Mass-Transport Complexes (MTC) – Pathfinders for Turbiditic Deposits in Deep-water Nigeria?

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ABSTRACT

The geomorphology, internal architecture and stratigraphic sequences of several Pleistocene turbiditic deposits in deepwater Nigeria were studied using a combination of 3D seismic geomorphologic and stratigraphic methods. Seismic facies description, geomorphology characterization, architectural elements (AEs) delineation and seismic stratigraphic interpretations were carried out in order to (1) establish channels/lobes geomorphology, internal architecture, and sediment fills, (2) understand temporal and spatial evolution of turbiditic channels/lobes and factors responsible for their depositional sequences, and (3) demonstrate how to predict the presence of turbiditic reservoirs using the established depositional sequence and associated gravity flow deposits. Strong links were established between the evolution of turbiditic deposits, stratigraphic succession of their sequences, and changes in relative sea-level, sediment type, and rate of sediment supply. The deepwater depositional sequences, as seen in Channel-5O, comprises an underlying Masstransport Complex (MTC) that precede a Lobe/Frontal-splay, followed by a Channel-levee, an overlying MTC that is finally capped by Hemipelagic/Pelagic drapes. The observed close link between turbiditic channels/lobes and mass-transport complexes suggests the later could serve as a pathfinder for the former. An integrated seismic geomorphologic and stratigraphic workflow, based on well-logs, biostratigraphic, and seismic data can be used to predict the presence of turbiditic reservoir. Given that explorers rarely have the complete suite of data needed for such an integrated workflow, ability to identify MTC through their diagnostic seismic characters can aid in locating associated turbiditic reservoirs.

Keywords: Mass-Transport Compleses, Geomorphology, Channels, Turbiditic, Stratigraphic sequences.

INTRODUCTION

Turbiditic reservoirs host significant HC pools in deep-water Nigeria (e.g., Bonga, Agbami, Akpo, Egina, Usan, Owowo, etc., Figure 1) and several other basins worldwide. These reservoirs are still targets of deep-water explorations. Their geomorphology and internal architectures are products of the complex interplay of controlling factors such as changes in relative sea level, the rate and type of sediment supply, and seafloor morphology (Pirmez and Imran, 2003; Posamentier and Kolla, 2003; Clark and Cartwright, 2009, 2011; Chima *et al.*, 2020; Busari and Adekeye, 2024).

Figure 1: Reginal sketch map showing the location of the Niger Delta in west Africa (inset map) and the seabed of the Niger Delta showing major oil and gas fields within and around the study area.

Unlike in fluvial or deltaic settings, where reservoirs are abundant, turbiditic reservoirs are dispersed sedimentary architectures in the sea of hemipelagic and pelagic drapes that dominate basinal deposits. Hence, the ability to predict turbiditic reservoirs' presence is key for successful exploration in deep-water settings.

High-quality three-dimensional (3D) seismic data from deep-water Nigeria provide unique opportunities for

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studying deep-water turbiditic deposits, focusing on architectural elements, geomorphology, internal architectures, depositional processes, and evolution in time and space.

These data display a wide range of depositional bodies (architectural elements) with different geometries, including straight, sinuous, and meander channels with stacking patterns raging from vertical to orthogonal and lateral, levees and overbanks, depositional and ponded lobes and a wide range of mass-transport complexes (MTC).

Understanding the geomorphology, internal architecture, and evolution of turbiditic deposits within sequence stratigraphic context and their relationships with associated gravity deposits (e.g., MTC) will aid our ability to predict turbiditic reservoir presence, especially when confronted with limited or poor-quality data.

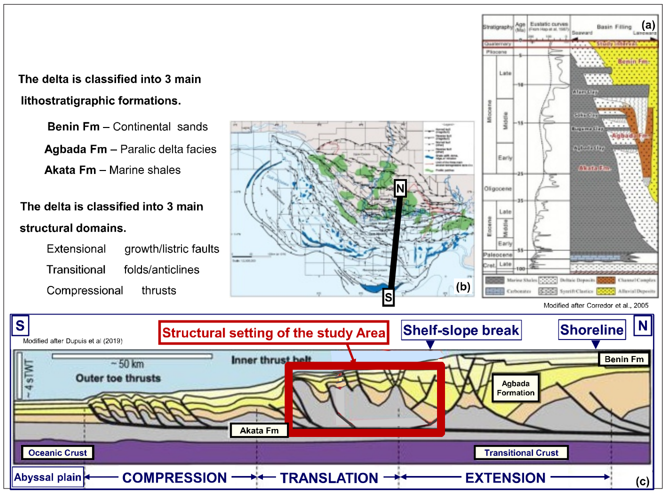
GEOLOGIC SETTING

The Niger Delta is located along the western margin of Africa (Figure 2), forming a symmetrical protrusion into the Gulf of Guinea that developed in response to rapid sedimentation rates and 'escalator regression' since the Eocene (Doust and Omatsola, 1989). The sub-aerial and marine parts of the delta have a combined area of about 140,000 km^2, reaching a maximum thickness of about 12 km (Damuth, 1994). The Niger Delta basin is considered a classical shale tectonic province (Wu and Bally, 2000), which undergoes gravity tectonics in response to high progradation rate (Damuth, 1994). With important sediment discharges from the mouth of Niger-Benue River, the evolution of the basin is controlled by the interplay between subsidence and sediment loading on unstable shaley sequences (Doust and Omatsola, 1990).

The subsurface of the Niger Delta shows that the vertical successions of the delta can be divided into three main facies units (Short and Stauble, 1967; Avbovbo, 1978; Doust and Omatsola, 1990; Corredor *et al.,* 2005). The basal lithostratigraphic unit is the Akata Formation consisting of up to 5000 m thick marine shales (Avbovbo, 1978). The marine shale is overlain by more than 3500 m thick (Corredor *et al.*, 2005) paralic Agbada Formation characterized by interbedded shallow marine and fluvial sands with siliciclastic turbidites. The shallowest lithostratigraphic unit is the Benin Formation, dominated by massive fresh water-bearing continental sands. All the three lithostratigraphic units are diachronous (Avbovbo, 1978; Doust and Omatsola, 1990, Figure 2).

Structurally, the Niger Delta is divided into three regional structural zones/domains (Doust and Omatsola, 1990; Damuth, 1994, Figure 3): (1) an upper extensional zone of listric growth faults beneath the outer shelf; (2) a translational zone of diapirs and shale ridges beneath the upper slope; and (3) a lower compressional zone of imbricated thrust structures (toe thrusts) beneath the lower slope and rise (Figure 3). Linked together on a regional scale, these structural styles suggest that large portions of this thick sediment prism are slowly moving downslope by gravity gliding or sliding in a manner analogous to giant mass movements or mega-slides (Damuth, 1994).

Most of the turbiditic deposits studied are on the continental slope within the translational structural domain (Figure 2).



Modified after Corredor et al., 2005

Modified after Dupuis et al (2019)

Figure 2: Niger Delta's main stratigraphic Formations and structural domains. a) Three main stratigraphic Formations. b) N-S line of section on Niger Delta structural map. c) schematic north-south cross-section showing the three Niger Delta structural domains.

