FACIES ARCHITECTURE AND CHARACTERIZATION OF FLUVIAL DOMINATED SANDSTONES OF NORTHERN BIDA BASIN, NORTH-CENTRAL NIGERIA

FINAL REPORT SUBMITTED TO THE UNIVERSITY BOARD OF RESEARCH (UBR), FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA

BY

OKOSUN, E. A., GORO, A. I., WAZIRI, N. M. and AKANDE, W. G.

DEPARTMENT OF GEOLOGY
FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA

2016

Abstract

This research characterized the reservoir geometry and architecture of fluvial dominated sandstones of the northern part of Bida Basin, North-central Nigeria. Detailed regional field studies were carried out and good snap shots of the vertical profiles of outcrop sections were taken at various locations visited. A careful study at an outcrop and reservoir scales as well as on photomosaics led to recognition of various architectural elements such as channel elements (CH), downstream accreting macroforms (DA), sandy bed forms (SB), lateral accretion deposit (LA) and overbank fines (OF), which record varied deposition and infilling mechanisms within the channel confines and adjacent sub-environments. The sandstone geometry and dimensional analyses revealed e average channel width-to-depth (W/D) ratios of 36.45, 19.37, 32.93 and 18.53 from channelized sand bodies in Manigi, Bida and Rabba areas respectively, and these values indicate that channel elements in these areas were generally mobile channels were filled by a process of channel migration or switching within a single major channel. The architectural element analyses show that reservoir architecture is scale dependent. Thus, on an inter-well to field scale, three reservoir architectures are recognized in the study area, namely: reservoir architecture 1 (mainly layer cake), reservoir architecture 2 (mainly jigsaw puzzle) and reservoir architecture 3 (labyrinth) style. Layer cake reservoir architecture is exemplified by Rabba outcrop, jigsaw puzzle reservoir system is illustrated by potential reservoirs in Kawo area, and labyrinth architectural styles characterizes Manigi's outcrop. This range of reservoir systems suggests that the potential reservoirs for hydrocarbons in the northern Bida Basin could be complex and far from simple, and that a variety of reservoir properties is not impossible. It could be concluded from the field evidences that the porosity-permeability (poroperm) values, vertical sweep efficiency, production performance and ultimately hydrocarbon recovery factors may be drastically reduced as one moves hydrocarbon production from layer cake through jigsaw puzzle to labyrinth reservoir system (e.g. from Rabba via Kawo to Manigi type reservoirs). The study recommends that an adequate knowledge and recognition of the reservoir architectural styles are critical to designing the initial field development plan (FDP) at the development phase in exploring for and production of hydrocarbon in the northern part of Bida Basin.

Table of Contents

List of Figures

List of tables

Acknowledgments

The authors thank the Tertiary Education Trust Fund (TETFUND) for the financial support to accomplish this work. We also appreciate the effort of the University Board of Research, Federal University of Technology, Minna for facilitating the release of the grant.

1. INTRODUCTION

In order to increase the treasure base of the country, the Federal Government of Nigeria has recently focused its attention on exploration for petroleum in the inland basins. Petroleum potentials of the Maastrichtian Bida Basin has been established by the existence of source rocks with great potential for gas and little oil (Obaje et al., 2013; Akande et al., 2005; Braide, 1992). The potential reservoir rocks are the sandy portions of Bida/Lokoja and Enagi/Patti formations while the potential regional seal is the Enagi/Patti Formation, and the potential traps were discussed by Braide (1992).

The mode of transport and deposition of sedimentary rocks are not uniform in nature. The result is that different processes deposit pockets of sandstones (reservoir rocks) and mudstones (non reservoir) in various parts of the broad environment. In reservoir studies, these sand bodies are referred to as architectural elements. The distribution of architectural element leads to inhomogeneity/heterogetneity at various scales. The scales range from microscopic through mesoscopic to macroscopic (inter-well scale) and megascopic (field scale) (e.g. Slatt, 2006).Tools such as seismic data, well log data are used in the industry to provide information about the expected heterogeneities within the reservoirs. It is often very difficult to assess these heterogeneities at inter-well scale due to limitations imposed by vertical and lateral resolution of these tools. Outcrop data are therefore more useful for providing this information to the petroleum engineers.

