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Facies Architecture and Sand Body Connectivity in Meandering River Deposits: Example from Enagi Formation, Northern Bida Basin, Northwestern Nigeria

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Abstract

Meandering river deposits of the Enagi Formation constitute potential reservoir rocks within the northern part of the Bida Basin, NW Nigeria. Well exposed parts of this deposit located on a road-cut around Kawo, Niger State was studied. Field assessment of their lithofacies, external and internal characteristics and bounding surfaces reveal the presence of conglomerate, sandstone and mudstone lithofacies as well as channel (CH), lateral accretion (LA), downstream accretion (DA), floodplain (FF) and abandoned channel (FF (CH)) architectural elements. The CH, LA, and DA elements are expected to constitute the potential reservoirs. They display multistory and multilateral stacking patterns with resultant vertical and lateral connectivity of the channel sandstone bodies which can be explained using the string-of-beads model as against the commonly used isolated sandstone geobodies. Extensive floodplain mudstones constitute vertical permeability barriers while abandoned channels, mud lenses, mud drapes on lateral accretion surfaces and fining-up grain size trend within channel sandstones are considered potential permeability baffles at inter-well to individual well-scales. This study suggests that detailed field assessment in addition to architectural element analysis of well exposed meandering river deposits is vital to understanding sub-seismic to field–scale heterogeneities that may not be possible even in mature oil fields where subsurface data are abundant.

Keywords: Bida Basin, Enagi Formation, Point bar, Meandering river deposit, Facies architecture, Fluvial channel

1. Introduction

Outcrop analogue studies are valuable especially when details of reservoirs are sought for. Well exposed outcrops provide sub-seismic information relevant to building 2D or 3D geologic models for reservoirs by development geologists and petroleum engineers. These information are paramount for reservoir simulation and well planning programs (e.g., Miall, 2006).

Hydrocarbon production histories have shown that fluid flow through fluvial reservoir units depend on such geological factors as lithofacies or facies associations (Hearn *et al.*, 1984; Ebanks, 1987); facies dimensions, orientations, and their vertical and lateral relations (Tyler *et al.*, 1991); lithofacies variation and sand body connectivity (e.g. Larue and Hovadik, 2006). Meandering river deposits are in the last decades believed to contain ribbon sands that are completely engulfed in floodplain mudstones (e.g., Schumm, 1977; Galloway, 1981; Friends, 1983; Xue, 1986; Ambrose *et al.*, 1991; Davies *et al.*, 1993). However, Donselaar and Overeem (2008) demonstrated that meandering river point bar sand bodies could be connected based on outcrop studies of parts of the Miocene Huesca fluvial deposits of Sarinena Formation, Ebro Basin, Spain.

The petroleum potential of the Bida Basin has been assessed by previous workers (e.g., Obaje *et al.*, 2013; Akande *et al.*, 2005; Braide, 1992), and there exists potential source rocks with great potential for gas and some oil. Potential regional seal is expected to be provided by the mudstone-prone upper part of the Enagi Formation while the potential reservoir rocks are the sandstones of Bida and Enagi Formations (Obaje *et al.*, 2013). Sandstone lithofacies capable of constituting potential reservoir rocks in the basin include the fluvial braided and meandering river deposits (e.g., Adeleye and Desauvagie, 1972; Braide, 1992 and Okosun *et al.*, 2009) as well as coastal to shallow marine tidal channel and shoreface deposits (Ojo and Akande, 2009).

This paper presents results of detailed study of well exposed road-cut outcrop along Tegina – Makera Trunk A road, NW Nigeria (Figure 1). It is an integral part of the on-going reservoir characterization studies in the northern part of Bida Basin, and it specifically involves the detailed assessment of the lithofacies, architectural elements and sand body connectivity of a meandering river succession in part of the Enagi Formation. The nearest locality to this exposure is a village called Kawo in Mashegu Local Government Area of Niger State, Nigeria. Because subsurface data are hitherto grossly unavailable in this basin, assessments of facies architecture could only be attempted using outcrops. The works of Goro *et al.,* (2014) and Goro *et al.,* (2015) which used the Miall's concept of architectural elements are good attempts in this direction. It is anticipated that the current study will provide invaluable information which is sometimes difficult to assess even in areas with sub-surface data.

2. Location and Geological Setting

The study area, with geographic coordinates N09˚55′21″ and E005˚43′48″, is near Kawo village (SW Tegina) and falls within the northern part of the Bida Basin in the north-western part of Nigeria (Figure 1). The Bida basin is a NW-SE trending structure which extends from Kontagora in the northern sector to Lokoja in the southern part covering a distance of about 400 km. It has a sedimentary fill of up to 4.7 km with an average of 3 km (Udensi and Osazua, 2004). Although the origin of the basin is a subject of debate among authors, the rift origin is favored by most writers.

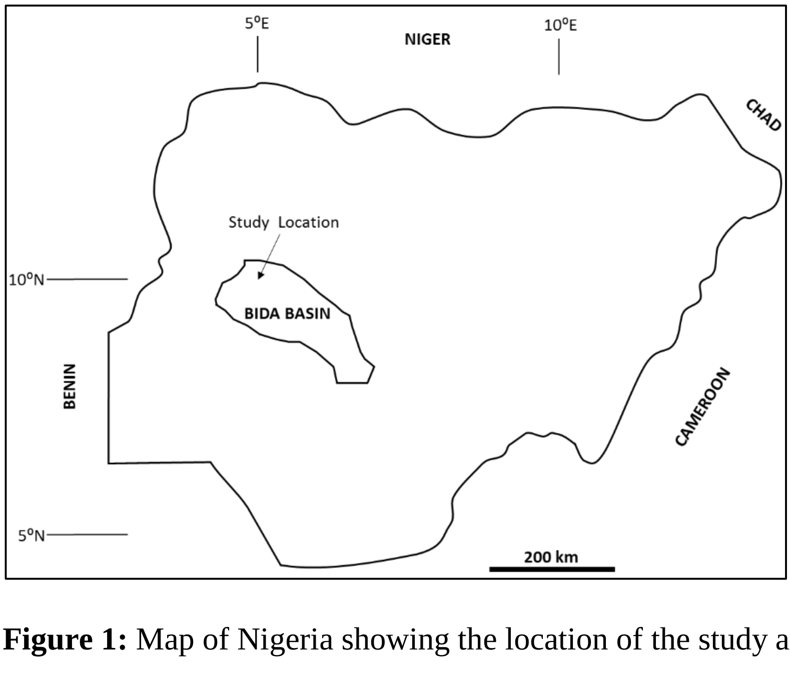

Figure 1: Map of Nigeria showing the location of the study area.