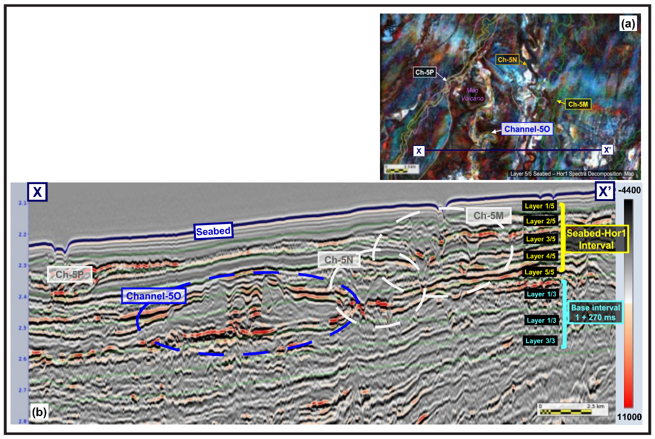
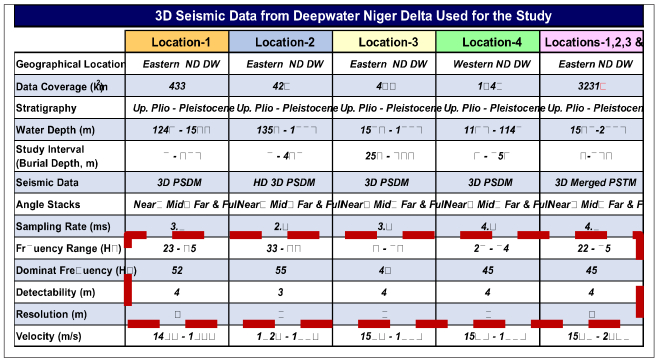


Figure 3: Layering of seismic cubes between key horizons for interval attributes computation. a) Spectra decomposition map of layer 5/5 between the seabed and Hor1 showing Channel-5O and other channels in location-5. b) E-W seismic section across channels 5M, 5N, 5O and 5P illustrating the layers used for interval attributes computations.

Data

Four high-resolution 3D seismic data and a semi-regional merged 3D seismic data covering five locations across the eastern and western deep-water Nigeria were used for this study. The seismic were processed to zero phase and displayed in SEG (Society of Exploration Geophysicists) positive standard polarity, such that an increase in acoustic impedance corresponds to a high-amplitude peak reflection (black/blue loop), while a decrease in acoustic impedance is represented by a trough (white/red loop). Details of these seismic data are presented in Table 1. Well logs and cores, where available, were used for seismic facies calibration. Field analogs from well exposed turbiditic outcrops were also used for morphologic and internal architecture calibrations.

Table 1: Seismic sets used for the study and their parameters.



3D Seismic Data from Deepwater Niger Delta Used for the Study

	Location-1	Location-2	Location-3	Location-4	Locations-1,2,3 &
Geographical Locatio	*Eastern ND DW*	*Eastern ND DW*	*Eastern ND DW*	*Western ND DW*	*Eastern ND DW*
Data Coverage (km^2)	*433*	*42*[illegible]	*4*[illegible]	*1*[illegible]*4*[illegible]	*3231*[illegible]
Stratigraphy	*Up. Plio - Pleistocene*	*Up. Plio - Pleistocene*	*Up. Plio - Pleistocene*	*Up. Plio - Pleistocene*	*Up. Plio - Pleistocen*
Water Depth (m)	*124*[illegible] *- 15*[illegible]	*135*[illegible] *- 1*[illegible]	*15*[illegible] *- 1*[illegible]	*11*[illegible] *- 114*[illegible]	*15*[illegible]*-2*[illegible]
Study Interval (Burial Depth, m)	[illegible] - [illegible]	[illegible] *- 4*[illegible]	*25*[illegible] *-* [illegible]	[illegible] *-* [illegible]*5*[illegible]	[illegible]*-*[illegible]
Seismic Data	*3D PSDM*	*HD 3D PSDM*	*3D PSDM*	*3D PSDM*	*3D Merged PSTM*
Angle Stacks	*Near*[illegible] *Mid*[illegible] *Far & Ful*	*Near*[illegible] *Mid*[illegible] *Far & Ful*	*Near*[illegible] *Mid*[illegible] *Far & Ful*	*Near*[illegible] *Mid*[illegible] *Far & Ful*	*Near*[illegible] *Mid*[illegible] *Far & F*
Sampling Rate (ms)	*3.*[illegible]	*2.*[illegible]	*3.*[illegible]	*4.*[illegible]	*4.*[illegible]
Fr[illegible]uency Range (H[illegible])	*23 -* [illegible]*5*	*33 -* [illegible]	[illegible] *-* [illegible]	*2*[illegible] *-* [illegible]*4*	*22 -* [illegible]*5*
Dominat Fre[illegible]uency (H[illegible])	*52*	*55*	*4*[illegible]	*45*	*45*
Detectability (m)	*4*	*3*	*4*	*4*	*4*
Resolution (m)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Velocity (m/s)	*14*[illegible] *- 1*[illegible]	*1*[illegible]*2*[illegible] *- 1*[illegible]	*15*[illegible] *- 1*[illegible]	*15*[illegible] *- 1*[illegible]	*15*[illegible] *- 2*[illegible]

METHODOLOGY

Seismic stratigraphy and geomorphology methods (Catuneanu, 2006; Posamentier *et al.*, 2007) were used to analyze shallow buried turbiditic deposits taking advantage of the high frequency and resolution of the available 3D seismic data at this shallow burial (0 – 600 m). Posamentier, 2008 explained the vital role that 3D seismic data can play in hydrocarbon exploration and development, especially with regard to mitigating risk associated with the presence of reservoir, source, and seal facies. Mayall and O'Byrne, 2002; Abreu *et al.*, 2003; Posamentier and Kolla, 2003; Adeogba *et al.*, 2005; Labourdette and Bez, 2010; Mulder, 2011; Bouchakour *et al.*, 2022; Busari and Adekeye, 2024 worked on gravity processes and deposits, the geomorphology,architectural elements and evolution and prediction of deep-water deposits in the gulf of guinea, gulf of Mexico and other passive margin fans.

Several 3D seismic volumes (full reflection amplitudes, near, mid, and far stack amplitudes, and coherency volumes) were screened for turbiditic deposits offshore Niger Delta. Selected data were quality controlled (Qced), leading to the determination of the phase, frequency range, resolution, and signal-to-noise ratios. Identified turbiditic deposits were analyzed using combined seismic geomorphologic and stratigraphic methods as outlined below with the view to understand their geomorphology, internal architecture, stratigraphy and evolution in time and space.

The combined seismic geomorphology and stratigraphy workflow comprised:

1) Key reflectors above, below, and within the identified turbiditic deposits were mapped. Key regional events such as seabed, top of extensive hemipelagic layers, and MTC adjacent to turbiditic deposits of interest were also mapped. The intervals between mapped horizons were divided into layers depending on the interval thickness and complexities of the turbiditic deposits (Figure 3). Horizon attributes (dip/azimuth, coherency, and amplitude) maps were generated from key horizons to appreciate sedimentological features at those horizons. For example, dip and coherency maps were generated for the seabed to understand the modern seafloor in terms of physiography and sedimentological features of channels and other gravity deposits that are active on the modern seafloor (Figure 4). Seismic attributes were extracted within defined layers (Figure 5) to enhance turbiditic deposits' morphologic, sedimentological, and architectural features.

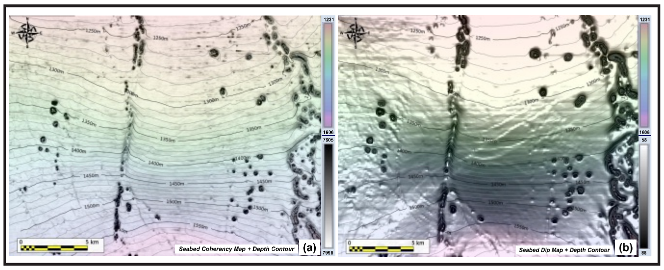


Figure 4: Horizon attributes. a) Location-1 seabed coherency map overlaid with depth contour showing Channel-1A and Channel-1B on modern seafloor. b) Location-1 dip map overlain with depth contour clearly expressing Channel-1A and Channel-1B reliefs on the seafloor.

