# Outcrop-Based Sequence Stratigraphic Analysis: An Analogue for Subsurface Reservoir Geometry

***Dim, Chidozie Izuchukwu Princeton[1], Muyiwa Olawoki[2], Bertram Maduka Ozumba[3] and Chizelum Frances Madukwe[1]**

[1]Department of Geology, University of Nigeria, Nsukka, Enugu State Nigeria.

[2]Geospectra Engineering Services & Consultant Limited.

[3]Formerly, Shell Petroleum Development Company, Port-Harcourt Rivers State, Nigeria.

## ABSTRACT

Outcrop analogues have been significant in advancing our knowledge of subsurface reservoir geology. Outcrops have been proven to be useful for sequence stratigraphic study. Across Nigeria's inland sedimentary basins, however, there is little or no literature on outcrop-based sequence stratigraphic analysis. This is most likely owing to the poorly exposed rock units that may be used to identify these stratigraphic characteristics. The research focuses on using outcrop-based sequence stratigraphic analytical methods to gain insight into stratigraphic frameworks and reservoir architectures as seen on well-exposed rock successions. The emphasis will be on recognizing sand geobody size, geometry, and potential connectivity using parasequence stacking pattern, stratigraphic bounding surfaces, and associated systems tracts analysis, all of which will be observed from these outcrop analogues. This would improve our understanding of the subsurface reservoir geometry and geobody distribution from an outcrop-based sequence stratigraphy standpoint. In addition, it would serve as a valuable tool for reservoir modeling and improved hydrocarbon exploration studies across Nigeria's Inland Basins.

**Keywords:** Outcrop Analogue; Sequence Stratigraphy; Reservoir Geometry; Inland Basin, Nigeria.

## INTRODUCTION

Outcrops or rock exposures provide critical tools for sequence stratigraphic analysis. However, little or no literatures exist on outcrop-based sequence stratigraphic analysis across the inland sedimentary basins of the southeasten province of Nigeria. This probably is due to few available poorly exposed rock units that could allow for recognition of these stratigraphic features. However, this work is aimed at highlighting key tools required for robust outcrop-based sequence stratigraphic analysis in the southeastern Nigeria's inland basins to better understand subsurface reservoir geometry (Fig. 1). Emphasis will be on; i) identifying parasequences and parasequence sets, ii) establishing parasequence stacking pattern (thinning upward and thickening-upward rock successions), iii) delineating erosional surfaces (sequence boundaries?), flooding surfaces (ravinement and maximum flooding surfaces?) and iv) Recognizing associated systems tracts observed on some outcropping stratigraphic successions and understanding its implications for subsurface reservoir geometry.

### Geologic Framework

The tectono-stratigraphic evolution of the southaetern Nigeria's sedimentary basins started with the separation of the African and South American plates in the Late Jurassic, which was initiated by the Y-shaped, RRR-triple junction ridge system (Burke *et al.,* 1971; Benkhelil, 1982). Basin fills were controlled by three mega-tectonic cycles (Albian, Santonian and the Late Eocene or Early Oligocene times), which resulted to the displacement of the axis of the main basin giving rise to these three successive basins, namely, the Southern Benue Trough, the Anambra and the Niger Delta Basin (Fig. 2; Murat, 1972; Benkhelil, 1986; Petters, 1991; Nwajide, 2013). Benkhelil (1989) observed that the compressional folding during the mid-Santonian tectonic episode affected the whole of the southern Benue Trough and was quite intense, producing many anticlinal and synclinal structures. The stratigraphic successions of the Southern Benue Trough comprises of three groups namely; Asu Group, Eze-Aku Group and Awgu Group (Fig. 3: Petters, 1978; Hoque,



The authors wish to thank the Department of Geology, University of Nigeria, Nsukka, Enugu State Nigeria, Geospectra Engineering Services & Consultant Limited, Shell Petroleum Development Company, Port-Harcourt Rivers State, Nigeria and NAPE for providing the platform to present the paper during the Annual Conference.