Adeleye (1972) identified four lithostratigraphic successions in the northern part of the basin (Figure 2). According to him, Bida Formation consists of massive gravelly, coarse to very coarse sandstones at the base (Doko Member) which is overlain by fine to medium-grained cross-bedded sandstones and mudstones (Jima Member). They were inferred to be deposited in braided and meandering river systems (Adeleye and Dessauvagie, 1972; Braide, 1992). Sakpe Formation overlies the Bida Formation and consists mainly of an alternation of oolitic and pisolitic ironstones. Next in the stratigraphy is the Enagi Formation, and it comprises predominantly siltstones, mudstones and sandstones deposited in lower reaches of fluvial system; and it is overlain by Batati Formation consisting mainly of ironstones with geothite and kaolinite (Adeleye, 1972). These formations have equivalent lateral formations such as Lokoja Sandstone, Patti Formation and Agbaja Formation in the southern arm of the basin (Figure 2).

AGE	BIDA BASIN		
	SOUTHERN BIDA BASIN	NORTHERN BIDA BASIN	
Campano-Maastrichtian	Agbaja Ironstone	Batati Ironstone	
	Patti Formation	Enagi Formation	
		Sakpe Ironstone	
	Lokoja Formation	Bida Sandstone	Jima Member
			Doko Member

Figure 2: Stratigraphic successions in the Bida Basin (modified from Adeleye, 1972).

3. Methodology

In order to achieve the objectives of this study, two outcrop locations were studied. The two locations were selected due to their well exposed nature and the preservation of the margins of some of the exhumed ancient channels. Careful characterization of orders of bounding surfaces based on the methodology of Miall (1985; 1988; 2006) were followed using field observations and measurements. Channel geometry measurement was conducted in the field through the documentation of the channel sand body depth (D) and width (W) and computation of the width to depth (W/D) ratio.

The stacking pattern of the sand bodies was also assessed in the field and good quality camera was used to obtain outcrop pictures which were later processed in the laboratory to generate photomosaics (photo panels) showing lateral and vertical terminations of the identified bounding surfaces. Detailed studies of the lithofacies along with facies architecture (both in the outcrop and photo panels) were used to build a 2D conceptual model for sandstone body continuity and connectivity. The potential permeability barriers and baffles useful for prediction of reservoir and fluid pressure communication within the potential reservoir system were also examined.

4. Results and Discussion

4.1 Facies and Architectural Elements

4.1.1 Lithofacies

Sandstone, mudstone and conglomerate lithofacies were identified from the studied interval. The conglomerate (Gm) consists of gravel to small pebble sized detrital clasts, mainly quartz as well as mud rip-up clasts ranging from a few grain diameters to medium pebble size (Figure 3). Local concentration of intra-formational conglomerates composed of indurated sandstones with large (pebble to cobble) grains occur overlying deeply eroded surface in one of the beds (Figure 3D, F).

The conglomerates are set in a matrix of fine to very coarse sands. They commonly appear massive and range in thickness from single grain diameter to up to 20 cm thick. Units thicker than 10 cm occasionally show crude cross-bedding (Figure 3B). The conglomerate lithofacies generally overlies sharp irregular contacts (Figure 3B, D).

The sandstone lithofacies commonly overlies the conglomerates and underlies the mudstone lithofacies. It consists of very fine to medium-grained sandstones. A variety of sedimentary structures including trough cross-bedding (St) and planar cross-bedding (Sp) (Figure 3C) as well as ripple cross lamination (Sr) (Figure 3H) and lateral accretion surfaces (Figure 3G) are displayed by this lithofacies.

The mudstone lithofacies consists of claystones and siltstones. It commonly overlies the sandstone lithofacies; may be massive (Fm) and colour mottled or may occur as thinly interbedded claystone and siltstone beds (Fl) (Figure 3J). Mottled intervals display shades of grey, purple, white and milky white colours.

4.1.2 Architectural Elements

Field assessments of the shape and internal structure of the exposed sediment bodies in the study area reveal the presence of five architectural elements, namely: channel (CH), lateral accretion (LA), downstream accretion (DA), abandoned channel (FF (CH)), chute channel and floodplain elements (FF).

4.1.2.1 Channel Element (CH)

Channel element is the dominant element in the studied exposure. Their well exposed nature is the reason why this location was chosen for the study. This element is characterized by concave-up basal scour surfaces and flat to convex-up upper surface. They display varied internal arrangement of lithofacies with generally abundant internal erosion surfaces. Some contain lateral accretion surfaces (Figures. 3G, 4E) while others display low angle 3rd order internal bounding surfaces (Figures 4A-C) while still others may contain downstream accretion macroform (Figure 5). The base of the 3rd order surfaces are commonly marked by coarse lag deposits (Figure 4C).

Overall, the channel elements display fining-up grain size profile (e.g. Figure 4E). The erosional basal contact is commonly overlain directly by sandstones or coarse lag sediments of the conglomerate lithofacies (Gm) overlain by cross-bedded fine to coarse-grained sandstones (Figure 4E). The cross-bedded sandstones may display medium-scale trough cross-bedding (St), large-scale planar cross-bedding (Sp) or large-scale low angle cross-bedding (Sl) separated by lateral accretion surfaces (Figsures 3B, 3C, 3G *and* 4E). Their upper parts are characterized by fine-grained sandstones some of which display ripple cross lamination (Figures 3H, 4E). Fining-upward grain size is also commonly observed at smaller scale between successive lateral accretion surfaces and internal 3rd other surfaces. Individual channel sandstones may contain several laterally restricted mud lenses especially towards their middle to upper parts (Figures 6, 7). Seven channel elements were mapped as shown on Figure 6 and representative graphic logs from each of the panels are displayed in Figure 7 while Figure 8 shows a composite cross-sectional model depicting the stacking of the studied exhumed channelized units.