Interval attributes used in this work include but are not limited to coherency, root mean square (RMS) amplitude, minimum and maximum in layer, and spectral decomposition. The interval attributes help to enhance structural and sedimentary features, as well as their evolution with time/depth.

2) Geomorphology and internal architecture delineation of seismically mappable architectural elements was done using simultaneous interpretations on seismic sections/profiles and attribute maps (Figure 7a). The interpreted seismic architectures were then calibrated using well data (logs and core) and outcrop analogs (Figure 7b-g).

3) Detailed geomorphology, stratigraphy, internal architecture, sedimentary fills and evolution of turbiditic deposits were studied using several seismic sections that are perpendicular to channels axes together with attribute maps of all the layers (Figures 8 & 9).

4) Channel dimensions were measured at intervals along

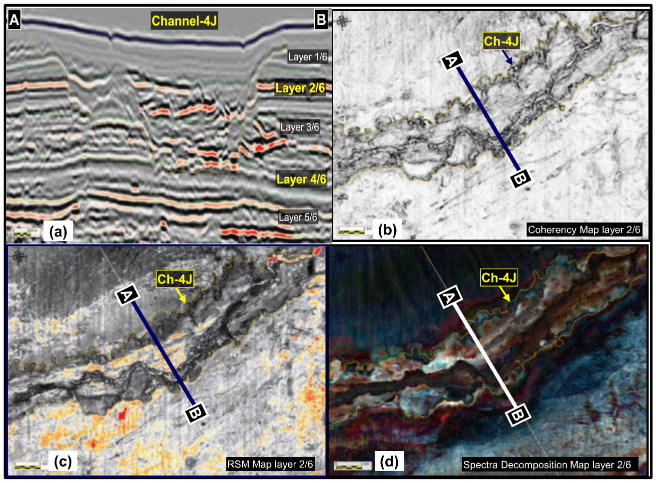


Figure 5: Layer attribute maps of Channel-4J in study location-4. a) NNW-SSE seismic section across Channel-4J showing 5 of the 6 layers in the interval of interest. b, c & d) coherency, RMS and spectra decomposition maps of layers 2/6. The interval attributes help to enhance structural and sedimentary features, as well as their evolution with time/depth.

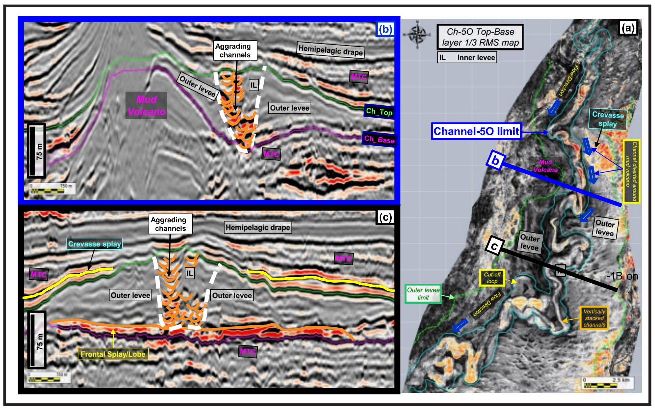


Figure 6: Main features of Channel-5O. a) Ch-5O Top-Base layer 1/3 RMS map showing the channel limit, vertically stacked unitary channels, inner and outer levees, older meander cut-off loop, overbank sediment waves on the shoulders of outer levees, mud volcano west of the channel, and lines of sections in figures 10b & c. b) NW-SE seismic section perpendicular to the channel axis and across the mud volcano west of the channel showing vertically stacked channels, inner and outer levees, bordering mud volcano and its relationship with the western outer levee, overlying and underlying MTC and hemipelagic drapes. c) NW-SE seismic section south of the mud volcano showing vertically stacked channels confined by outer levees, basal frontal splay/lobe, overbank sediment waves, the overlying MTC and hemipelagic drape.

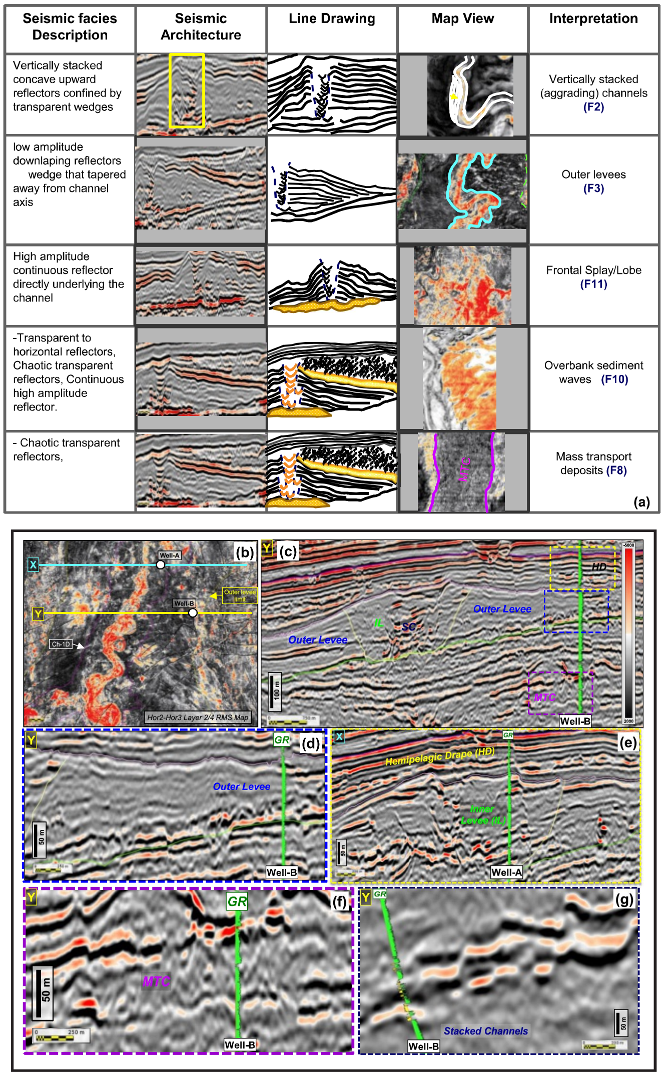


Figure 7: Seismically mappable architectural elements and their calibrations. a) Seismically mappable architectural elements interpreted using seismic sections and layer attribute maps. b) Hor2 – Hor3 layer 2/4 RMS map showing Channel-1D (Ch-1D), its outer levees limits and lines of sections used for architectural elements calibration. c) E-W seismic section perpendicular to Ch-1D axis showing the various architectural elements calibrated by gamma ray (GR) log. d-g) E-W seismic sections across Ch-1D, adjacent and deeper intervals illustrating the gamma ray (GR) logs calibration of outer levee, inner levee, hemipelagic drape, MTC and stacked channels

the channel belt, depending on the complexity of the channel. They were measured from seismic lines perpendicular to the channel axis and on attribute maps, following the methods described in previous studies (Deptuck *et al.*, 2007; Clark and Cartwright., 2009; Catterall *et al.*, 2010; Hansen *et al.*, 2015; Qin *et al.*, 2017; Zhao *et al.*, 2019, Bouchakour *et al.*, 2022; Busari and Adekeye, 2024). We have used the channel dimensions at the scale of channel elements, referred to as unitary channels and channel complexes (Sprague *et al.*, 2002; Abreu *et al.*, 2003). Channel elements are taken as unitary channels within a larger channel complex. Unitary channels are usually between 100 and 300 m but always under 300 m. Channel complexes range between 100%