Most previous works in this basin provided information based on the general sedimentology and stratigraphy as well as their reviews (e.g. Adeleye, 1987 and Zaborski, 1998). Of importance to reservoir studies are those of Braide (1990, 1992) and Okosun et al. (2009) where detailed facies studies were carried out. Field outcrop studies using the concept of architectural elements which is useful for reservoir studies were carried out in parts of the basin (e.g. Goro et al., 2014; Goro et al., 2015). The predominant architectural elements include downstream accretion, sandy bedform, lateral accretion, channel and overbank elements (Goro et al., 2014). Akande et al. (2005) mentioned the above units as potential reservoir rocks in the basin. Petr et al. (2000) obtained porosity values of 9 - 29%and permeability values of 3.3 Darcy for sediments of Lokoja Formation and sandy parts of Patti Formation exposed in southern Bida basin using Hezan and Bayer, as well as Sherpherd's formula. These values were based on statistical treatment of grain size data which may not be reliable unless if no other data is available.

The present work seeks to assess reservoir heterogeneities at inter-well to field scale within the potential reservoir rocks of the Bida basin based on regional field outcrop studies covering the northern part of the basin (Fig. 1). Data from this study is useful at exploration, appraisal and even production phases as it is capable of generating required inputs for static reservoir model which is to be updated as dynamic data such as pressure becomes available when the basin is fully developed and hydrocarbons are produced.

The objectives include:

(1) Documentation of sand body geometry within the sediments of Northern Bida Basin

(2) Determination of reservoir architectural types in the potential reservoir analogues of the Northern Bida Basin

(3) Assessment of possible effects of reservoir architectural types on reservoir performance at production, and recovery stages.

