness gradually lessens, a different narrative unfolds in the stages of canyon development. Sinuosity, the degree of meandering and curving within canyons, starts to increase. With reducing slope gradients, canyons exhibit a more sinuous character. Additionally, branching becomes more pronounced as the landscape's inclination becomes gentler (Figure 3). The once linear and parallel canyons take on a more intricate and interconnected form, portraying the close relationship between gradient and canyon morphology (Figure 3; 5; 6).

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4.9: Clear Indication of Gradient Control on Canyon Development:

The slope of the landscape, whether steep or gentle, serves as a guide to the type of canyon that could be created. It determines the linearity or sinuosity of canyon branches and determines the degree of branching. The canyon's form and characteristics are linked to the gradient it traverses, making the gradient an important factor that controls canyon development.

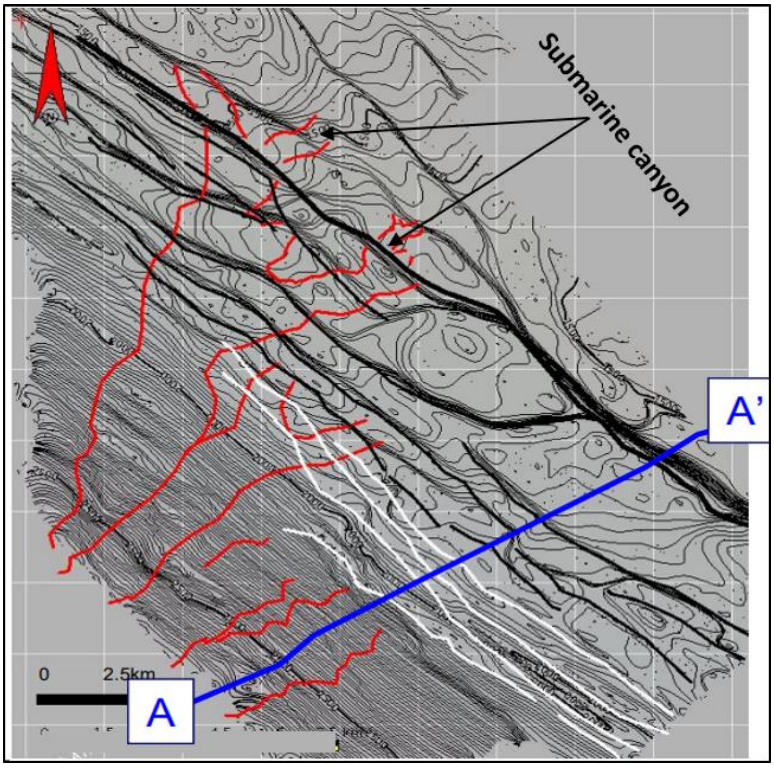

Fig. 6: Seismic contour map with traced submarine canyon location and identified faults (Ujowundu 2007)

5.0: Canyon formation dynamics - Structural framework

5.1: Major Growth Fault with Associated Rollover:

Growth faults is an output of lithospheric movement. These geological features, often created from tectonic forces, are instrumental in shaping earth's processes. They play a role in the initiation of rollovers. Rollovers represent areas where strata have undergone tilting due to the movement along these growth faults. It is within these rollovers that understanding of the forces that shape the land emanate.

5.2: Probable Cause of Post-Erosional Tilting:

Post-erosional tilting, a phenomenon that alters the orientation of geological layers and rock formations, emerges as a profound consequence of the interplay between major growth faults and rollovers. The probable cause of this tilting, which carries with it profound implications for the landscape's character, involves tectonic forces and geological history. Major growth faults, as dynamic agents of change, lead to the creation of rollovers, a pivot point where tilting begins to occur. It is this tilting that subsequently sets the stage for high gradient values in the landscape.

The high gradients, a characteristic feature of the aftermath of post-erosional tilting, holds evidence to the changes of major growth faults. These gradients, often steep and abrupt, reflect the dynamic nature

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of earths geological evolution. They showcase the influence of tectonic forces and the continuous changing architecture of the earth's geologic surfaces (Figure 6, 7 and 8).

In this study, major growth faults and their associated rollovers offer a clue into the complex interplay of tectonic events, and their role in post-erosional tilting, and the subsequent creation of high gradients, is a captivating episode of geological history.

Major growth fault with associated rollover: Probable cause of the post erosional tilting resulting in high gradient values

