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Continental Facies Architecture and Hydrocarbon-Stained Shale Intervals of the Bima Formation at Yarandua, Upper Benue Trough, Northeastern Nigeria

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Abstract

The Bima Formation forms the basal Cretaceous siliciclastic succession of the Upper Benue Trough and records early continental sedimentation associated with rift initiation. This study documents the facies architecture and depositional significance of Bima Formation outcrops at Yarandua, northeastern Nigeria, with emphasis on continental facies relationships and hydrocarbon-stained shale intervals. Three outcrop sections were logged and interpreted using lithology, texture, bed geometry, sedimentary structures, weathering character, nature of contacts, fracture patterns, and bituminous staining. Five recurring facies were identified: weathered basement, conglomerate, massive to cross-bedded sandstone, siltstone/mudstone, and shale. These facies are grouped into three facies associations: proximal braided fluvial-alluvial fan deposits, fluvial channel-bar to overbank deposits, and floodplain-ponded overbank/lacustrine shale deposits. The conglomeratic and poorly sorted sandstone units indicate high-energy traction deposition close to uplifted basement source areas, whereas interbedded sandstone, siltstone, mudstone, and shale reflect fluctuating discharge, channel migration, floodplain aggradation, and localized ponding. Oil-wet and dark bituminous shale surfaces in section OJ-003 suggest hydrocarbon impregnation, organic enrichment, or migration staining along fractures and weathered bedding surfaces. These features indicate that fine-grained intervals within the Bima Formation should not be treated only as passive floodplain deposits; locally, they may represent source-prone, seal, or migration-related facies within a simple continental petroleum-system framework. The studied successions therefore record deposition in a tectonically active continental rift setting dominated by braided fluvial, alluvial-fan, overbank, and shallow lacustrine processes. The results refine the sedimentological interpretation of the Bima Formation at Yarandua and highlight its relevance for reservoir heterogeneity and hydrocarbon prospectivity

Keywords

Bima Formation;
Yarandua;
Upper Benue Trough;
Continental facies;
Fluvial sedimentology;
Hydrocarbon-stained shale;
Reservoir heterogeneity

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1. Introduction

The Benue Trough of Nigeria is a major NNE–SSW-trending intracontinental rift system in central West Africa. It developed in association with Early Cretaceous lithospheric extension linked to the opening of the South Atlantic Ocean and subsequently experienced important compressional deformation during the Santonian tectonic episode (Benkhelil, 1989; Guiraud, 1990; Obaje, 2009). The trough forms one of the most significant sedimentary basins in Nigeria and contains thick Cretaceous to younger sedimentary successions that preserve the tectono-sedimentary evolution of a rift-related basin. These successions provide valuable records of basin development, sediment dispersal patterns, palaeoenvironmental evolution, and reservoir architecture, making the Benue Trough an important analogue for continental siliciclastic reservoir systems worldwide.

The Upper Benue Trough is commonly subdivided into the Gongola and Yola arms, with some workers also recognizing the Lau-Lamurde/Lau-Gombe axis as a distinct structural and depositional segment (Carter et al., 1963; Zaborski et al., 1997; Dike, 2002). This subdivision reflects variations in structural configuration, sediment accumulation patterns, and depositional history across the basin. The stratigraphic succession of the Upper Benue Trough records several phases of tectonic activity and sedimentation that accompanied the evolution of the rift basin during the Cretaceous.

The basal unit in this region is the Albian Bima Formation, which unconformably overlies the Precambrian Basement Complex and is dominated by continental sandstones, conglomerates, mudstones, and shales. The formation represents the earliest phase of Cretaceous sedimentation in the basin and records the initial infilling of syn-rift accommodation space generated during crustal extension. These lithologies preserve evidence of fluvial, alluvial, and associated continental depositional processes and provide a useful framework for reconstructing palaeoenvironmental conditions, sediment routing systems, reservoir distribution, and stratigraphic heterogeneity. Consequently, the Bima Formation has attracted considerable attention because of its significance in understanding basin evolution and its potential role as a reservoir interval within the petroleum systems of the Benue Trough.

Despite extensive regional studies on the stratigraphy, sedimentology, and petroleum prospectivity of the Benue Trough, detailed outcrop-based facies documentation remains essential because the Bima Formation is laterally heterogeneous and strongly controlled by local palaeotopography, syn-rift accommodation, and sediment supply. Variations in facies architecture, grain-size distribution, sedimentary structures, and vertical stacking patterns provide critical insights into depositional processes and environmental evolution that may not be fully resolved from subsurface data alone. Furthermore, detailed field-based studies contribute to a better understanding of reservoir quality distribution and stratigraphic compartmentalization within continental successions.