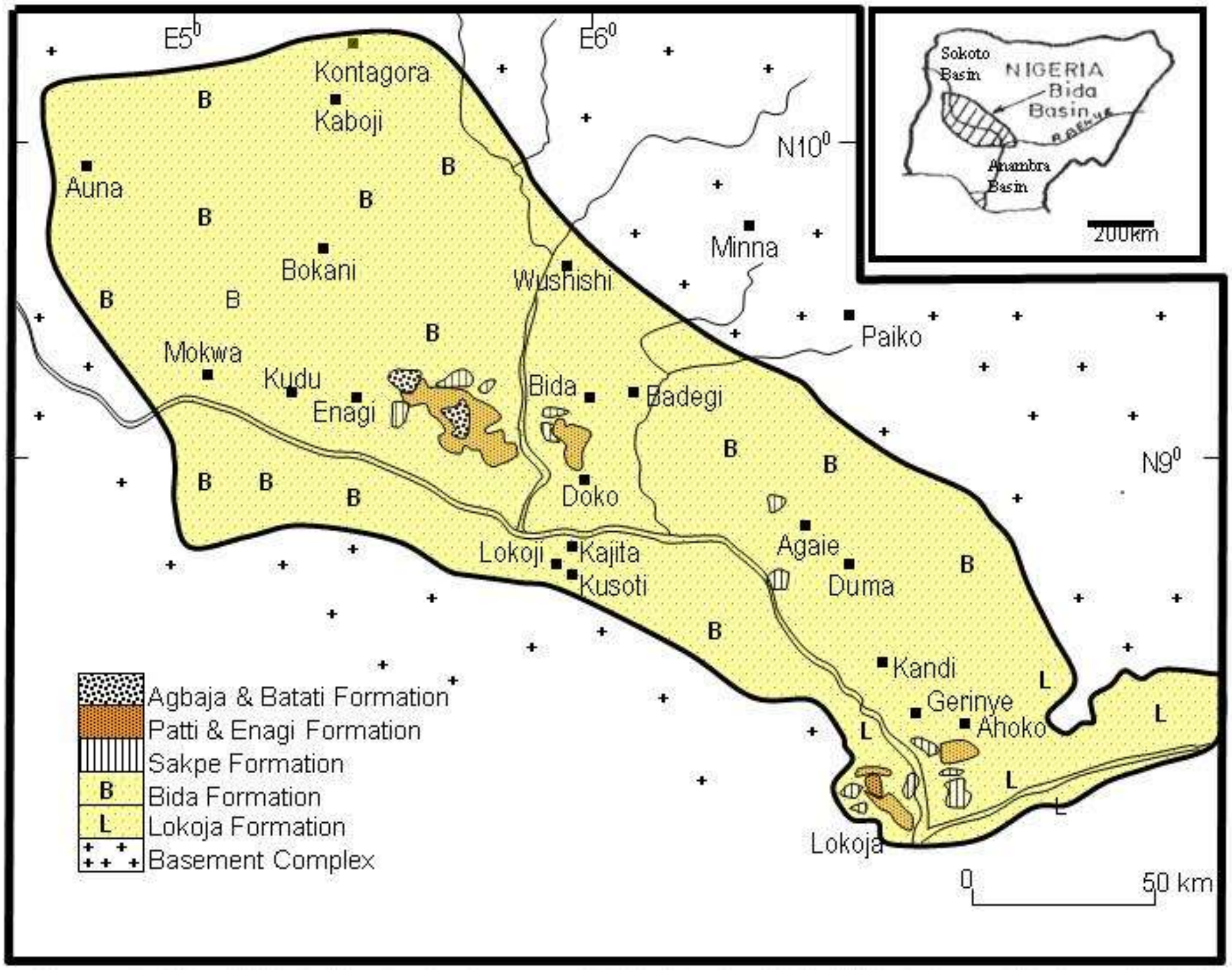

Figure1. Simplified Geological map of Bida Basin (Modified from Adeleye, 1976).

2. METHODOLOGY

The report is based on regional field outcrop studies covering the northern part of the Bida Basin. Representative well exposed outcrops were selected from the different stratigraphic levels of the sedimentary units. The areas mapped include Manigi and Kawo along Mokwa – Tegina – Kaduna road, Doko and Jima near Bida town, Kutigi, Enagi, Rabba, and Jebba section near Mokwa town.

In all localities visited, the stratigraphic position, geometry and size as well as the architectural elements represented by the sandstone and mudstone units were carefully assessed. The architectural elements were delineated using the concept of Mial (1985, 1996, 2006). Sand body geometries and size were assessed by measuring the depth and width of all identified architectural elements. This is achieved by tracing and measuring their bounding surfaces with the aid of measuring tape. The stacking pattern of the sand-bodies was also assessed in the field and good quality camera was used to obtain pictures. The outcrop pictures were processed in the laboratory and photomosaics showing lateral and vertical termination of the identified boundaries between the architectural elements were marked.

The juxtaposition of the sandstone and mudstone units was interpreted by comparing with the three main reservoir models that are in common use in the oil industry to assess degree of compartmentalization of reservoirs. The scale considered in this report are the inter-well to field-scale which highlights reservoir heterogeneities ranging from approximately 0.3 – 10 km.

3. RESULTS AND DISCUSSION

3.1 Sandstone Body Geometry and Dimensions

The geometry of sandstone bodies encountered in the study area is rather diverse. In some localities sandstone bodies are channelized while in others they are blocky and sheet-like. Some measurements of Channel width (W) and Channel depth (D) made in localities where the channel geometries are much clearer and the estimated dimensions are shown in Table 1. The table shows that Width–to–depth (W/D) ratios for various localities generally range from 3.75 to 95.29, and the averages for Kawo, Manigi, Bida and Rabba are 36.45, 19.37, 32.93 and 18.53 respectively. It is noteworthy that the geometry of the sandstone bodies in Doko, Jima, Kutigi and Enagi is not well defined and this made observation and estimation of channel dimensions almost practically impossible.

Due to wide variations in the geometry of channel-fill which normally constitute the best reservoirs, Friend (1983) proposed a classification into three main types of geometry: Fixed channels (W/D ratio <15), mobile channels (W/D ratio = 15 to 100) and sheet sandstones (W/D ratio > 100). The average W/D values of 36.45, 19.37, 32.93 and 18.53 recorded for Kawo, Manigi, Bida and Rabba show that the channel elements are generally mobile channels that have been filled by a process of channel migration or switching within a single major channel. The channel fills are complex and typically include elements such as DA, LA and SB (e.g., Fig. 2). It is important to stress that in some cases, the OF may fill abandoned channels such that they show the characteristic concave-up basal contact and lensoid geometry of the channel as shown in Fig. 2.

Table 1: Channel width – to – depth ratios for parts of the northern Bida basin sedimentary succession.

