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### Seismic expression of submarine channels and seafloor morphology, deepwater western Niger delta

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#### ABSTRACT

Submarine channels are the primary targets of deep-sea hydrocarbon exploration and production. They are repositories for huge accumulation of reservoir sands. With the increased focus on deep-sea hydrocarbon exploration, it is imperative to continue to advance research relating to these significant underwater sediment host structures. We have, in this study, utilized a high-resolution, 3D seismic reflection dataset covering an area of 950 km<sup>2</sup> in the deepwater western Niger delta to characterize and understand interactions between these subaqueous channels and seafloor. Our study revealed a seafloor characterized by crescent-shaped, low-angle, gentle dipping-walled submarine channels, fault scars, pockmarks, and a shale-cored anticlinal fold structures. The seismic facies associated with the channels includes moderate to high amplitudes and discontinuous to continuous seismic reflections. The channels were mainly associated with reservoir sands and followed topographic lows, trending downflow, NW–SE of the study area. A major low sinuosity (<1.10) channel of about 15.4 km long, with a vertical relief of over 200.0 m to the channel floor traversed the study area. Although there is no evidence of seabed incision and erosion of this major channel, there is a tendency for channel deflection away from the seafloor relief due to the growth of anticlines above the toe-of-thrust area which could result in an increase in channel width and thus more accommodation space for reservoir sands deposition.

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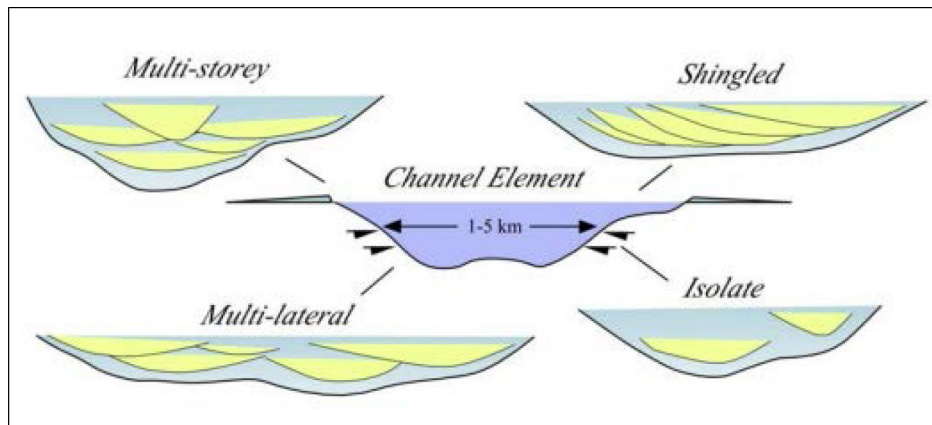
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#### 1. Introduction

Submarine channels are major conduits for sediment transport across continental shelves, continental slopes to the deep ocean, and are important morphological features on continental slopes and the seafloor (Deptuck et al., 2007; Mayall et al., 2006; Sylvester et al., 2012; Wynn et al., 2007). Submarine channels' lengths can be tens to thousands of kilometers long; the width could be 10 to 100 of km; and the depth, a few meters to hundreds of meters. Smaller scale channels, however, may be stacked in a wide variety of ways with vertical, lateral, and shingled geometries (Fig. 1).

Submarine channels are important repositories for the accumulation of reservoir sands and are thus primary targets of deep-sea hydrocarbon exploration and production (Deptuck et al., 2003). Prior to the introduction of 3D seismic technology, studies on submarine channels relied primarily on surface and subsurface morphology measurements employing acoustic sonar systems and 2D seismic data to explore channel architecture (Damuth et al., 1983; Damuth and Flood, 1988; McHargue and Webb, 1986). The current understanding of subaqueous channel shape, architectural styles, and depositional processes is a direct outcome of the

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**Figure 1.** Submarine channel geometries (adapted from [Mayall and O’Byrne, 2002](#)).

acquisition of high-quality 3D seismic datasets that have improved submarine channel system imaging ([Arnott, 2007](#); [Deptuck and Sylvester, 2018](#)).

Because submarine channels are known to play a key role in the architecture of slope deposits ([Syvitski and Schafer, 1996](#)), knowledge with regard to the processes that lead to their formation are very important. Likewise, many internal architectural components of most submarine channel reservoirs are often below seismic resolution and thus confronted with scaling issues, prompting sedimentary outcrop studies which have lately become a vital part of submarine channel studies for a better understanding. Sedimentary outcrops are now fundamental tools used to calibrate seismic facies ([Abreu et al., 2003](#); [Cross et al., 2009](#); [Macauley and Hubbard, 2013](#)), and to date have proven to be excellent analogs to subsurface systems. Due to the evident difficulties in directly viewing the dynamics of submarine channels, comparisons with their subaerial counterparts are frequently made to provide important insights into submarine channel depositional processes. Significant morphological, flow process dynamics and deposit differences, as well as similarities between these channels, have also become extensively recognized. A comprehensive comparison of these sediment and fluid flow features has been stated in [Kolla et al. \(2007\)](#), [Wynn et al. \(2007\)](#), [Arnott \(2007\)](#), [Peakall et al. \(2007\)](#), and [Kolla et al.’s \(2001\)](#) studies. In terms of plan view morphology, both submarine and fluvial channels resemble each other in appearance by appearing sinuous. Other planform similarities include being bounded by natural levees, having overbank splays, and maintaining equilibrium gradients ([Arnott, 2007](#)). By demonstrating considerable downstream migration and bend cutoffs, erosive undersea channels are strikingly comparable to fluvial channels ([Abreu et al., 2003](#)). There are substantial