This study reviews and restructures outcrop evidence from Yarandua, focusing on lithofacies, facies associations, vertical facies trends, depositional processes, and the significance of oil-wet shale intervals observed in the field. Particular attention is given to the sedimentological characteristics of the exposed succession and their implications for depositional environment reconstruction and petroleum-system evaluation. The specific objectives are to:

1. Describe the principal lithofacies exposed in the studied Bima Formation sections;
2. Group the facies into genetically meaningful facies associations;
3. Interpret the depositional environments represented by each section; and
4. Evaluate the implication of hydrocarbon-stained shale for the petroleum-system significance of the continental Bima succession.

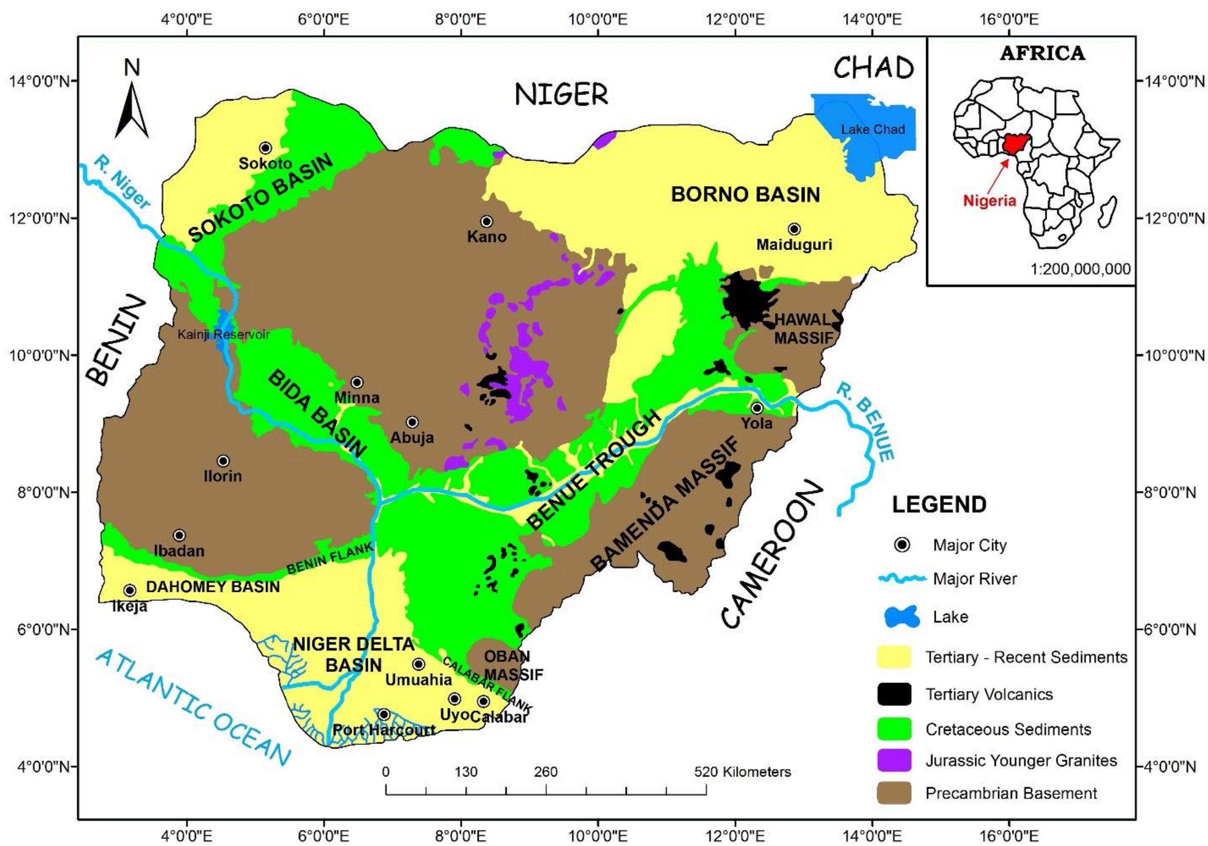

Figure 1. Geological map of Nigeria showing major sedimentary basins and the regional position of the Benue Trough (After Bata et al., 2018).