Locality	Channel width (W) (metres)	Channel depth (D) (metres)	Width–to–depth (W/D) ratio	Average W/D ratio

Kawo	100	3.1	32.26	36.45
	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	
Manigi	22.5	0.6	37.50	19.37
	25	1.1	22.73	
	2.5	0.4	6.25	
	2.2	0.2	11.00	
Bida	53	1.5	35.33	32.37
	58	1.9	30.53	
Rabba	3.0	0.38	7.89	18.53
	35	1.2	29.17	

3.2 Reservoir Architectures and Heterogeneities

This study confirms the presence of channel elements (CH), downstream accretion macroforms (DA), sandy bed forms (SB), lateral accretion deposit (LA) and overbank fines (OF) within the stratigraphic successions of the northern Bida basin. Detailed description of these architectural elements was presented by Goro et al. (2014), Okosun et al. (2015) and Goro et al. (2015). Field investigation of the lateral and vertical distribution and connectivity of the identified sand bodies (sandy architectural elements) at macroscopic to megascopic scale show that they can be described in terms of three types of broad reservoir architecture.

3.2.1 **Reservoir Architecture 1**

The sand body distribution in this type of architecture is dominated by the SB and DA elements with subordinate OF elements. They occur at the lower part of the study interval comprising the Doko Member of Bida Sandstone (Adeleye, 1974). The reservoir architecture show distinctive features of the layer cake reservoir geometry of Weber and van Geuns (1990) at both inter-well and field scales. This is because the reservoirs are characterized by lateral continuity of the sand bodies, gradual lateral changes in bed thickness and inherent reservoir properties.

A well-exposed example of this architecture type is exposed at Rabba locality near Mokwa town where the sand bodies (CH) and overbank deposit (OF) have lateral variation in continuity and thicknesses of the beds (Fig. 1). For instance, while the upper erosive-based channelized sand body thins out in both directions, the lower channelized unit gradually decreases in thickness from left to right, and the overbank deposit (OF) has its thickness decreasing leftward. As exploration well becomes available in this part of the basin, this reservoir architecture will make both external and internal well-to-well correlation comparatively simple and may allow a realistic reservoir modeling during the appraisal stage.

3.2.2 Reservoir Architecture 2

The reservoir architecture here can be treated as a layer cake at field scale but as a jigsaw puzzle at an inter-well scale. This is because the reservoirs are often characterized by complex, cross-cutting relationships.

As exploration well becomes available in this part of the basin, this reservoir architecture will make correlation and delineation of general zones of high permeability relatively simple but internal correlation will be more difficult. The reservoirs here are usually compartmentalized, and it is this reservoir segmentation as well as abrupt textural contacts that guide the fluids flow.

A road-cut outcrop at Kawo along Mokwa-Tegina-Kaduna Expressway exemplifies this reservoir architecture. At a megascopic scale, the sandstone bodies and associated overbank deposit (fines) generally appear as having a layer cake reservoir system. However, at a macroscopic scale (individual reservoir scale), one can observe a lateral cross-cutting relationship (multi-lateral) and vertical stacking of sandstone and/or abandoned channels (multi-storey) among the sandstone bodies (Fig. 2).