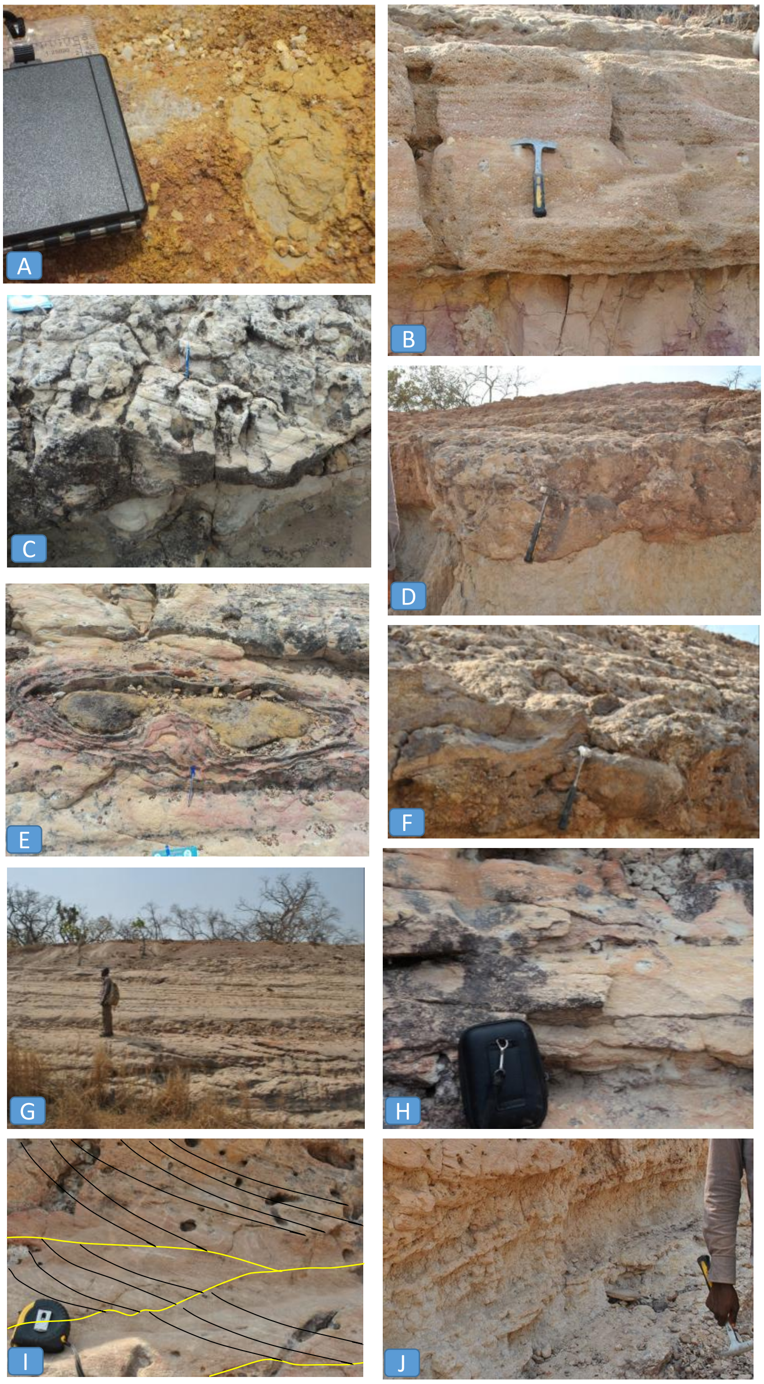

Figure 3: Outcrop details of the lithofacies. [A] conglomerate facies (Gm), note pebble sized mud rip-up clast on the right-hand side. [B] rare cross-bedded conglomerate (Gc). [C] planar cross bedded sandstone (Sp) overlying mudstone [D] conglomerate containing large pebble to cobble sized clast overlying massive mudstone (Fm). [E] large elliptical concretion in very fine to fine grained sandstone [F] close up of (D) showing large grain size` of part of Gm sediment [G] mud draped lateral accretion surfaces. [H] ripples on very fine-grained sandstones [I] three sets of trough cross-beds in fine to medium grained sandstone. [J] mudstones interbedded with very thin fine-grained sandstones

Cross-sectional geometry of the channels shows both vertical stacking and lateral amalgamation of the sandstone bodies similar to the multistory and multilateral architecture (Collison, 1996 Giblin, 2006). Individual channel sandstone bodies are 0.8 – 3. 32 m thick (Table 1) and widths ranging from 27.3 – 162 m, and computed channel width to depth ratio falls between 23.81 and 95.29 and averages 36.45 (Table 1).

Minor channels also form part of the components of the studied interval. A minor channel with thickness of 1.2 m and channel width of 6 m is mapped in location 1 (Figure 5). Fine-grained sandstone makes up the bulk of its sediment fill. This channel is associated with the mudstone prone floodplain element (Figure 5).

4.1.2.2 Downstream Accretion (DA)

This element is characterized by several cosets of trough and planar cross bedded units as well as ripple cross laminated sets. It also contains several 2nd and 3rd order internal surfaces between which the cross bedded cosets occur. The sloping direction of the internal surfaces as well as the general direction of dip of the cross beds are commonly the same within this element. Upward decrease in thickness of sets/cosets as well as upward grain size decrease is also common.

4.1.2.3 Lateral Accretion (LA)

This element is marked by the presence of lateral accretion surfaces and constitute major part of some of the identified channel elements. It consists mainly of fine to coarse grained sandstones with generally fining up grain size trend. The element show thicknesses ranging from 3-5 m. Sedimentary structures include large-scale, trough cross stratification at the basal to middle apart and smaller scale trough cross bedding and ripple lamination towards the upper part. Alternation of finer and coarser bedding/lamina is discernible throughout the element. Some of the surfaces are mud-draped.

4.1.2.4 Floodplain Element (FF)

This element constitutes part of the architectural elements of the overbank environment (Miall, 2006). It consists of mudstones and/or siltstone of the Fl (laminated mudstones/silstone) and Fm (massive mudstone) lithofacies. They display sheet-like geometry with thicknesses ranging from a few cm to 2.7 m. This element commonly overlies the CH, LA, DA elements and is associated with the FF (CH) element (Figure 5). This element is commonly truncated by the basal scour surface of the CH element and commonly overlies 4th order surfaces (Figures 5, 6).

