Facies architecture and sequence stratigraphy of Early Cretaceous Lower Bima Member from Yola Sub-basin, Northern Benue Trough, NE Nigeria

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ABSTRACT
Sedimentology, facies architecture, and sequence stratigraphic studies were conducted on the exposed sediments of Lower Bima Member from the Yola Sub-basin with the aim of interpreting the depositional environment within stratigraphic framework. From texture and sedimentary structure, 10 lithofacies were identified and the facies were associated into three as follows: gravelly dominated, the sandy dominated, and the fine-grained dominated facies associations. The three facies associations formed the alluvial-braided river, braided river, and lacustrine facies successions. Analysis of facies has permitted an overall determination of five architectural elements: gravelly-bedded set, tough cross-stratified set, planar cross-stratified set, horizontally stratified set, and overbank stratified set. Sequence stratigraphic framework shows alluvial fan (proximal and distal facies) at the base, temporally transiting into lacustrine as the lake level rose, followed by a period perhaps due to rift margin faults reactivation and re-establishment of alluvial fan-braided river and braided river deposits on toward the top. Transition from alluvial-lacustrine and alluvial-fluvial reflects a vertical and lateral facies distribution.

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1. Introduction
The Benue Trough was formed during the Early Cretaceous rifting and strike-slip faulting or movement of the Central West African Basement Complex (e.g., Abubakar, 2006; Benkhelil, 1989; Carter et al., 1963). Grant (1971), Kogbe (1976), Benkhelil (1989) and many others suggested rifting and strike-slip faulting as the basis for the evolution of the Benue Trough. The acceptable model is that of the Grant (1971). The Benue Trough trends northeast-southwest for 1,000 km in length and 150 km in width, bounded by Niger Delta Basin at the southern end and the Chad (Bornu) Basin in the northern end (Sarki Yandoka et al., 2014).

The Benue Trough contains Cretaceous to Cenozoic sediments for up to 6,000 m associated with volcanism. On the basis of geographical view, the trough was divided into Southern (Lower), Central (Middle), and Northern (Upper) Benue basins (Sarki Yandoka et al., 2014; Zarborski et al., 1997) (Fig. 1). The Northern or Upper Benue Trough consists of the Gongola Sub-basin and Yola Sub-basin (Fig. 1). The geology and stratigraphy of Northern or Upper Benue Trough were described in detail by earlier workers, such as Carter et al. (1963), Aybovo et al. (1986), Tukur et al. (2015), Sarki Yandoka (2015), and many others.

The Early Cretaceous sediments of Bima Formation formed the basal part of the sedimentary succession.
in the Northern Benue Trough (Carter et al., 1963; Sarki Yandoka et al., 2014). The formation was earlier believed to have deposited in a continental environment under different conditions of deposition which include alluvial fans, braided river (channel and floodplain), and lacustrine systems (e.g., Carter et al., 1963; Guiraud, 1990; Guiraud and Maurin, 1992; Samaila et al., 2006; Sarki Yandoka, 2015; Sarki Yandoka et al., 2014).

This paper describes the facies architecture based on detail facies, facies associations, facies succession, and stratigraphic relationships of Early Cretaceous continental sediments of Lower Bima Member with the aim interpreting the depositional environment within sequence stratigraphic framework. The work is also a follow-up of Sarki Yandoka et al. (2014) so as to compensate for missing information particularly on architectural and sequence stratigraphic investigations.

2. Stratigraphy

The Yola Sub-basin consists of continental Early Cretaceous Bima Formation, the Cenomanian shallow-marine sequences of Yolde Formation, and the coastal-shallow marine sediments of the Late Cenomanian to Santonian age: the Dukul, Jessu, Sekulie Formations, Numanha Shales and Lamja Formations (Abubakar, 2006; Carter et al., 1966) (Fig. 2). The Bima Formation is the oldest found at the base of the successions (Fig. 2). The sediments were believed to be derived from basement complex rocks deposited within continental environment (Guiraud, 1990; Sarki Yandoka, et al., 2014). It consists of sedimentary structures which includes trough cross bedding, planar cross bedding, groove marks, and soft sediment deformed structures (Guiraud, 1990, Obaje et al., 2000; Offodile, 1976; Samaila et al. 2006).