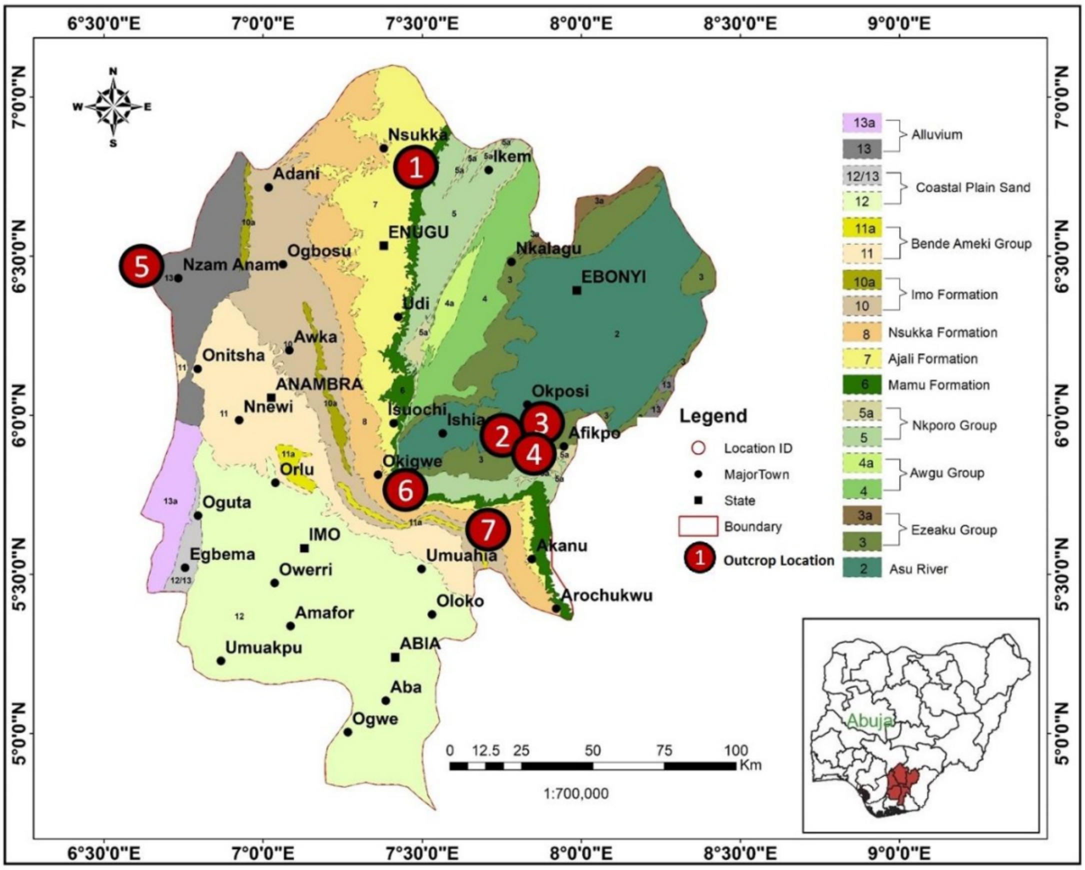


**Figure1:** Geologic map showing outcrop locations across the various lithostratigraphic units spanning through the Southern Benue Trough, Anambra Basin and Niger Delta Basin in the southeastern province of Nigeria.

1976 and Ojoh, 1992).

Deposition started in the Anambra Basin after the Santonian Orogeny in the Campanian and ended in Maastrichtian. Anambra Basin consists of two groups (Nkporo and Coal Measures Groups) that were deposited across prodelta to marginal marine/continental environments. (Nwajide, 2013; Dim *et al.,* 2017). The Niger Delta Basin structures and stratigraphy of the basin have been controlled by pre- and syn-sedimentary tectonics related to the interplay between rates of sediment supply and subsidence (Doust and Omatsola, 1990). The Niger Delta Basin stratigraphic sequence comprises three lithostratigraphic units (Akata Formation, Agbada Formation and Benin Formation) all of which are diachronous, spanning from Paleocene to Recent (Knox and Omatsola, 1989).

## METHODOLOGY

Seven outcrop sections spanning through the Southern Benue Trough, Anambra Basin and Niger Delta Basins, were utilize in highlighting bounding surfaces and recognize system tracts which are key sequence stratigraphic tools. These outcrop locations were plotted on a newly generated geologic map across the southeastern province of Nigeria (Fig. 1). Outcropping beds and bedsets successions (thinning upward and thickening-upward rock successions) were used in recognizing the parasequence stacking patterns. These stacking patterns characterised by succession of outcropping rock facies were used in establishing system tracts (lowstand, transgressive and highstand systems tracts packages?). Erosional surfaces and ravinement aided the interpretation of sequence boundaries? and flooding surfaces? (Mitchum *et al.,* 1994). A modified van Wagoner et al. (1990) workflow was utilized, and template for outcrop sequence stratigraphic analysis was developed for this study (Figs. 3 and 4).

## Results and Discussion

### Outcrop Sequence Stratigraphy

Sequences and parasequences, with the associated stratigraphic bounding surfaces and system tracts seen in outcrops are key in sequence stratigraphic analysis. These sequences are conformable, genetically related succession of strata bounded top and base by unconformities or and their related conformities, and usually deposited within a single cycle of sea level rise

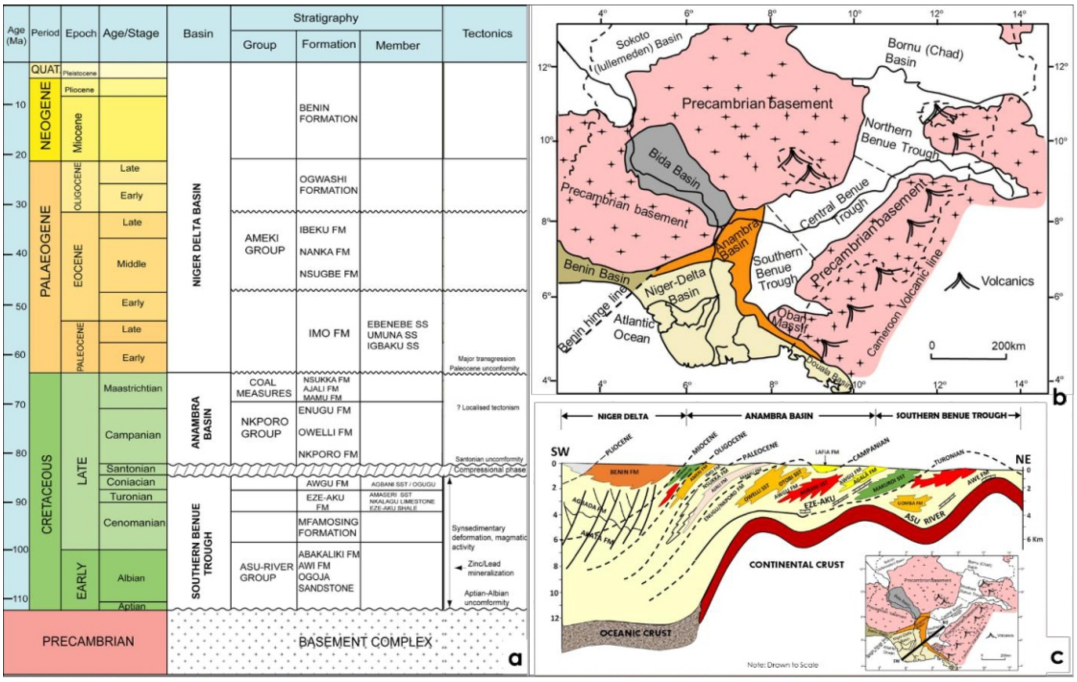


**Figure 2:** a) Geologic time scale and stratigraphic succession of the south-eastern Nigeria (after Ekwenye *et al.,* 2017). b) Map of Nigeria showing areas underlain by sedimentary and basement rocks (after Edegbai *et al.,* 2019). c) Cross section of the showing lithostratigraphic units of Southern Benue Trough, Anambra and Niger Delta Basins (after Benkhelil, 1986).