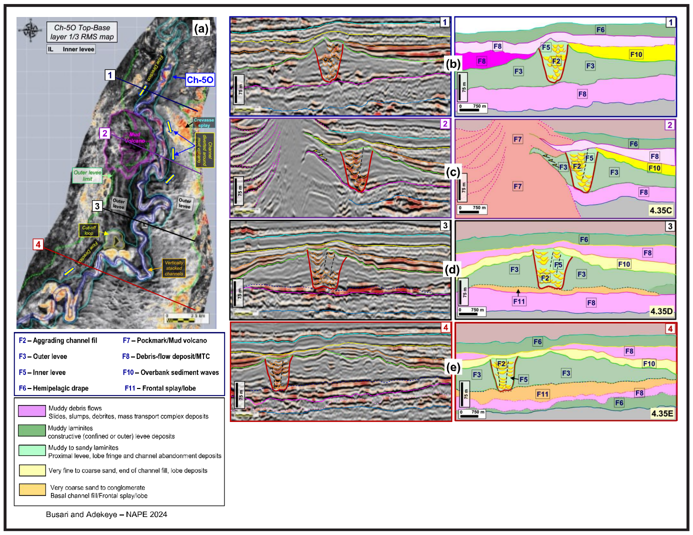
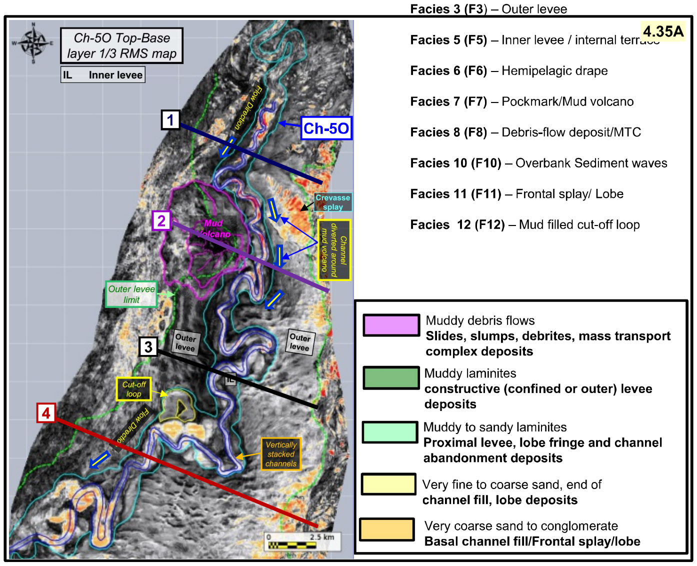


Figure 8: Seismic sections perpendicular to Channel-5O axis and their interpretations. a) Ch-5O Top-Base layer 1/3 RMS map showing main channel features on planform and four NWSE random lines perpendicular to the channel axis (1-4). b-e) illustrate interpretations of seismic sections perpendicular to channel axis with details of the stratigraphy and sedimentary fills of the channel.



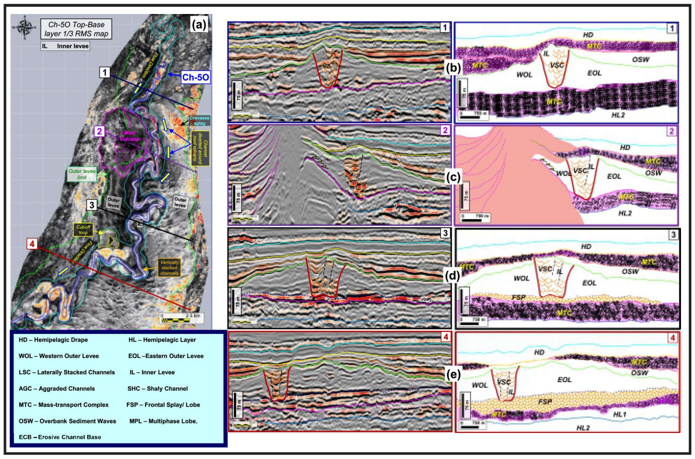
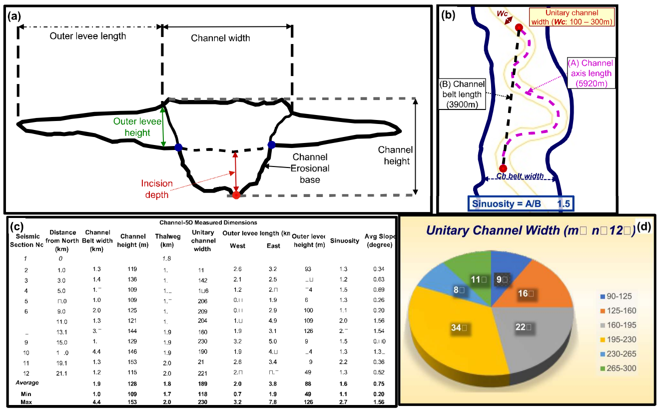


Figure 9: Seismic sections perpendicular to Channel-5O axis and their interpretations. a) Ch-5O Top-Base layer 1/3 RMS map showing main channel features on planform and four NW-SE random lines perpendicular to the channel axis (1-4). b-e) illustrate interpretations of seismic sections perpendicular to channel axis with details of geomorphology and internal architecture of the channel.



(c) Channel-5O Measured Dimensions

Seismic Section No	Distance from North (km)	Channel Belt width (km)	Channel height (m)	Thalweg (km)	Unitary channel width	Outer levee length (km) West	Outer levee length (km) East	Outer levee height (m)	Sinuosity	Avg Slope (degree)
1	0			1.8						
2	1.0	1.3	119	1.	11	2.6	3.2	93	1.3	0.34
3	3.0	1.4	136	1.	142	2.1	2.5	[illegible]	1.2	0.63
4	5.0	1.[illegible]	109	1.[illegible]	1[illegible]6	1.2	2.[illegible]	[illegible]4	1.5	0.69
5	[illegible].0	1.0	109	1.[illegible]	206	0.[illegible]	1.9	6	1.3	0.26
6	9.0	2.0	125	1.	209	0.[illegible]	2.9	100	1.1	0.20
	11.0	1.3	121	1.	204	1.[illegible]	4.9	109	2.0	1.56
[illegible]	13.1	3.[illegible]	144	1.9	160	1.9	3.1	126	2.[illegible]	1.54
9	15.0	1.	129	1.9	230	3.2	5.0	9	1.5	0.[illegible]0
10	1 .0	4.4	146	1.9	190	1.9	4.[illegible]	[illegible]4	1.3	1.3[illegible]
11	19.1	1.3	153	2.0	21	2.6	3.4	9	2.2	0.36
12	21.1	1.2	115	2.0	221	2.[illegible]	[illegible].[illegible]	49	1.3	0.52
Average		**1.9**	**128**	**1.8**	**189**	**2.0**	**3.8**	**88**	**1.6**	**0.75**
Min		**1.0**	**109**	**1.7**	**118**	**0.7**	**1.9**	**49**	**1.1**	**0.20**
Max		**4.4**	**153**	**2.0**	**230**	**3.2**	**7.8**	**126**	**2.7**	**1.56**

Figure 10: Channel dimension measurements. a) Schematic diagrams showing the methodology used for channel parameter measurements (i.e., channel belt width and height, outer levee height and length) in cross-section. b) channel dimension measurements in planform including sinuosity and unitary channel and channel belt width. c) Channel-5O measured dimensions. d) Pie chart showing distribution of unitary channel width from 120 measurements (modified after Bouchakour *et al.*, 2022; Busari and Adekeye, 2024).