It is differentiated into two members; the Lower Bima (B1) and the Upper Bima (B3) (Tukur et al., 2015). The Lower Bima (B1) is the oldest member (Late Jurassic—Berremian—Aptian). It consists of conglomerates, gravels, and sands with poor internal structures and fining upward successions (Guiraud, 1990). The Late Aptian-Albian Upper Bima (B1) unconformably overlies the Lower Bima Member. It composed of feldspathic sandstones in cross beddings interbedded with clays (Zarborski et al., 1997), considered as deeply entrenched braided river system. The Bima Formation is overlying by Cenomanian shallow marine Yolde Formation and followed by the marine Turonian-Coniacian Dukul, Jessu, Sukulie, and Numanha (Shales) Formations (Sarki Yandoka, 2015).

The Lamja Formation, a delta sequences overlies the Numanha (Shales) Formation (Fig. 2).
3. Methodology

Fieldwork was conducted on the exposed sediments of Lower Bima Member from the Bima Formation in the Yola Sub-basin. Descriptions and measurements of thicknesses, lithology, beddings, attitudes, and contact relationship were carried out. Stratigraphic sections (10 in total) were studied for facies and architectural analyses with the aim of: (1) characterizing precisely the depositional processes and paleoenvironments, (2) interpreting the paleoenvironments and a depositional framework, and (3) reconstructing the stratigraphic architecture of the successions. The facies architectural elements were studied following the works of Miall (1985; 1996).

4. Results and Discussions

4.1. Facies analysis

On the basis of texture and sedimentary structures, 10 lithofacies were described and identified (see Table 1 and Fig. 3). The facies were associated into three facies: gravelly dominated, the sandy dominated, and the fine grained dominated. The gravelly dominated facies association consist of two lithofacies identified (Gmm and Gcm) on the basis of texture and of their internal structure (Table 1) (Miall, 1985; 1996; 2010).

The facies contain gravels, matrix to clast supported with various sizes and nature. The sedimentation of massive matrix supported gravel (Gmm) facies is sediment-gravity flow oriented to alluvial fan settings. At high sedimentation rate, the flow become hyper concentrated as the matrix become cohesive with strength adequate to support larger boulders (Miall, 1996). The massive clast supported gravels (Gcm) facies deposited from pseudoplastic flow deposit of upper alluvial fan (distal facies) or gravel bed and gravel form, channel and bar formation with a characteristic feature of braided river deposits (Miall, 1996).

The sandy dominated facies association is classified on the basis of dominant primary sedimentary
Determination of modal grain size was carried out in the field for the purpose of detailed facies analysis. The facies association consists of fine to medium and coarse to very coarse grained sandstones containing pebbles and rare cobbles. The association composed of five lithofacies: the trough cross-bedded sandstone (St), the planar cross-bedded sandstone (Sp), the horizontally bedded sandstone (Sh), the ripple laminated sandstone (Sr), and the convoluted sandstone (Fc) facies.

The lithofacies were inferred to results from transport of sand by traction currents, as bed loads and in intermittent suspension. There nature depends largely on the sand grain sizes, flow depth, and velocity (Miall, 1996). They occurred in the dune form; 3-D dunes with linguid and lobate bars formed the trough cross-bedded sandstone (St) facies. At relatively lower flow regime with transverse bars and sand waves, the 2-D dunes occurred and give rise to the deposition of planar cross-bedded sandstone (St) facies. Post-depositional deformation also leads to deposition of the convoluted sandstone (Fc) facies. The migration of current ripples during low rate of sedimentation from suspensions leads to the deposition of ripple cross-laminated sandstone (Sr) facies. Horizontally-bedded sandstone (Sh) facies distinguished by parallel laminations occurred on bedding planes and is inferred to be generated by small longitudinal bars. The fine-grained dominated facies association composed of three lithofacies recognized on the basis of gradation in grain sizes and bedding characteristics: Fm, Fl1, and Fl2 facies. The mud and silts (Fm) are inferred to be deposited in floodplain areas, in abandoned channels or, in abandoned areas of active channels of rivers. The shale/mudstone (Fl1) and rippled laminated sandstone (Fl2) facies were deposited in lacustrine environment (Sarki Yandoka et al., 2014).