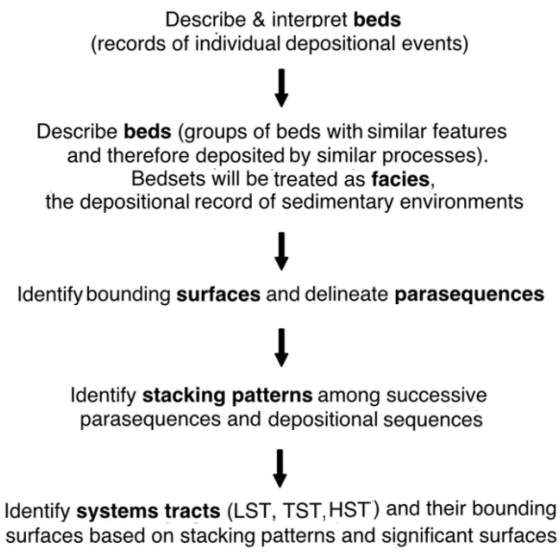


**Figure 3:** Workflow of outcrop-based sequence stratigraphic analysis (After van Wagoner *et al.,* 1990)

and fall (van Wagoner *et al.,* 1990; Catuneanu, 2006). Parasequence is a relatively conformable, genetically related succession of beds and bedsets bounded by marine flooding surfaces and their correlative surfaces (Fig. 5). These parasequences, sequences, bounding surfaces and systems tracts have been identified on outcropping units of key formations across the southern inland basins of Nigeria.

*Opi–Abakpa Nike By-pass Road-cut Section – Mamu Formation (Outcrop Location 1)*

This outcrop section is made up amalgamation of sand and heterolithic- channel fills (Fig. 6). The basal section, which comprises sand-silt-shale heterolithic channel-fill with sandier dominance of sand at the upper part showing a thickening upward sediment package form depicts progradational stacking pattern within highstand deposits (Dim, 2017; Dim et al., 2017). A sharp erosional surface with a relatively thick sand fill channel overlies this and represents a lowstand deposit, which in turn is overlain by clayey heterolithic interval that could make the transgressive packages, characterised by a thinning upward interval associated with a retrogadational stacking pattern (Fig. 6).

*Ibii sandstone ridge Section – Eze-Aku Formation (Outcrop Location 2)*

The Ibii outcrop section is characterized by interstratification of sandstone and shale units, showing a thinning-upward sand and thickening-upward shale succession (Fig 7). These thinning upward sand parasequences with a retrogradational stacking pattern, are typical of lower shoreface deposits. The thickening shale sequence depicts deposits of deep marine setting. The section shows a retrogradational stacking pattern typical transgressive package at the basal part with a thin overlying highstand package, all deposits of a deepening depositional setting (Kendall, 2007; Dim, 2017; Dim *et al.,* 2017).

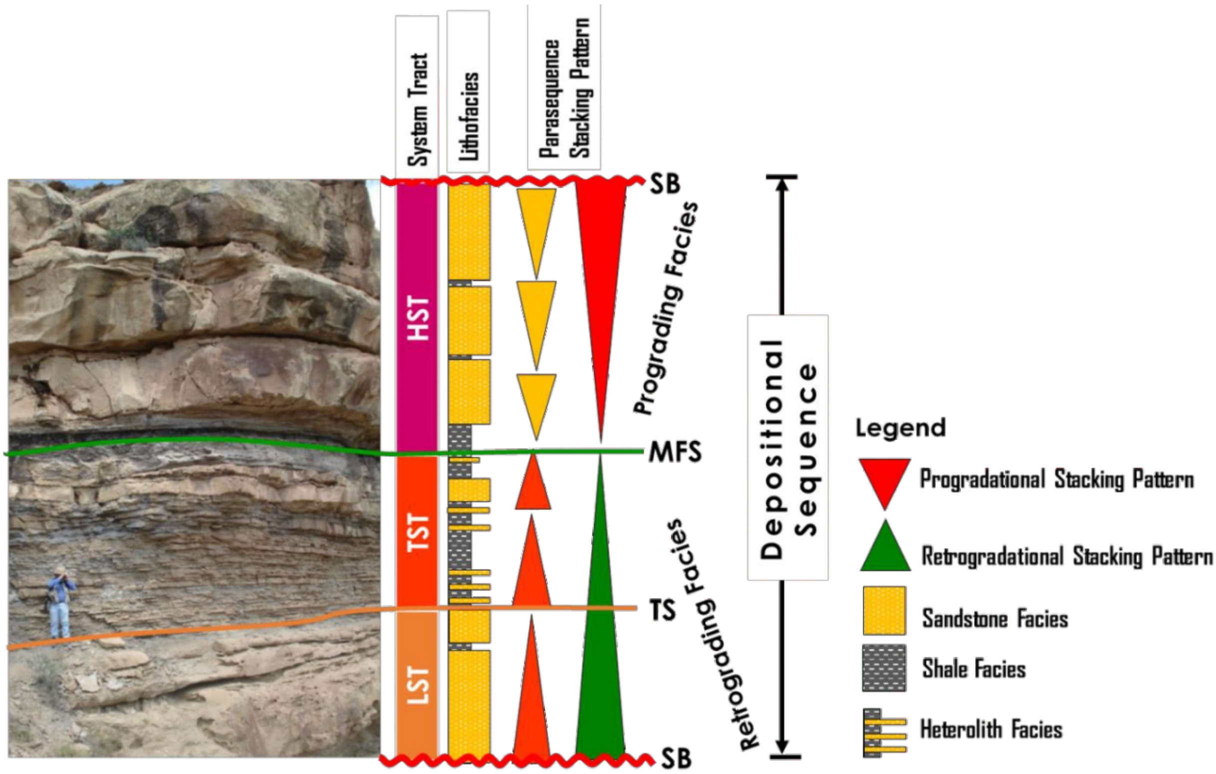


**Figure 4:** Sequence stratigraphic interpretation template for outcrop studies. Note: Outcrop section is Book Cliffs, Utah, U.S.A (Les and Rex, 2011). Abbreviation: Bounding surfaces: SB – Sequence Boundary, TS – Transgressive Surface, MFS – Maximum Flooding Surface; Systems Tracts: HST – Highstand System Tract, TST – Transgressive System Tract, LST – Lowstand System Tract.