differences, however, mostly in the flow mechanics and the resulting deposits. In subaerial channels, sediment and fluid movement is normally controlled by traction (bed load) and can be slow around channel bends, whereas transport in submarine channels is controlled by suspension and is usually quite fast. When compared to fluvial channels, submarine channels have substantially higher natural levee heights and sand units that can be rather extensive ([Clemenceau et al., 2000](#); [Damuth et al., 1998](#)). The downstream channel widths and depths decline, whereas the fluvial channel widths and depths increase ([Covault et al., 2016](#); [Deptuck and Sylvester, 2018](#)). Submarine flow deposits are typically devoid of structural elements such as planar lamination and cross stratification, while these are abundant in fluvial channels. Asymmetry due to the Coriolis force is seen in channels with very big submarine fans, but it is not visible in channels with the largest subaerial fans ([Imran et al., 1998](#)). The average width/depth ratios for submarine channels are generally smaller than their subaerial counterparts and are particularly low for some of the largest high-sinuosity systems (Amazon, 10; Indus, 8–50; data from [Clark and Pickering, 1996](#)). Extensive works have been undertaken to investigate the interactions between submarine channel systems and seafloor structures ([Gee and Gawthorpe, 2006](#); [Hansen et al., 2017](#); [Huyghe et al., 2004](#); [Deptuck et al., 2007](#); [Pirmez et al., 2000](#); [McHargue et al., 2011](#)). Likewise, the study of the influence of deformation on channel morphology has been documented in [Mitchell et al. \(2021\)](#), [Pizzi et al. \(2021\)](#), [Ashiru et al. \(2020\)](#), [Jolly et al. \(2017\)](#), and [Morgan et al. \(2004\)](#). Despite these contributions, many aspects of submarine channels interact with active structures on the seafloor in many deepwater settings as it affects channel pathways, geometry as well as sediment transport, and distributions are yet to

be fully understood. Therefore, it is critical to initiate this fundamental research with a view to contributing to a better understanding and providing new insight on the submarine channel–seafloor interaction in an actively deforming structural setting like the deepwater Niger delta. We are utilizing a 3D seismic reflection data with area coverage of approximately 950.0 km<sup>2</sup> within the toe-of-thrust area of the deepwater Niger delta to identify and describe the channel systems and understand their interactions with seafloor structures such as the growing anticlinal folds/thrust in the area.

### 1.1. Geologic setting

The study area covers about 950 km<sup>2</sup> and it is within the toe-of-thrust belt of the deepwater Niger delta. The toe-of-thrust fold belt is located about 150 km off the Nigerian coast, in water depths well above 3,000 m. Both the subaerial and subaqueous units of the Niger delta make up approximately a 12 km thick sediment cover of about 140,000 km<sup>2</sup> area (Whiteman, 1984). The Niger delta basin is situated along the west coast of Africa in the Gulf of Guinea, off the southern Atlantic shores of Nigeria. It is a prominent basin in West Africa and at present ranking the ninth largest deltaic system in the world (Doust and Omatsola, 1990; Grimaud

et al., 2018). The Niger delta is a major prolific petroleum-producing tertiary delta that together accounts for about 5% of the world's oil and gas reserves.

Rifting in Niger delta began in the Late Jurassic and stopped in the Cretaceous. This period witnessed the development of major faults including normal and listric faults, as well as thrust faults. Deltaic sedimentation was initiated in the Palaeocene, with the delta assuming its arcuate wave-dominated morphology in the early Miocene (Doust and Omatsola, 1990; Whiteman, 1982). The subaerial portion of the Niger delta covers approximately 75,000 km<sup>2</sup> and stretches for about 200 km from apex to mouth (Fig. 2). Reijers (2011) described the Niger delta as an overall succession of regressive, offlapping sediment cycles with three diachronous mixed siliciclastic units; the over-pressured Akata, Agbada, and Benin formations. The Akata formation is basically a Paleocene to recent shale sequence of about 3–4 km thick consisting of parallel-laminated, basin-floor, prodelta shales, marine muds, turbidite sands, and minor quantities of silt and clays. It is conventionally regarded as the host to the principal source rock for hydrocarbons in the Niger delta (Doust and Omatsola, 1990; Haack et al., 2000). The Agbada formation (Eocene to recent)