From the descriptions, interpretations, and associations of the facies, three facies successions were

Table 1. Summary of facies description and interpretation.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>Massive matrix supported gravel (Gmm)</td>
<td>Massive matrix supported gravels, poorly to moderately sorted, sub-angular clasts of various sizes, units up to 2.5 m thick</td>
<td>Plastic debris flow (high strength viscous) or sheetflood deposits</td>
</tr>
<tr>
<td>Massive clast supported gravel (Gcm)</td>
<td>Massive clast supported gravels, angular to sub rounded clasts, ungraded, poorly sorted, rarely imbricated, gravels up to 1.5–2 m, erosive base,</td>
<td>Pseudoplastic debris flow or longitudinal bars, sheet flood to channel deposits</td>
</tr>
<tr>
<td>Trough cross-bedded sandstone (St)</td>
<td>Medium to coarse grained sandstone, moderately to well sorted, sub angular to sub rounded clast, beds ranges from 3 to 4 m thick, basal are sharp or erosional</td>
<td>Linguoid and lobate bars (High flow regime), 3-D dunes</td>
</tr>
<tr>
<td>Planar cross-bedded sandstone (Sp)</td>
<td>Medium to fine grained sandstone, moderately sorted, buff colored, planar beds form in coarse to medium sands, thickness of beds up to 4 m thick, beds are traced up to for tens of meters parallel to bedding.</td>
<td>Transverse bars and sand waves (Lower flow regime), 2-D dunes</td>
</tr>
<tr>
<td>Horizontally bedded sandstone (Sh)</td>
<td>Medium to fine grained sandstone, moderately to moderately well sorted, buff colored, beds up to 2 m, display parallel and horizontal laminations, low angle cross beds, plane bedded to plane laminated.</td>
<td>Planar bed flow (sheet flood to channel deposits)</td>
</tr>
<tr>
<td>Ripple cross-stratified sandstone (Sr)</td>
<td>Medium to fine grained sandstone, moderately to well sorted, beds thickness up to 2 m, rippled cross laminated, parallel beds present.</td>
<td>Ripples (Lower flow regime)</td>
</tr>
<tr>
<td>Convoluted sandstone (Fc)</td>
<td>Medium to fine grained sandstone, convolute bedded, thickness of beds up to 0.5 to 1 m</td>
<td>Post – depositional soft sediment deformation deposit</td>
</tr>
<tr>
<td>Mud and silts (Fm)</td>
<td>Mud drapes occurred between gravel and sandstone beds, thickness of beds up to 0.4 m</td>
<td>Overbank or drape deposits</td>
</tr>
<tr>
<td>Shale/mudstone (Fl1)</td>
<td>Laminated dark to grey shale, thickness of beds up to 10 m, absence of bioturbations, trace and body fossils</td>
<td>Suspension settling from standing waters or shallow lacustrine deposits</td>
</tr>
<tr>
<td>Rippled laminated sandstone (Fl2)</td>
<td>Fine grained sandstone and siltstone, rippled, up to 1.5 m thick</td>
<td>Suspension settling from weak currents or shallow lacustrine</td>
</tr>
</tbody>
</table>

Facies are adapted from Miall (1996 and 2010).
identified; the alluvial-braided river, the braided river, and the lacustrine facies. The alluvial-braided river facies succession composed of gravelly dominated facies associations. The succession resembles the gravel-bed braided river of the sediment gravity flow model of Miall (1996) associated with distal debris and sheet flow deposits. The braided river facies succession composed of sandy dominated facies associations. The lacustrine facies succession composed of Fl1 and Fl2 facies with vertically arranged coarsening upward successions. Many fluvial systems drains into lakes and the sediments are intimately interbedded in many settings (Miall, 1996). The lacustrine facies relatively shows progradational succession (both vertically and laterally) trending into gravelly and sandy dominated facies associations.