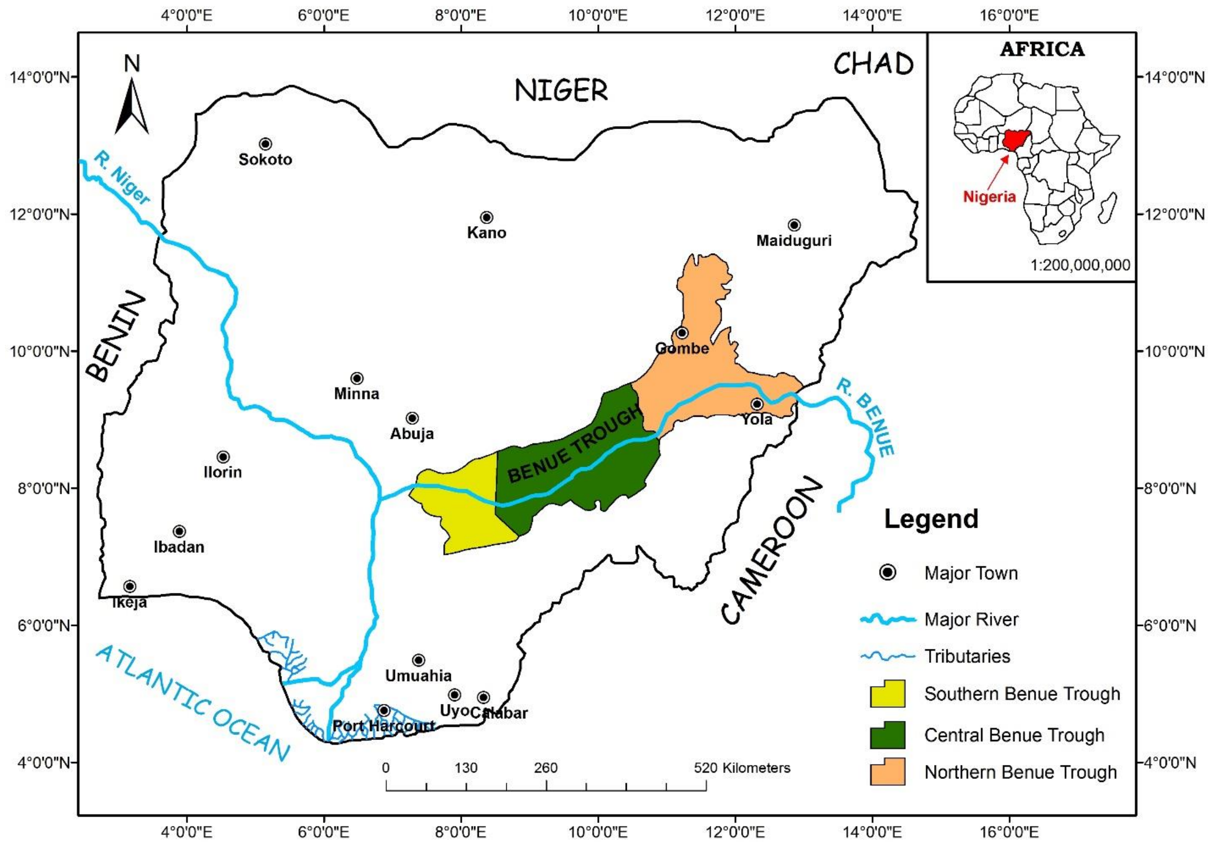

Figure 2. Outline map of Nigeria showing the Southern, Central and Northern segments of the Benue Trough (After Bata et al., 2018).

2. Geological and Stratigraphic Setting

The Upper Benue Trough forms the northeastern segment of the Benue rift system and displays a characteristic Y-shaped geometry composed of the Gongola Arm, Yola Arm and Lau-Lamurde axis. This structural configuration reflects the interaction of basement fabric, Early Cretaceous extension, syn-rift subsidence, sediment supply from adjacent uplifted basement blocks and later compressional reactivation (Benkhelil, 1989; Guiraud, 1990; Zaborski et al., 1997).

The sedimentary succession in the Upper Benue Trough generally comprises the Bima Formation, Yolde Formation, Gongila/Pindiga formations, Fika Shale, Gombe Formation and the Tertiary Kerri-Kerri Formation (Carter et al., 1963; Zaborski et al., 1997; Obaje, 2009; Shettima et al., 2016). The Bima Formation is the basal Cretaceous unit and consists mainly of coarse- to medium-grained sandstones, conglomerates, siltstones, mudstones and subordinate carbonaceous or argillaceous intervals. It has been subdivided into Lower, Middle and Upper Bima units based on lithologic and stratigraphic variations (Carter et al., 1963).

