Incised Valley Depositional System of the Cretaceous Yolde Formation of the Gongola Sub-Basin Northern Benue Trough N.E. Nigeria

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Abstract—This research was carried out in the Gongola Sub-basin of the Northern Benue Trough aimed at deciphering of the paleo-depositional environment of the Yolde Formation based on facies on facies analysis. Six lithofacies were identified to include trough crossbedded sandstone facies (St), massive bedded sandstone facies (Sm), planar crossbedded sandstone facies (Sp), ripple laminated sandstone facies (Sr), parallel sandstone facies (Sl) and mudstone facies (Fm). These build into two facies association of fluvial channel and tidally influenced fluvial channel facies associations. The fluvial successions typical characterizes the lower stratigraphic horizons and their contained dominances of trough crossbedded sandstone facies with high channel to overbank facies and contained mud-clast reflecting deep, high energy braided river system. The submergences of these channels by surging sea level rise generated the tidally influenced fluvial facies association and this package characteristically defines the upper interval stratigraphic architecture of this formation, displaying occasional bi-directional current system and abundant marine ichnogenera. This architectural symmetry is reflective of an incised valley fills, developing as a consequence of Cenomanian transgressive phase induced by the mid-Cretaceous global marine transgression.

Index Terms—Benue Trough, Facies, Incised Valleys, Yolde Formation.

I. INTRODUCTION

The Gongola Sub-basin forms part of the Northern Benue Trough, trending north-south at a bifurcation from the main Arm, Muri-Lau Sub-basin with its northern boundary at Dumbulwa Bage High marking the southern boundary of the Chad Basin (Fig.1). This basin originated and evolved due to the breakage and separation of the South American plates from the African plates during the late Jurassic to early Cretaceous times, however the resulting mechanism remained controversial but with two favored opposing theories trending as an account. The rift model theory was the earliest and supported to date by several workers [1; 2; 3; 4] which indicated initiation through tensional regimes induced by mantle plume convection activities [5; 6]. Absences of boundary fault that are diagnostic to rift systems, the pull-apart model was proposed, considering the trough as of strike-slip tectonic origin, as it falls in the same orientation to the major transcurrent fault systems of the Romanche, Chain and Charcott suture zones [7; 8; 9]. The opening of the trough in the Aptian-Albian times is followed by a transgressive event that terminated in the Northern Benue Trough which is characterized by continental depositional regimes. The marine inundation of the trough commenced in the Cenomanian, depositing transitional-marine sequences of the Yolde Formation. This researched is aims to evaluate the facies and facies association of this formation at Pantami stream that represents one of its major outcrops in the Gongola Sub-basin in order to establish depositional model that characterizes its development.

II. GEOLOGIC AND STRATIGRAPHIC SETTINGS

The Benue Trough represents the Nigeria part of the rift basin that characterizes the Central West African Rift Systems that extends in NNE-SSW direction for about 1000 km in length and 50-150 km in width [3; 10]. The southern limit of this basin is the northern boundary of the Niger Delta, while the northern limit is at the Dumbulwa-Bage High, which marks the southern boundary of the Chad Basin (Fig.1.a) [11]. The Benue Trough is arbitrarily subdivided into Northern, Central and Southern Benue Trough (Fig.1.a), where the Northern Benue Trough made up of three arms is further sub-divided into the N-S striking Gongola Arm, E-W striking Yola Arm and the NE-SW striking Muri-Lau Arm [12] (Fig.1.b). The Trough host over 6000m of Cretaceous to Tertiary sediments of which those predating the mid-Santonian have been tectonically deformed, to form major faults and fold systems across the basin. The Aptian-Albian deposits is represented by the Bima Group which are the oldest sedimentary units in the Gongola Sub-basin, conformably overlying the Basement Complex Rocks (Fig.2) [13; 11; 14; 15]. The syn-rift sequences thereof is largely defined by the tectonics of the horst and graben networks and is represented by the alluvial fan-lacustrine deposits of the Bima I Formation, the lowermost in the group. This is unconformably superposed by the post-rift braided river sequences of the Bima II and III Formations [11; 14; 15]. The Yolde Formation conformably succeeds, marking the deposition of transitional-marine sequences [16] in the Cenomanian, reflecting the commencement of the mid-Cretaceous global marine transgression in the basin [e.g. 17]. This event climaxed in the Turonian and deposited the shallow marine shale and limestone sequences of the Kanawa.
Member of the Pindiga Formation [11; 18]. Regressive Sandy Members of the Dumbulwa, Deba-Fulani and Gulani sandstones conformably followed in the mid- Turonian with decelerating transgressive conditions (Fig.2) [11; 10]. Further rising relative sea levels in the late Turonian moving into the Coniacian and early Santonian led to deposition of the deep marine blue-black shales of the Fika Member, which represents the youngest units of the Pindiga Formation [11]. This marine transgression is inter-phased with compressional tectonics in the mid-Santonian [19], which resulted from changing orientation of the displacement vectors between the African plate and European/Tethys plates [20]. This event led promoted the thrusting of the pre-Maastrichtian sediments towards the western part of the Gongola Sub-basin, creating an accommodation for the deposition of the Campano-Maastrichtian regressive deltaic sequences of the Gombe Formation [21;22]. The mid-Maastrichtian is witnessed another pulse of compressional phase and it is unconformably succeeded by the deposits of the Paleogene fluvio-lacustrine Kerri Kerri Formation [23; 24] (Fig.2). The Paleogene-Neogene is characterized by volcanic events, that emplaced the Biu basaltic plateau along the eastern margin of the Gongola Sub-basin [25].