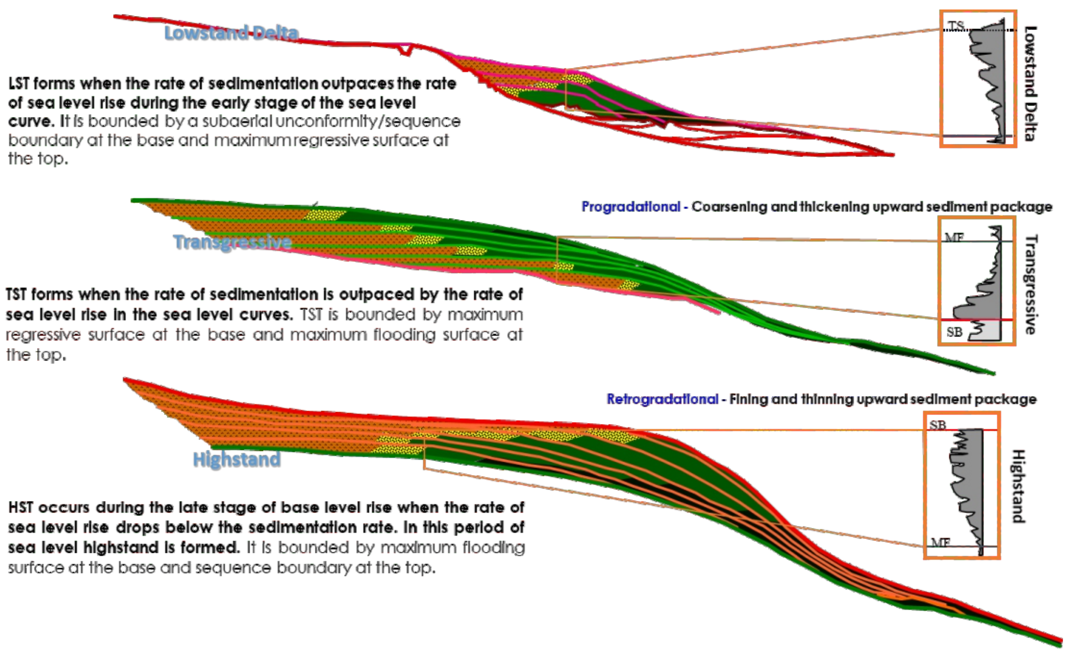


**Figure 5:** Conceptual models of parasequences and stacking patterns, bounding surfaces and systems tracts (Van Wagoner and Bertram, 1996).

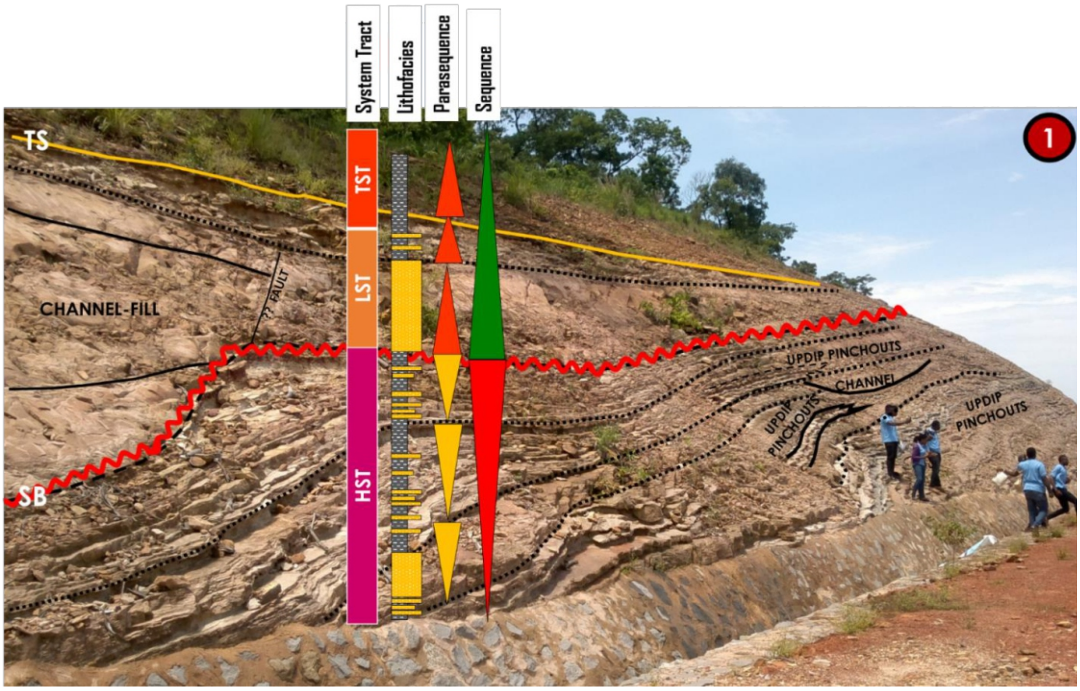


**Figure 6:** Outcrop Location 1 - Thickening and thinning succession of the Maastrichtian Mamu Formation (Anambra Basin) showing stratigraphic succession of thick interlaminated sandstones and shale/claystone units with some prominent sand-filled channels, exposed long Opi–Abakpa Nike By-pass, SE Nigeria.