4.2. Architectural analysis

Architectural elements are the components of depositional systems equivalent in grain size, or larger than a channel fill and larger than an individual facies unit characterized by individual facies assemblage, internal geometry and external form, amenable to descriptive and genetic classification as their components lithofacies (Miall, 1985; 1996). The arrangement is as a result of spatial relationship between morphological units and movement of channel and bars within channel belts (Miall, 1996). From facies analysis, five architectural elements were identified (e.g., Miall, 1996). Table 2 shows the summary architectural elements.

4.2.1. Gravelly bedded set (GB)

This consists of sheets and lobes of massive matrix and clast supported gravels (Gmm and Gcm Facies) that are poor sorted. It has a thickness of about 8–10 m. The gravel bed sets passes or trends into trough cross-stratified units. This element is interpreted as sediment gravity flow transiting into gravel bed
braided river. Similar element was interpreted as a sediment gravity flow deposit (element SG) which is typically and intimately interbedded with gravel bar and bedforms deposits (element GB) or sandy bedforms (element SB) (Miall, 1985; 1996).

4.2.2. Trough cross-stratified set (TCS)

This consists of sheet-like and lobes of trough cross-stratified set with erosional surface (St Facies). Sets range in thickness from 3 to 8 m thick and commonly shows fining upward decrease in grain size. It is interpreted as aggradation of 3-D sandy dunes (Ashley, 1990). This is similar to sandy bedforms (element SB) that formed in sandy dominated river systems occupying the deeper portions of active channel (Miall, 1985). The trough cross-stratified sets may be cut by broad, shallow scours, and erosional surfaces indicating second and third order stage fluctuations.

4.2.3. Planar cross-stratified set (PCS)

This consists of planar cross-stratified sets that are laterally extensive with occasionally internal erosive surfaces. Foresets range in thickness from 3 to 10 m. It is interpreted to occur at the shallower part of channel where transverse bedforms and sand waves (2-D dunes) are common thus, generating sheets of planar tabular cross beddings (Sp Facies) (Miall, 1996), trending to convolute stratified beds (Fc Facies). Similar sets were also interpreted as downstream migration of sandy bars: transverse bars, alternate bars, and tributary mouth bars.

4.2.4. Horizontally stratified set (HSS)

This consists of horizontally stratified tabular sets that are laterally extensive with parallel laminations. Sets range in thickness from 1 to 3 m. It is interpreted as upper flow regime plane bed conditions (Sh Facies) occurring in laminated sand sheets (element LS) with minor Sp, St, or Sr facies (Miall, 1985). Similar sets were interpreted as downstream migration of broad, plane-bedded bedforms or low-relief bedforms (Allen, 1983).

4.2.4. Overbank stratified sets (OSS)

This consists of fine-grained sheets of overbank stratified sets (Fm Facies overlain the Sr Facies) with...
a thickness range of 0.5–1 m. The set resembles the overbank fines (element FF) of Miall (1985). It is interpreted as deposits of overbank sheet flow. Sheets may be deposited kilometers in lateral dimensions and tens of meters thick where it is associated with Fl and Fsm Facies; interpreted as floodplain ponds and swamps deposits (Miall, 1985; 1996).

### 4.3. Sequence stratigraphic analysis

The evolution of sedimentary basin is influenced by factors, such as base level changes, sediment supply, and subsidence rate (Anadon et al., 1994). Facies distributions in rifted (pull-apart) basins are controlled by climatic, tectonic, sediment supply, and base level changes (Bohacs et al., 2000; Nichols, 2009; Nichols and Uttamo, 2005). The ten facies identified are closely related and their inter-relationship supports their spatial and temporal evolution from lacustrine prograding to alluvial fan and braided river.

A preliminary deduction on the stratigraphy of Lower Bima Member is suggested (Figs. 6 and 7).