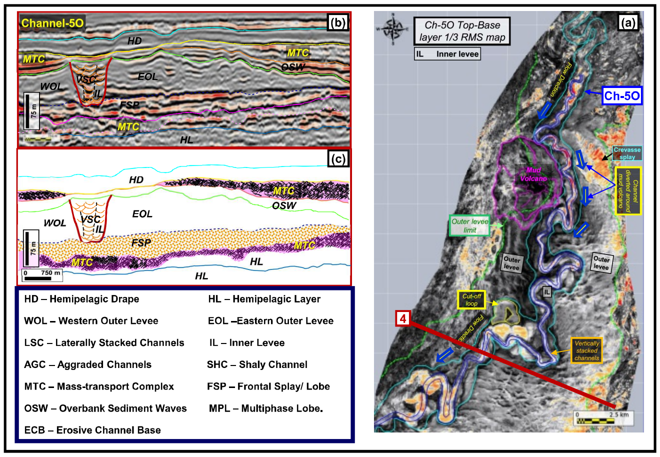


Figure 12: Deepwater depositional sequence in Channel-5O. a) Ch-5O top-base layer 1/3 RMS map showing the channel's main features and line of section '4' perpendicular to the channel axis. b-c) Seismic section '4' and its interpretation illustrating the deep-water sequences in offshore Nigeria comprises (from base to top) of the underlying MTC - Lobe/ Frontal splay – Leveed Channel – the Overlying MTC – Hemipelagic Drape.

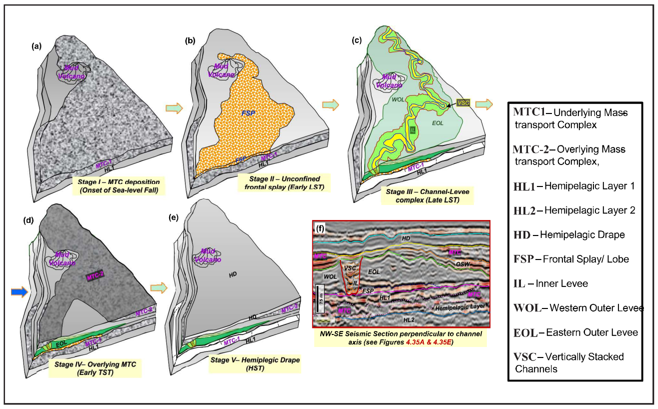


Figure 11: Geomorphologic and internal architectural evolution of Channel-5O. a) Stage I, when falling sea level resulted in instability on the shelf edge and the upper slope leading to MTC deposition in the mid and lower slope. b) Stage II dominated by the deposition of unconfined sand-rich basal frontal splay/lobe during early LST. c) Late LST that witnessed the deposition of channel-levee complexes on the slope by mud-rich turbidites during stage III. d) stage IV, was during rising sea-level when loading at shelf-edge resulted in unstable shelfedge and upper slope resulted in MTC deposition. e) Stage V was during HST when the sand deposition was restricted to inner and middle neritic, and the basin was dominated by hemipelagic/pelagic draping and formation of the condensed layer. f) Seismic section in the southern part of the study area showing deposits during all the five stages of Channel-5O evolution.

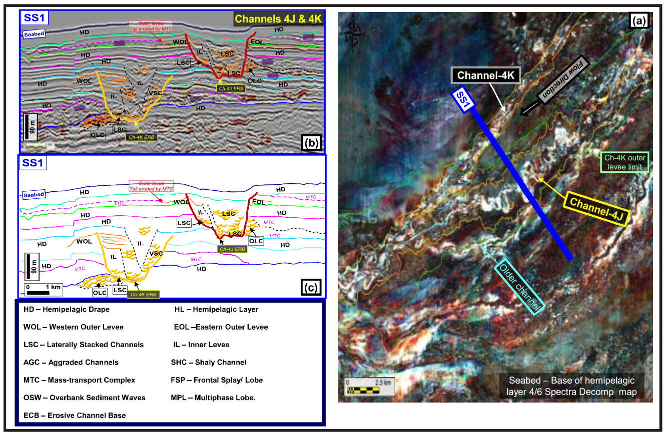


Figure 13: Deepwater depositional sequence in Channels 4J & 4K. a) Loaction-4 Seabed-Base of hemipelagic layer 4/6 spectra decomposition map showing the channels and line of section 'SS1' perpendicular to their axes. b-c) Seismic section 'SS1' and its interpretation illustrating the deep-water sequences similar to what we observed in Channel-5O.

erosive to erosive-constructive and 100% constructive with a channel width of more than 500m (can be up to 4km wide). Other channel dimensions measured include height, incision depth, outer levees height and length, and channel sinuosity. Channel sinuosity was calculated as the ratio between the channel-axis length and channel-belt length (Figures 10a & b). The results of the measurements were synthesized and used to create a turbiditic analogs database for deep-water Nigeria (Figures 10c & d).

5) Turbiditic deposits evolution were put in sequence stratigraphic context (Figure 16) to establish the impacts

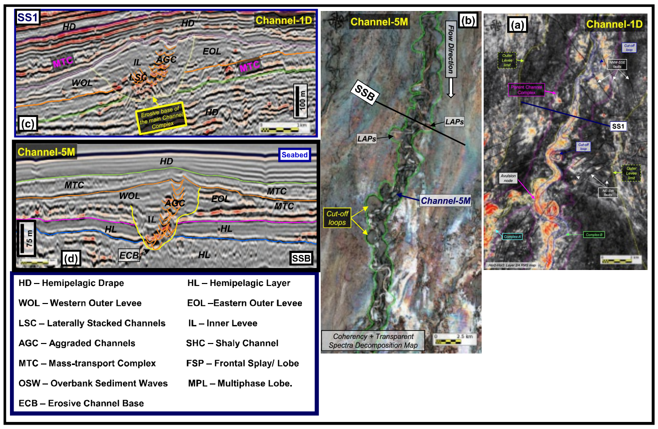


Figure 14: Deepwater depositional sequence in Channels 1D & 5M. a) Ch-1D Hor2-Hor3 layer 2/4 RMS map showing the channels main features and line of section 'SS1'. b) Ch-5M coherency + spectra decomposition map showing its main features and line of section 'SSB'. c-d) Seismic sections 'SS1' and 'SSB' and their interpretations illustrating the deep-water sequences similar to what we observed in Channel-5O.

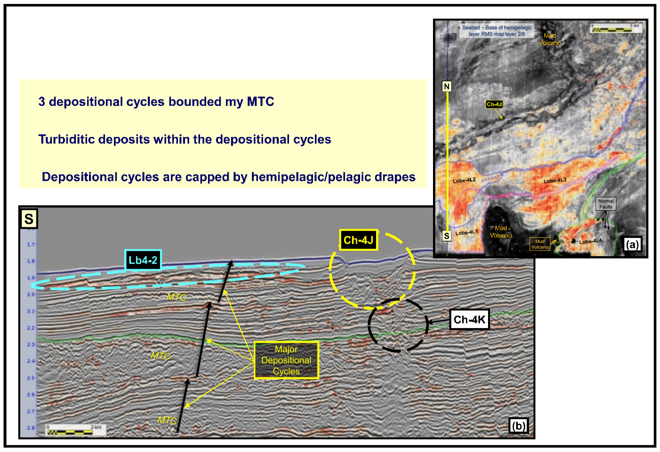


Figure 15: Deepwater depositional sequence – depositional cycles in location-4. a) Loaction-4 Seabed-Base of hemipelagic layer 4/6 RMS map showing Ch-4J, transient and terminal lobes of Adeogba *et al.*, 2005 and a N-S and line of section perpendicular to the channel axis. b) N-S seismic sections showing repeated depositional cycles of turbiditic deposits bounded by MTC and capped by hemipelagic drapes.

of controlling factors such as relative sea level changes, sediment type and supply rate, and seafloor morphology on their geomorphology, internal architecture and evolution.