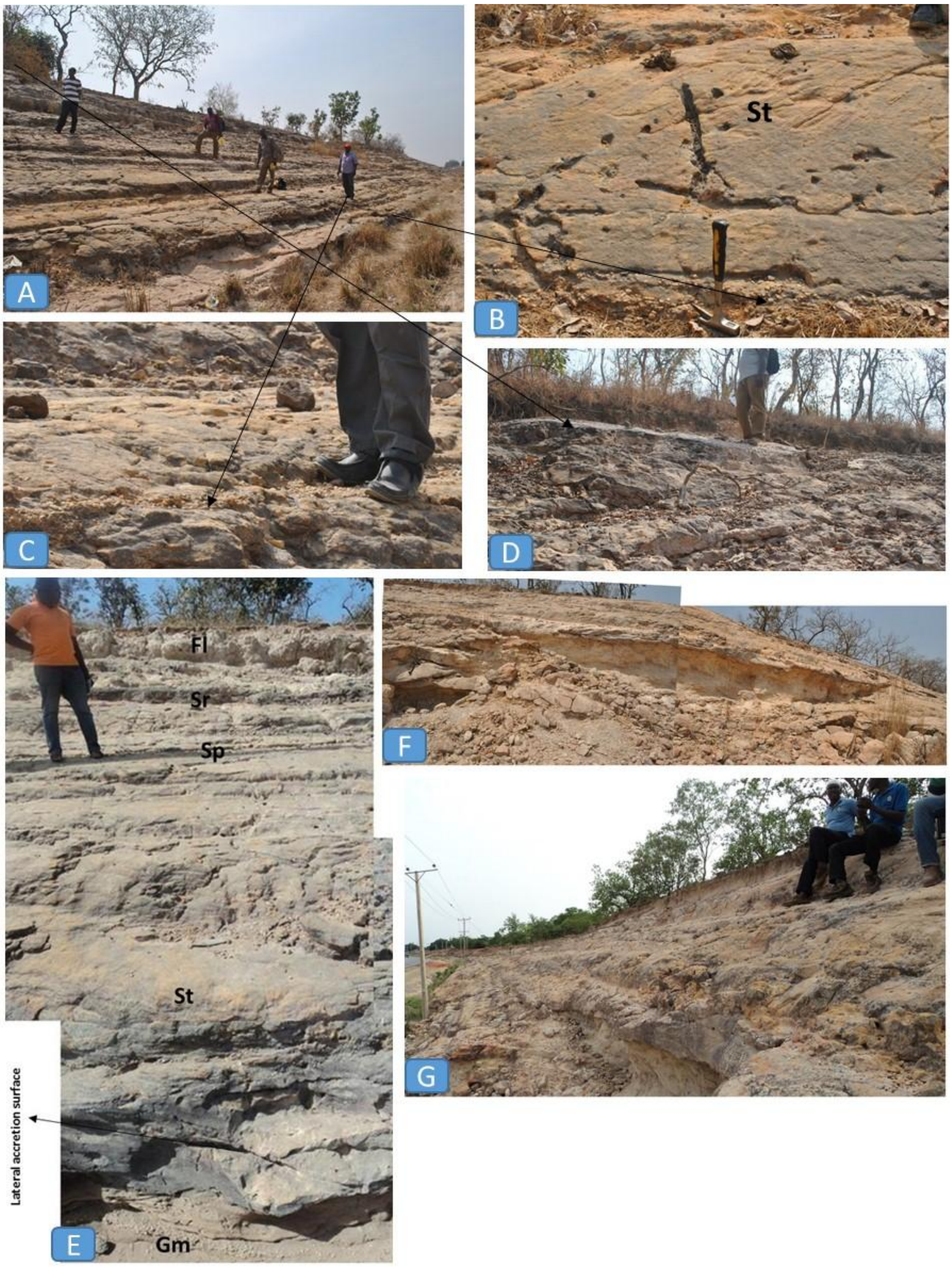

Figure 4: Outcrop pictures showing [A] numerous internal low angle 3rd order surfaces within channel element, each person on the picture is standing on a surface; [B] coarse lag deposits on the basal scour surface of the channel; [C] closer view of (A) showing coarse lag on the lowermost 3rd order surface; [D] closer view of (A) showing the top convex-up 4th order bounding surface of the channel element; [E] typical fining-up lithofacies arrangement in a channel element composed of lateral accretion surfaces; [F] mud fill channel shaped element; [G] irregular erosional basal surface of channel element.

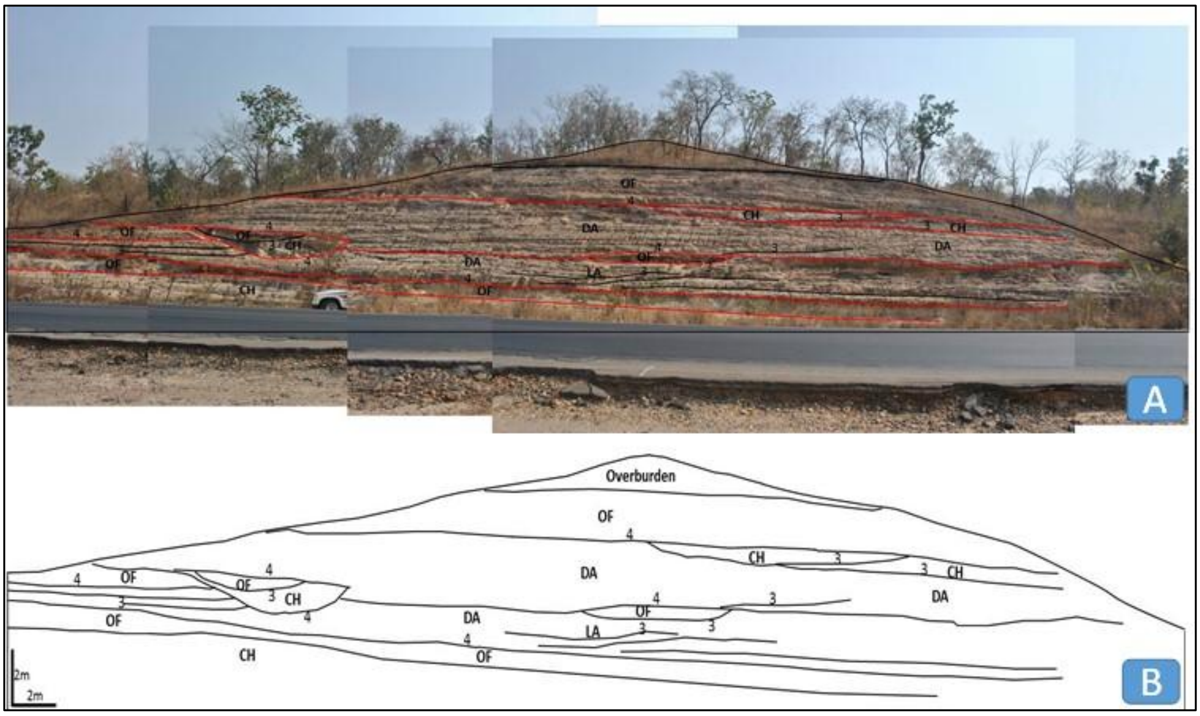

Figure 5: Photomosaic and sketch interpretation of observed architectural elements (Below) of the road-cut at Location 1, near Kawo village, along Tegina-Makera Trunk “A” road, northern Bida basin NW Nigeria.

4.1.2.5 Abandoned Channel Element (FF(CH))

This element displays lensoid geometry and commonly contains mudstones of Fm lithofacies. It is associated with the FF element and typically occurs overlying the CH element (Figures 5, 6 and 8). They are observed as clay plugs overlying channels D, E and F (Figures 6, 10), where they occur towards the western margins of the channels. Thicknesses range from few centimeters to 1.5 m.