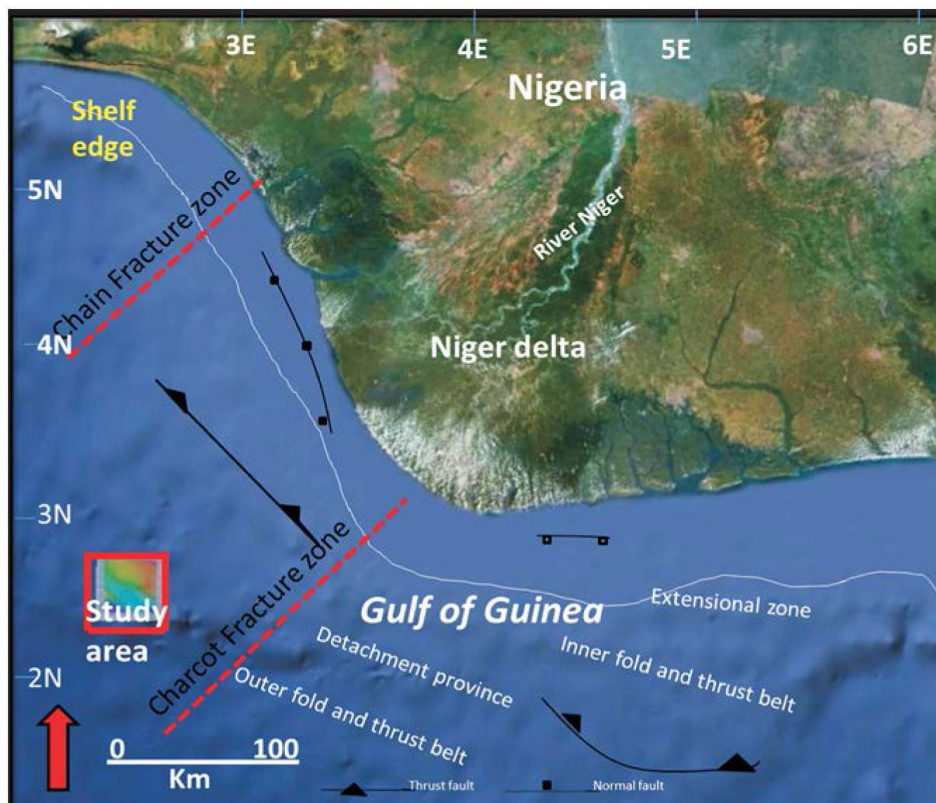
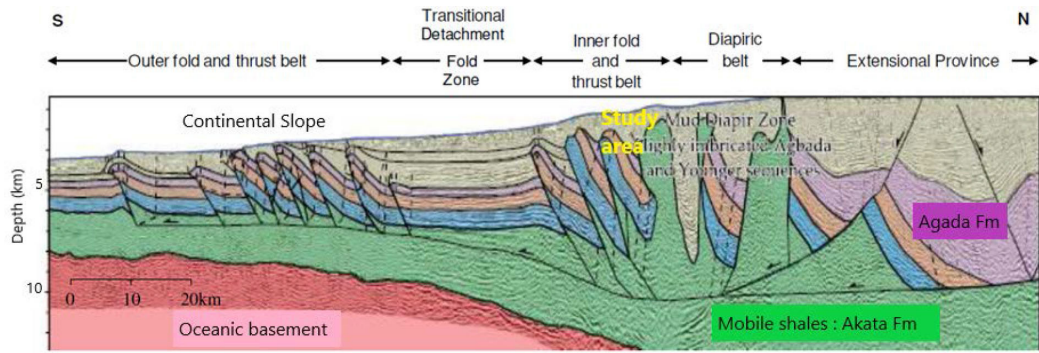
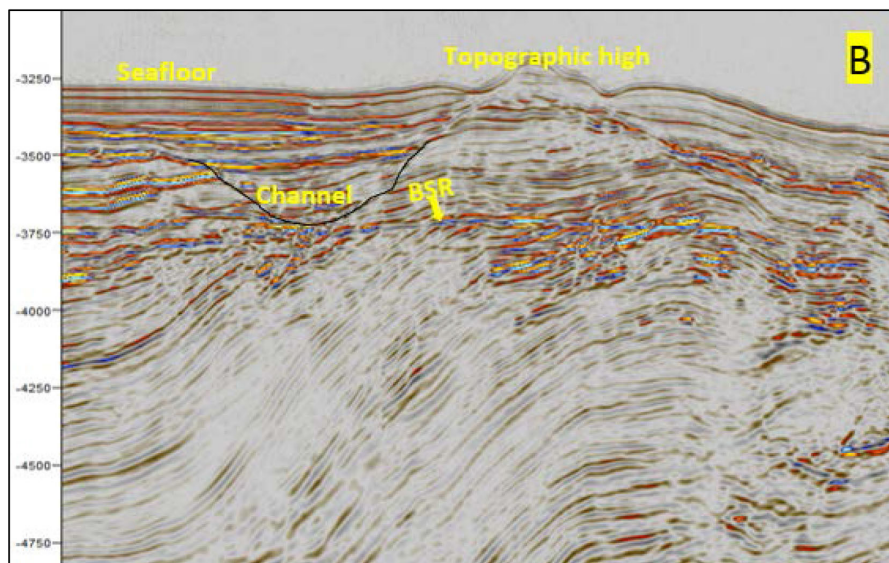
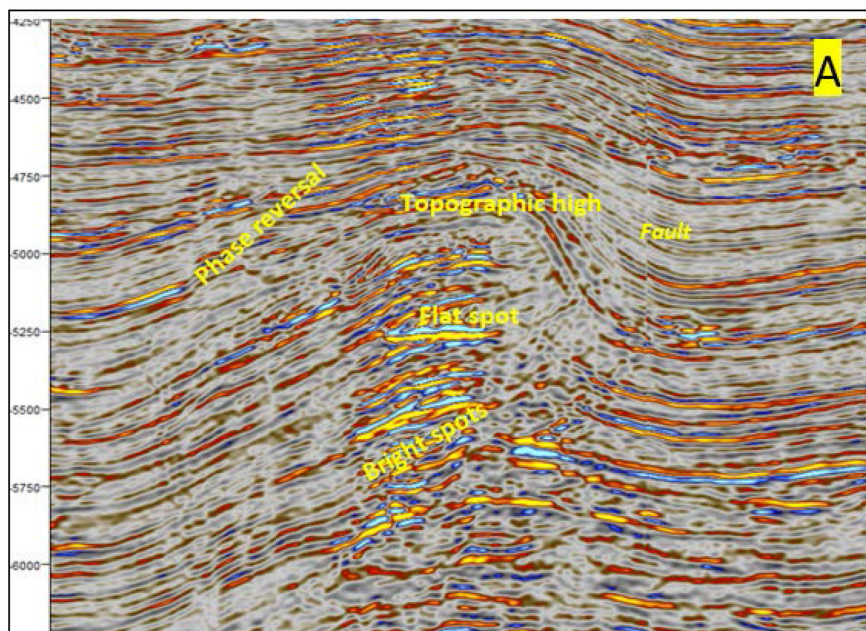


Figure 2. Map showing the deepwater Niger delta and location of study area.