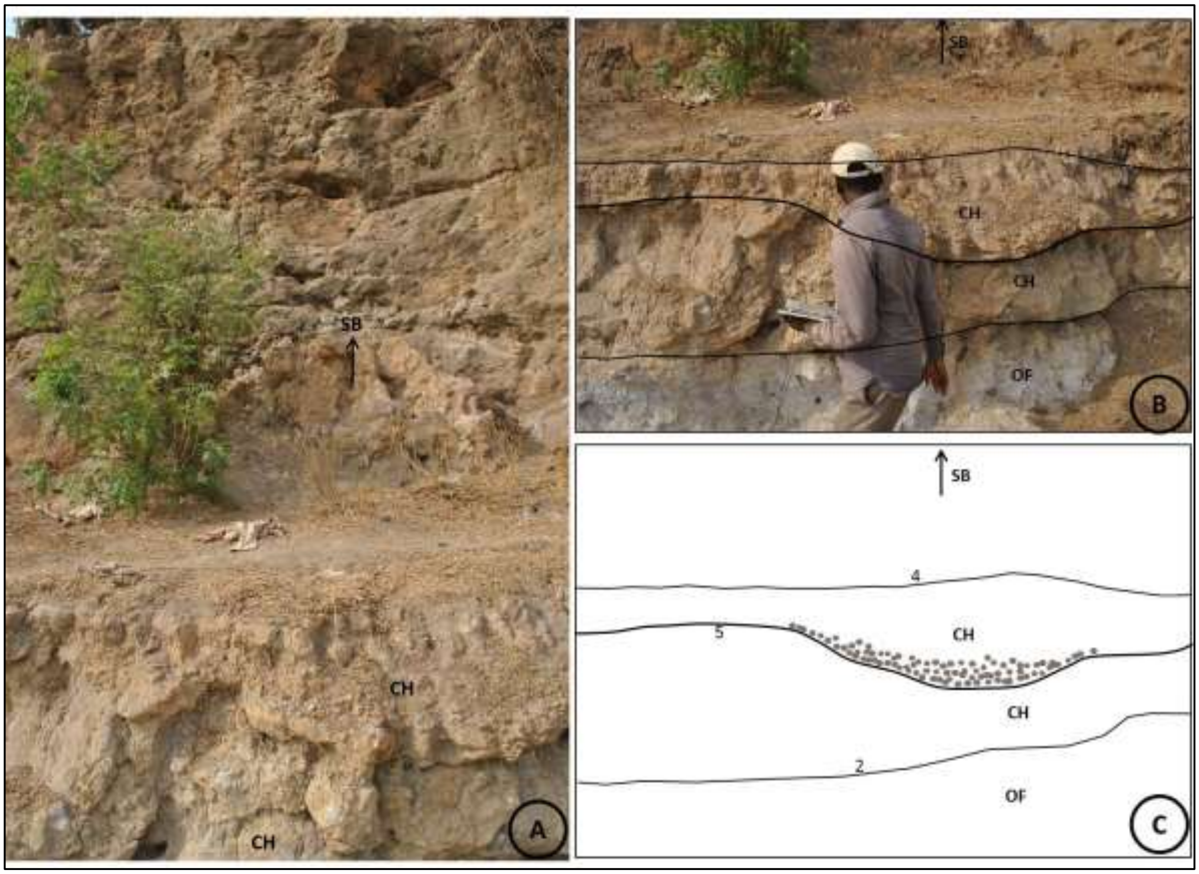

Figure 2: A. Photo of the outcrop exposed along a cliff at Rabba village in northern Bida basin (Left), B. Enlarged photo of the lower part of Photo A (Right, Upper) and C. the sketch interpretation of the observed architectural elements in Photo B (Right, Lower).

3.2.3 Reservoir Architecture 3

In this reservoir architecture the overbank element becomes very important, because the sand bodies (permeable units) are either partially or completely isolated or engulfed by overbank deposits. This broad architecture is typical of the labyrinthine reservoir type, it is well exposed in Manigi's outcrop (Fig. 3). Upon the availability of exploratory and/or production wells in this part of the basin, both internal and external well-to-well correlation will be rather difficult because the dimensions of labyrinthine units may be significantly less than spacing of test or monitor wells. Quantification of sand-body distribution and interconnectivity, which is a necessity for input data to flow simulation models, may require statistical methods/treatments for this reservoir architectural type.