4.2. Discussion

As a result of the inherent inadequacies of the use of vertical facies profile alone in the interpretation of fluvial successions, the architectural element concept (Allen, 1963; Miall 1985; 1988) was introduced to account for the 3D geometry and bounding surfaces of component lithosomes (elements) that constitute the sediments. Features of the elements that are useful to their recognition such as the lithology, external and internal geometries, bounding surfaces, scale and paleocurrent pattern (Miall, 2006) are usually considered in explaining their sedimentology.

The generally fining-upwards grain size recorded in individual channel elements as well as between internal erosion surfaces indicate upwards waning current energies between the lower and upper parts of channels as well as between successive erosion events during the deposition of sediments within the channels (e.g. Goro *et al.,* 2015; Collinson, 1996 and Miall, 1985).

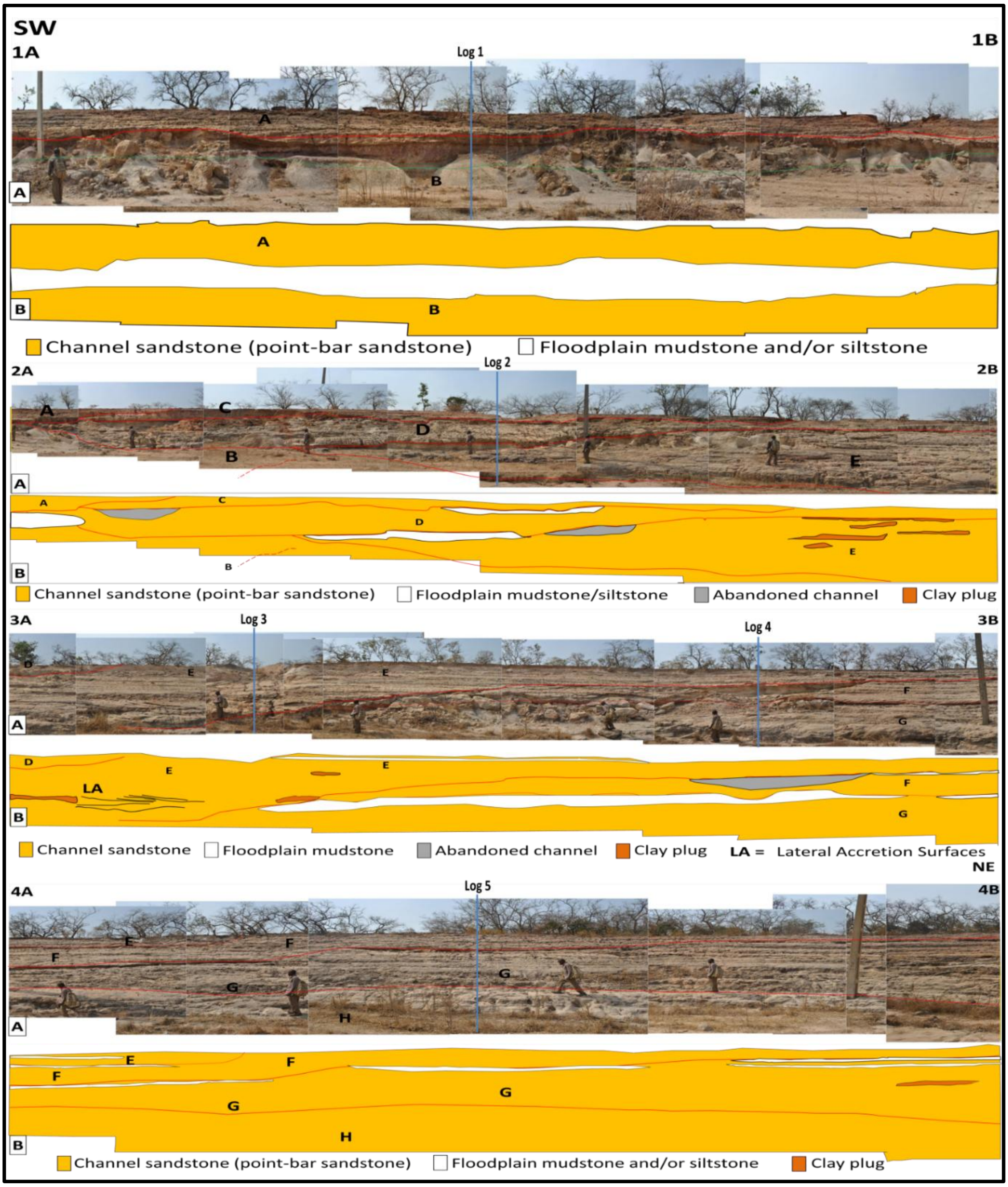

Figure 6: Photo panel and interpretation of multistorey and multilateral meandering river sandstone bodies. A – H represents identified channels. Sediment bodies with the same letter are interpreted to belong to the same point bar. Panels 1A-1B, 2A-2B, 3A-3B and 4A-4B are laterally continuous from southwest – northeast. The total width of the exposure is approximately 300 m (Person of 1.73 m height as a scale).

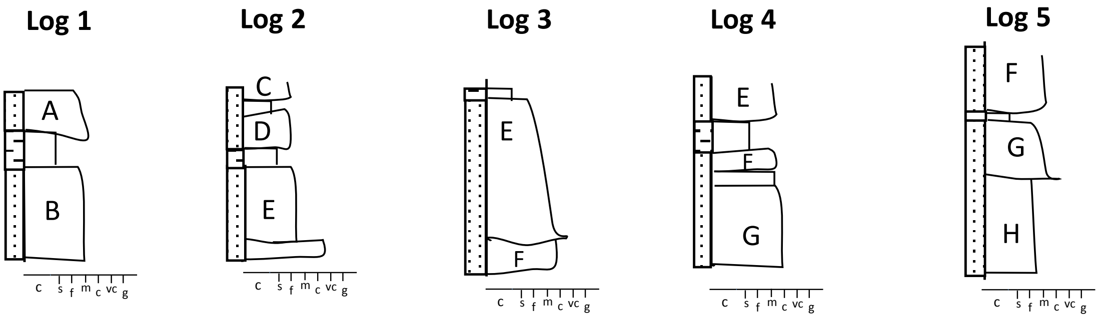

Figure 7: Sedimentoligical graphic logs through parts of the meandering river deposits in Figure 6.