**Figure 3.** Regional seismic profile across the Niger delta showing the link between the extensional province on the shelf and the contraction in the toe-of-thrust systems in the deepwater (Corredor et al., 2005).



**Figure 4.** a and b. An overview of observations in seismic reflection profile in-line 1,107 showing some seismic amplitude anomalies, channels, bright spots, flat spots, fault lines, and polarity change.

is about 3.2 km thick and consists of mixed clastic sediments, including fluvial sands whose rapid sedimentation and accumulation contributed to the diapiric nature of the Agbada shales. The Agbada formation provides the main reservoir rocks for hydrocarbons and little or no overpressure has been recorded within it. Finally, the Benin formation (Late Eocene to recent) is largely continental and fluvial in origin and characterized by floodplain sand as well as alluvial deposits (Reijers, 2011). Three major structural domains (Fig. 3) are recognized in the delta region and are described in Damuth (1994), Connors et al. (1998), and Corredor et al.'s (2005) studies, among many others. This includes the following:

- (a) An inner fold and thrust belt, characterized by a higher structural dip with an average distance between imbricated thrust sheets of between 1 and 2 km and with the formation of occasional piggyback basins (Corredor et al., 2005);
- (b) A detachment fold belt, characterized by large areas of minor deformation from thrust- or shale-induced folding (thrusting and folding due to shale swelling), with a long-transport thrust sheet dimensions ranging from 2 to 5 km;
- (c) Outer fold and thrust belt, comprising local depocenters and both basinward and hinterland verging thrusts. This domain is situated further down dip, with channelized turbidite sands trapped in broad-wavelength anticlines above incipient thrust propagation zones.

## 2. Data and Methods

### 2.1. Seismic reflection data

The entire 3D seismic reflection data used for this research cover an area of approximately 950 km<sup>2</sup>. The dataset is a zero-phase, time-migrated volume with a positive amplitude represented by a red, yellow, or brown peak and negative amplitude by a light blue or dark blue trough, respectively, signifying an increase and decrease in acoustic impedance, respectively. The seismic survey consists of 1,185 NW–SE in-lines spaced at 28 m and 1,057 SW–NE cross lines spaced at 27 m. Velocity data obtained from sonic logs for TWT intervals of 3,100–3,400 (shallow sections) was 1,541.6 m/second; 4,500–5,000 (middle section), 2,809 m/second; and 5,600–6,000 (deep section), 3,119.6 m/second. Due to variation in frequency in the dataset at the shallow, middle, and deeper sections, ranging from 27 Hz at the shallow intervals to 17.5 Hz at the deeper section, the estimated vertical resolution is 14, 39, and 45 m at 3,400, 5,000, and 6,000 ms, respectively. The general principles of seismic stratigraphy

(Posamentier et al., 2007) were used as guide for seismic interpretation such as defining the reflection packages, which comprise the seismic facies, continuity of seismic events (either continuous or discontinuous), internal geometry within each seismic package (parallel, subparallel, and chaotic), and generation of surfaces, amplitude extraction, and attribute analysis.

### 2.2. General observations of seismic amplitude anomalies

Seismic amplitude anomalies characterized by local increase or decrease of seismic reflection amplitude were identified across the seismic reflection profile and they include the following:

#### 2.2.1. Bright spots

These represent a local increase in positive or negative amplitude along a reflection. Bright spots commonly indicate the presence of hydrocarbons. Most of the observed bright spots were at the anticlines and at the base of the channels.

#### 2.2.2. Flat spots

These are relatively flat seismic events that cut across the stratigraphic reflection. Flat spots may represent contact between a gaseous hydrocarbon, with low acoustic impedance and oil, with higher acoustic impedance.

#### 2.2.3. Phase reversal

This is otherwise called a polarity change. It is a shift along a continuous reflection so that a peak becomes a trough.

#### 2.2.4. Bottom simulating reflector (BSR)

This was observed at the upper half of the profile close to the anticlinal structure. Normally, a BSR develops at the contact between a low acoustic velocity and an overlying higher acoustic velocity zone. These are anomalous seismic reflectors, characterized by high amplitude and negative polarity, as well as intersect sedimentary strata of host sediments (Berndt et al., 2004; Kvenvolden, 1983; Rodrigo et al., 2009). BSR appears as flat spots, but are very extensive and tend to mimic the topography of the seafloor. The identified BSRs tend to follow the up-dip strata formed by the anticlinal structures.

### 2.3. Seismic facies analysis

Three distinct seismic facies types characterize the depositional sequence of the study area. These were identified based on the lateral continuity, truncation, reflection amplitude, and internal reflection geometry.

Figure 5 briefly describes the three types of facies observed from arbitrary seismic section in the study area. Other facies observed include the transparent hummocky reflectors which are typical of shale diapirs occurring in the area.