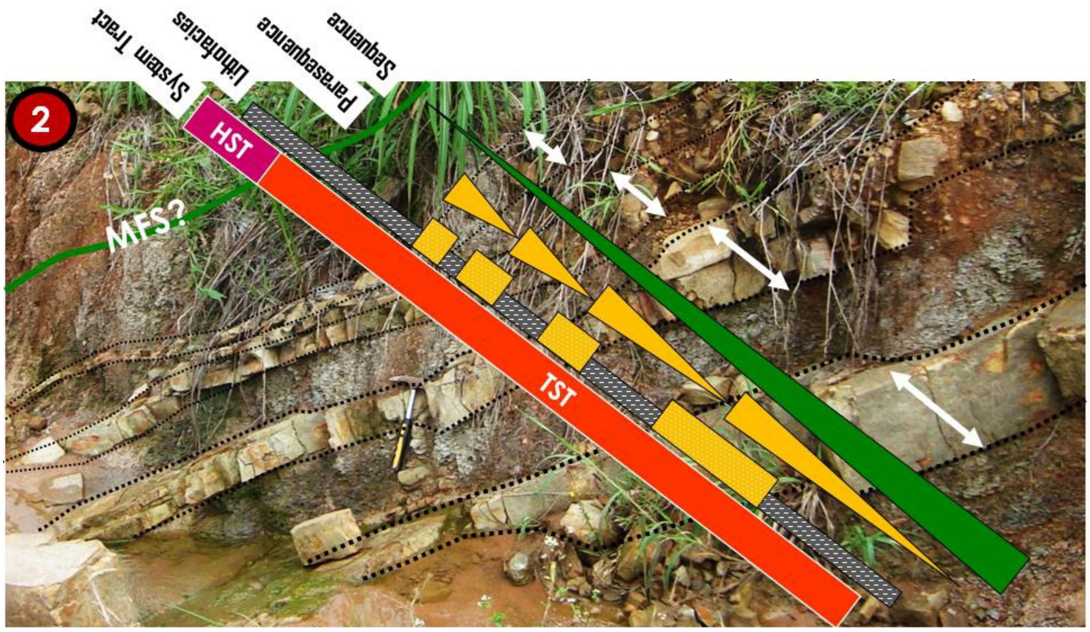


**Figure 7:** Outcrop Location 2 - Interstratification of sandstone and shale unit showing a thinning-upward sand and thickening-upward shale succession (outcrop Eze-Aku Formation exposed on Ibii sandstone ridge (Marlum Civil Engineering quarry site) off Akpoha-Afikpo road, Afikpo, southeastern, Nigeria).

*Akpoha sandstone ridge section – Eze-Aku Formation (Outcrop Location 3)*

The section comprises well-stratified sediment package of thickening and thinning upward succession (Fig. 8). Evident in this section are the tilted silty-sandstone units that are partly fractured. These siltstone and sandstone units are highly fossilferous and calcareous. These basal thickening silty-sandstone packages represent shoreface deposits during the highsand. Observable extensive erosive surface, a possible sequence boundary overlain by is seen with some thin fining upward lowstand package within a retrogradational stack typical of a transgressive deposit with a ravinement surface/transgressive surface of erosion (Dim *et al,* 2017).

*Ibii-Akpoha Section – Eze-Aku Formation (Outcrop Location 4)*

The outcropping units at Ibii-Akpoha section are characterized by thinning-upward sand succession at the lower part and a thickening upward package at the upper part of the section (Fig. 9). These are progradational and retrogradational parasequence stacks that indicates deposits in a highstand systems tract.

*Ebu Road-Cut Section (Outcrop Location 5)*

The Ebu section is characterized by channel-fill package

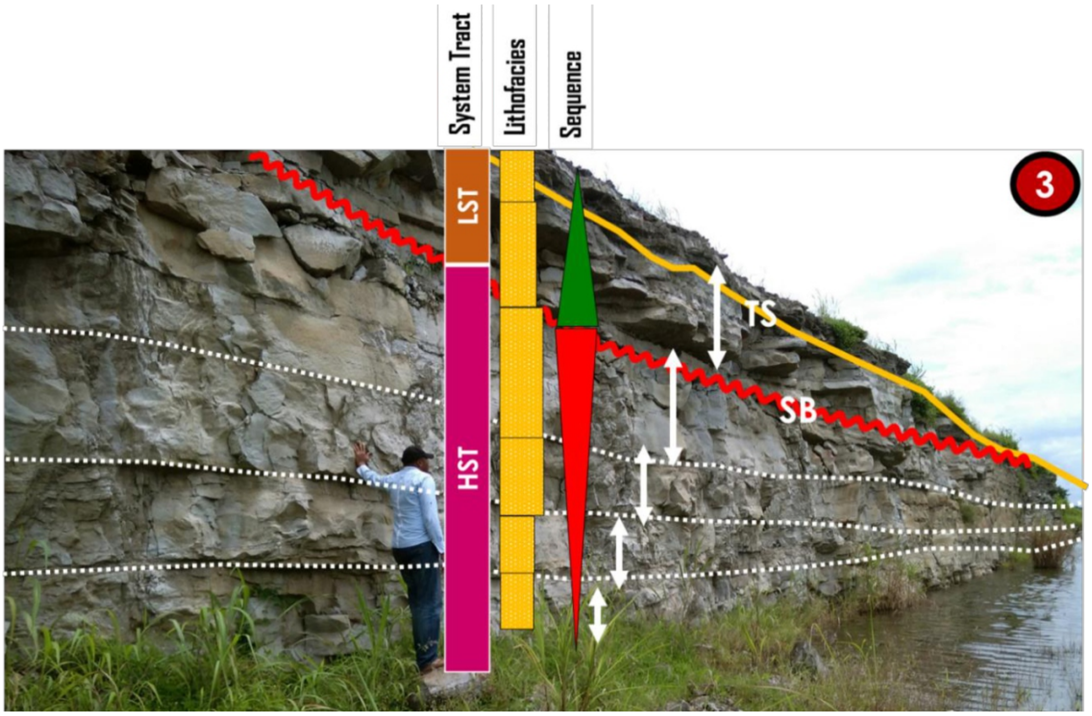


**Figure 8:** Outcrop Location 3 - Thickening and thinning upward succession of well stratified thick tilted section of highly fossilferous, calcareous silt to very fine-grained sandstone to coarse-grained sandstone, partly fractured (joints) exposed at Julius Berger Quarry along Abba Omega road, Afikpo North, southeastern, Nigeria.