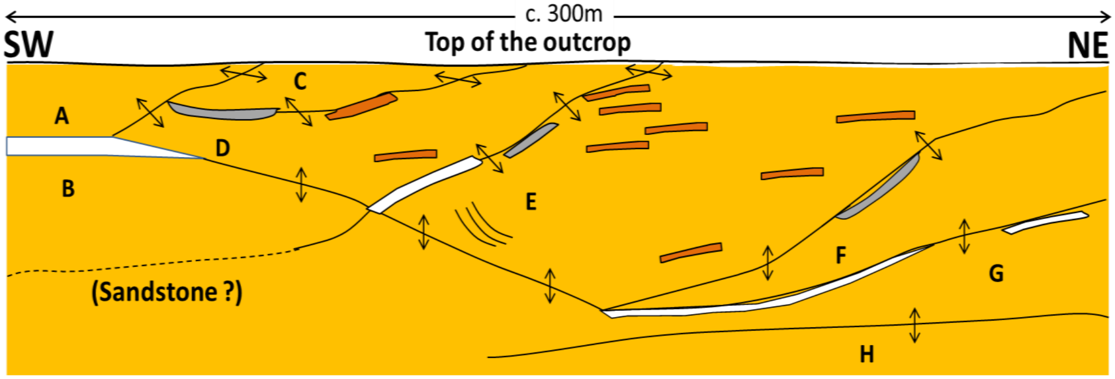

Figure 8: Composite cross-sectional model depicting the stacking of the studied exhumed channelized units and the interbedded floodplain elements [Yellow: channelized sandstone, White: Floodplain mudstone, Grey: Abandoned channel, Orange: Clay plugs]. The double-ended arrows show possible connectivity between adjacent sandstone bodies (not drawn to scale).

Table 1: Channel width – to – depth ratios for channelized sandstone bodies around Kawo village in the northern Bida Basin.

Locality	Channel width, W (m)	Channel depth, D (m)	W/D
Kawo area	100	3.1	32.26
	95	3.2	29.69
	27.3	0.8	34.13
	162	1.7	95.29
	162	3.23	50.15
	80	3.23	24.77
	50	2.10	23.81
	6.0	1.6	3.75
	51.3	1.5	34.20
	35	1.2	29.17
Average	**76.86**	**2.17**	**36.45**

The studied exhumed channels can be interpreted as ancient mobile channels based on the measured width to depth ratios (Table 1) in addition to the laterally amalgamated nature of the channels (Gibling, 2006). Furthermore, the occurrence of lateral accretion sets indicates the presence of point bars which suggests deposition in rivers with meandering plan form (Gibling, 2006). The deposition of point bars in meandering river systems is well documented (Allen, 1963, 1970). Based on this model, the conglomerate lithofacies represents channel lag deposits at the base followed upwards by the sandstone lithofacies which are products of channel-floor bed-load sedimentation in the inner bend of meandering river system. The driving force of these channel floor deposits is the helical flow that are commonly generated at the outer part of the meander bend and their gradual upward energy dissipation record the development of the fining upwards St – Sp - Sr profile as observed in the studied section. The presence of abandoned channels also suggests that, processes of migration and avulsion played key roles in deposition of the sediments on the meander belt (Gibling, 2006) while the internal 3rd order surfaces indicate periods of large-scale reactivation or incision within the channels (Miall, 1988; Gibling, 2006). The large grain size exhibited by the localized intraformational conglomerates (Figure 3D, F) suggests deposition due to stream bank collapse rather than measure of the stream energy (e.g. Gibling and Rust, 1984). They are interpreted as fallen blocks from cut-banks due to erosion related to channel migration (Collinson, 1996).

Disconnected mud lenses observed within the channel elements are similar to the mud sheets described in the point bar deposits of the modern Mississippi (Jordan and Pryor, 1992). They were inferred to have been deposited as broad mud sheets that drape sand dunes at high river stages. The mudstones were deposited in ponds created by the water levels. Similar mud drapes were reported in the River Brazos (Bernard *et al.,* 1970). Furthermore, the laminated (Fl) and massive mudstones (Fm) lithofacies that constitute the floodplain element represents deposition from suspension as well as weak traction current (Miall, 2006) while the Fm mudstones that make up the abandoned channel architectural element record vertical aggradation through suspension sedimentation in ponds during low stage channel abandonment (Miall, 2006).

4.2.1 Sand body connectivity and its implications for reservoir modelling

Assessment of connectivity of sandstone bodies in fluvial reservoirs is fundamental because hydrocarbon production is governed by the percentage of the sandstone bodies that are interconnected (Colombera *et al.,* 2012). In addition, connectivity of sandstone bodies is controlled by sandstone to mudstone ratio as well as sandstone-body depositional architectures (Ainsworth, 2005). In the present study, it is evident from the composite cross-section (Figure 8) that the identified channel sand bodies could actually be connected at positions indicated by the double ended arrows (Figure 8). This static sand-sand connectivity is possible by the direct superposition of channel floor point bar sandstones without intervening floodplain or abandoned channel mudstone units. This connectivity is possible because of the preservation of channel floor deposits below the clay plugs of abandoned channels (e.g. Figures 6, 8). The scenario records sedimentation on channel floor due to gradual avulsion and abandonment in low gradient mixed-load meandering river systems (e.g. Collinson, 1996; Donselaar and Overeem, 2008). This interpretation was also suggested by De Rooij *et al.* (2002), based on reservoir simulation studies. Therefore, the abandoned channel mudstones cannot be regarded as effective permeability barriers and that all the identified channel sandstones in the studied interval are potentially vertically and horizontally connected (Figure 8).

Figure 9 illustrates two scenarios to explain the cross-sectional view of how abandoned channel mud plugs may occur in the case of complete or partial filling. In the first instance (Figure 9A), the mud plug filled the channel to bank full. Here, the mud plugs separate the point bar sandstones and the deposits are commonly modelled as containing isolated point bar sandstones surrounded on all sides by floodplain and abandoned channel mudstones (e.g. Xue, 1986; Ambrose *et al.*, 1991; Davis *et al.*, 1993) (Figure 10A). The second case (Figure 9B), where the channel floor sandstones of the point bar were deposited as the channel was being filled, better explains the results of this work. In order to elucidate the connectivity inherent in these deposits, Donselaar and Overeem (2008) proposed a conceptual model of point bar sandstone connectivity in form of strings of beads as depicted in Figure 10B. This model illustrates that successions developed by a single meandering river point bar sandstone occurs in form of one, continuous string-of-beads sandstone geobody and that meander belt successions create interconnected sandstone geobodies (Donselaar and Overeem, 2008). One of the implications of this model includes increased net-to-gross ratio which is a key factor in the computation of volumetrics especially at exploration and appraisal stages of oil fields. For example, Donselaar and Overeem (2008) noted an increase of more than 54% in the net-to-gross ratio of a well-studied point bar deposit. Also, Sloan (2009) reported similar results on modeling and simulation of a low net-to-gross fluvial deposit of the lower part of Williams Fork Formation in Piceance Basin, Colorado. Here, it was noted that the string-of-beads model displayed maximum net-to-gross ratio of about 48% as against 38% of the mudstone plug model (Figure 9A).