At Yarandua, the studied exposures display sandstone-, conglomerate- and shale-dominated intervals of the Bima Formation. The sections show a range of continental facies, including proximal high-energy deposits directly overlying weathered basement and finer-grained intervals interpreted as overbank, ponded floodplain, abandoned-channel or shallow lacustrine deposits. The local occurrence of oil-wet shale surfaces makes the area particularly relevant for evaluating the petroleum-system significance of fine-grained continental facies within the Bima succession.

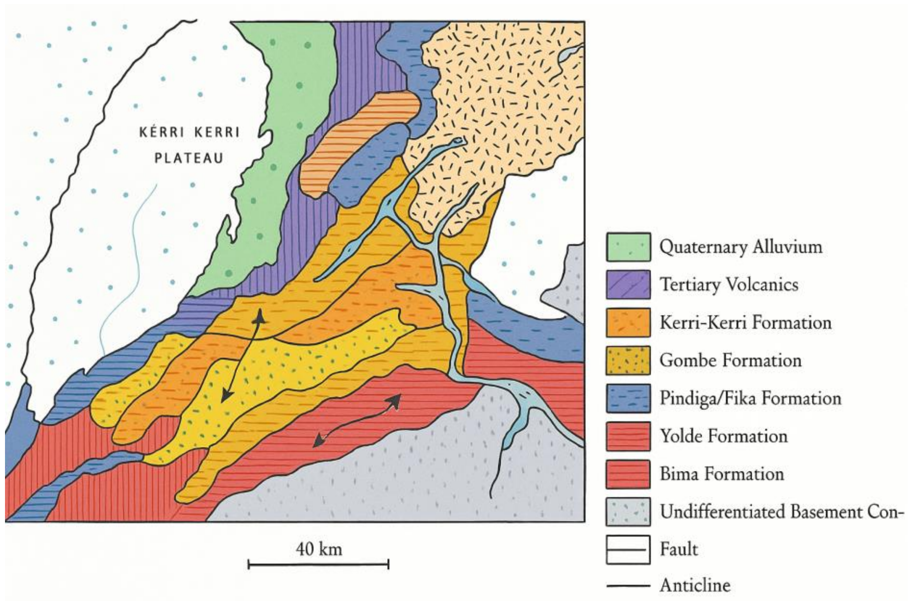

Figure 3. Geological map of the Northern Benue Trough showing the distribution of major stratigraphic units, faults and fold structures (modified after Zaborski et al., 1997; Obaje, 2009).

3. Materials and Methods

The study is based on field-scale sedimentological logging and facies interpretation of three exposed sections of the Bima Formation at Yarandua. The outcrops were examined for lithology, grain size, sorting, colour, bed thickness, bed geometry, sedimentary structures, vertical facies changes, erosional contacts, nature of fractures, weathering style, concretionary features and evidence of hydrocarbon staining. Field photographs and hand-sketched sedimentological logs were used to document the sections and support facies interpretation.

Facies were classified using a process-based approach consistent with standard fluvial and continental facies analysis (Miall, 1996; Reading, 1996; Bridge, 2003). The facies were then integrated into facies associations based on vertical stacking patterns, grain-size trends, bounding surfaces and inferred depositional processes. Particular attention was given to the dark oil-wet shale observed in section OJ-003 because hydrocarbon staining may indicate organic enrichment, migration pathways, bitumen residue, or localized retention of petroleum along fractures and weathered surfaces.

4. Results

4.1 Lithofacies

Five major lithofacies were recognized in the Yarandua sections. These facies are summarized in Table 1 and described below.

Table 1. Summary of lithofacies identified in the studied Yarandua sections of the Bima Formation.

Facies code	Facies name	Diagnostic features	Process interpretation
WB	Weathered basement	Light grey to whitish, highly weathered crystalline substrate; locally fractured and decomposed along joints.	Pre-Cretaceous basement surface exposed to subaerial weathering before deposition of the Bima succession.
Gcm/Gmm	Clast-supported to matrix-supported conglomerate	Poorly sorted pebbles, cobbles and locally boulders in sandy matrix; erosional bases and irregular bed contacts.	High-energy traction and debris-flow deposition in proximal braided channels or alluvial-fan settings.
Sm/St/Sp	Massive to cross-bedded sandstone	Light grey to buff, medium- to coarse-grained sandstone; massive, thick-bedded, locally cross-bedded and jointed.	Channel-bar, channel-fill and sandy bedform migration under moderate- to high-energy fluvial flow.
Fl/Fm	Siltstone/mudstone	Reddish brown, greenish-grey or brown fine-grained intervals; faint lamination, fissility and recessive weathering.	Overbank, floodplain, abandoned-channel or ponded low-energy deposition from suspension.
Sh	Shale	Dark grey, purplish grey or light grey shale; fissile to weakly laminated; locally nodular, concretionary, oil-wet or bituminous-stained.	Low-energy floodplain, shallow lacustrine or abandoned-channel sedimentation; locally affected by diagenesis and hydrocarbon migration or staining.