6) Applications of the understanding of channels/lobes geomorphology, stratigraphy, internal architecture, and evolution to the prediction of turbiditic reservoir presence and/or robust reservoir modeling were demonstrated (Figures 17 & 18).

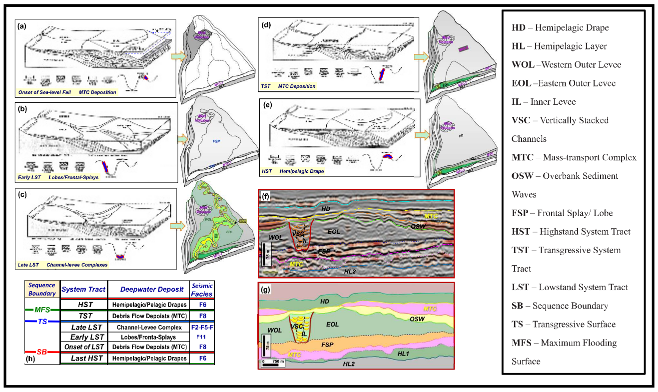


Figure 16: Sequence stratigraphic framework for depositional sequence in deep-water Nigeria. a-e) 3D illustrations of the impacts of changes in relative sea-level on deep-water sequences, and demonstration with Channel-5O evolution (modified after Howard, 2006). f) Seismic section (NW-SW line 4 on Figure 12a) illustrating MTC - Lobe/Frontal splay – Leveed Channel – MTC – Hemipelagic Drape sequence in Channel-5O. g) Interpretation of geomorphology and sedimentary fills of the seismic section in 'f'. h) Links between sequence stratigraphic boundaries, system tracts and the observed deep-water sequence.

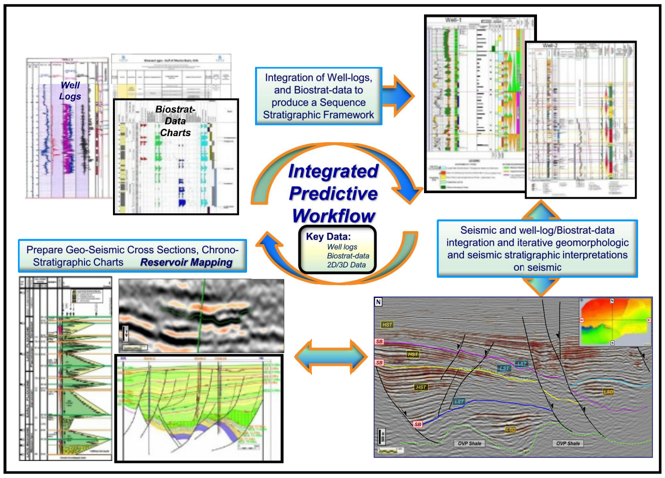


Figure 17: Integrated predictive workflow. The workflow uses well logs, biostratigraphy, and seismic data interpretations iteratively to generate geo-seismic cross-section and chrono-stratigraphic charts needed for turbiditic reservoir prediction.

RESULTS AND ANALYSIS

Channel-5O Main Features

Channel-5O is a northeast-southwest constructive channel-levee complex (Figure 6). The main channel complex width ranges between 1 to 4.4 km; channel height ranges between 109 and 153 m, and outer levees height between 49 and 126 m. There is a significant difference between the western and eastern outer levees lengths due

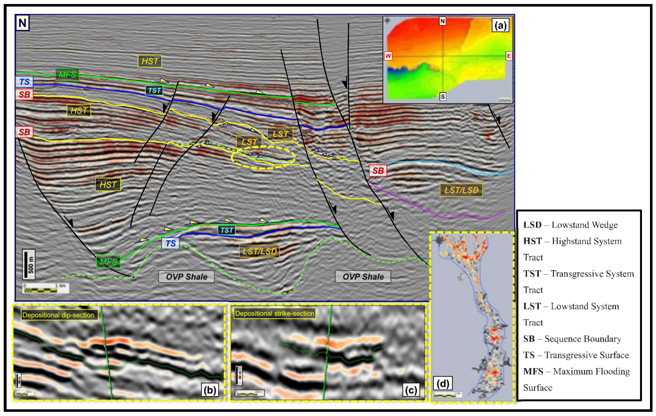


Figure 18: Turbiditic channel prediction using an integrated seismic geomorphology and stratigraphy workflow. a) Identification of LST turbiditic deposits on a north-south seismic section using the integrated geomorphologic and sequence stratigraphic workflow. b) N-S seismic section showing the calibration of the turbiditic channel identified in 'a'. c) E-W seismic section perpendicular to channel axis illustrating the channel identified in 'a'. d) Amplitude map of the identified turbiditic channel.

to the impact of the mud volcano west of the channel in the northern half of the study area (Figures 6a, 6b & 10c). The western outer levee length ranges between 0.7 and 3.2 km, while the eastern outer levee length ranges between 1.9 and 7.8 km. The channel is highly sinuous to meandering, with unitary channels generally vertically stacked and confined by shaly outer levees (Figure 6b). The basal part of the channel, south of the mud volcano, is dominated by continuous high amplitude reflectors interpreted as unconfined frontal splay/lobe deposited on the basin floor during the early LST and before the development of outer levees that confine the overlying vertically stacked channels (Figures 6a & c). The western and easter outer levees' shoulders are draped by continuous high-amplitude reflectors interpreted to be overbank sediment waves (Figure 6c). The channel is usually sandwiched by the underlying and overlying MTC and the hemipelagic drapes of the previous and later sea-level highstands (Figures 6, 8, 9, 11 & 12).

Seismically Mappable Architectural Elements (Seismic Architectures)

Seismically mappable architectural elements (seismic architectures) in Channel-5O were interpreted using seismic sections and attribute maps (Figure 7a). These seismic facies are diagnostic and enhance the understanding of the channel's internal architecture.

Facies 2—Vertically stacked concave upward medium/high-amplitude reflectors are interpreted as aggrading channels confined by outer levees (Figure 7a).

Facies 3 – Wedge-shaped architectures bordering both sides of the channel complex margin and tapering away from the channel axis are characterized by low to moderate amplitude downlaping reflectors and interpreted as outer levees (Figure 7a).

Facies 6 – Horizontal, well-layered, mainly transparent reflectors encasing Channel-5O have been interpreted as hemipelagic drapes (Figure 7a).

Facies 7 – Conical positive relief on the seafloor with a transparent core and flowery planform architecture has been interpreted as a mud volcano (Figure 7a).

Facies 8 – Chaotic to transparent reflectors overlying overbank sediment waves/outer levees of Channel-5O have been interpreted as debris-flow deposits or mass-transport complexes (MTC, Figure 7a).

Facies 10—Continuous high-amplitude reflectors, sometimes wavy, directly overlying outer levees have been interpreted as overbank sediment waves deposited when sandy turbiditic flows overflown the channel overbank (Figure 7a).

Facies 11—Laterally continuous, unconfined high-amplitude reflectors at the base of the channel with fan-like planform architecture have been interpreted as frontal splay/lobes deposited when turbiditic flows with medium to coarse grains breached the levee and formed tabular/sheet sands (Figure 7a).

Seismically mappable architectures were calibrated with well logs from similar architectural elements in deep-water Nigeria (Figures 7b-g). Where available, core and outcrop information are also used to calibrate seismic architectures in terms of sedimentary fills.