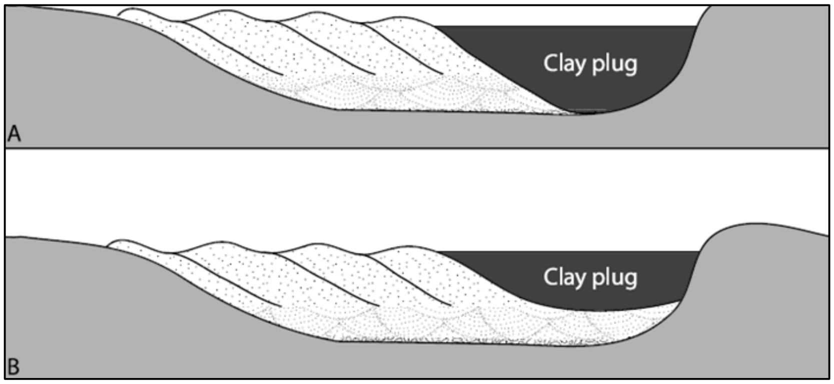

Figure 9: Cross-sectional view of two scenarios of mud plug filling abandoned channel in low gradient mixed-load fluvial system. [A] Mud plug filled abandoned channel to bank full. [B] Mud plug partially filled abandoned channel (Donselaar and Overeem, 2008).

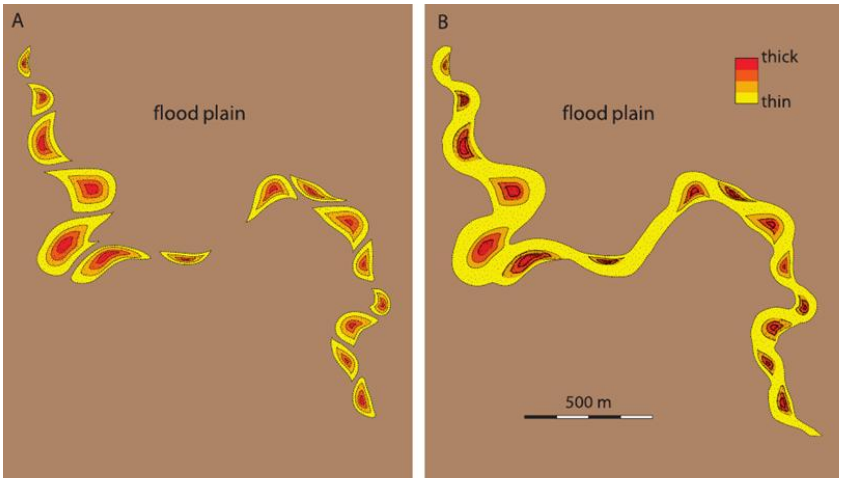

Figure 10: Isopach maps of two scenarios for the spatial distribution of meandering river sandstone bodies. [A] The point bars form isolated sandstone bodies surrounded on all sides by impermeable fine-grained floodplain and abandoned channel mud clay. [B] Channel floor sandstones are preserved below mud plugs. Successive point bar sandstones are connected forming one continuous string-of-beads sandstone body (Donselaar and Overeem, 2008).

4.2.2 Heterogeneity Assessment

Based on the data presented in this study, three levels of potential reservoir heterogeneities are envisaged. The largest scale reservoir heterogeneities are expected to occur at meander belt scale which is equivalent to macroscopic or field-scale heterogeneity (e.g. Jordan and Pryo, 1992; Krause *et al.*, 1987). The geometry at this scale is represented by a complex of vertically and laterally stacked string-of-beads sandstone geobodies embedded in floodplain mudstones (Figure 8). Heterogeneity at this scale is mainly in the form of vertical permeability barriers provided by the laterally extensive mudstones of the floodplain architectural elements (Figure 8). Heterogeneities at the scale of reservoir pool within oil fields is the next in rank and it is in the form of horizontal permeability baffles provided by the mud plugs of the abandoned channel mudstones. This may be manifested in form of baffles to lateral migration of fluids between adjacent point bar sandstones. Considering the proposed model, however, the abandoned channel mudstones of the studied interval are not expected to serve as significant permeability barriers. At the level of individual channel fill, the mud lenses, the lateral accretion surfaces as well as the fining up grain size profile of the sandstones are expected to act against smooth fluid flow thereby constituting heterogeneities. The vertical migration of fluid are expected to be reduced by the presence of mud lenses while lateral migration would be affected by the lateral accretion surfaces because they can act as permeability baffles at inter-well scale. At well scale, the fining up grain size trend means upwards decrease in permeability (e.g. Slatt, 2006). The implication of this, especially at production stage is that, during waterflood the lower part of the sandstone unit is commonly more efficiently swept to the well bore while the upper finer grained parts of the sandstones still retain a lot of the oil (e.g. Slatt, 2006).

5. Conclusions

Field assessment of the architectural element of exhumed meandering river deposits around Kawo area in northern part of Bida Basin, NW Nigeria shows that the sediments contain conglomerate, fine to coarse-grained sandstone and mudstone lithofacies. The lithologic association, internal and external characteristics as well as bounding surfaces allowed the definition of five architectural elements including channel (CH), downstream accretion (DA), lateral accretion (LA), abandoned channel (FF (CH)) and floodplain elements (OF).

The outcrop made possible the delineation of the external geometry of most of the channel elements which commonly contain point bar sandstones with associated channel floor sandstones. Cross-sectional view of the channels display both multistory and multilateral stacking patterns allowing both vertical and lateral connectivity of the sandstone bodies. This is possible because the mud plugs of the abandoned channels were only partially filled.

The connectivity inherent in the studied interval has important implications for reservoir modelling. The results of this study suggest a string-of-beads model where point bar sandstones are vertically and laterally connected rather than isolated point bars embedded in floodplain mudstones that are in common use for meandering river deposits. Net-to-gross thickness which is a vital component of the reservoir interval is expected to increase if this model is considered, thereby making the interval of study more attractive to the oil company.

Within the studied interval, the mudstones of the floodplain element are expected to constitute the key vertical permeability barriers at field scale. The abandoned channel mudstones between channel sandstones, mud lenses and mud-drapes on lateral accretion surfaces within channel fills are expected to serve as horizontal and vertical permeability battles within oil pools especially at inter-well scale. Vertical, well-scale heterogeneities are expected to be provided by the generally fining-upward grain size profiles of individual channel sandstones.

This work demonstrates that field assessment of well exposed meandering river deposits can reveal important sub-seismic scale information relevant to reservoir geologists and engineers. These information are often not accessible even in mature fields because of the limitations of resolutions imposed by the seismic as well as well data.

Acknowledgments

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References

Adeleye, D. R., Dessauvagie, T.F.J. (1972). Stratigraphy of the Middle Niger Embayment near Bida, Nigeria, African Geology, University of Ibadan Press, 181-186.