III. MATERIALS AND METHODS

Topographic, structural and geological maps of Gombe town and environs which are located within the Gongola Sub-basin were employed in the fieldwork of this research in order to identify potential areas where the Yolde Formation are well exposed. Along these well exposed outcrops identified, lithostratigraphic sections of this formation outcropping around Pantami stream (Fig. 4) were systematically logged to record data on lithologic variations, texture, bed geometry, paleocurrents, sedimentary structures and fossil content. Based on facies concept and application of Walters law in conjunction with facies relation provided by sedimentologic studies on ancient and modern environment, these data were utilized in designating lithofacies assemblages representing particular depositional environment. Paleocurrent measurements were also carried out on the abundant planar and trough crossbedded sandstones and the various orientations determined were used to evaluate provenance and hydrodynamic processes [26]. The dip and strike as well as the azimuth of the crossbeds were measured using compass clinometers in this analysis, and considering that the regional dips of the beds are generally greater than 100, tilt correction was also carried out on the values using the procedure adopted by [26].

IV. RESULTS

A. Facies Analysis

1) Facies St: Trough crossbedded sandstone facies

This lithofacies composes of medium – very coarse grained sandstone, dominantly poorly sorted with sub – angular to sub – rounded grains, ranging in thickness from 1 – 2m. They commonly compose of erosional basal
boundaries typically associated with mudclast and streaks and dominantly bioturbated with *thalassinooides* ichnogenera (Fig.3a). This lithofacies was interpreted to have formed from migrating sinuous 3-D dunes that stack up to generate bar forms in channel ([27; 28; 29; 30; 31].

2) **Facies Sm: Massive sandstone facies**

The massive sandstone facies are moderately sorted with fine – medium grained sandstone that are commonly bioturbated. It ranges between 70cm – 1m in thickness and commonly buildup to form thicker units usually overlain by trough crossbedded sandstone (St) or parallel laminated sandstone facies (Sr) (Fig.3b). This facies is generally deposited as plane beds in lower flow regime and/or rapid sedimentation due to high deposition rates with no preservation of sedimentary structures. It is commonly deposited on bars by stream floods and mostly associated with channelized flood flows around bars [29; 31].

3) **Facies Sp: Planar crossbedded sandstone facies**

This lithofacies composed of fine – medium grained sandstone with sub – rounded to well-rounded grains and typically occurs above trough crossbedded sandstone facies with thicknesses in the range of 40cm – 1m, individual foresets ranged from 1cm – 3cm. they are commonly bioturbated with mud-drapes and parting occurring along corset and forest planes (Fig.3c). This lithofacies was interpreted to have been produced from migration of 2-D dunes or sheet loading and/or interpreted as transverse bars formed under lower flow regime [26; 29].

4) **Facies Sl: Parallel laminated sandstone facies**

This lithofacies is generally fine grained with thicknesses ranging between 30 – 80cm. It is commonly associated with trough crossbedded sandstone facies (St), ripple laminated sandstone facies (Sr) and mudstone facies (Fm). Bioturbations and mica flakes are common associated attributes and boundaries are generally sharp. Laminations mostly show variation in grain size or mineral composition (Fig.3d). This facies is produced by less severe or short-lived fluctuations in sedimentation conditions than those that generate beds. They result from changing depositional conditions that causes variation either in grain size, content of clay and organic material, mineral composition or microfossil content of sediments [26].

