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Petrography, Diagenetic Evolution and Reservoir Quality Implications of the Bima Formation Sandstones in the Yola Sub-basin, Northern Benue Trough, Northeastern Nigeria

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Abstract

The Lower Cretaceous Bima Formation constitutes the basal siliciclastic succession of the Upper Benue Trough and represents one of the most significant continental sandstone reservoirs and reservoir analogues in northeastern Nigeria. This study integrates field sedimentology, grain-size analysis, petrographic examination, and scanning electron microscopy (SEM) to investigate the depositional characteristics, diagenetic evolution, and reservoir quality of selected Bima Formation sandstones exposed within the Yola Sub-basin. Field observations reveal thick-bedded to massive sandstone bodies characterized by planar stratification, erosional bounding surfaces, and vertically stacked channel architectures indicative of deposition within high-energy braided fluvial systems. Grain-size analyses demonstrate predominantly fine- to coarse-grained sediments exhibiting moderate to good sorting, reflecting variable hydraulic conditions and fluctuating sediment transport regimes during deposition. Petrographic observations indicate that the sandstones are composed predominantly of monocrystalline and polycrystalline quartz with subordinate feldspar and lithic fragments, suggesting moderate to high compositional maturity resulting from prolonged transport and sediment recycling. SEM investigations reveal a complex diagenetic history involving mechanical compaction, grain rearrangement, quartz overgrowth development, authigenic clay mineral precipitation, carbonate cementation, and localized dissolution. Mechanical compaction and cementation constitute the principal porosity-reducing processes through progressive pore-throat occlusion and destruction of primary intergranular pore networks. Conversely, dissolution of unstable framework grains and cements has generated localized secondary porosity, partially enhancing pore connectivity and storage capacity. The integrated sedimentological and petrographic evidence indicates that reservoir quality evolution in the Bima Formation is controlled by the combined influence of depositional texture and subsequent diagenetic modification. Reservoir quality varies from moderately good intervals characterized by preserved intergranular porosity to tight sandstone zones dominated by intense compaction and cementation. The study establishes a diagenetic framework for understanding pore system evolution and reservoir heterogeneity within the Bima Formation and provides valuable insights for the exploration and characterization of fluvial sandstone reservoirs in the Northern Benue Trough and analogous continental rift basins.

Keywords

Bima Formation; Diagenesis; Reservoir Quality; Petrography; SEM Analysis; Yola Sub-basin

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1. Introduction

The Bima Formation constitutes the oldest and most extensive sedimentary unit within the Upper Benue Trough and forms the basal fill of the Yola Sub-basin. The formation was deposited during the Early Cretaceous in response to continental rifting associated with the fragmentation of Gondwana and the subsequent opening of the South Atlantic Ocean (Benkhelil, 1989; Guiraud, 1990; Obaje, 2009). The unit is dominated by continental siliciclastic sediments comprising conglomerates, coarse- to fine-grained sandstones, siltstones, and subordinate mudstones deposited within fluvial, alluvial fan, and braided river environments.

Fluvial sandstone reservoirs constitute important hydrocarbon-bearing intervals in numerous sedimentary basins worldwide owing to their favourable porosity and permeability characteristics. However, reservoir quality is rarely controlled solely by depositional processes. Instead, it evolves through complex interactions between depositional facies architecture, burial history, fluid-rock interactions, and diagenetic modifications (Worden and Burley, 2003; Morad et al., 2010; Ajdukiewicz and Larese, 2012). Consequently, understanding the relative contributions of depositional and diagenetic processes is critical for accurate reservoir prediction and characterization.

Previous investigations of the Bima Formation have primarily focused on regional stratigraphy, sedimentology, provenance, and basin evolution (Carter et al., 1963; Zaborski et al., 1997; Obaje, 2009; Bata et al., 2017). Although these studies provide valuable insights into the depositional history of the formation, detailed investigations integrating grain-size characteristics, petrography, SEM observations, and diagenetic evolution remain relatively limited. Such studies are essential because diagenetic processes including compaction, cementation, authigenic mineral growth, and dissolution can significantly modify primary pore systems and ultimately determine reservoir performance.

Therefore, this study aims to (1) characterize the petrographic and textural attributes of selected Bima Formation sandstones, (2) identify the principal diagenetic processes affecting pore evolution, (3) reconstruct the diagenetic history of the sandstones, and (4) evaluate the implications of these processes for reservoir quality development within the Yola Sub-basin.

2. Geological Setting

The Benue Trough is a major NE-SW trending intracontinental rift basin extending approximately 1000 km across Nigeria (Figure 1). It developed during the Early Cretaceous as part of the tectonic events associated with the separation of Africa and South America. The trough is conventionally divided into the Lower, Middle, and Upper Benue segments (Bata et al., 2017).