A composite stratigraphic framework of Lower Bima Member shows alluvial fan (proximal and distal facies assemblages) at the base, temporally transiting into lacustrine (lacustrine shales and delta) as the lake level rose, expanded, and deepened. This was followed by a period (perhaps due to rift margin faults reactivation) and re-establishment of alluvial fan-braided river (with sediment gravity flow-gravel bed braided river) and braided river (channels and overbank) deposits. The transition from alluvial-lacustrine and to alluvial-fluvial reflects a marked changed in fluvial styles with vertical and lateral facies distribution.

The paleoenvironmental relationship of Lower Bima Member with the West and Central African Rift System suggests that the sedimentary successions of the Lower Bima Member are Cretaceous in age,

### Table 2. Summary of description and interpretation of elements.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravelly bedded sets (GB)</strong></td>
<td>Sheets and lobes of massive matrix and clast supported gravels, ungraded, poor sorted, 8–10 m thick, trends into trough cross stratified units</td>
<td>Sediment gravity to gravel bed braided river</td>
</tr>
<tr>
<td><strong>Trough cross-stratified sets (TCS)</strong></td>
<td>Sheet-like and lobes of trough cross stratified sets, erosive surfaces, 3–8 m thick, showing fining upward decrease in grain size</td>
<td>Aggradations of 3-D dunes or sandy bedforms</td>
</tr>
<tr>
<td><strong>Planar cross-stratified sets (PCS)</strong></td>
<td>Sets of planar cross stratified, occasionally internal erosional surfaces, extended vertically and laterally, 3–10 m thick with fining upward decrease in grain size, trending into convoluted sandstone</td>
<td>Sandy bars; transverse bars, tributary mouth bars and alternate bars</td>
</tr>
<tr>
<td><strong>Horizontally stratified sets (HS)</strong></td>
<td>Tabular sets horizontally stratified with parallel lamination, 1–3 m thick, laterally extensive.</td>
<td>Downstream migration of broad, planar bedforms</td>
</tr>
<tr>
<td><strong>Overbank stratified sets (FF)</strong></td>
<td>Sets of fine grained; mud and silts, 0.5–1 m thick overlain rippled cross-stratified beds.</td>
<td>Overbank or abandoned channel</td>
</tr>
</tbody>
</table>

Figure 6. Stratigraphic trend of the progradational successions going from lacustrine to upper alluvial—braided river (HST delta followed by less braided at top). LST—Lowstand System Tract, SB—Sequence Boundary, HST—Highstand System Tract.

Figure 7. Composite stratigraphic section of Lower Bima Member (modified from Rebelle, 1990) showing the paleoenvironments and stratigraphic surfaces using model of Van Wagoner et al. (1990) and Christie-Blick (1991). SB—Sequence Boundary, MFS—Maximum Flooding Surface, MRS—Maximum Regressive Surface.
probably deposited between the pre-Aptian to Aptian, and can be chronocorrelated with other sequences recognized in adjacent rifted basins. The depositional style corresponds to the fluvial-lacustrine system. Similar depositional systems were analyzed in Sudan for Muglad Basin (Schull, 1988) and Cameroun for Lower Mundeck Formation (Ntamak-Nida et al., 2010).

5. Conclusion

Based on facies, architecural, and sequence stratigraphic analyses, the Early Cretaceous (pre-Aptian to Aptian) Lower Bima Member exhibits a vertical and lateral facies transition from alluvial fan at the faulted basin margin to lacustrine environment along the basin axis. The basal succession indicated retrogradation, which was followed by progradation of the lacustrine on to the alluvial and braided river systems. Mass flow processes dominated the deposition of the alluvial fan suggesting that tectonic activity continued throughout most of the depositional history of the Lower Bima Member which was considered as syn-rift. The presence of gray to black laminated shale associated with wave ripples of very fine- to fine-grained sandstone and siltstones suggest a deposition of lacustrine environment along the axial part of the basin. Matrix and clast supported conglomerates indicates mainly debris flow alluvial fans, while the channel sandstones with majorly trough or planar cross beds and fine-grained overbank facies were constructed to be of the braided river processes.

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References


Miall AD. The geology of fluvial deposits, sedimentary facies, basin analysis, and petroleum geology. Springer, New York, p 582, 1996.