5) **Facies Sr: Ripple laminated sandstone facies**

The ripple laminated sandstone facies compose of fine–very fine grained sandstone that are well sorted with rounded grains. Thicknesses ranges from 50cm–1m and it is mostly associated with parallel lamination (Sl) and siltstone (FmI) (Fig.3e). Asymmetrical forms are the commonly dominate and they are mostly bioturbated. This facies forms either when the water surface show little disturbance, or when water waves are out of phase with bedforms during lower flow regime, or forms through migrating current ripples, under lower flow regime ([29; 31].

6) **Facies Fm: Mudstone facies**

This lithofacies is dominantly grey coloured and commonly bioturbated with thicknesses ranging from 60cm – 4.5m. It is usually interbedded with ripple laminated sandstone facies (Sr) and massive sandstone facies (Sm) or define the base of trough crossbedded sandstone facies (Fig.3f). This facies forms under environmental conditions where sediments are abundant and water energy is sufficiently low to allow settling of suspended fine silt and clay. They are characteristic of marine environment where seafloor lies below the storm base, but can form in lakes and quite part of rivers, lagoons, tidal flat and deltaic environment [26].

B. Sedimentary Facies Associations

The Six (6) facies elements characterizing the structural configuration of the depositional setting of the Yolde Formation forms two (2) preferentially distinctive facies assemblage that includes: Facies Association (FA1): Fluvial Channel Deposits and Facies Association (FA2): Tide Influenced Fluvial Channel Deposits.

1) **Facies Association (FA1): Fluvial Channel Deposits**

This comprises of a sequences of individual channels element built-up to generate successive cycles of 1-4 m thick units stacked into amalgamated complexes (Fig.3g). Channel elements hosts sequences of up to 7.5 m in exceptional cases, and commonly, basal contacts are generally erosional, marking rejuvenation of in-channel elements that grades spatio-temporarily into laterally accreted over-bank architectural fines (Fm). Couplet horizons of multiple basal and internal erosional surfaces are also predisposed within the channel sequences. The lenticular channel sandstone body fill comprises of medium – very coarse-grained units, having dominantly poorly sorted texture organized in a transcending order of fining up sets. Individual cycles contain large scale low angle (4-11°) pebbly trough crossbedded sandstone facies (St) with erosional basal contact associated with abundant mud-clast and grossly limited pebble lags of 1-2 m thick. This is mostly succeeded by small – medium scale trough crossbeds (40-60cm). Planar crossbedded units (Sp), massive beds (Sm) and ripple or parallel laminated sandstones (Sr/Sl) are occasionally intercalated with small scale trough crossbedded units as they grade vertically into the mudstone facies (Fm) of 40-70 cm thick with infrequent rootlet structures (Fig.3g). Bioturbations are generally absent in the mudstone facies (Fm), but rhizome rootlet traces are locally present. Paleocurrent evaluation of these coset units indicate a range from 220-290°, suggesting a unidirectional paleoflow pattern (Fig.4).
Fig. 3a) Trough crossbedded sandstone, b) Massive bedded sandstone, c) Planar crossbedded sandstone, d) Ripple laminated sandstones, e) Parallel laminated sandstone, f) Mudstones, g) Fining upward cycles of fluvial units, h) Fining upward cycle of tidally influenced fluvial channels, i) Skolithos ichnogenera, j) Thalassinoides ichnogenera, and k) Diplocraterion ichnogenera
2) **Facies Association (FA2): Tide Influenced Fluvial Channel.**

This appears at several stratigraphic levels, as amalgamated fining upward cycles (Fig.3h), intermittently sandwiched between successive sequences of fluvial units (FA1). Individual packages are 2-4 m (Fig.3h), constituting of lenticular sandbodies with slightly concave erosional base showing abundant mud rip-up clast (Fig.8c and d), occasional pebble lags and starved occurrence of carbonaceous materials. Basal sequences are mostly pebbly, very coarse grained trough crossbedded sandstone facies (St) with poorly sorted texture, but local interwoven fabric of trough cosets and muds are common. Planar crossbedded sandstone facies (Sp) usually follows with sets interfingered with mud-drapes at bedding surfaces and foreset planes of high dip angles of (20-30°), commonly of bipolar relationship with the underlying trough crossbedded sandstone facies (St), and reactivation surfaces are generally rare. Farther upward, uncommon and irregular association of massive beds (Sm), parallel (Sl) and ripple laminated sandstones facies (Sr) occurs, often displaying crude wavy bedding, though occasionally, superposing heterolithic assemblage are present. Boundaries are typically sharp at this level and grain sizes are fine-medium with dominantly sub-angular grains, while textures are moderate with
disseminated mica flakes. Mudstone facies (Fm) usually supersedes, mostly occurring mottled and bioturbated with occasional caliche nodules and carbonate concretions. Bioturbations are low/moderate in intensity and occurs dominantly on bed surfaces with trace fossil diversity constituting of skolithos, thalassinoides, and diplocraterion ichnofacies (Fig.3i-k). Paleocurrent measurement derived from cross-strata (planar and trough crossbeds) and ripple cross-lamination depicted a bipolar flow pattern trending southwest to northwest at 265° – 300° and southeast at 160° (Fig. 4).