4.2 Section OJ-004: Shale, Weathered Basement and Proximal Coarse Clastics

Section OJ-004 exposes a shale-dominated interval overlain by a resistant ferruginized sandy to conglomeratic cap. The lower portion includes weathered basement or highly weathered crystalline material, above which occur massive sandstone and conglomeratic deposits. The shale interval is dark grey to purplish grey, massive to weakly laminated and locally fissile. Nodular to concretionary forms produce an irregular cauliflower-like outcrop morphology, most likely due to early to intermediate diagenetic cementation followed by differential weathering.

The upward transition into coarser sandy and conglomeratic units records an increase in depositional energy. The facies arrangement is interpreted as a proximal braided fluvial to alluvial-fan association developed close to an uplifted basement source area. The coarse grain size, poor sorting, abundant cobble-grade clasts and erosional contacts indicate episodic high-discharge events, strong traction currents and rapid sediment accumulation in a tectonically active continental setting.

Figure 4. Field photograph of section OJ-004 showing nodular shale and weathered fine-grained intervals overlain by ferruginized sandy to conglomeratic deposits of the Bima Formation at Yarandua.

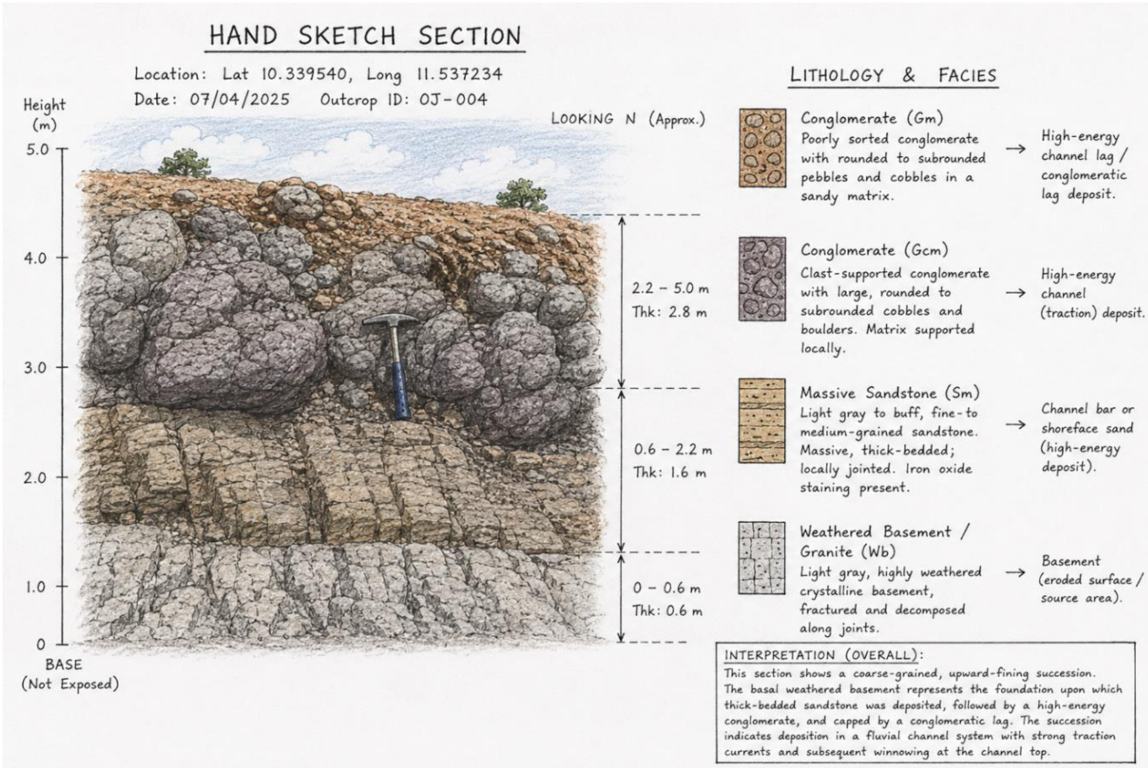

Figure 5. Hand-sketched sedimentological log of section OJ-004 showing weathered basement, massive sandstone and overlying conglomeratic facies.