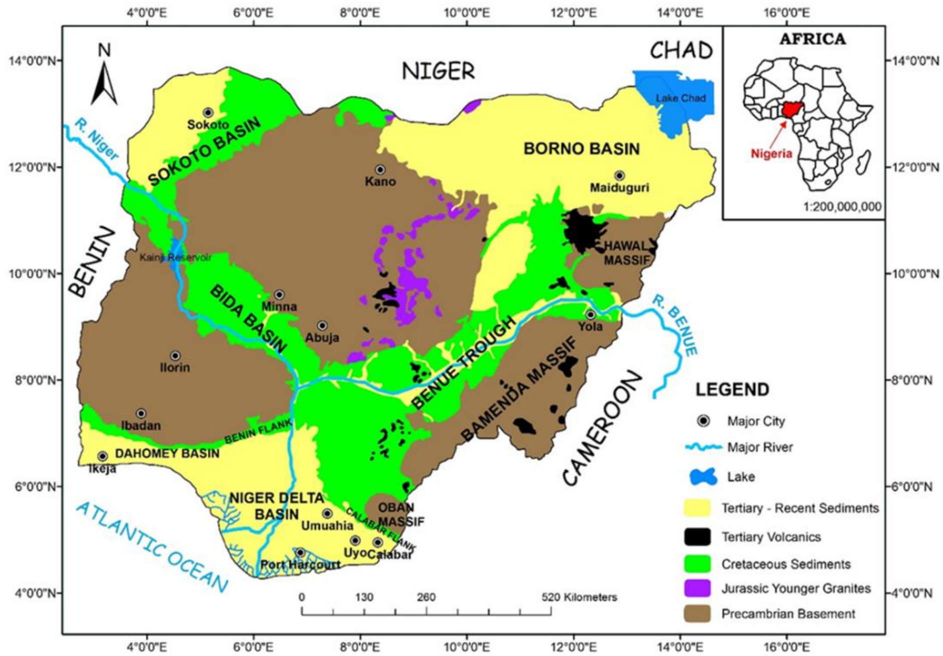

Figure 1. Geological map of Nigeria showing the distribution of major sedimentary basins and the location of the Benue Trough (After Bata et al., 2017)

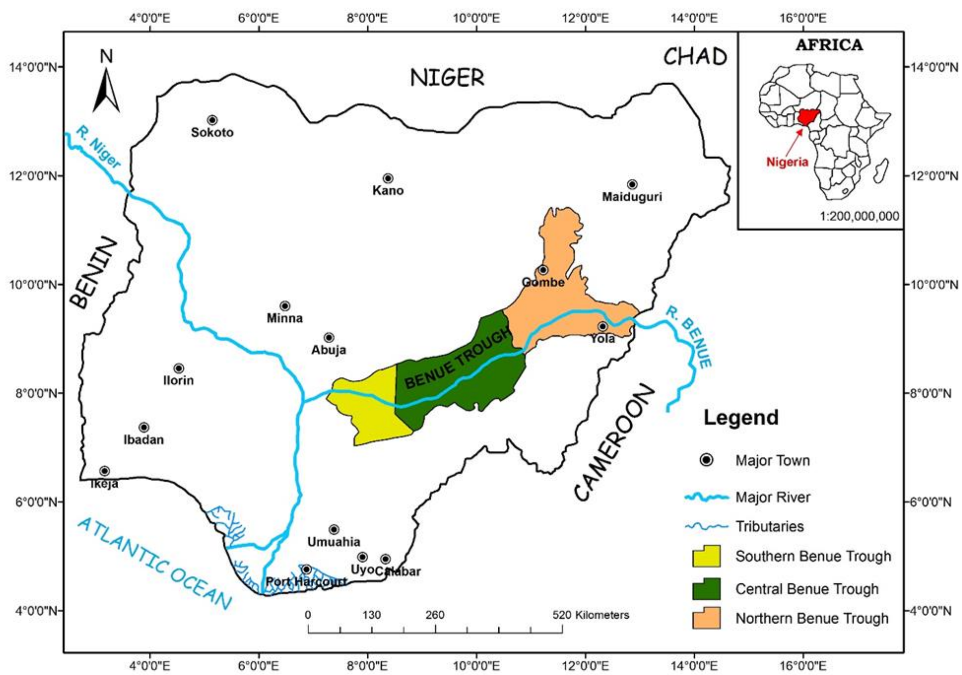

Figure 2. Location map of the Benue Trough showing the Yola Sub-basin within the Northern Benue Trough (After Bata et al., 2017).

3. Materials and Methods

3.1 Field Investigation

Field studies involved geological mapping, lithologic description, bedding measurements, and systematic sampling of representative sandstone units. Standard field equipment including a geological hammer, compass-clinometer, GPS receiver, field notebook, and sample bags were utilized.

The exposed sandstone succession exhibits thick-bedded, laterally continuous sandstone units with planar stratification and stacked bed architectures. These features suggest deposition within channelized fluvial systems characterized by repeated sediment influx and migration of channel bars.

3.2 Laboratory Analysis

Laboratory investigations comprised:

- Thin-section petrography
- Scanning Electron Microscopy (SEM)
- Grain-size analysis
- Reservoir quality assessment

Thin sections were used to determine mineral composition, grain texture, sorting, roundness, and diagenetic modifications. SEM analyses provided high-resolution imaging of pore structures and cement distribution (Taylor et al., 2010)

4. Results

4.1 Field Sedimentology

The studied outcrops consist predominantly of thick-bedded medium- to coarse-grained sandstones arranged in stacked units. Bedding surfaces are generally planar and locally exhibit erosional contacts.

The observed architecture suggests deposition in braided fluvial channels where repeated episodes of sediment transport and channel migration generated vertically stacked sandstone packages. The scarcity of mudstone interbeds indicates persistent high-energy depositional conditions (Ajdukiewicz and Larese, 2012 Taylor et al. (2010).

The field exposure further reveals relatively resistant sandstone bodies, suggesting moderate to strong cementation during burial diagenesis.

Figure 3. Field photograph of thick-bedded sandstone exposure of the Bima Formation showing stacked sandstone beds and planar bedding.