Channel-5O Internal Architecture and Channel Fills

Complex internal architecture observed in Channel-5O reflects impacts of seafloor morphology, turbidity flow composition, and changes in relative sea level (Posamentier and Kolla, 2003). The channel experienced several cut-and-fill episodes, lateral migration, meander cuts, and changes in channel stacking patterns from the early lateral unconfined to vertically stacked channels confined by outer levees. Four seismic sections (1, 2, 3 & 4, Figure 8) were used to illustrate internal architecture variability and complexity.

NW-SE seismic section 1 – Channel-5O is 100% constructive without any erosion into the underlying hemipelagic substrates. Unitary channels are generally aggrading and confined by outer levees (Figure 8b). Vertically stacked channel fills are mainly fine-medium-grained sands (F2) with adjacent very fine to shaly inner levee (F5). The confining outer levees are overlaid on the west by an MTC (F8) and on the east by overbank sediment waves (Figures 6a & 8b). The generally shaly outer levees (F3) are believed to have been built by the spillover of the upper part of turbidity currents dominated by fines (Babonneau, 2002). The overlying MTC and the encasing hemipelagic drapes (F6) are believed to have been deposited during rising and highest sea levels, respectively. The overbank sediment waves (F10) overlying the eastern outer levee are believed to be essentially very fine to fine sands deposited when sand-rich turbiditic flow overflown the outer levee.

NW-SE seismic section 2 – illustrates essentially the same facies and stratigraphic arrangements as section '1' and the impact of a mud volcano (F7) on the western outer levee. The mud volcano is an overpressured shale vent on the seafloor that significantly impacted the morphology of Channel-5O's western outer levee (Figure 8c).

NW-SE seismic section 3 – this section in the southern half of the study area illustrates the basal frontal splay deposited in the unconfined seafloor at the base of Channel-5O (Figure 8d). The medium to coarse-grained frontal splay (F11) is believed to have been deposited during the early stage of falling sea level (early LST) when the turbiditic flow is rich in coarse sediment. They are generally known as High-amplitude reflection packets – HARPs (Babonneau, 2002). Evidence of cut-and-fill episodes is evident in this section, while the channels, as seen in previous sections, are generally aggregated and confined by the outer levees.

NW-SE seismic section 4 – In addition to underlying frontal splay, vertically aggrading channels confined by the outer levees and overlying MTC and encasing hemipelagic drapes, this section illustrates the underlying MTC believed to have been deposited at the onset of sea-level fall when decreasing overburden resulted in instability in the upper slope and deposition of debris-flow and mass-transport complex in middle and lower slopes (Posamentier and Kolla, 2003). This section illustrates an ideal stratigraphic succession of a deep-water sequence (see Figure 24 of Posamentier and Kolla, 2003).

Geomorphologic and Internal Architectural Evolution of Channel-5O

Geomorphologic and internal architectural evolution of Channel-5O reflects the impacts of controlling factors such as changes in relative sea-level, type of sediment at the shelf-edge (i.e., the staging area), rate of sediment supply and seafloor morphology (Posamentier and Kolla, 2003; Morgan, 2004; Clark and Cartwright, 2009, 2011; Hansen et al., 2015, 2017; Chima et al., 2020; Bouchakour et al., 2022; Busari and Adekeye, 2024). The geomorphologic evolution of the channel was studied using four (4) seismic sections perpendicular to the channel axis (1 – 4, Figure 9).

The channel morphology varies from U- to V-shaped and symmetric to asymmetric walls. As observed in other studied turbiditic channels, Channel-5O's cross-sectional morphology changes correspond closely to planform geometry variations. Inner versus outer channel bends and straight channel segments can usually be identified from their cross-sectional motifs (Figure 9). The most symmetrical channel cross-sections correspond to the relatively straight channel segment (Figures 9a & b), while the steepest channel margins are typically on the outer meander bends (Figures 9a & d). The noticeable difference in western and eastern outer levees lengths between 5-13km from the north (Figures 9a, 9c & 10c) is linked to the impact of the mud volcano on the channel fairway and morphology. The change in the channel fairway and diversion around the mud volcano suggests that the mud volcano was a positive relief on the seafloor at the time of the deposition of Channel-5O. However, the volcano continues to be active until the present, as indicated by its positive relief on the modern seafloor (Figure 9c).

Channel-5O's internal architecture has evolved through frontal playing, cut-and-fill episodes, inner and outer levee deposition, meander cut-off, and vertical aggradation of most of the unitary channels confined by outer levees. Its internal architecture evolution can be explained in five stages (Figure 11). The evolutionary history of Channel-5O is like the stratigraphic succession of a deepwater sequence model of Posamentier and Kolla (2003).

Stage-I – deposition of MTC in the distal part of the system during very early relative sea-level fall when reduction in overburden/water column at the shelf resulted in increased pore pressure and overpressure leading to the unstable shelf edge and upper slope failure. The slope failure is believed to have resulted in the MTC deposition on the middle and the lower continental slope (Figure 11a).

Stage II – deposition of sand-rich unconfined basal frontal splay/lobe during early LST, when deposition moved to the staging area/shelf edge, and there was the fluvial erosion of the shelf, with associated incise valleys and shelf edge canyons released sand-rich turbidite flows into the slope and basin floor (Figure 11b).

Stage III – deposition of constructive channels that are dominantly aggrading and their confining mud-rich levees during Late LST and Early TST (Figure 11c). Over-spilling of late arrival turbidite flows that are low in fines, due to their depletion through spilling to form outer levee upslope, is believed to have resulted in the overbank sediment waves (Figure 6).

Stage IV - MTC deposition during TST (rising sea level) due to loading of the outer shelf and upper slope with sediments and water column, which resulted in upper slope failure (Figure 11d).

Stage V - Deposition of hemipelagic drapes during HST (the highest relative sea level), when sediment deposition was restricted to the inner and middle shelf and the basin dominated by deposition of a condensed section comprising hemipelagic and pelagic sediments (Figure 11e).

Figure 11f is a seismic section (Figure 8e) that captures deposits of all the above evolutionary stages of Channel-5O.

Deep-water Depositional Sequence

Most of the channels studied have been observed to have similar stratigraphic succession of architectural elements. Typical stratigraphic succession in most of the studied turbiditic deposits starts with a debris-flow and slide/slump deposits herein referred to as MTC, followed by basal lobe/frontal splay overlain by the leveed channel deposit and an overlying MTC before the encasing hemipelagic drapes (Figure 12). The complete depositional sequence, similar to the offshore Indonesia example in Figure 24 of Posamentier and Kolla (2003), among the studied deposits in deep-water Nigeria is Channel-5O. The underlying MTC in Channel-5O is overlain by the basal frontal splay/lobe underlying the constructive channel-levee complex. The leveed channel is, in turn, overlain by another MTC and eventually capped by a layer of hemipelagic drape (Figure 12b & c). Similar succession, except for the frontal splay, is seen in Channel-4J, Channel-4K, Channeel-5M, Channel-1D, and other studied deposits (Figures 13 & 14). Apart from the similar stratigraphic successions mapped in most of the studied turbiditic deposits, one key observation is the association between MTC and turbiditic deposits in most studied channels/lobes. The siamese-like relationship between these gravity flow deposits suggests a strong link between the processes and factors that control their deposition. Figure 15 illustrates the close links between MTC and turbiditic channels and lobes. The three depositional cycles shown on the north-south seismic section across location-4 channels and lobes are bounded by MTC and hemipelagic drapes. Figure 15b suggests that cyclic successions are abundant in deep-water Nigeria, and that turbiditic deposits and MTC have the same or closely linked sources.