4.3 Section OJ-002: Interbedded Sandstone-Shale Succession

Section OJ-002 is characterized by an interbedded succession of indurated sandstone and subordinate shale or mudstone. The sandstone beds form prominent resistant ledges and are light grey to buff, medium- to coarse-grained, thick to medium bedded, and locally massive or blocky. Numerous fractures and joints divide the sandstone into irregular polygonal blocks, suggesting post-depositional brittle deformation, unloading or weathering-enhanced joint development.

Thin dark grey to brown shale or mudstone partings occur between the sandstone beds and weather recessively. These finer-grained intervals record periodic reductions in hydraulic energy and accumulation of suspended mud in overbank, abandoned-channel or floodplain settings. The vertical facies trend is upward coarsening, reflecting progressive shallowing, progradation of sandy channel systems and increasing hydrodynamic energy. The section is therefore interpreted as a fluvial channel-bar to overbank facies association, with repeated alternation between sandy channel deposition and low-energy mud accumulation.

Figure 6. Field photograph of section OJ-002 showing fractured, indurated sandstone beds separated by thin recessive shale/mudstone intervals.

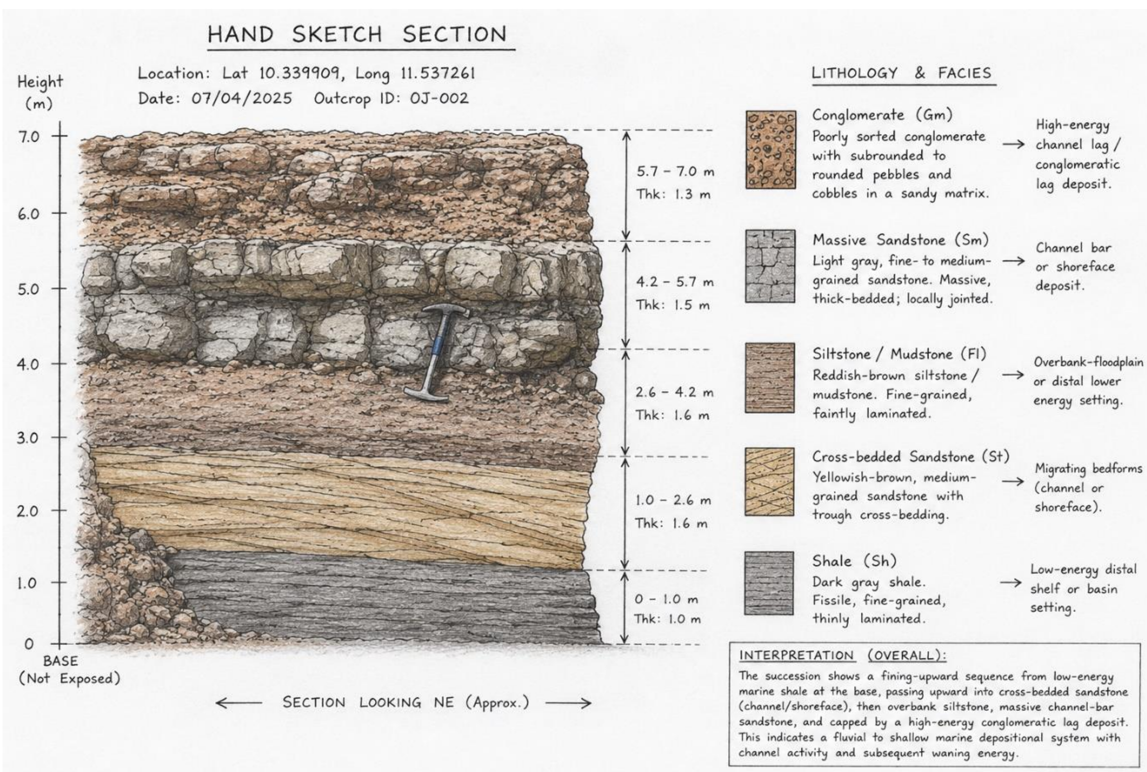

Figure 7. Hand-sketched sedimentological log of section OJ-002 showing upward-coarsening sandstone, mudstone and conglomeratic facies.

4.4 Section OJ-003: Oil-Wet Shale and Fluvial Channel Sandstone

Section OJ-003 comprises fine-grained argillaceous deposits overlain by massive sandstone and capped by recent colluvial or slope-wash material. The shale and mudstone facies are light grey to pale greenish grey, with localized dark brown to black bituminous or oil-wet staining. The staining occurs as patches, coatings and fracture-bound concentrations along bedding surfaces, weathered faces and zones of enhanced permeability.