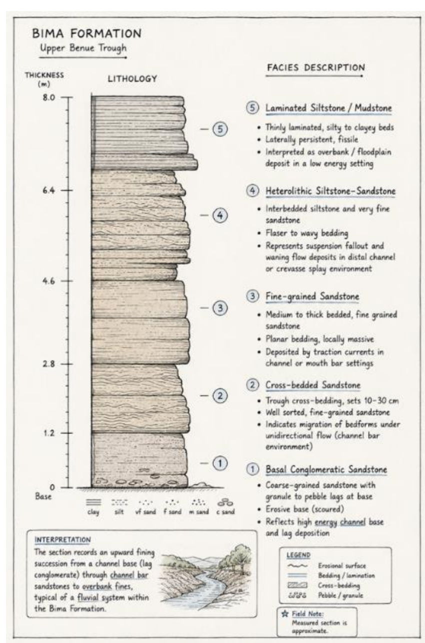

Figure 4. Interpreted lithologic log and facies succession derived from the outcrop shown in Figure 3.

Figure 5. Field photograph of medium- to thick-bedded sandstone succession showing laterally continuous sandstone bodies.

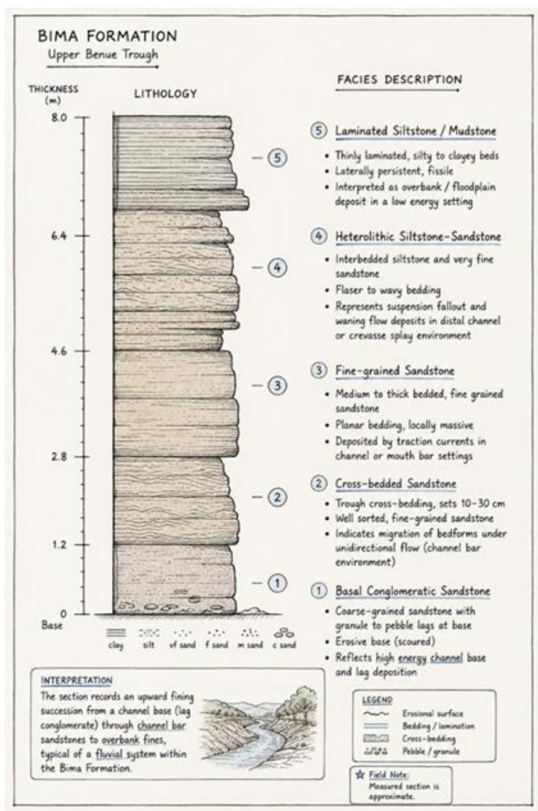

Figure 6. Interpreted lithologic log and facies architecture corresponding to Figure 5.

4.2 Grain-Size Analysis

Sample L1

The histogram and cumulative grain-size curve indicate dominance of fine sand fractions (approximately 70–190 µm) with minor very fine sand contributions. The relatively narrow grain-size distribution suggests moderate hydraulic sorting.

Interpretation indicates deposition under relatively uniform flow conditions within low- to moderate-energy fluvial settings. Such deposits are characteristic of distal channel bars or overbank splays.

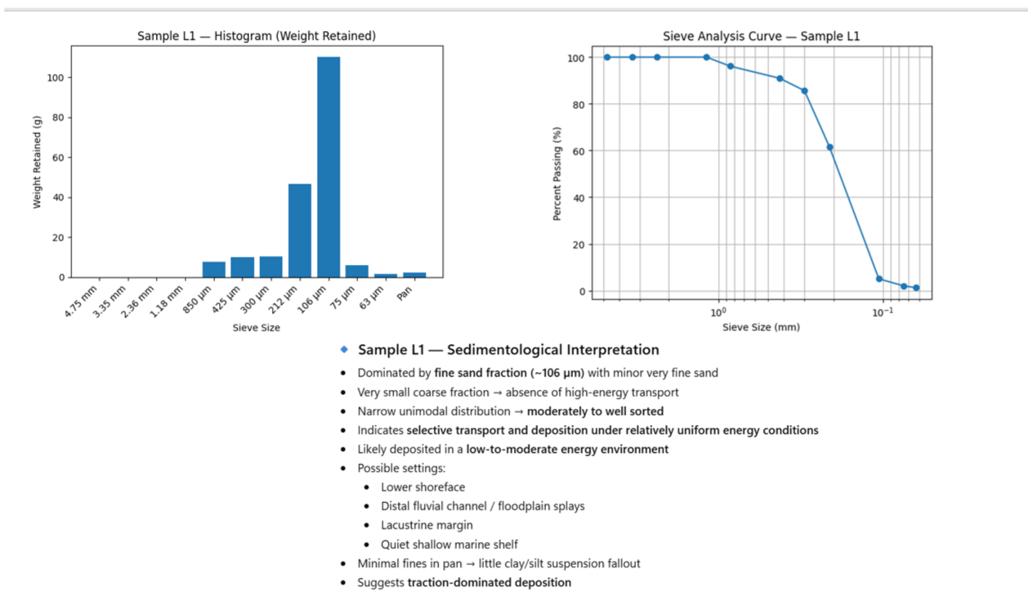

Figure 7. Grain-size histograms and cumulative frequency curves for samples L1

Sample L2

Sample L2 exhibits a broader grain-size distribution ranging from approximately 300–1060 µm. Moderate sorting and increased coarse-grained components suggest higher depositional energy compared to Sample L1.