### 3. Results and Discussion

#### 3.1. Tectono-stratigraphic framework of the study area

Interpretations were carried out mainly by identifying major seismic events using arrival times and defining distinct seismic reflection packages. Relative ages were assigned to identify units based on the premise that within the Niger delta, sediments build out in depobelts, and thus get younger basinward. It is assumed that within the Niger delta toe-of-slope, the prodelta mobile shale unit is Paleogene. The overlying paralic sequence is Neogene (Upper Tertiary) and includes the Miocene and Pliocene ages (Haack et al., 2000; Lehner and De Ruiter, 1977). Six major seismic events excluding the seafloor were identified for picking, although some other distinct surfaces, based on seismic facies characters, were also picked. The six major seismic events represent tops of chronostratigraphic intervals (Fig. 6). These events have been labeled top Tertiary mobile shale unit, top lower Miocene unit I, top lower Miocene unit II, top mid-Miocene unit III,

top upper Miocene unit IV, and top Pliocene unit. Brief descriptions of the seismic stratigraphic units are given below.

#### 3.2. Top Tertiary mobile shale unit

This represents the basal unit of the sedimentary sequence. The arrival time corresponding to this unit is 6,000 ms. It is characterized by chaotic, discontinuous, and low-to-medium amplitude reflections. The unit represents the top of the less dense, overpressured mobile shale unit. The unit usually serves as the detachment zone for the thrust fault that develops in the area. The unit corresponds to the Akata formation, which is the known host of the source rocks for hydrocarbon generation (Avbovbo, 1978).

#### 3.3. Top lower Miocene unit I

This is assumed to represent the base of unit I of the stratigraphic sequence. It corresponds to an arrival time of 5,500 ms. The unit is characterized by low-to-high, bright amplitude, semi-continuous, subparallel reflections. This unit directly overlies the shale detachment unit and appears to be an erosional surface.

#### 3.4. Top lower Miocene unit II

This key surface corresponds to the arrival time of 5,000 ms. The unit is characterized by medium-to-high

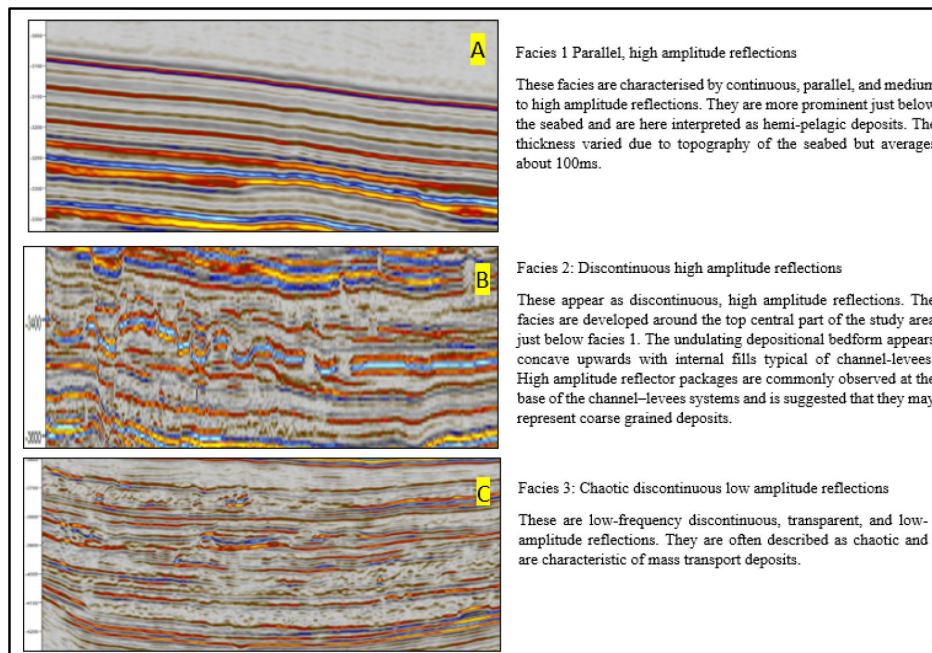
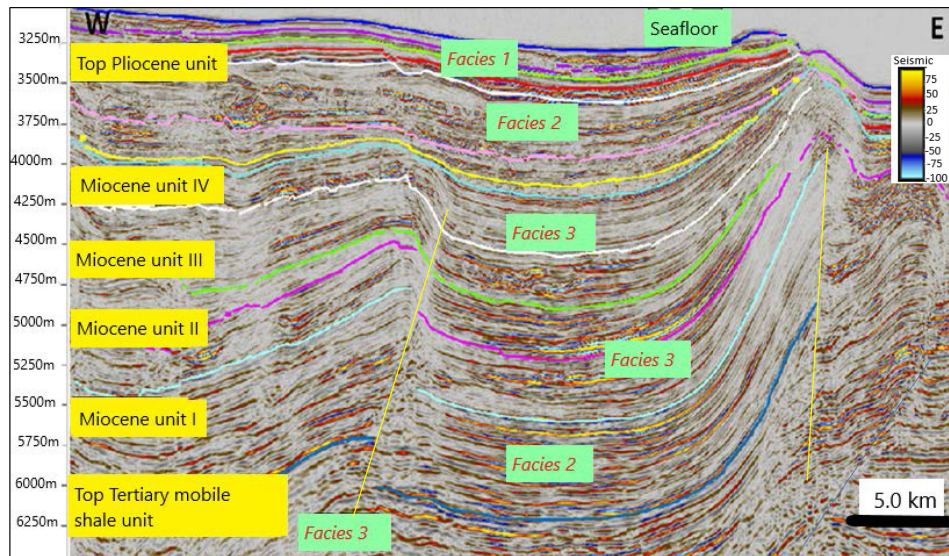


Figure 5. Arbitrary seismic section showing the three distinct seismic facies in the study area.



**Figure 6.** Seismic section showing the tectono-stratigraphic framework of the study area.

amplitude continuous reflections. There are some erosional channels within this unit. The unit is marked by a prominent uplift of strata, at the central and north-eastern parts of the basin, creating a mini basin. The uplift is assumed to be due to shale tectonics which could be a direct consequence of plastic flow of the top Tertiary mobile shale units.