The oil-wet surfaces and dark bituminous patches suggest hydrocarbon impregnation, organic enrichment, oxidized petroleum residue or migrated hydrocarbons retained along fracture networks. This interpretation is supported by the fractured character of the shale and the concentration of staining along discontinuities. The fine-grained facies is therefore interpreted as a floodplain-ponded overbank to shallow lacustrine shale association, rather than a simple floodplain mudstone. The overlying massive sandstone represents a higher-energy channel-bar or channel-fill deposit, whereas the upper loose sandy and gravelly interval is interpreted as recent colluvial cover.

Figure 8. Field photograph of section OJ-003 showing oil-wet shale and dark bituminous staining concentrated along fractures and weathered surfaces within a light grey argillaceous host rock.

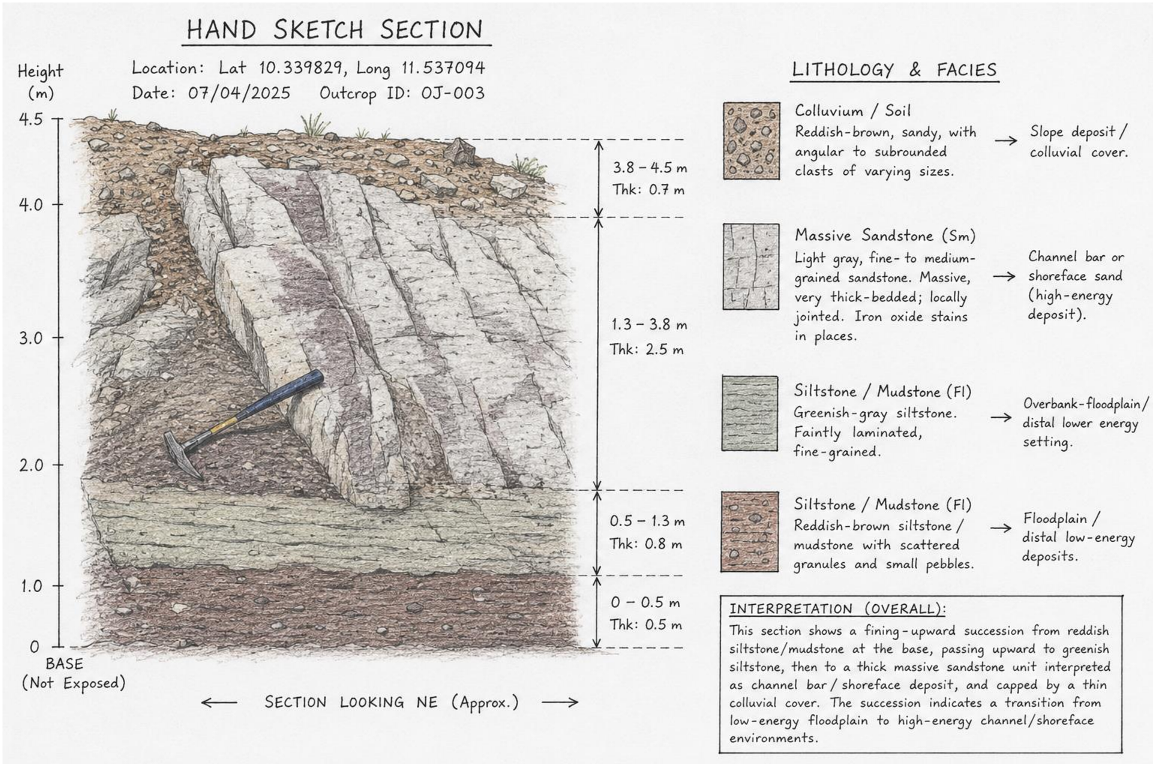

Figure 9. Hand-sketched sedimentological log of section OJ-003 showing oil-stained fine-grained facies, overlying massive sandstone and colluvial cover.

4.5 Facies Associations

Table 2. Facies associations and depositional interpretations for the studied Bima Formation outcrops at Yarandua.

Facies association	Constituent facies	Key evidence	Depositional interpretation
FA1: Proximal braided fluvial-alluvial fan	WB, Gcm/Gmm, Sm	Basement contact, coarse poorly sorted conglomerate, massive sandstone, erosional surfaces and upward increase in energy.	High-gradient channels and alluvial fan lobes close to uplifted basement margins.
FA2: Fluvial channel-bar to overbank	Sm/St/Sp, Fl/Fm, Sh	Thick resistant sandstone beds interbedded with recessive fine-grained partings and local upward-coarsening trends.	Channel migration, bar accretion, overbank flooding and floodplain aggradation.
FA3: Floodplain-ponded overbank/lacustrine shale	Sh, Fl/Fm, Sm	Fine-grained shale/mudstone, weak lamination, fissility, nodular/concretionary forms and oil-wet or bituminous staining.	Low-energy ponded floodplain, abandoned-channel, swampy or shallow lacustrine deposition, locally influenced by organic enrichment and hydrocarbon migration.