The sediment was likely deposited within active fluvial channels experiencing variable discharge conditions. The mixed grain-size population reflects fluctuating flow regimes and episodic sediment influx.

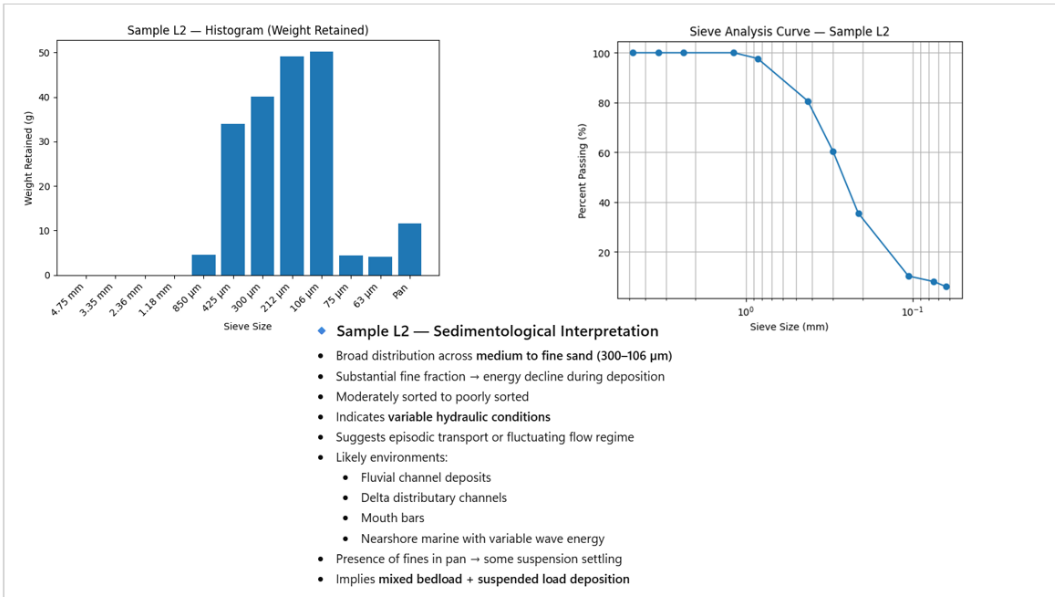

Figure 8. Grain-size histograms and cumulative frequency curves for samples L2

Sample L3

Sample L3 is dominated by medium sand (approximately 212 µm) and displays moderate sorting. The grain-size distribution suggests sustained transport under relatively stable hydraulic conditions.

These characteristics are consistent with deposition in channel bars, point bars, or high-energy nearshore settings where prolonged sediment reworking enhances textural maturity.

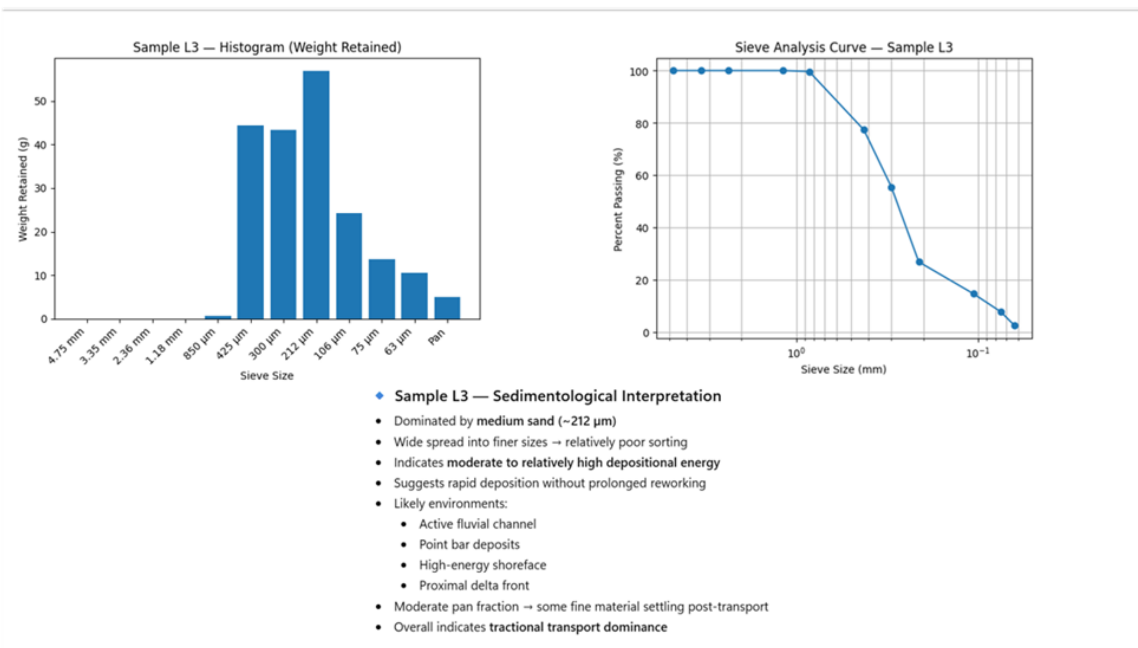

Figure 9. Grain-size histograms and cumulative frequency curves for samples L3

Sample L4

Sample L4 contains the coarsest sediment population among the analyzed samples, peaking near 425 µm. Poorer sorting and abundant coarse fractions indicate deposition under high-energy conditions.

The presence of coarse grains and fines together suggests rapid deposition during waning flood events or within proximal braided-channel environments.