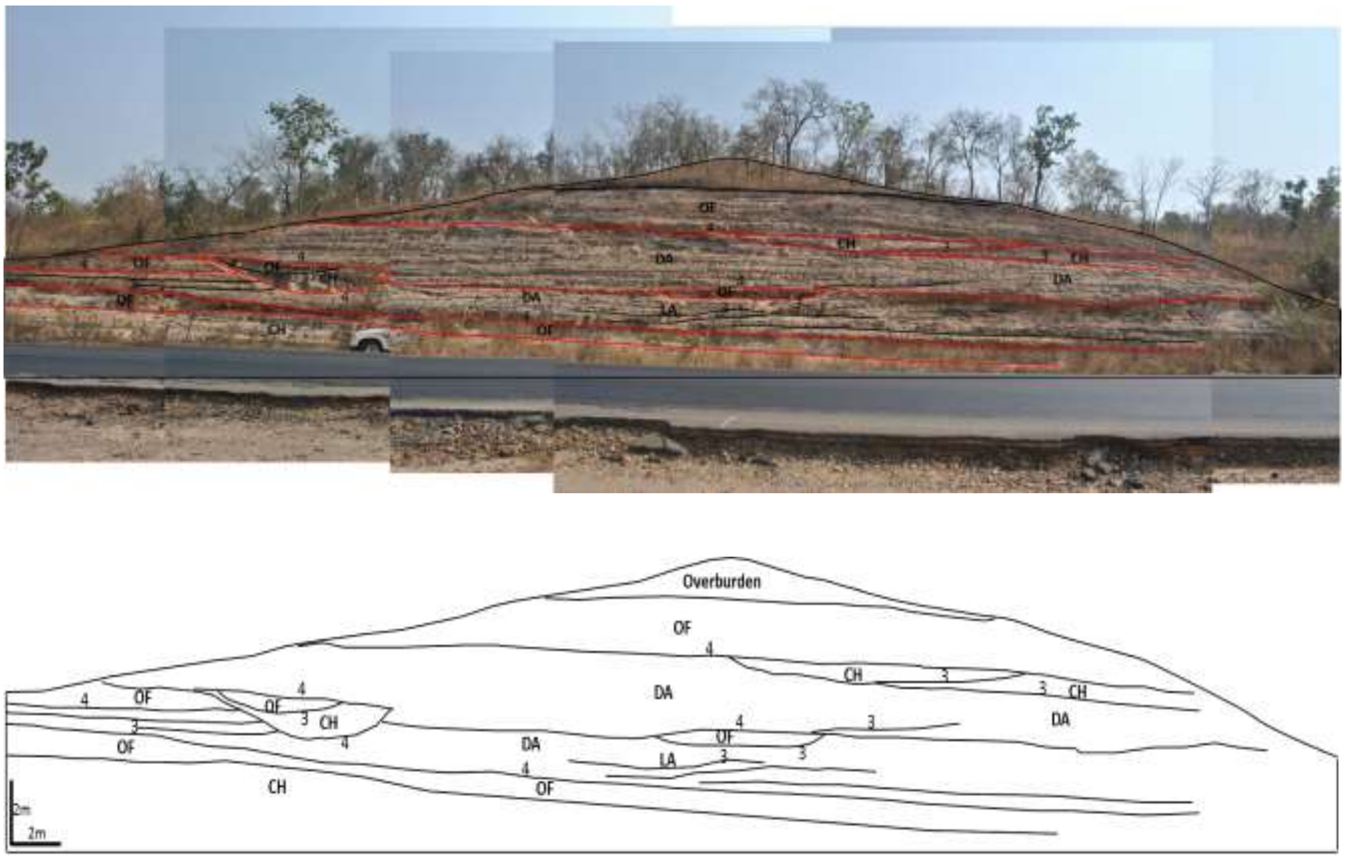

Figure 3: Photomosaic of the road-cut outcrop near Kawo, northern Bida basin (Upper), and the sketch interpretation of the observed architectural elements (Below).