### 3.5. Top mid-Miocene unit III

This surface corresponds to arrival time 4,600 ms. It is characterized by low-to-medium amplitude semi-continuous reflections. It is similar to unit II apart from the relatively thicker package.

### 3.6. Top upper Miocene unit IV

This is an erosional surface which appears to on-lap on the anticlinal structure close to center and on the eastern end of the section. It is characterized by medium to high amplitude reflection. There are erosional channels within this unit.

### 3.7. Top Pliocene unit

This unit is relatively thick with many stacked channels within it. The unit has two distinct layers of mass transport deposits separated by a sandy interval. This unit also has a prominent BSR that crosscuts the sedimentary strata and distinctly marks the top of free gas and base of gas hydrate zone. Seismic facies characters include a chaotic, discontinuous to semi-continuous, and low-to-medium amplitude reflections.

#### 3.7.1. Seafloor

The seabed is characterized by a continuous high amplitude reflection.

### 3.8. Seafloor morphology

The seafloor is a very important key surface in this research. We used a seismic velocity of 1,500 m/second to generate a depth structure map of the surface to depict the seafloor bathymetry of the area (see Figs. 7 and 8). It was observed that active channeling of the seafloor dominates the southeastern portion of the study area and a major channel traverses the area between two anticlinal structural highs which allowed the transport of sediments. Apart from the channels, other seabed expressions, such as fault scars and pockmarks, were also observed at the northern part of the study area, close to the anticlinal highs (Fig. 7). The presence of the fault scars and pockmarks associated with faults and faulted anticlines suggest gas venting near the seabed (such as the occurrence of gas hydrates) (Cathles et al., 2010), as well as a reflection of shallow fluid flow linked to a likely buried reservoir facies that is part of the submarine channel fill (Heggland, 1998).

### 3.9. Submarine channels

3D seismic interpretation revealed the presence of three Eocene to recent channels (Channels AB-1, AB-2, and AB-3). Morphologically, the channels were observed to be U-shaped and crescent-shaped, with low-angle gentle dipping walls. Linear channels generally tend to follow the topographic lows of the study area and show a flow pathway trending NE-SW, with a relatively moderate slope. In the shallow part of the study area, between 3.5 ms and 3.7 ms, we identified channel AB-2, a very prominent large channel (Fig. 9b) that runs across the area, measuring about

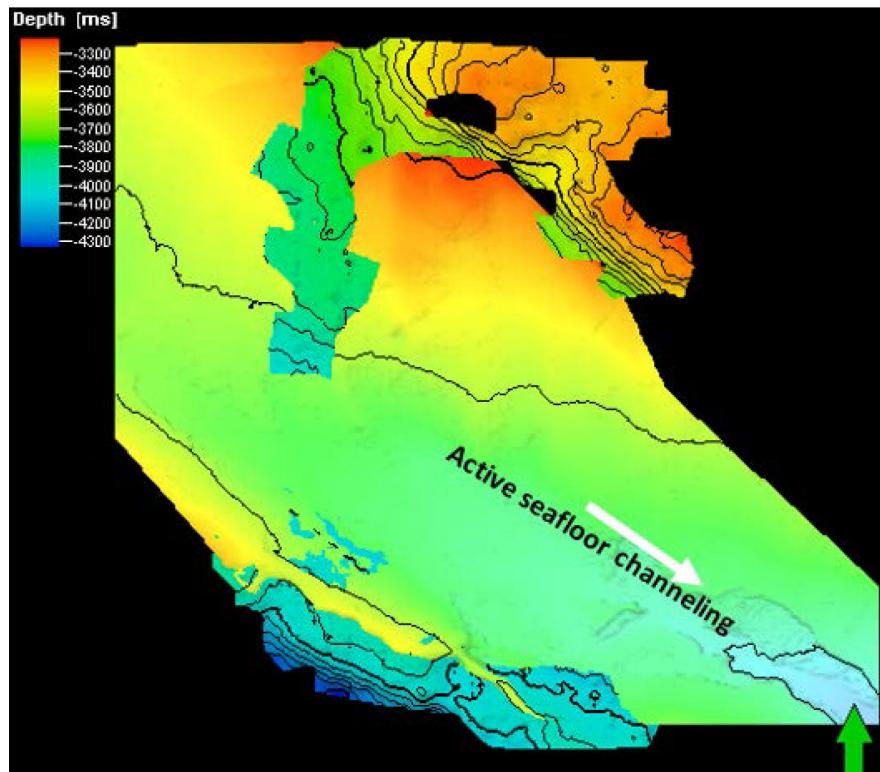


Figure 7. Seafloor surface map showing the area of active channeling.