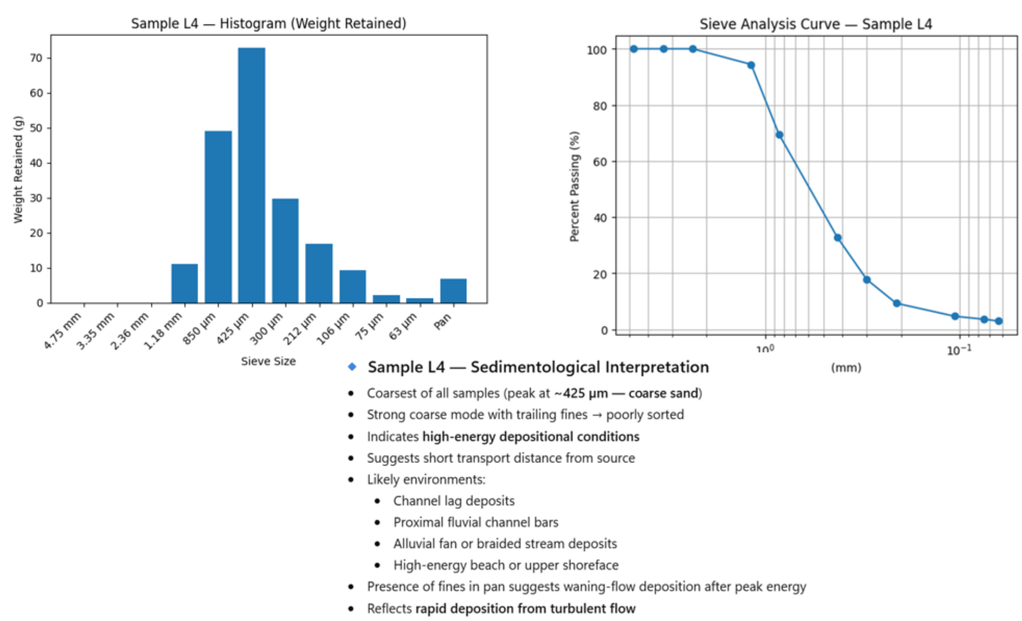

Figure 10. Grain-size histograms and cumulative frequency curves for samples L4

4.3 Petrographic Characteristics

Sample L1

SEM observations reveal relatively clean quartz grains with limited pore-filling material. Intergranular pores remain partially preserved, indicating only moderate diagenetic alteration.

Minor authigenic clay coatings are present but do not completely obstruct pore connectivity. Grain contacts are primarily point-to-long contacts, suggesting moderate burial compaction.

Reservoir Implication

Sample L1 exhibits the most favorable reservoir characteristics among the studied samples due to preserved porosity and moderate permeability potential.