Sequence Stratigraphic Context

The deep-water depositional sequence, as seen in Channel-5O and other studied deep-water deposits, consists of an underlying Mass-transport Complex (MTC) that precedes a Lobe/Frontal splay, followed by a Leveed Channel and an overlying MTC that is finally capped by Hemipelagic/Pelagic drapes, has been linked to key controlling factors namely changes in relative sea-level, the seafloor morphology, sediment type and rate of sediment supply (Pirmez and Imran, 2003; Posamentier and Kolla, 2003; Morgan, 2004; Clark and Cartwright, 2009, 2011; Hansen *et al.*, 2015, 2017; Chima *et al.*, 2020). However, changes in relative sea level is believed to have played the most critical role in the deposition of the observed stratigraphic successions. At the onset of relative sea-level fall, after a long period of high relative sea-level during which hemipelagic layers were deposited, the reducing water column and overburden at the shelf edge/upper slope is likely to have resulted in increased pore pressure and instability of the shelf edge and upper slope. The slope failures due to the instability linked to falling relative sea level are believed to be responsible for the debris-flow deposits (MTC) seen overlying the hemipelagic drapes of the previous highest relative sea level (HST, Figure 16a). Due to the period and processes of the MTC deposition, their positions are sometimes flexible. As the sea level begins to fall and rivers are able to bring their loads into the shelf-edge, the sand-rich sediment load of the river is deposited on the basin floor and slope as lobes/frontal splays (Figure 16b).

During the late Lowstand, when the relative sea level is at the lowest and turbidity flows tend to be mud-rich, leveed channels are deposited on the slope (Figure 16c). In a situation where there is a basinward shift of the system, it is possible for the channel-levee complex of the late LST to be deposited directly on the lobe/frontal splay of the early LST, as seen in Channel-5O and Figure 24 of Posamentier and Kolla (2003). As the sea level rises during TST, the water column and overburden increase can destabilize the shelf-edge and result in the deposition of another masstransport complex, as seen in most of the studied channels (Figures 13, 14 & 16d). During the following highest relative sea level, when volumetric partitioning restricted clastic sediment deposition to mainly the inner and middle shelf, sediment supply to the outer shelf and the basin is reduced to almost zero.

Deposition in the basin generally consists of condensed sections comprising mostly of hemipelagic and pelagic drapes (Figure 16e). Figures 12b and c illustrate a complete deep-water Nigeria stratigraphic succession (depositional sequence) as observed in Channel-5O, while figure 4.68H links the architectural elements to seismically mappable facies, sequence stratigraphic boundaries, and system tracts.

Deep-water stratigraphic successions, like those observed in this study, have been observed by others to varying degrees (Weimer, 1991; Piper et al., 1997; Manley and Flood, 1998; Maslin *et al.*, 1998, Beauboeuf and Friedman, 2000; Brami *et al.*, 2000; Winker and Booth, 2000; Posamentier and Kolla, 2003). Posamentier and Kolla (2003) also established a close link between changes in relative sea-level and deep-water stratigraphic succession observed in Indonesia and proposed an idealized deep-water depositional sequence (see Figure 24 of Posamentier and Kolla, 2003).

However, because of the complexities inherent to deep-water depositional environments, the idealized sequence proposed by Posamentier and Kolla (2003) or the ideal subsurface sequence observed in Channel-5O and Figure 24A of Posamentier and Kolla (2003) is not observed at every location because the variable shelf edge area conditions and variations in the basin caused by other controlling factors. For example, in slope settings, debris-flow (MTC) and lobe/frontal splay components can be thin to absent, whereas in basin floor settings, the channel-levee component can be thin to absent. In deep-water settings, where no sand-rich shelf-margin/shelf-edge is present directly upslope, a deep-water environment may completely lack turbidite deposits and be represented only by debris-flow deposits (Posamentier and Allen, 1999; Posamentier and Kolla, 2003).

Integrated Predictive Workflow and MTC as pathfinders for Turbiditic Deposits

Based on the observed links between sea-level change and deposition in the basin, this study has come up with an integrated predictive workflow that is based on integrated sequence stratigraphy and seismic geomorphology approaches (Figure 17). Like any other tool, the workflow is highly iterative and data dependent. The more relevant data there is, the more predictive the workflow.

Critical data for this tool are well-logs, biostratigraphy and seismic (3D and regional 2D) data. Well logs such as gamma ray (GR), neutron and density will be adequate, but having sonic and image logs will aid the interpretation of stacking patterns. Availability of regional 2D or merged 3D seismic, in addition to good quality 3D seismic data, is desirable as it can help to establish the stratigraphic link between the shelf area and the basin. Depositional stacking patterns and sequence stratigraphic surfaces are interpreted using both well logs and biostratigraphy data to produce a sequence stratigraphic framework (Figure 17). Seismic stratigraphic and geomorphologic interpretations were integrated with well logs and biostratigraphic generated framework to define important sequence stratigraphic surfaces (SB, MFS, TS) and system tracts (LST and HST normal regressions, LST forced regression & transgressive) packages. The end products are Geo-Seismic Cross Sections and Chrono-Stratigraphic charts for predicting reservoir presence (Figure 17).

The integrated workflow assumes an ideal world where all the needed data is available. Given that explorers rarely have the complete suite of data needed for such an integrated workflow, the ability to use what is available and fill the gap with concepts and diagnostic features becomes critical. Having established the vital link between mass-transport complexes (MTC) and turbiditic channel-levee/lobes, the study considers the presence of MTC as a pathfinder for turbiditic deposits. Hence, having 2D and 3D seismic data, a few wells for calibration at shelf area, and the ability to combine seismic stratigraphy and geomorphology approaches may suffice for predicting turbiditic reservoirs' presence. Figure 18a illustrates sequence stratigraphic surfaces interpretation, identification of system tracts, key deposits and turbiditic channel-levee complex on a north-south seismic section. The identified channel-levee complex was calibrated by gamma-ray logs, as shown by seismic sections across and along the channel (Figures 18b & c).

CONCLUSIONS

In this paper, we demonstrated the application of a combined seismic stratigraphy and seismic geomorphology approach to studying the geomorphology, internal architecture, stratigraphy, and evolution of turbiditic deposits. Several turbiditic deposits, together with associated debrisflow deposits and other seabed features, were studied across deep-water Nigeria for their geomorphology, seismic facies, internal architecture, sedimentary fills, and evolution in time and space. These turbiditic channel-levee complexes and lobes are found to have complex geomorphology and internal architectures linked to their evolutions. The study established how factors such as sea-level change, rate and type of sediment supply, and seafloor morphology shape channel geomorphology and internal architecture and their variability. Dimensions of the studied turbiditic deposits, such as unitary channel width, channel belt width and height, incision depths, outer levee height and length, channel slope gradient, and sinuosity, were measured, and a database of the measurements was created. The data have been carefully synthesized for use as analogs by researchers/explorers working in similar settings or deeper exploration intervals with limited or poor-quality data.

As in similar basins, deep-water deposits in Nigeria were deposited in repeated cyclic succession. Deep-water depositional sequence, as seen in Channel-5O, usually consists of an underlying Mass-transport Complex (MTC) that precedes a Lobe/Frontal splay, followed by a Channel-levee, and an overlying MTC that is finally capped by Hemipelagic/Pelagic drapes. These stratigraphic successions have been linked to relative sea-level changes, the type of sediments supplied, and the rate at which the sediments were supplied from the shelf-edge (staging) area.

An integrated sequence stratigraphy and seismic geomorphology workflow has been proposed as a tool for predicting turbiditic reservoir presence in deep-water Nigeria. In a situation of limited data, the observed close link between turbiditic deposits and mass-transport complexes (MTCs) makes the latter a possible pathfinder for the former. Identification of mass-transport complexes, through their diagnostic seismic characteristics, is crucial as they (MTC) can serve as a pathfinder for turbiditic deposits.

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