V. DISCUSSION

Incised valleys are generally stratigraphic entities that develop in response to a regional decrease in relative sea level, where hinterland fluvial activities buoyantly interact with marine processes. Within this context, incised valleys form under two fairly distinct phases along the coastal systems, one dominated by fluvial processes during valley incision, and one influenced by fluvial, estuarine, and marine processes during subsequent infilling of the valley.

The first two phase are recognized herein. The facies attributes and association in the architectural element assemblage of FA1 reflects an account of a channelized system with high incision and channel avulsion as depicted by the multiple erosional basal surfaces and contained rip-up clast [30]. Thinning and fining upwards succession of trough crossbedded units with local intercalations of planar, massive units, moving into ripple laminations and mudstone facies points to gradual dissipation and damping energy condition across the channel stratigraphic profile [32]. The dominoengineering presences of trough crossbedded units in this channel architecture indicates a sedimentation predominantly typified by dune migration and accumulation [33], and this coupled with the rarity of associated planar crossbedded unit indicative of bar migration, deposition in a relatively deep channel setting is quite plausible [34]. Stacked successive succession of these channel units with contrastingly similar facies signature presents a constant and uniform rejuvenation of depositional conditions. This is seemingly accompanied by repeated cycles of cut and fill process due to high degree of channel switching, as evident from relic of over-bank materials occurring as mud-clast at channel base and extensively strong unidirectional current system maneuvering within the realms of 220°SW to 290°NW depositional trend, at dispersion angle of 70° [35]. The over-bank fines are typically thin, hence susceptibility to erosion, thus unstable floodplain deposits, whereas occasional resistant thicker units are resultant product of channel abandonment [32]. This reflects product of a high energy fluvial system of most likely braided river type [35; 31].

The predominantly large-scale trough crossbedded sandstone facies (St) with erosional contacts composed of abundant mud-clast and pebble lags defining the base of individual amalgamated fining upward cycles of the FA2 facies association are also in consonance with channelized flow systems [e.g. 37]. Furthermore, the textural immaturity therein invariably indicates a unidirectional transport and depositional regime likely generated by turbulent fluvial current system with high discharge owing to the coupled abundant rip-up clast and rare bioturbations [38]. Though that the dune migration in response to these current dynamics continuously accreted successive complexes of crossbedded facies (St and Sp), the subordinate opposing opposite paleo trend from the Sp facies, indicates relative phases of tidal incursion [30; 26]. Presences of reactivation surfaces in this bar complexes with apparent mud-drapes and moderate bioturbation suggest a relatively strong tidal modulation [39], where fluvially derived sediments at confluence zones during interflood period were dominantly reworked by tidal current. Ubiquitous nature of these mud-drapes indicates deposition in a zone characterized by maximum turbidity [e.g.40]. Localized occurrences of mica rich wavy beddings embedded in mudstone account for a depositional phase characterized by tidally driven slackwater regime with low suspended sediment laden, typical of fluvial-tidal transition zone [41]. Overlying mudstone facies (Fm) represent a very low energy depositional stage as a consequence of waning episode of river flooding events [42]. Low diversity trace fossil assemblage comprising of ophiomorpha, skolithos and thalassinoides ichnofacies reflects marine inundation of fluvial channels, thus development of brackish conditions [43].

VI. CONCLUSION

The facies evaluation and characterization of the Cretaceous Yolde Formation at Pantami stream in the Gongola Sub-basin of the Northern Benue Trough indicated the occurrence of incised valley fills in its stratigraphic architecture. These temporal stratral packages evolved through two distinct but genetically related phases of fluvial channel systems and tidally influenced fluvial channel system. The former typically defines the basal succession of the Yolde Formation which is progressively superposed by the later at upper intervals showing abundant marine signature consisting of ichnofacies and bidirectional current system. These packages reflect accounts of a fluvial channel inundation by continuous advancing sea, a likely transgressive regime accompanying the mid-Cretaceous global marine transgression.

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