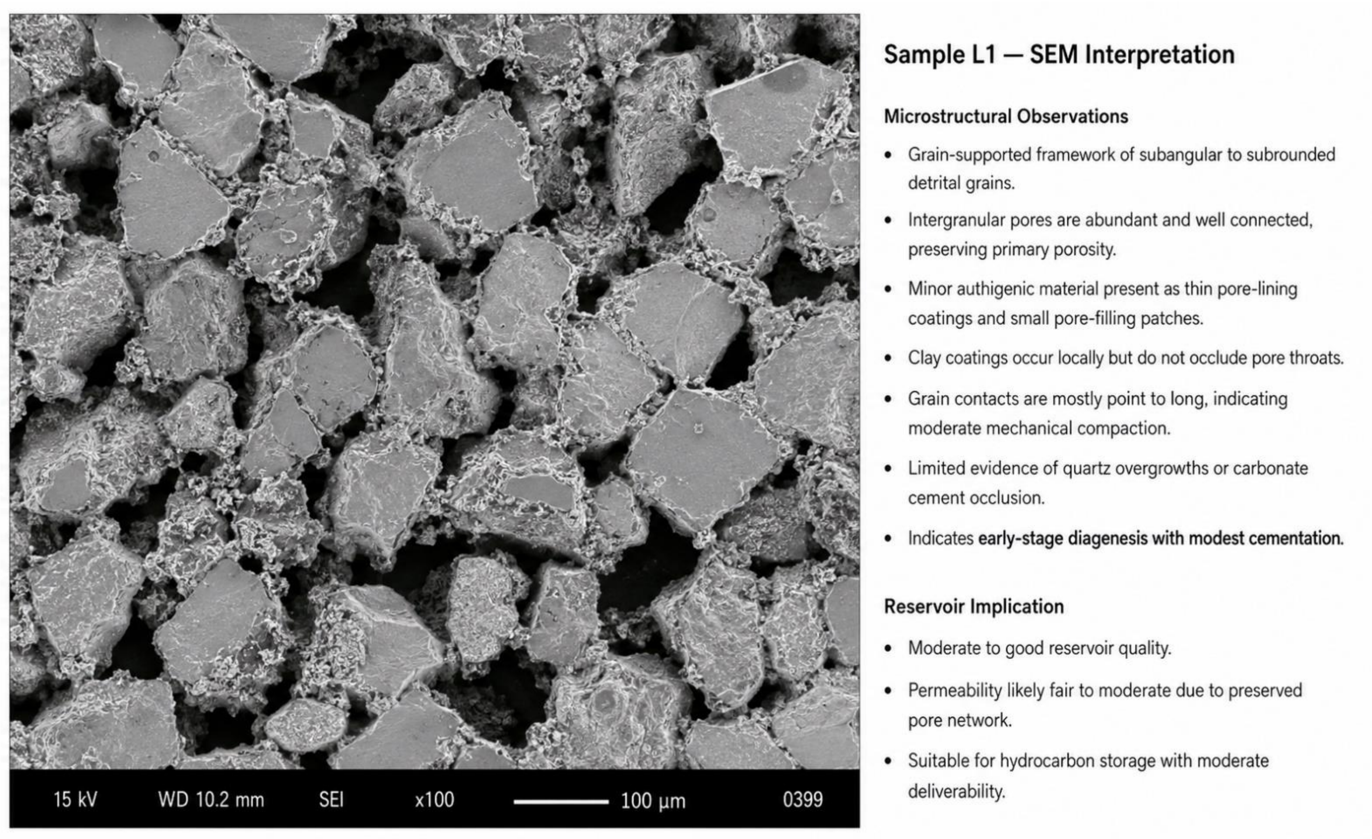

Figure 11. SEM photomicrographs of Sample L1 illustrating progressive diagenetic modification from preserved intergranular porosity to strongly compacted and cemented sandstone.

Sample L2

Sample L2 displays increased clay mineral precipitation and partial pore-filling by authigenic material. Pore throats are narrower, reflecting progressive cementation.

Clay aggregation and cement precipitation reduce pore connectivity and impede fluid flow.

Reservoir Implication

Moderate porosity may still be present, but permeability has likely been significantly reduced.

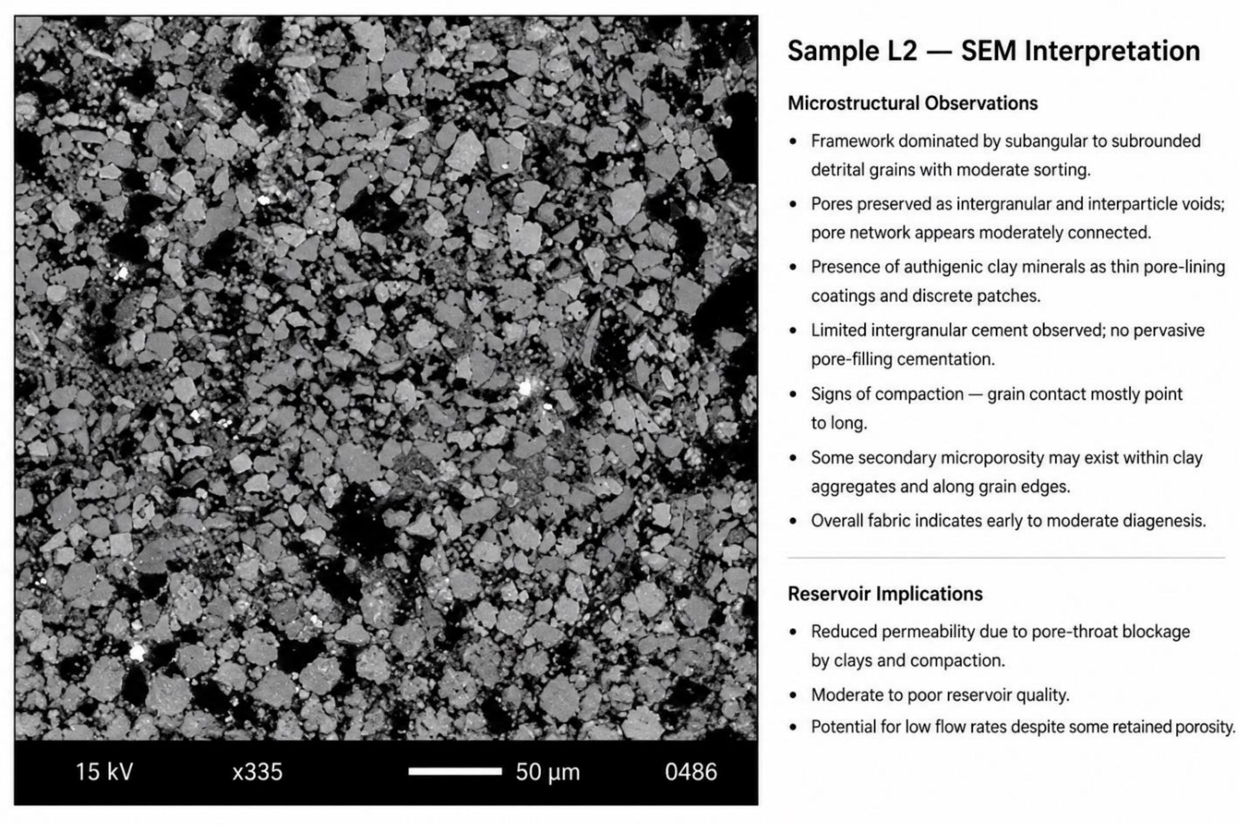

Figure 12. SEM photomicrographs of Sample L2 illustrating progressive diagenetic modification from preserved intergranular porosity to strongly compacted and cemented sandstone.

Sample L3

Sample L3 shows substantial cementation accompanied by grain contacts indicating advanced mechanical compaction. Local dissolution features suggest that secondary porosity has developed after cement precipitation.

The coexistence of compaction, cementation, and dissolution demonstrates a complex diagenetic history.

Reservoir Implication

Reservoir quality is highly heterogeneous, with isolated zones of enhanced porosity occurring alongside heavily cemented intervals.

