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Sedimentology and stratigraphic development of sandy members of Pindiga formation, GONGOLA SUB-BASIN, northern Benue trough, Nigeria: A mixed wave, tide and fluvially influenced coastal system

Isah Aliyu Goro [a,*], Muhammad Bello Abubakar [b], Shettima Bukar [c], Wan Hasiah Abdullah [d]

[a] Department of Geology, Federal University of Technology, P.M.B 65, Minna, Nigeria
[b] National Center for Petroleum Research and Development, Abubakar Tafawa Balewa University, P.M.B. 0248, Bauchi, Nigeria
[c] Department of Geology, University of Maiduguri, P.M.B 1069, Maiduguri, Nigeria
[d] Department of Geology, University of Malaya, 50603, Kuala Lumpur, Malaysia

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ABSTRACT

This paper documents the detailed sedimentology and stratigraphic evolution of the Sandy members of the Pindiga Formation. Good understanding of this succession is relevant to resource exploration and exploitation in the frontier Gongola Sub-basin of the Northern Benue Trough and similar Cretaceous strata in general. Detailed facies analysis based on examination of twelve well exposed outcrops revealed four facies successions. Field relations show that the deposits are stratigraphically partitioned by a disconformity surface into two parts. The lower part consists of regressive wave-storm dominated deltaic and wave-storm dominated offshore to nearshore facies successions, while the upper part comprises of transgressive wave dominated estuary and tide dominated estuary successions. Fourteen facies were identified and organized into nine facies associations. Field observations show that the upper boundary of the Sandy members is an angular unconformity represented by the development of a thick paleosol unit below the Fika Shale. Conversely, the lower boundary is transitional. Contrary to earlier fluvial and coastal to littoral interpretation of the Sandy members, this work demonstrates that marine processes were important for facies development. It is shown that an integration of detailed facies and ichnological analyses is valuable in determining robust paleoenvironmental interpretations of sedimentary successions.

1. Introduction

Coasts occur between land and marine zones and sedimentation within them are affected by complex interaction of fluvial, wave and tide processes (Reading and Collinson, 1996: Bhattacharya, 2010; Boyd et al., 1992). Coastal deposits serve as host to significant amount of water, coal, hydrocarbon and solid mineral resources. For example, about 30% of hydrocarbon and coal reserves are contained within Deltas (Tyler and Finley, 1991). Exploration and exploitation of these resources necessitates a good understanding of both modern and ancient coastal depositional systems in terms of their sedimentological and stratigraphic evolution.

Several factors are used as variables to classify coastal systems including, for example, river mouth processes and sediment dispersal system at delta front (Galloway, 1975), and sediment reworking due to wave and tide processes (Hayes, 1979). The grain size and volume of sediment supply are further important parameters for coastal classification (Orton, 1988; Orton and Reading, 1993). Other factors include the feeder system, gravitational reworking processes, stream gradient, basin gradient and depth (Postma, 1990). Classification of coasts based on the variable sea-level change dates back to Johnson (1919) and Curray (1964) as well as Boyd et al. (1992) and Posamentier et al. (1992).

All the schemes have their merits, but the variables to use depends on the objectives of the study (Reading and Collinson, 1996). Nevertheless, in common use is the triangular diagram of Dalrymple et al. (1992) which is a modification of the Galloway (1975) scheme. It considers both river and sea sediment inputs, dominant processes at the coast (fluvial, wave or tide) and whether the coast is transgressive or regressive. Detailed analysis of ancient clastic coasts have shown that a mix

* Corresponding author.
E-mail address: isahgoro@futminna.edu.ng (I.A. Goro).

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rather than the ideal end member models are common (e.g. Lambiase et al., 2003; Fan et al., 2004; Rebata et al., 2006; Amir Hassan et al., 2013).

The recently delineated and approximately 200 m thick Upper Cretaceous Sandy Members of Pindiga Formation in the Gongola Sub-basin (Fig. 1) have been interpreted as fluviatile, coastal marine to littoral deposits by Zaborski et al. (1997) and Zaborski (1998). These authors, however, did not discuss the sub-environments as well as the nature of the upper bounding surface of the rocks. The influence of fluvial, tide and wave processes within the Sandy members were emphasised by Maigari (2011). He divided the Sandy members into lower and upper parts with the lower part consisting of wave dominated shoreface deposits and the upper half comprising of tide dominated estuary and fluvial channel associations. Nonetheless, gaps still exist in terms of understanding the nature of the bounding surface that separates the Sandy members into two, as well as the upper bounding surface that separates the Sandy members from the overlying Fika Shale. Recent fieldwork presented in this paper revealed significant details based on facies analysis that have not been earlier reported. The documentation of these field observations provides additional insights into the hydrodynamic conditions, especially the interplay of wave, tide and fluvial currents as well as base level trajectories in the Upper Cretaceous (probably Turonian) coastal to shallow marine system of the Benue Trough.

The aim of this work is to apply detailed outcrop facies analysis to reconstruct the stratigraphic evolution of the Sandy members of the Pindiga Formation in the Gongola Sub-basin of the Northern Benue Trough using integrated sedimentologic, stratigraphic and ichnologic evidences. Specific objectives include the following: (1) the documentation of detailed outcrop facies, facies associations and facies successions of the Sandy members; (2) the interpretation of the facies successions based on the dominant (fluvial, wave, or tide) processes during their deposition; (3) a discussion of the major bounding surfaces of the Sandy members and (4) the development of depositional model for the Sandy members based on the distribution of the sedimentary facies. The stratigraphic position occupied by the Sandy members suggest that this investigation will enhance our understanding of the evolution of the frontier Gongola Sub-basin with important implications for hydrocarbon, solid mineral and ground water exploration in this sub-basin and the Benue trough at large (Fig. 1).