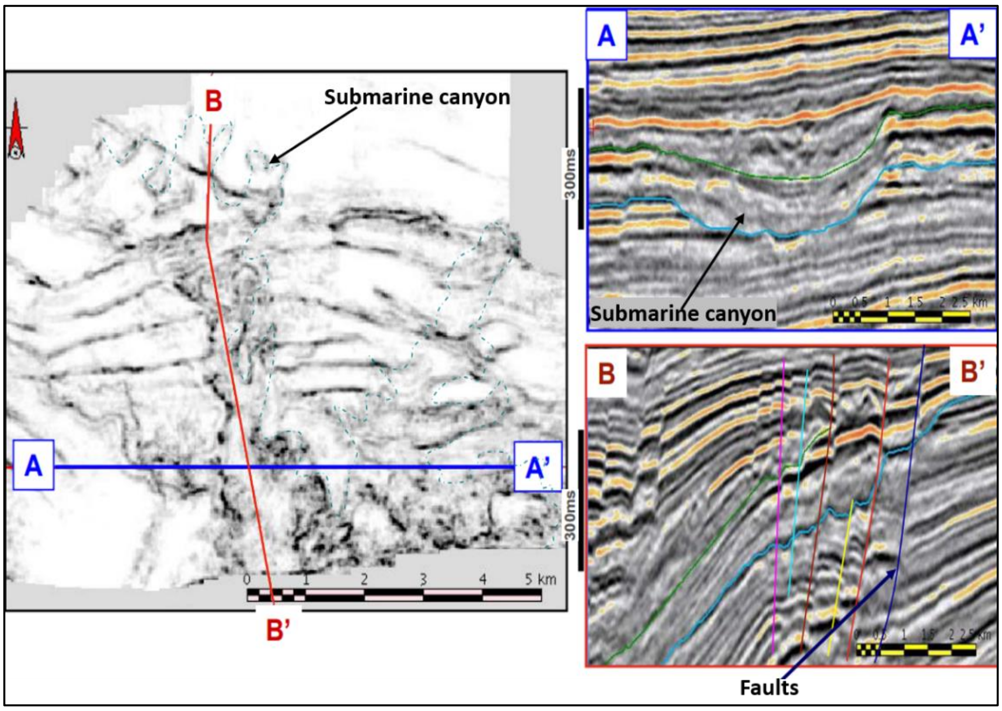

Fig. 7: On the left is a coherency map with A-A" and B-B" line across observed canyon system and on the right are the Inline and Cross line Seismic cross-sectional view showing the locations of the canyon (Ujowundu 2007)

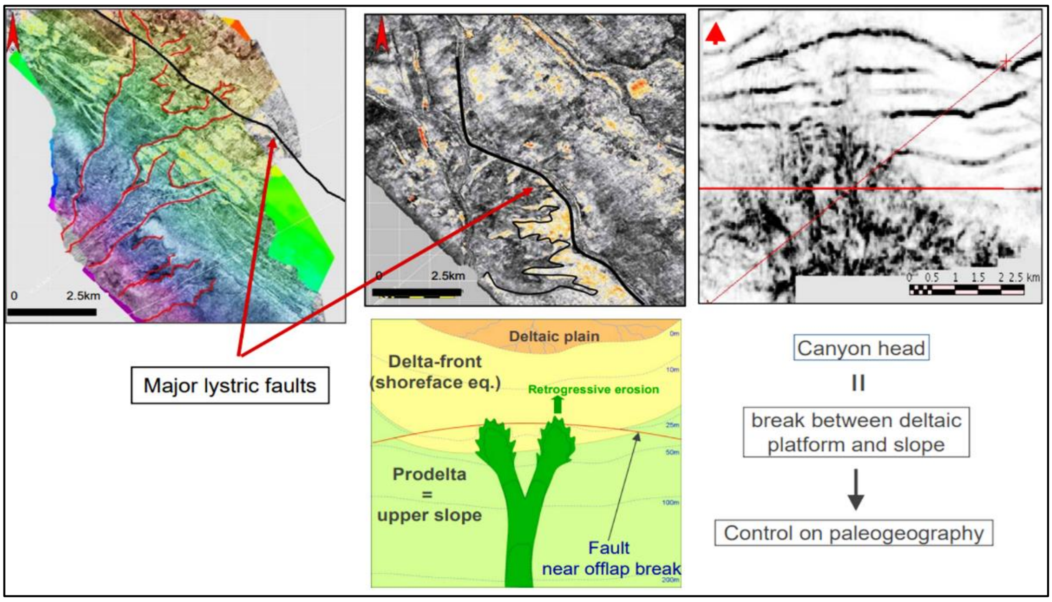

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Fig. 8: On the left is a coherency map with A-A” and B-B” line across observed canyon system and on the right are the Inline and Cross line Seismic cross-sectional view showing the locations of the canyon (Ujowundu 2007)

Conclusion

In conclusion, this study underscores the feasibility and significance of employing 3D seismic imaging in the study of geomorphology, particularly within canyons. The results of our investigation shed light on several key aspects that shows the intricate dynamics at play in canyon development.

Firstly, findings from this study reveal the influence of growth faults as major drivers of slope instability and, consequently, the formation and evolution of canyons. These geological features play an important role in shaping the landscape and are essential in understanding the broader geological context.

Additionally, the structural settings of canyons, often adhering to certain stereotypes, provide crucial insights into the patterns and behaviors of these geological formations. This structural understanding serves as a foundational building block for further research and exploration.

One of the most striking revelations from our study is the fundamental importance of gradient as a first-order control on both the initiation and propagation of canyons. The gradient's influence extends beyond mere topography and serves as a critical determinant in the evolution of these geological features.

Furthermore, our study highlights the indirect yet profound connection between the distribution of growth faults and sediment routing within canyons. This link has far-reaching implications, particularly in the realm of paleogeography and reservoir distribution, where understanding the interplay between growth faults, sediment, and canyon development is of paramount importance.

Finally, the findings of this study not only deepen our understanding of canyon geomorphology but also offer valuable insights that have the potential to revolutionize geological exploration and reservoir management. These discoveries emphasize the need for continued research and exploration in this field, with the goal of harnessing this knowledge for enhanced geological and geophysical applications.

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