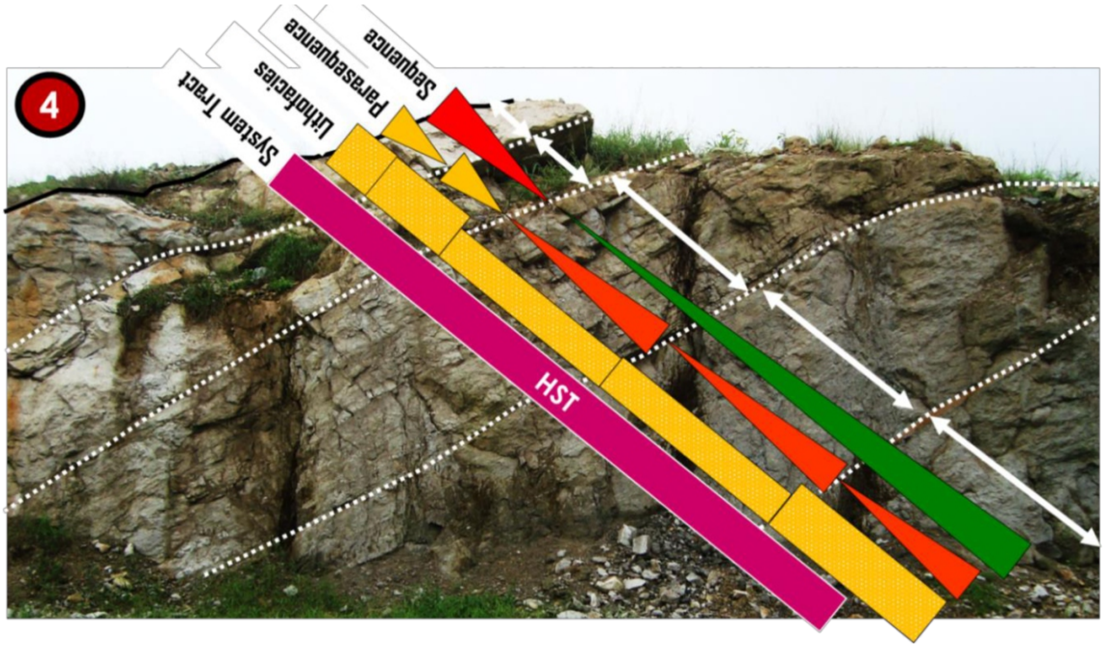


**Figure 9:** Outcrop Location 4 - Thinning-upward sand and succession of outcropping Eze-Aku Formation (Amaseri Member) exposed on Ibii sandstone ridge (Marlum Civil Engineering quarry site) of Akpoha-Afikpo road, Afikpo, southeastern, Nigeria).

with an erosive base. This partly cross-stratified channel-fill depicts a lowstand package, bounded bottom and top by sequence boundary and ravinement surface (transgressive surface) respectively (Fig. 10). The upper part of this section comprise a thin mud dominated hetrolith that belongs to the transgressive package bounded by a possible maximum flooding surface?.

*Ikpankwo Quarry section - Nsukka Formation*
The Ikpankwu section is characterized by a sandstone and shale interstratification, with a thinning upward sandstone package typical of deposit of transgressive episode (Fig. 10). These packages show a basal thick sand deposited during lowstand and a mud dominated heterolithic package of the transgressive system stand. Generally, the section shows a retrogradational stack typical of deepening depositional environment (Kendall, 2007).

*Umuasua Road-Cut section – Nsukka Formation*
The outcrop of the Umuasua section shows sediment packages deposited within the transgressive systems tract with a retrogradational stacking pattern and a highstand systems tracts with a progradational stack. The basal shale represent offshore deposits and the interstratified

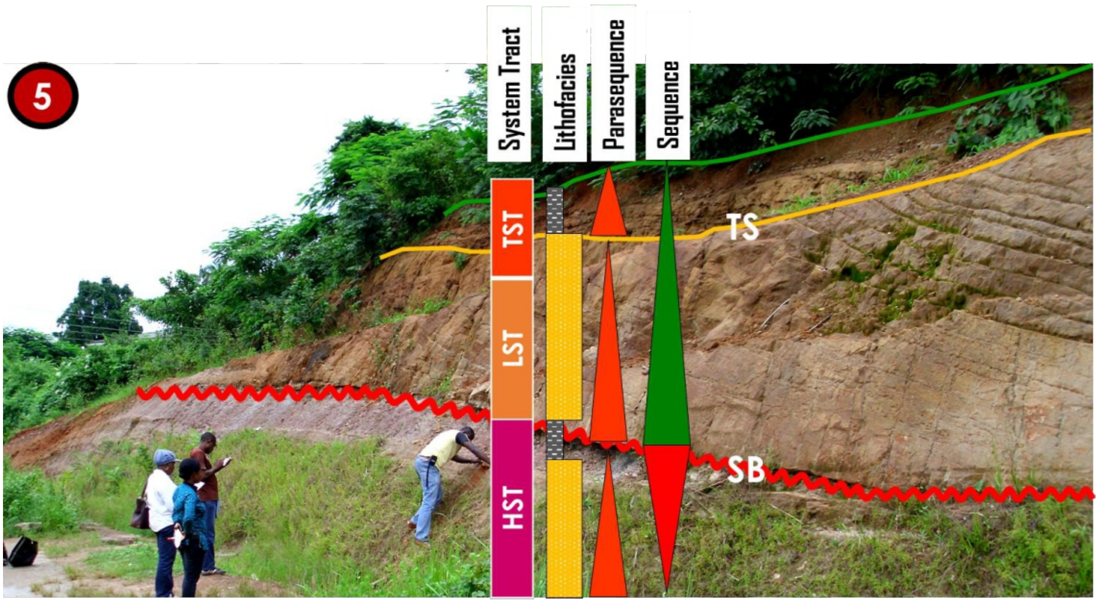


**Figure 10:** Outcrop Location 5 - Thickening and thinning upward succession exposed at Ebu, a road-cut along Abuja Road with classic channel–fill sediment package.