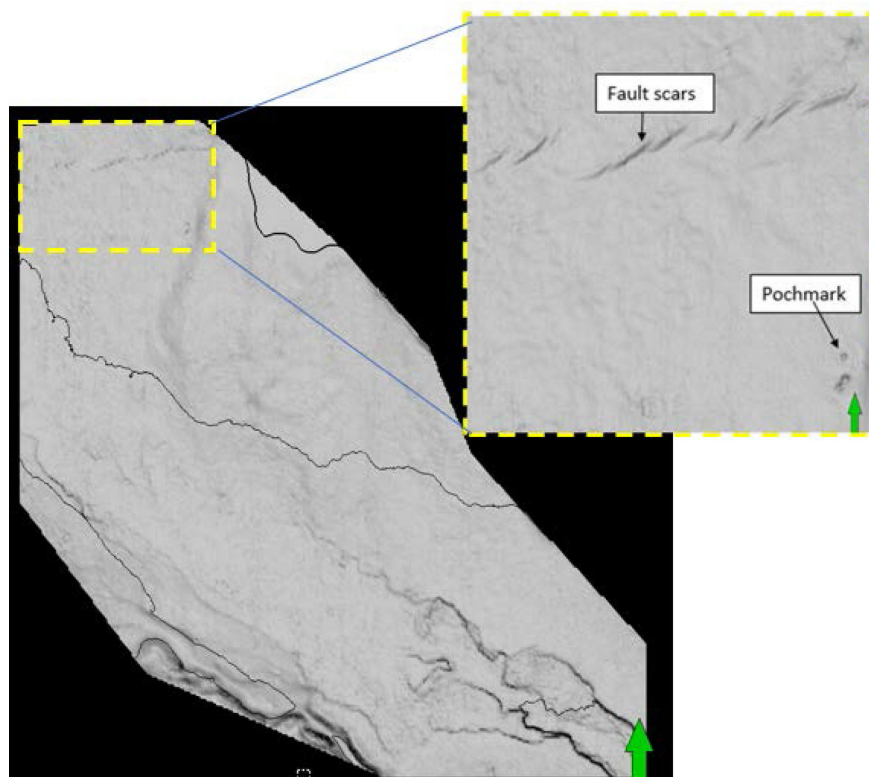
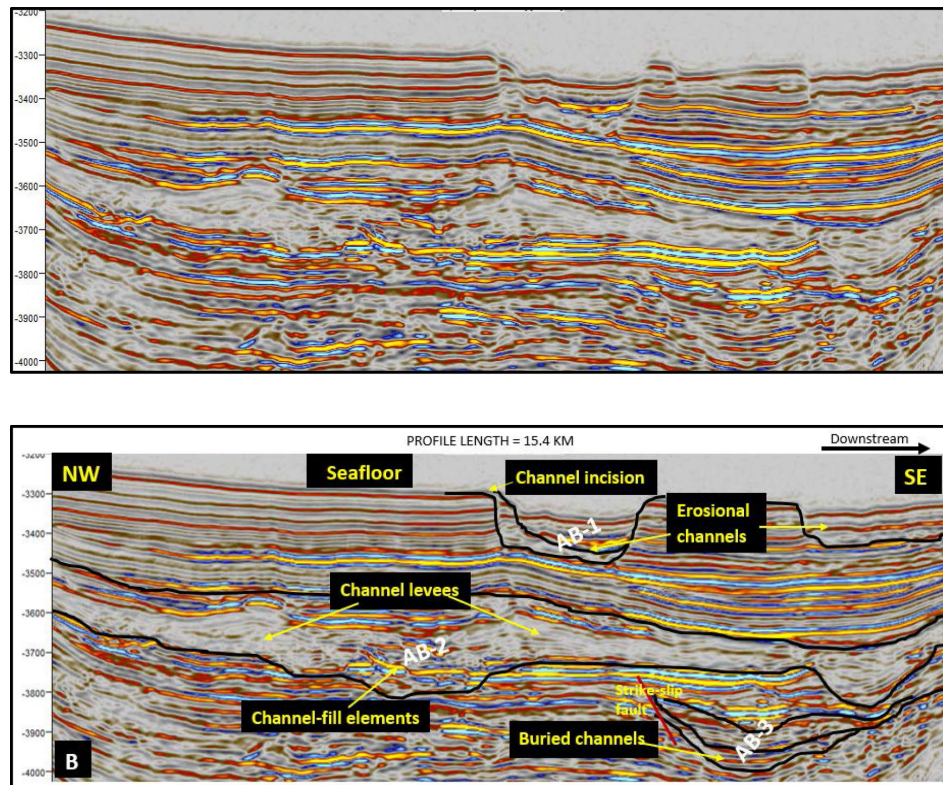


Figure 8. Plan view of the seafloor; yellow outline shows the fault scars and identified pockmarks.