5. Discussion

5.1 Depositional Model

The facies assemblages indicate deposition within a continental rift-basin system dominated by proximal braided fluvial, alluvial-fan, floodplain and shallow ponded environments. The occurrence of weathered basement beneath coarse siliciclastic deposits indicates that sedimentation began on an irregular erosional surface produced by pre-depositional exposure and weathering of crystalline basement. The overlying conglomerates and massive sandstones reflect high-energy sediment delivery from nearby uplifted source areas, consistent with syn-rift fault-controlled topography and rapid accommodation development.

The interbedded sandstone-shale successions record fluctuations in channel activity and discharge. Sandstone-dominated intervals represent channel-fill, channel-bar and sandy bedform deposits, whereas mudstone and shale intervals accumulated during periods of waning flow, overbank flooding, ponding, or abandonment of channels. Such vertical alternations are characteristic of fluvial systems in which hydrodynamic energy, accommodation and sediment supply vary through time (Miall, 1996; Bridge, 2003).

5.2 Significance of Oil-Wet Shale Intervals

The oil-wet shale in OJ-003 is a key feature because it implies that at least some fine-grained intervals within the Bima Formation may have petroleum-system significance. Possible explanations include primary organic enrichment in ponded floodplain or shallow lacustrine settings, migration of hydrocarbons through fracture networks, retention of bitumen along weathered bedding planes, or concentration of oxidized petroleum residues during near-surface alteration. Field evidence alone cannot distinguish these possibilities conclusively; however, the observed staining justifies follow-up organic geochemical screening, including total organic carbon, Rock-Eval pyrolysis, solvent extraction, biomarker analysis and petrographic assessment.

From a petroleum geology perspective, the association of oil-stained shale with overlying massive sandstone suggests a potential continental source-reservoir-seal arrangement at outcrop scale. The shale may represent a source-prone or sealing interval, whereas the massive sandstone may function as a reservoir facies. Fractures may have enhanced secondary permeability and provided migration pathways. This interpretation is consistent with broader evidence that inland basins of Nigeria contain localized petroleum-system elements, although their maturity, charge history and preservation vary considerably across the Benue Trough and associated basins (Obaje et al., 1999; Obaje et al., 2004; Bata et al., 2024).

5.3 Implications for Reservoir Heterogeneity

The studied sections show that reservoir quality in the Bima Formation is likely to be heterogeneous. Coarse conglomerates and massive sandstones may provide relatively high primary permeability where cementation is limited, but poor sorting, ferruginization, compaction and diagenetic cement can reduce effective porosity. Fine-grained shale and mudstone intervals introduce vertical and lateral baffles, whereas fractures may enhance localized permeability. Consequently, the Bima Formation should be evaluated as a compartmentalized continental reservoir system with strongly variable facies-controlled flow units.

6. Conclusion

The Yarandua exposures belong to the Bima Formation and comprise weathered basement, conglomerate, massive to cross-bedded sandstone, siltstone/mudstone and shale facies.

Three facies associations were identified: proximal braided fluvial-alluvial fan deposits, fluvial channel-bar to overbank deposits, and floodplain-ponded overbank/lacustrine shale deposits.

The coarse conglomeratic and sandstone facies record high-energy continental sedimentation close to uplifted basement source areas under tectonically active rift-basin conditions.

The shale, siltstone and mudstone facies record low-energy floodplain, abandoned-channel, ponded overbank and shallow lacustrine deposition.

Oil-wet shale surfaces in section OJ-003 suggest hydrocarbon staining, organic enrichment or migration-related bitumen concentration, making the interval important for petroleum-system evaluation.

The Bima Formation at Yarandua should be interpreted as a heterogeneous continental succession with potential reservoir, seal, migration-pathway and source-prone facies elements.

7. Recommendations for Further Work

Future work should include measured stratigraphic logging at higher resolution, grain-size analysis, petrographic point counting, X-ray diffraction of shale and mudstone samples, TOC/Rock-Eval pyrolysis, extractable organic matter analysis, biomarker geochemistry and stable isotope analysis of concretionary materials. These datasets would test the field-based interpretation of oil-wet shale, constrain reservoir quality and improve the petroleum-system model for the Bima Formation in the Yarandua area.

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