Adeleye, D. R. (1972). Stratigraphy and sedimentation of the Upper Cretaceous strata around Bida, Nigeria, PhD Dissertation, University of Ibadan, Ibadan, Nigeria, 297.

Akande, S. O., Ojo, O. J., Ladipo, K. (2005). Upper Cretaceous sequences in the southern Bida Basin, Nigeria: A Field Guidebook. Ibadan, Mosuro Publishers, 60.

Ambrose, W. A., Tyler, N., Parsley, M. J. (1991). Facies heterogeneity, pay continuity, and infill potential in barrier island, fluvial, and submarine-fan reservoirs: Examples from the Texas Gulf Coast and Midland Basin. In Miall, A. D., Tyler, N., (eds.). The three-dimensional facies architecture of terrigenous clastic sediments, and its implications for hydrocarbon discovery and recovery, SEPM Concepts in Sedimentology and Paleontology, 3: 13–21.

Braide, S. P. (1992). Alluvia Fan Depositional Model in the Northern Bida Basin, Jour. Min. Geol., 28: 65-73.

Collinson, J. D. (1996). Alluvial sediments, In Reading, H.G., (ed). Sedimentary Environments: Processes, Facies and Stratigraphy, Oxford, Blackwell Science, 37–82.

Davies, D. K., Williams, B. P. J., Vessell, R. K. (1993). Dimensions and quality of reservoirs originating in low and high sinuosity channel systems, Lower Cretaceous Travis Peak Formation, East Texas, USA. In North C. P., Prosser, D. J., (eds). Characterization of fluvial and aeolian reservoirs, Geological Societyof London, Special Publication, 73: 95-121.

Donselaar, M. E., Overeem, I. (2006). Connectivity of fluvial point-bar deposits: An example from the Miocene Huesca fluvial fan, Ebro Basin, Spain, AAPG Bulletin, 92(9): 1109–1129.

Ebanks, W. J. Jr. (1987). Flow Unit Concept-Integrated Approach to Reservoir Description for Engineering Projects, Abst. AAPG Bulletin, 71(5): 551–552.

Galloway, W. E. (1981). Depositional Architecture of Cenozoic Gulf Coastal plain alluvial systems. In Ethridge F. G., Flores, R. M.,(eds). Recent and ancient nonmarine depositional environments: models for exploration, SEPM Special Publication, 31: 127 - 155.

Gibling, M. R. (2006). Width and Thickness of Fluvial Channel Bodies and Valley Fills in the Geological Record: A Literature Compilation and Classification, Journal of Sedimentary Research, 76: 731–770.

Goro A. I., Okosun, E. A., Salihu, H. D., Tenimu, S. (2015). Analysis of Intermediate-scale Reservoir Heterogeneity Based on Well Exposed Outcrop Analogue within the Maastrichtian Enagi Formation, Bida Basin, North Western Nigeria,Universal Journal of Geoscience, 3(4): 127-134.

Goro A. I., Salihu, H. D., Jibrin, B.W., Waziri, N.M., Idris-Nda, A. (2014). Characterization of a Massive Sandstone Interval: Example from Doko Member of Bida Formation, Northern Bida Basin, Nigeria,Universal Journal of Geoscience, 2(2): 53-61.

Hearn, C. L., Ebanks, W. J. Jr., Tye, R. S.,Ranganathan, V. (1984). Geological factors influencing reservoir performance of the Hartzog Draw field, Journal of Petroleum Technology, 36: 1335-1344.

Krause, F. F. Collins, H. N. Nelson, D.A., Machemer, S. D., French, P. R. (1987). Multiscale anatomy of a reservoir: Geological characterization of the Pembina-Cardium Pool, west-central Alberta, Canada, AAPG Bulletin, 71: 1233-1260.

Larue, D. K., Hovadik, J. (2006). Connectivity of channelized reservoirs: A modeling approach. Petroleum Geoscience, 12: 291–308.

Miall, A. D. (1985). Architectural-element analysis: A new method of facies analysis applied to fluvial deposits,Earth Science Reviews, 22: 261-308.

Miall, A. D. (1988). Facies architecture in clastic sedimentary basins. In Kleinspehn, K., Paola,C.,(eds). New perspective in sedimentary basin analysis: a symposium in honour of F. J. Pettijohn, New York: Springer-Verlag, 67 – 81.

Miall, A. D. (1996). The Geology of Fluvial Deposits: Sedimentary facies, Basin analysis and petroleum geology, Heidelberg, Springer-Verlag, 582.

Miall, A. D. (2006). Reconstructing the architecture and sequence stratigraphy of the preserved fluvial record as a tool for reservoir development: A reality check, AAPG Bulletin, 7: 989–1002.

Obaje, N. G., Balogu, D. O., Idris-Nda, A., Goro, I. A., Ibrahim, S. I., Musa, M. K., Dantata, S. H., Yusuf, I., Mamud-Dadi, N., Kolo, I. A. (2013). Preliminary Integrated Hydrocarbon Prospectivity Evaluation of the Bida Basin in North Central Nigeria,Petroleum Technology Development Journal, 3(2): 36-64.

Ojo, O. J., Akande, S. O. (2009). Sedimentology and depositional environments of the Maastrichtian Patti Formation, southeastern Bida Basin, Nigeria, Cretaceous Research, 30: 1415-1425.

Okosun, E. A., Goro, A. I., Olobaniyi, S. B., Shekwolo, P. D.,Nwosun, J. E. (2009). Stratigraphy of Bida Formation, Bida Basin, Nigeria, Borno Journal of Geology, 4: 21-37.

Schumm, S. A. (1977). The fluvial system, New York: John Wiley and Sons, 338.

Slat, R. M. (2006). Stratigraphic reservoir characterization for petroleum geologists, geophysicists, and engineers. Hand book on petroleum exploration and production 6. Amsterdam, Elsevier, 478.

Tyler, N., Barton, M. D., Finley, R. J. (1991). Outcrop Characterisation of flow unit and seal properties and geometries, Ferron Sandstone, Utah. Paper SPE 22670, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6 – 9, 1991.

Udensi, E. E., Osazuwa, I. B. (2004). Spectral determination of depths to magnetic rocks under the Nupe Basin, Nigeria, Nigeria Association of Petroleum Explorationists Bulletin, 17: 22-37.

Weber, K. J., van Geuns, L. C. (1990). Framework for constructing clastic reservoir simulation models, Journal of Petroleum Technology 42(10): 1248-1297.

Xue, P. (1986). A point bar facies model-Semi-communicated sand body: Proceedings of Society of Petroleum Engineers, International Meeting on Petroleum Engineering, SPE Paper 14837, 103–115