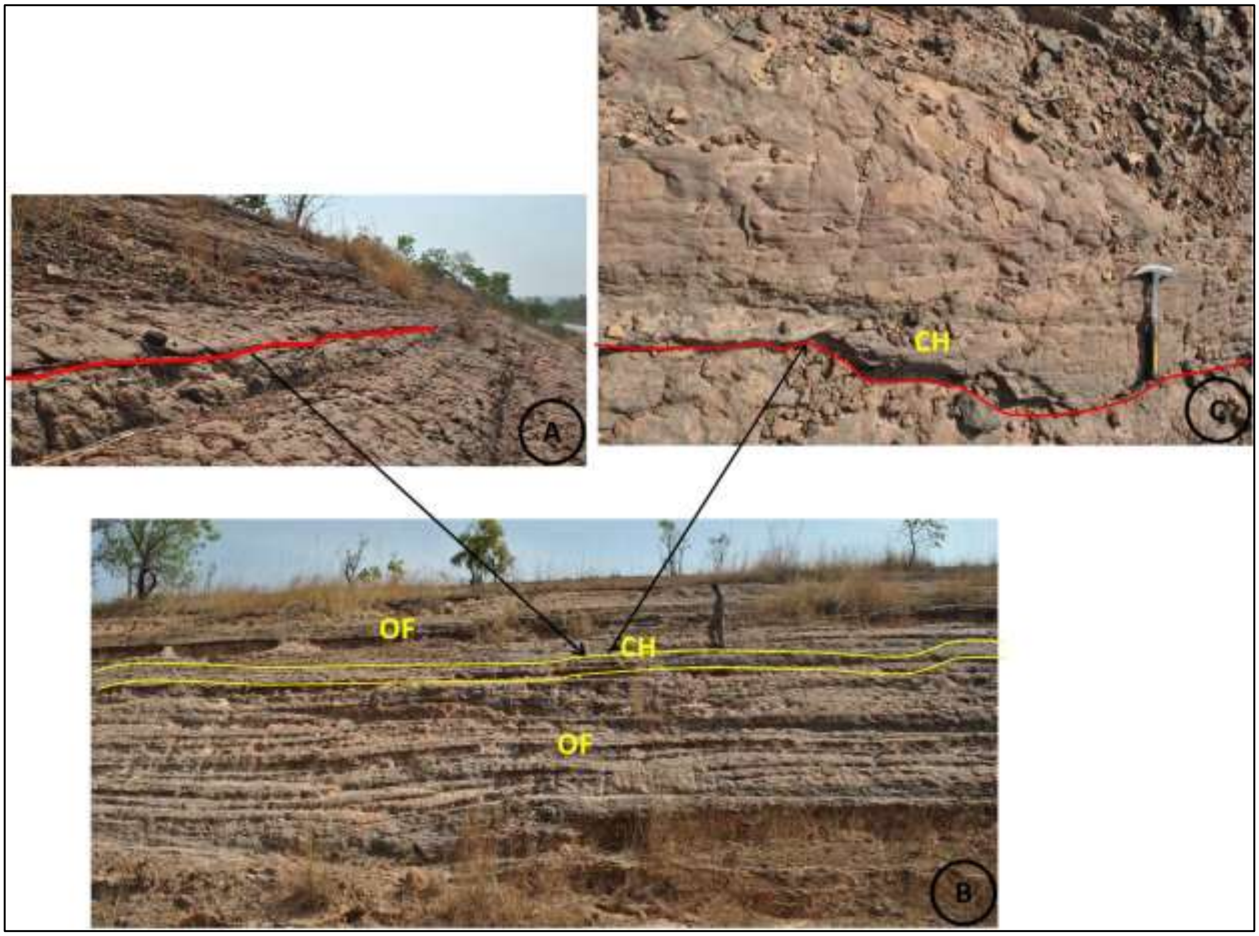

Figure 4: Photo of the road-cut outcrop at Manigi locality in northern Bida basin: B is an enlarged 2D version of A while C is a closer view of the channel architectural element.

3.3 Implications for Reservoir Performance and Hydrocarbon Recovery

The reservoir architectural styles and heterogeneities observed in this study have several implications for reservoir performance, and hence a first order control on the ultimate hydrocarbon recovery. For example, in Kawo as well as Doko areas, fining-upward cycles were observed and in some cases sandstones become progressively thinner bedded stratigraphically upward. The implication is that they will also become progressively less permeable upward so that during production as well as waterflood process, both gravity and higher permeability toward the bottom will pull water down (Lassiter *et al*., 1986; van de Graaff and Ealey, 1989) and this will result in slower rate of drainage and waterflood, and hence poor and inefficient vertical sweep may perhaps be expected.

For jigsaw puzzle reservoirs typical of Kawo area, where there are unusual high permeable and perhaps fractured zones especially those caused by channeling and fracturing often referred to as 'thief zones', there will be uneven sweep during waterflooding (reservoir management phase) leading to early water break through. Muggeridge *et al.* (2014) noted that 'thief zones' are one common adverse manifestation of geological heterogeneity, where the injected water flows preferentially through these zones, bypassing volumes of oil contained in the lower permeability portions of the reservoir. This may result in early water production along with the oil and a reduced recovery factor. Equally important are the local baffles, represented by overbank fines (OF) as well as mud drapes between lateral accretion surfaces (Goro et al., 2015), within the sand bodies that are capable of making some hydrocarbons to be bypassed during waterflood process. It is therefore of paramount importance to incorporate information on reservoir architecture during well design and other engineering processes to develop and produce hydrocarbons from the potential reservoirs in Kawo area.

At the extreme case, the potential reservoir at Manigi which displays labyrinth architectural style may be extremely difficult to produce hydrocarbons. This is because labyrinth reservoirs with partially/completely isolated channelized sand bodies are characterized by poor aquifer support and anisotropy due to orientation of the flow units; poor drainage and rapid reservoir depletion resulting from considerably low net-to-gross (N/G) ratio reservoir units. This scenario could lead to poor reservoir performance, and drastically reduced recovery factor.