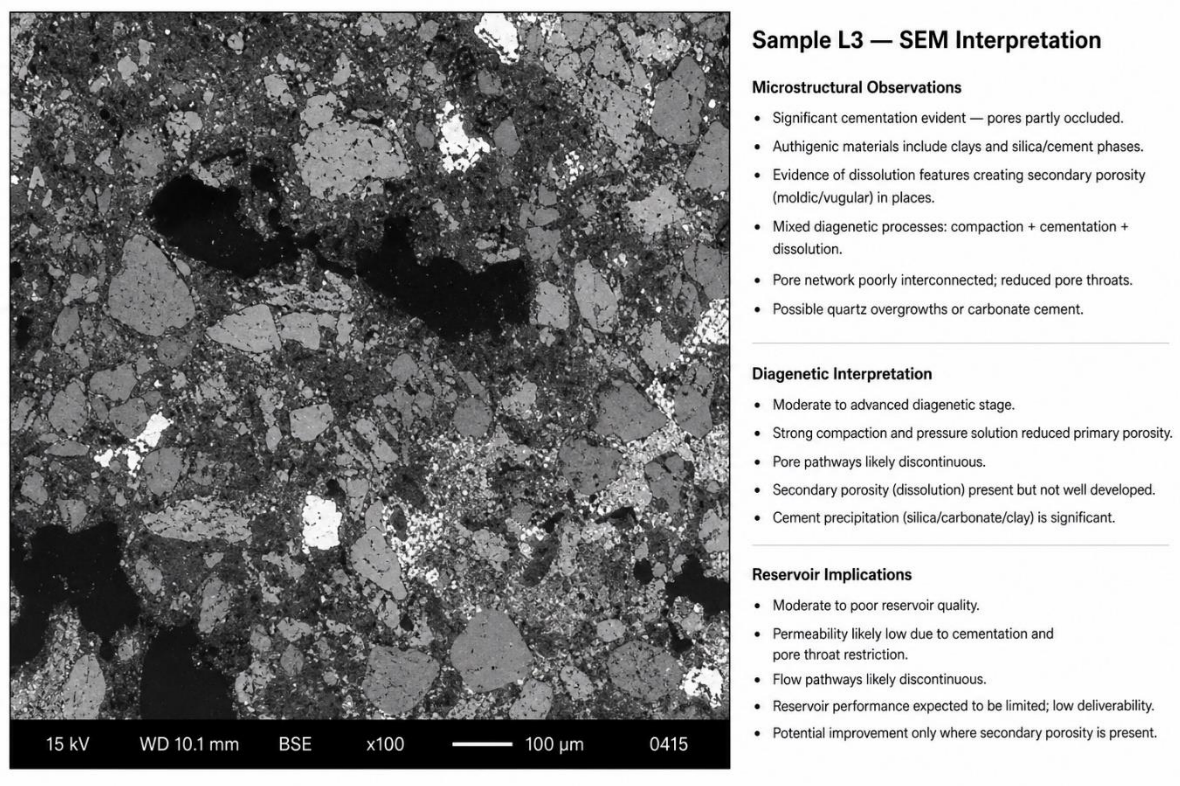

Figure 13. SEM photomicrographs of Sample L3 illustrating progressive diagenetic modification from preserved intergranular porosity to strongly compacted and cemented sandstone.

Sample L4

Sample L4 exhibits the most advanced stage of diagenetic alteration. Grain packing is tight, pore spaces are significantly reduced, and evidence of late-stage diagenetic cementation is widespread.

Mechanical compaction has substantially destroyed primary porosity.

Reservoir Implication

This sample represents a tight sandstone interval with poor storage capacity and limited permeability.