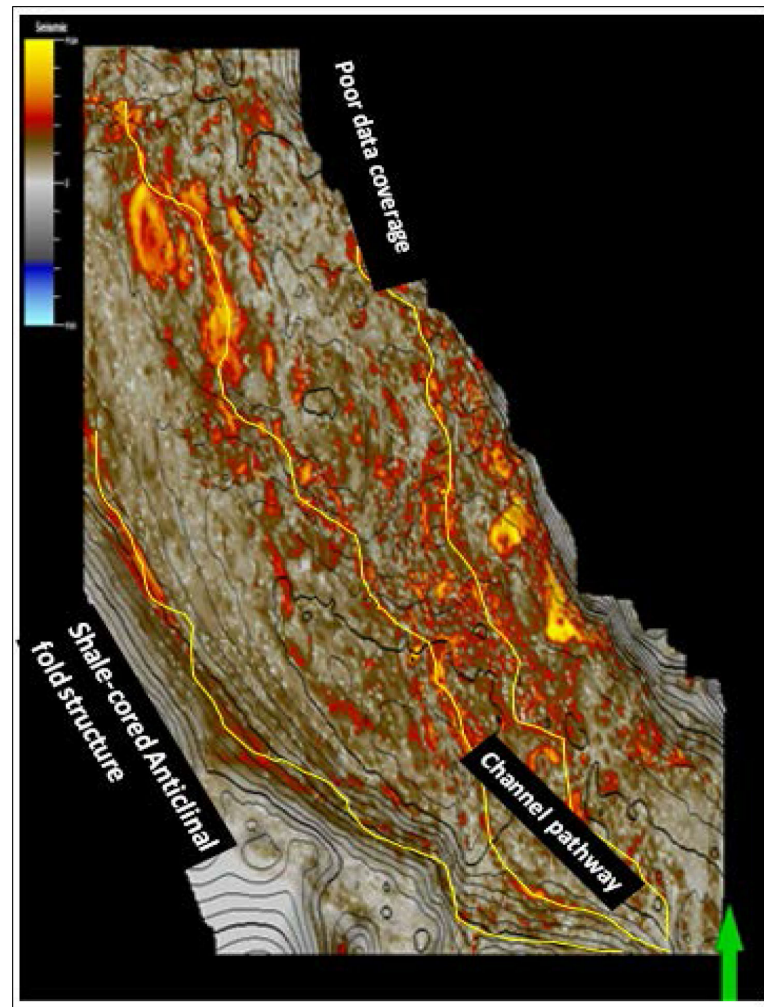


**Figure 9.** a: Uninterpreted seismic section b: Interpreted seismic section showing submarine channels, channel fills, and internal levees.

15.4 km and trending in a NW–SE direction. The channel was observed to be flanked on both sides by structural highs (mobile shale ridges) with vertical relief of over 200.0 m to the channel floor. The outer levee height in relation to the channel thalweg was about 40.0 m. This large channel, AB-2, had a sinuosity of <math><1.1</math>, which may have been influenced by the anticlinal structure that shows prominent relief on the seafloor. Although channel complexes tend to follow the topographic lows of the study area, the deflection of some of the channels away from the seafloor relief due to the growth of anticlines above the toe-of-thrusts could not be ascertained. Other small-scale channel forms (AB-1 and AB-3) tend to be erosional in character, as shown in [Figures 9b and 10](#), where slumping of sediments on the seafloor could have triggered erosion by submarine gravity flows (see [Fig. 4b](#)). Also, there was no evidence of channels incising the active growing anticlines in the study area. However, these smaller scale channels showed higher sinuosity of >1.5 and observed to deflect away from the shale-cored anticlines and mud diapirs on and near the seafloor. Buried stacked channels, AB-3, proximal to a strike-slip fault were also observed at a stratigraphic interval just below the major NW–SE trending channel.

In terms of seismic reflection signatures, the channel facies were characterized by a medium-to-high amplitude discontinuous reflection and the well-developed flanking outer levees having continuous, relatively low-to-high amplitude convergent reflections. Channels with their associated levees were found to occur at stratigraphic intervals in the depositional sequence, about 300 m below the seafloor. These levees were observed both within and outside the main channel (AB-2). The outer levees had a geometry which appears as wedge-shaped and flanking the channel axis. These outer levees were also observed to thin as well as dip away from the channel. Their thickness ranged from 40.0 m at the proximal channel margin to about 20.0 m at the distal end. The seismic reflection character for the outer levees was generally low amplitude continuous reflections. On the contrary, the inner levees were confined within the channel. [Deptuck et al. \(2003\)](#) noted that within a submarine channel system, the inner levees may represent over-bank sediments.

On the seafloor, a relatively smaller erosional channel of less than 2.0 km was observed. The channel fill elements observed within the channels were characterized by high amplitude reflections, but in most



**Figure 10.** Plan view image of an RMS amplitude map of a submarine channel AB-2 as observed in the study area. The amplitude extraction was taken from a 20 ms window on the horizon.

cases, the reflections were discontinuous. High amplitude reflections within a channel system are considered sand-rich in terms of lithologic interpretation (Posamentier and Kolla, 2003). The interaction of submarine channels and the seafloor topography in the study area may not be unconnected with the influence of basin tectonics (Clark and Cartwright, 2011; Jobe et al., 2015; Heiniö and Davies, 2007; Reading and Richards, 1994; Morgan, 2003; Saller et al., 2004; Wynn et al., 2007). Two different scenarios can come to play. The first is the influence of tectonic-related processes on channel widths and sediment fill. Tectonic-related process involving high degree of channel incision of the seafloor and possible erosion could impact on channel morphology and cause a reduction in channel width and the amount of sediments being transported by the channel. Conversely, when there is a deflection of channels away from the growing anticlinal fold structure, it could lead to more accommodation space

for sediment infill of the channels due to an increased channel width and this could serve as depocenters for sediment repository (Heiniö and Davies, 2006; Jolly et al., 2017; Pirmez et al., 2000). Consequently, the evolution of channels in the study area is considered to be significantly influenced by basinal tectonics on and near the seafloor channel incision, as well as the prevailing depositional process.

#### 4. Conclusion

In this study, we have used 3D seismic reflection data with area coverage of approximately 950 km<sup>2</sup> to identify submarine channels and understand how seafloor morphology may impact on channel pathways and creation of accommodation space for sediment deposition. A generated RMS seafloor bathymetry of the study area showed the presence of submarine channels, fault scars, pockmarks, and a shale-cored anticlinal fold structure. The channel facies were characterized

by a medium-to-high amplitude discontinuous reflection having well-developed flanking outer levees characterized by continuous and relatively low-to-high amplitude convergent reflections. In terms of geometry, the channels were crescent-shaped, with low-angle gentle dipping walls. The channels in the area followed topographic lows, trending downflow, NW–SE and parallel to structure. Deflection of channels away from the seafloor relief due to the growth of anticlines above the toe-of-thrusts could not be ascertained. However, small-scale channel forms (AB-1 and AB-3) tend to be erosional in character where slumping of sediments on the seafloor could have triggered erosion by submarine gravity flows. Channels evolution has been attributed to basinal tectonics on and near the seafloor, which is likely to cause an increase in channel width for more sediment infill.

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