4.0 CONCLUSIONS

This study characterizes the reservoir architecture of fluvial dominated sandstones of northern Bida Basin, North-central Nigeria. Extensive regional field outcrop studies led to delineation of various architectural elements such as channel elements (CH), downstream accreting macroforms (DA), sandy bed forms (SB), lateral accretion deposit (LA) and overbank fines (OF). The sandstone geometry and dimensional analyses reveal that Manigi, Bida and Rabba areas have channel elements which are generally mobile channels that have been filled by a process of channel migration or switching within a single major channel, and that in some cases, the OF may fill abandoned channels such that they show the characteristic concave-up basal contact and lensoid geometry typical of fluvial channels.

The architectural element analyses show that on an inter-well to field scale, three reservoir architectures are present in the study area, namely: reservoir architecture 1 (mainly layer cake), reservoir architecture 2 (mainly jigsaw puzzle) and reservoir architecture 3 (labyrinth) styles. Layer cake reservoir architecture is exemplified by Rabba outcrop, jigsaw puzzle reservoir system is illustrated by potential reservoirs in Kawo area, and labyrinth architectural styles characterizes Manigi's outcrop. This range of reservoir systems indicates that the potential reservoirs for hydrocarbons in the northern Bida Basin are rather complex and far from simple, and that a spectrum of reservoir properties is possible. It could be concluded from the field evidences that the porosity-permeability (poroperm) values, vertical sweep efficiency, production performance and ultimately recovery factors may be drastically reduced as one moves hydrocarbon production from layer cake through jigsaw puzzle to labyrinth reservoir system (e.g. from Rabba via Kawo to Manigi reservoirs).

The work is critical to designing the initial field development plan (FDP) at the development phase in exploring for and production of hydrocarbon in the northern part of Bida Basin because it provides basis for some key parameters which could be integrated with subsurface data from the seismic, wireline logs and drill core samples to build the FDP.

REFERENCES

Adeleye, D. R. 1989. The Geology of the Mid-Niger Basin. In: Kogbe, C. A. (Ed.), Geology of Nigeria, 2nd ed. Elizabethan Publishing Co., Lagos, pp283–287.

Akande, S.O., Ojo, O.J. and Ladipo, K; 2005. Upper Cretaceous sequences in the southern Bida Basin, Nigeria. A Field guidebook.Mosuro publishers, Ibadan, 60pp.

Braide, S. P. 1992a. Syntectonic fluvial sedimentation in the central Bida Basin. Journal of Mining and Geology **28**, 55–64.

Braide, S. P. 1992b. Geologic development, origin and energy mineral resource potential of the Lokoja Formation in the southern Bida Basin. Journal of Mining and Geology 28, 33–44.

Friend, P.F., 1983, Towards the field classification of alluvial architecture or sequence, in Collinson, J.D., and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 345–354.

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 MaastrichtianEnagi 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.

Lassiter, T. K., Waggoner, J. R., Lake, L. W. (1986). Reservoir heterogeneities and their influence on ultimate recovery, in Lake, L. W., Carroll, N. B., Jr., eds., Reservoir Characterization: Orlando, FL, Academy Press, p. 545–560.

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

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, v. **7**, p. 989–1002.

Miall, A.D., 1996. *The Geology of Fluvial Deposits*, Blackwell Scientific Publications, Oxford.

Muggeridge, A., Cockin, A., Webb K., Frampton, H., Collins, I., Moulds, T., Salino, P. (2014). Recovery rates, enhanced oil recovery and technological limits. Phil. Trans. R. Soc. A372: 20120320. http://dx.doi.org/10.1098/rsta.2012.0320

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 (ISSN 1595-9104): An International Journal; July 2013 Vol.3 No.2

Okosun, E. A., Goro, A. I., Olobaniyi, S. B., Shekwolo, P. D., and Nwosun, J. E., 2009, stratigraphy of Bida Formation, Bida Basin, Nigeria. BornoJornal of Geology, **4**, 21-37.

Slatt, R. M. (2006). Stratigraphic Reservoir Characterization for Petroleum Geologists, Geophysicists, and Engineers.Handbook of Petroleum and Production Volume 6. Elsevier: United Kingdom.

van de Graaff, W. J. E. andEaley, P. S. (1989). Geological modeling for simulation studies: AAPG Bulletin, v. 73, p. 1436–1444.

Weber, K. J. and van Geuns, L. C. (1990). "Framework for constructing clastic reservoir simulation models", JPT (October) Journal of Petroleum Technology 42(10): 1248-1253, 1296 1297.

Zaborski, P.M.(1998). A Review of the Cretaceous System of Nigeria.*Africa Geoscience Review, 5(4),* 358-483