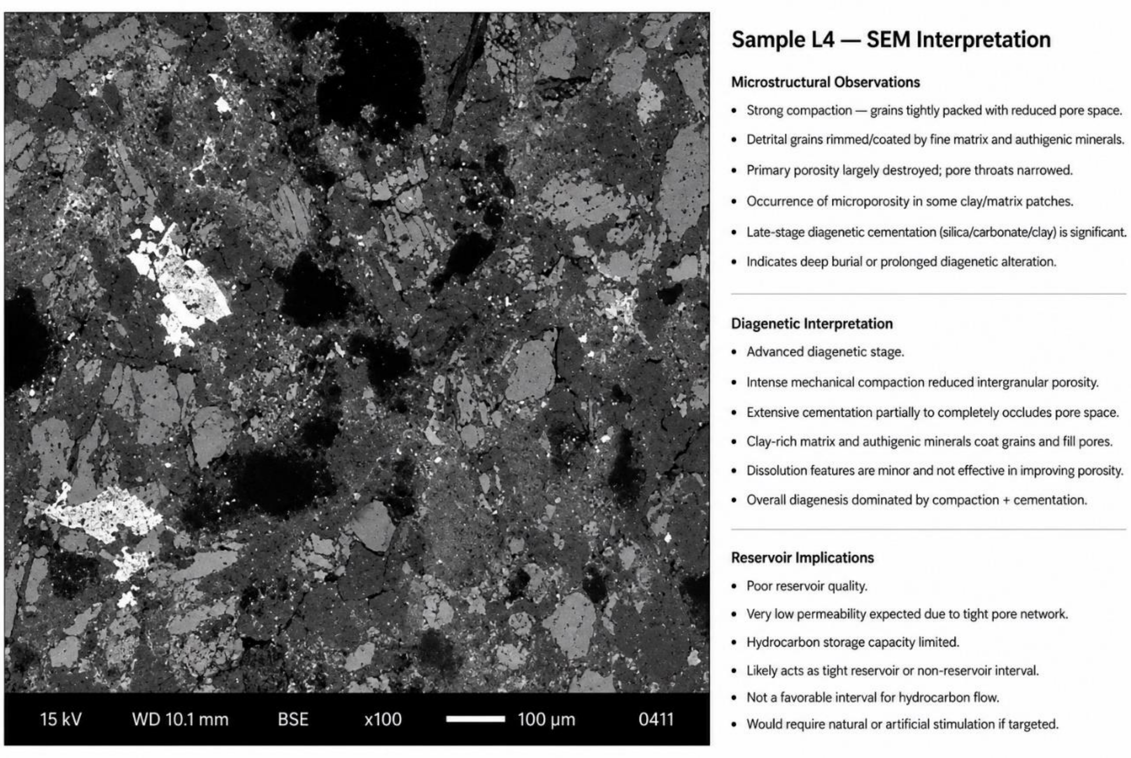

Figure 14. SEM photomicrographs of Sample L4 illustrating progressive diagenetic modification from preserved intergranular porosity to strongly compacted and cemented sandstone.

5. Diagenetic Evolution Model

The combined petrographic and SEM evidence suggests the following diagenetic sequence:

Stage 1: Early Burial

- Mechanical compaction begins.
- Grain rearrangement reduces primary pore volume.
- Initial clay coatings develop on grain surfaces.

Stage 2: Progressive Burial

- Quartz overgrowths precipitate.
- Clay minerals accumulate within pore spaces.
- Carbonate cements locally develop.
- Porosity and permeability decline substantially.

Stage 3: Late Diagenesis

- Partial dissolution of unstable grains and cements occurs.
- Secondary porosity develops locally.
- Reservoir heterogeneity increases.

Depositional Control on Reservoir Quality

The grain-size distributions and facies associations indicate deposition within a braided fluvial system characterized by repeated channel migration and episodic high-energy discharge events. Braided river deposits commonly exhibit significant vertical and lateral heterogeneity resulting from rapid sediment accumulation and channel avulsion. Consequently, reservoir quality variations may originate from primary depositional differences including grain size, sorting, and framework grain composition.

Diagenetic Control on Reservoir Quality

The SEM observations demonstrate that diagenesis exerts a fundamental control on reservoir evolution. Mechanical compaction resulted in grain rearrangement and progressive reduction of intergranular pore volume. Quartz overgrowths precipitated during mesogenesis further reduced pore connectivity by occupying available pore spaces. Authigenic clay minerals significantly reduced permeability through pore-throat blockage, whereas carbonate cements locally occluded primary porosity. In contrast, dissolution processes generated secondary porosity that partially enhanced reservoir quality.

Reservoir Heterogeneity

Reservoir heterogeneity within the Bima Formation reflects the combined influence of depositional facies variability and diagenetic overprinting. The best reservoir intervals are associated with well-sorted quartz-rich sandstones exhibiting limited cementation and preserved primary porosity. Poor-quality intervals correspond to highly compacted and extensively cemented sandstones characterized by reduced pore connectivity.

6. Discussion

The integration of field, grain-size, petrographic, and SEM data reveals that depositional and diagenetic processes jointly control reservoir quality.

The field evidence indicates deposition within braided fluvial systems characterized by repeated channel migration and episodic high-energy sediment transport. Grain-size distributions support this interpretation, demonstrating a spectrum from moderately sorted fine sands to poorly sorted coarse channel deposits (Ajdukiewicz and Larese, 2012; Morad et al., 2010; Worden and Burley 2023).

However, depositional texture alone does not determine reservoir quality. Post-depositional diagenesis exerts a dominant influence on pore evolution. Mechanical compaction progressively reduces pore volume, while quartz and clay cementation further occlude pore throats. These processes are particularly evident in Samples L3 and L4.

Conversely, localized dissolution creates secondary porosity that partially offsets porosity loss. Sample L1 represents intervals where diagenetic modification has been relatively limited, preserving favorable reservoir characteristics. Sample L4 represents the opposite extreme, where intense compaction and cementation have transformed the sandstone into a tight reservoir.

The study therefore demonstrates that reservoir quality in the Bima Formation is inherently heterogeneous and cannot be predicted solely from depositional facies.

7. Conclusions

1. The Bima Formation sandstones were deposited predominantly within braided fluvial channel systems characterized by variable hydraulic energy.
2. Grain-size analyses indicate moderate to poor sorting and variable transport conditions consistent with channel-bar and flood-related deposition.
3. Quartz is the dominant framework mineral, with subordinate feldspar and lithic fragments.

4. Major diagenetic processes include mechanical compaction, quartz cementation, clay mineral precipitation, carbonate cementation, and dissolution.
5. Mechanical compaction and cementation constitute the principal porosity-reducing mechanisms.
6. Secondary porosity generated through dissolution locally improves reservoir quality.
7. Reservoir quality varies significantly between samples due to differences in diagenetic overprint.
8. Sample L1 exhibits the best reservoir potential, whereas Sample L4 represents a tight sandstone interval.
9. Integrated petrographic and SEM analyses provide valuable insights into pore evolution and reservoir heterogeneity within the Bima Formation.
10. The Bima Formation remains a promising reservoir analogue in the Northern Benue Trough, although reservoir performance is strongly controlled by post-depositional diagenetic processes.

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