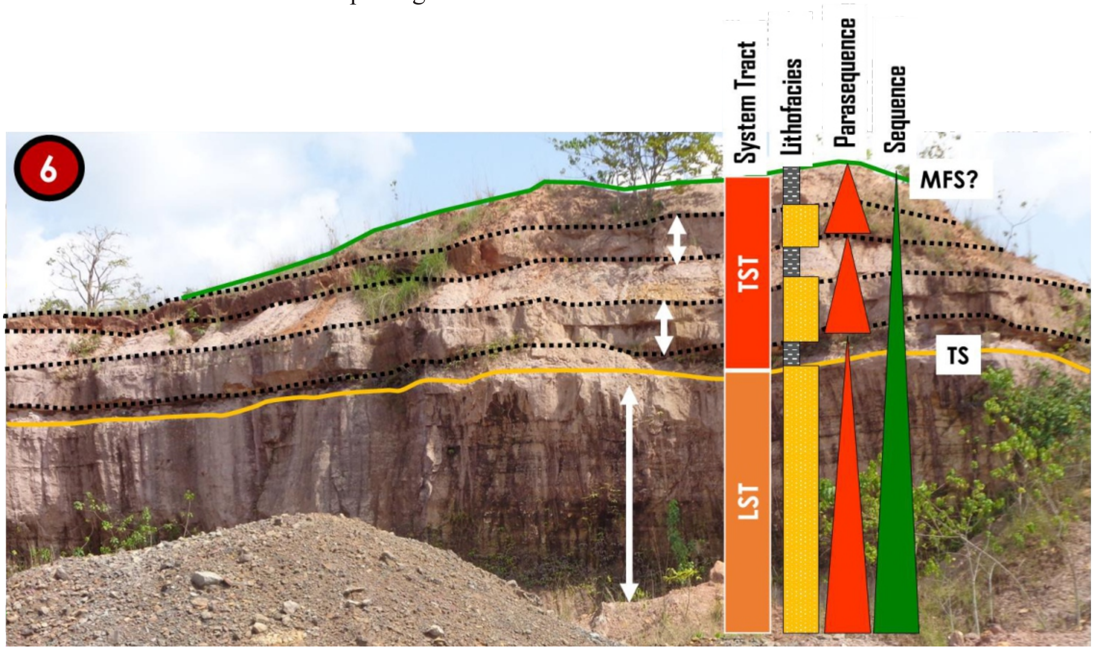


**Figure 10:** Outcrop Location 6 - Thinning upward succession of outcropping Nsukka Formation of Anambra Basin exposed at Ikpankwo quarry, off Enugu–Port Harcourt express expressway, SE Nigeria.

sandstone and thinning shale unit depicts a lower shoreface deposit capped by a sequence boundary. Overlying this package is upper shoreface sandstone deposit in the highstand. (Fig. 11).

mainly deposit of lowstand system tracts. The retrogradational and progradational packages depicts episodes of sea level rise and fall (Fig. 6; Posamentier and Allen, 1999). These channels are very small and localized

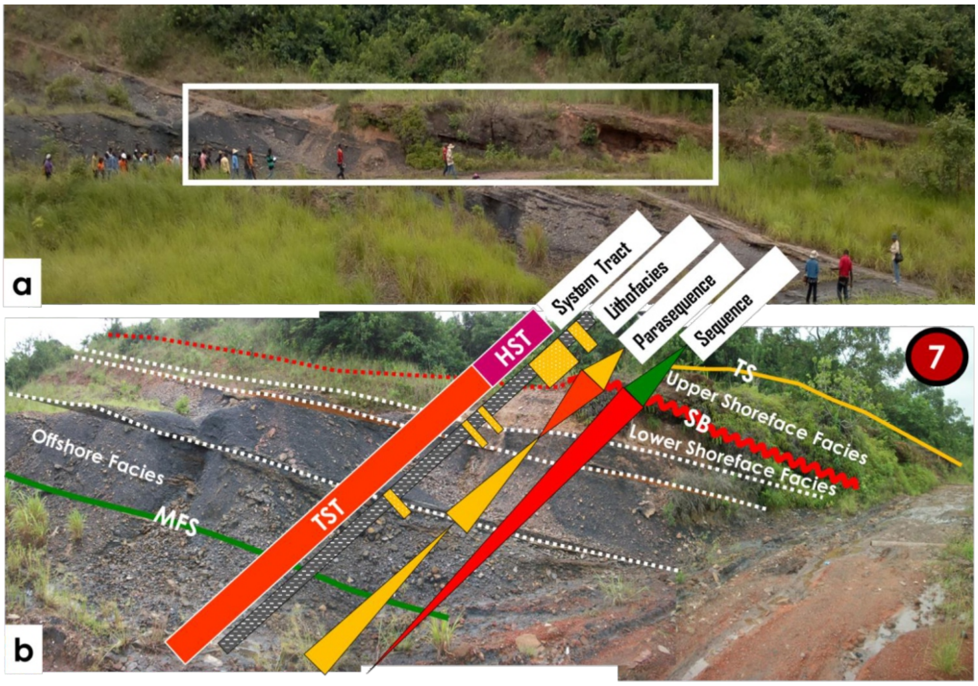


**Figure 11:** Outcrop Location 7 - Road-Cut Exposure of Maastrichtian Nsukka Formation showing thich shale unit with interstratified siltstone and sandstone units at Umuasua, southeastern, Nigeria (Note: Fig. 11b is a close-up on the white rectangle in Fig. 11a).

**Outcrop Analogue for Subsurface Reservoir Geometry**

Parasequence sets recognized in outcropping rock units give insights to stratigraphic succession, and depositional environments such as; a) finning/thinning upward facies successions (deepening upward cycles) that depicts transgressive episode and are associated with retrograding facies (Meandering, fluvial channel, Tidal point bar, Deep tidal channel fill and Tidal flat), b) coarsening/thickening upward facies successions (shoaling upward cycles) that depicts regressive episode, associated with prograding facies (Crevasse spray, River mouth bar, Delta front, Shoreface, Submarine fan lobe) (Van Wagoner, 1990; Kendall, 2007).

These outcropping sand deposits depicting various environments are replica of subsurface reservoirs. The thickening sand sequence are deposits of lower shoreface and upper shoreface have good lateral continuity (except where channel incision has occurred) with transition to lower shoreface basinward (Fig. 11; Dim *et al.,* 2017).

The exposed channel-fills, which are partly heterolithic,with sand bodies and shales vertically stacking over small thicknesses as seen in this study are (< 2km wide). With prolonged channelization, multi-story channels build up where the lateral migration of channels forms a channel sheet (Fig. 6). Channel heterolithics observed on outcrops, generally represent intervals 5 ft – 10 ft thick, with an erosional base (sequence sboundaries?). Identification of flooding surfaces (and associated shales) caps these sand dominated channels (reservoirs), whereas erosional surfaces (sequence boundaries) underlie these reservoirs.

The fining or thinning succession typical of retrogradational packages are characterized by thinning upward sandstone package (decrease in reservoir thickness) with decreasing upward grain size, and shows upward decrease in net-to-gross and reservoir quality. Reservoirs of this succession are deposits within the lowstand and transgressive systems tracts. The coarsening or thickening upward succession typical of progradational packages in a shoreface are characterized by thickening upward sandstone package (increase in reservoir thickness) with increasing upward grain size, and shows upward increase in net-to-gross and reservoir quality. Reservoirs of this succession are deposits within the highstand systems tracts (Van Wagoner and Bertram, 1996; Kendall, 2006; Dim *et al.,* 2017).

## CONCLUSION

The key to using sequence stratigraphy as a tool for interpreting outcropping sedimentary section are the major bounding and subdividing surfaces. These surfaces are commonly generated by the changes in relative sea level

In addition, parasequence sets also helps for better understanding of subsurface reservoirs characteristics. Overall, this research work presents evidence of some parasequence stacking pattern (thinning upward and thickening-upward rock successions), erosional surfaces (sequence boundaries?), flooding surfaces (ravinement and maximum flooding surfaces?) and associated systems tracts (lowstand, transgressive and highstand systems tracts packages?), observed on some outcropping stratigraphic successions that could allow for better understanding of the sequence stratigraphic framework in the southeastern Nigeria's inland basins. This would improve our understanding of the subsurface reservoir geometry and geobody distribution from an outcrop-based sequence stratigraphy standpoint. In addition, it would serve as a valuable tool for reservoir modeling and improved hydrocarbon exploration studies across Nigeria's Inland Basins.

## REFERENCES CITED

Benkhelil, J., 1982. Benue Trough and the Benue Chain. Geological Magazine, vol. 119, p.155–168.

Benkhelil, J., 1986. Structure et evolution geodynamique du bassin intracontinental de la Benoue (Nigeria). Doctoral dissertation, University of Nice, pp. 226.

Benkhelil, J., 1989. The origin and evolution of the cretaceous Benue Trough, Nigeria. Journal of African Earth Sciences, vol. 8, pp. 251–282.

Burke, K. C., Dessauvagie, T. F. J. and Whiteman, A. J., 1971. Opening of the Gulf of Guinea and geological history of the Benue Depression and Niger Delta. Nature Physical Science, vol. 233, pp. 51–55.

Catuneanu, O., 2006. Principles of sequence stratigraphy, (1st ed.) Elsevier, 375 p.

Dim, C. I. P, Onuoha, K. M, Okeugo, C. G, and Ozumba, B. M. 2017. Petroleum system elements within the Late Cretaceous and Early Paleogene sediments of Nigeria's inland basins: An integrated sequence stratigraphic approach. Journal of African Earth Sciences, vol. 130, pp. 76-86.

Dim, C. I. P. and Onuoha, K. M., 2017. Insight into sequence stratigraphic and structural framework of the onshore Niger Delta Basin: integrating well logs, biostratigraphy, and 3D seismic data. Arabian Journal of Geosciences, vol. 10 (14), pp. 1–20.

Dim, C. I. P., 2017. Hydrocarbon Prospectivity in the Eastern Coastal Swamp Depo-belt of the Niger Delta Basin – Stratigraphic Framework and Structural Styles. SpringerBriefs in Earth Sciences, Springer International Publishing AG, Gewerbestrasse, Switzerland, 71 p.

Edegbai, A.J., Schwark, L., Oboh-Ikuenobe, F.E., 2019. A review of the latest Cenomanian to Maastrichtian geological evolution of Nigeria and its stratigraphic and paleogeographic implications. J. Afr. Earth Sci. 150, 823–837. https://doi.org/10.1016/j.jafrearsci.2018.10.007.

Ekwenye, O. C., Nichols, G. J., Okogbue, C. O., Dim, C. I. P. and Onyemesili, O. C., 2017. Architecture and Reservoir Potential of a Macrotidal Estuarine System: Eocene Ameki Group, South-Eastern Nigeria. In: Onuoha, K. M. (Ed.), Advances in Petroleum Geoscience Research in Nigeria, Edition: 1, Chapter: 20, pp. 369-405. ISBN 978-1-4276-5590-5.

Hoque, M. (1976).Significance of textural and petrographic attributes of several cretaceous sandstones, southern Nigeria. Bull. Geol. Soc. India, vol. 17, pp. 514-521.

Kendall, C. G. St. C., 2003. Use of well logs for sequence stratigraphic interpretation of the subsurface. USC Sequence Stratigraphy Web. http://strata.geol.sc.edu/index.html, University of South Carolina. South Carolina.

Les, B. D. and Rex, K. (2011). Bioturbation and Its Effects on Permeability in Wave-Dominated Shoreface Rocks of the Spring Canyon Member, Blackhawk Formation, Utah, USA. AAPG Annual Convention and Exhibition, Search and Discovery Article #50425.

Mitchum, R. M., Sangree, J. B., Vail, P. R. and Wornardt. W. W., 1994. Recognizing sequences and systems tracts from well logs, seismic data and biostratigraphy: examples from the Late Cenozoic of the Gulf of Mexico. In: Weimer P, Posamentier HW (eds) American Association of Petroleum Geologists Memoir, vol. 58, pp 163–197.

Murat, R. C., 1972. Stratigraphy and Palaeogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. In: African Geology. F.J. Dessauvagie, and A.J. Whiteman, (eds). University of Ibadan Press: Ibadan, Nigeria, pp. 251–266.

Nwajide, C. S., 2013. Geology of Nigeria's Sedimentary Basins. CSS Bookshops Limited, Lagos. 565 p.

Ojoh, K. A., 1992. The southern part of the Benue Trough (Nigeria) Cretaceous stratigraphy, basin analysis, paleo-oceanography and geodynamic evolution in the Equatorial domain of the South Atlantic. Nigerian Association of Petroleum Explorationists' Bulletin, vol. 7, No. 2, pp. 131–152.

Petters, S. W., 1978. Mid-cretaceous paleoenvironments and biostratigraphy of the Benue Trough, Nigeria. Geol. Soc. Am. Bull. 89, 151–154.

Petters, S. W., 1991. Regional Geology of Africa (Lecture Notes in Earth Sciences). Springer-Verlag, Berlin 40, 722 p.

Posamentier, H. W. and Allen, G. P., 1999. Siliciclastic sequence stratigraphy: concepts and applications. Society of Economic Paleontologists and Mineralogists (SEPM), Concepts in Sedimentology and Paleontology, 7, 210 p.

Van Wagoner J.C., Bertram G.T. (eds) 1996. Sequence Stratigraphy of Foreland Basin Deposits. Outcrop and Subsurface Examples from the Cretaceous of North America. AAPG Memoir no. 64. 487 pp. Tulsa: American Association of Petroleum Geologists.

Van Wagoner JC, Mitchum RM, Campion KM, Rahmanian VD (1990). Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. American Association of Petroleum Geologists, Tulsa, p 55.

NIGERIAN ASSOCIATION OF PETROLEUM EXPLORATIONISTS

SINCE 1975