2. Geological background

The Gongola Sub-basin constitutes the NS trending arm of the Northern Benue Trough (NBT), Nigeria, while the EW trending and the southern parts of the NBT are referred to as the Yola and Muri-Lau Sub-basins (Fig. 1c) (Nwajide, 2013). Several lines of evidence suggest that the Benue Trough is part of the larger West and Central African Rift System basins that developed as a consequence of separation of the African and South American Plates during the Jurassic times (Genik, 1992; Guiraud et al., 2005; Fairhead et al., 2013). The origin and evolution of the basins is proposed to have been controlled by rift-fault bounded tensional basement flexuring initiated by intermittent uplift of the Gulf of Guinea dome built from mantle convection around discrete hot spots (Farrington, 1952; Cracthley and Jones, 1965; Wright, 1989). This resulted in development of a failed arm in the RRR of the tipple junction of the Gulf of Guinea, hence, an aulocogen and emergence of the Benue Trough (Olade, 1974). Opposing theories are in favour of wrench fault tectonics because of the perceived absence of discernible boundary faults typical of rift systems (Benkhelil, 1989; Guiraud and Maurin, 1992; Aribiyi et al., 2004; Likkason et al., 2005). Though the origin remains controversial, tectonics created and structured a deep depression that controlled the accumulation of over 6000 m of Cretaceous-Tertiary sediments (Shettima et al., 2018).

The Aptian-Albian syn-rift to post-rift fluvial to lacustrine successions of the continental Bima Formation forms the oldest sedimentary unit in the Gongola Sub-basin, directly overlying the Basement Complex Rocks (Fig. 2) (Guiraud, 1990; Tukur et al., 2015; Shettima et al., 2018). With the commencement of the mid-Cretaceous global marine transgression in the Cenomanian (e.g. Carter et al., 1963; Haq et al., 1987; Abubakar, 2014 and Sarki Yandoka et al., 2014), the transitional-marine deposits of the Yolde Formation were deposited conformably on the continental units (Shettima et al., 2011; Sarki Yandoka et al., 2015). The peak of this transgressive phase in the Turonian led to the deposition of the shallow marine shales and limestones of the Kanawa Member of the Pindiga Formation (Zaborski et al., 1997; Zaborski, 1998; Aliyu et al., 2016), and following a relative sea level fall in the mid-Turonian, the regressive Sandy Members of the Dumbulwa, Deba-Fulani and Gulani sandstones were deposited (Fig. 2) (Zaborski et al., 1997; Nwajide, 2013). Renewed transgression in the late Turonian through the Coniacian and early Santonian deposited the deep marine shales of the Fika Shale above the Pindiga Formation (Zaborski et al., 1997). This incursion was accompanied by a compressional tectonic pulse in the mid-Santonian (Genik, 1993) that resulted from a change in displacement vectors between the African plate and European/Tethys plates (Fairhead and Binks, 1991). This activity thrusted the pre-Maastrichtian sediments westwards of the Gongola Sub.

Basin, creating a depositional locus receiving the Campano-Maastrichtian regressive deltaic packages of the Gombe Formation (Dike, 1993). The mid-Maastrichtian experienced a folding event, and was subsequently followed by sagging which set the stage for the development of fluvio-lacustrine Kerri Formation (Dike, 1993) in the Paleocene (Fig. 2), accounting for the only record for Paleogene sedimentation in the sub-basin (Adegoke et al., 1986). Paleogene-Neogene volcanics thereafter formed. The volcanics occur as localized sills and plugs across the sedimentary fill of the Gongola Sub-basin (Wilson and Guiraud, 1992).

3. Method of study

Fairly well exposed stream sections, quarry faces, burrow pits and sandy hills constituting the Sandy Members (Dumbulwa, Deba-Fulani and Gulani Members) of the Pindiga Formation in the northwest, eastern and southern part of the Gongola Sub-basin of the Northern Benue Trough were studied in this research (Figs. 2 and 3). The outcrop data enabled the construction of a total of twelve lithologic sections that capture the sedimentological details of the overall exposures. The Badabdi Hill (L1), upper part of Badabdi Hill (L2), Ashaka quarry (L3), southern part of Ashaka quarry (L4) and Gongila sand quarry (L5) sections were selected from the north western part of the sub-basin; the Maliya (L6), Gulani (L7) and Dogon Zagga (L8) sections were studied in the eastern part and the Sabon Gari (L9), Malam Macci (L10), Deba burrow pit (L11) and Dampami stream (L12) sections were selected for the southern part of the sub-basin (Fig. 3). Because of the lateral continuity of the exposures and the consistency in the vertical profiling of the facies of these sections, three composite logs were developed, one each for the northwestern, eastern and southern segments of the study area, revealing the base to top of the Sandy Members. The character of.

The upper boundary of the Sandy Members was unravelled at the Dampami stream section (L12) while the basal part was assessed at locations L3, L7 and L11 (Fig. 3). The facies (denoted by S1 – S14) were identified based on lithology, texture, bed geometry and sedimentary structures as well as trace fossil contents. The abundance, diversity and distribution of trace fossils within the identified lithofacies were used to further characterize the environments of deposition. Finally, a facies analysis concept was employed in arranging the lithofacies data sets into facies associations and facies successions following Dalrymple (2010).

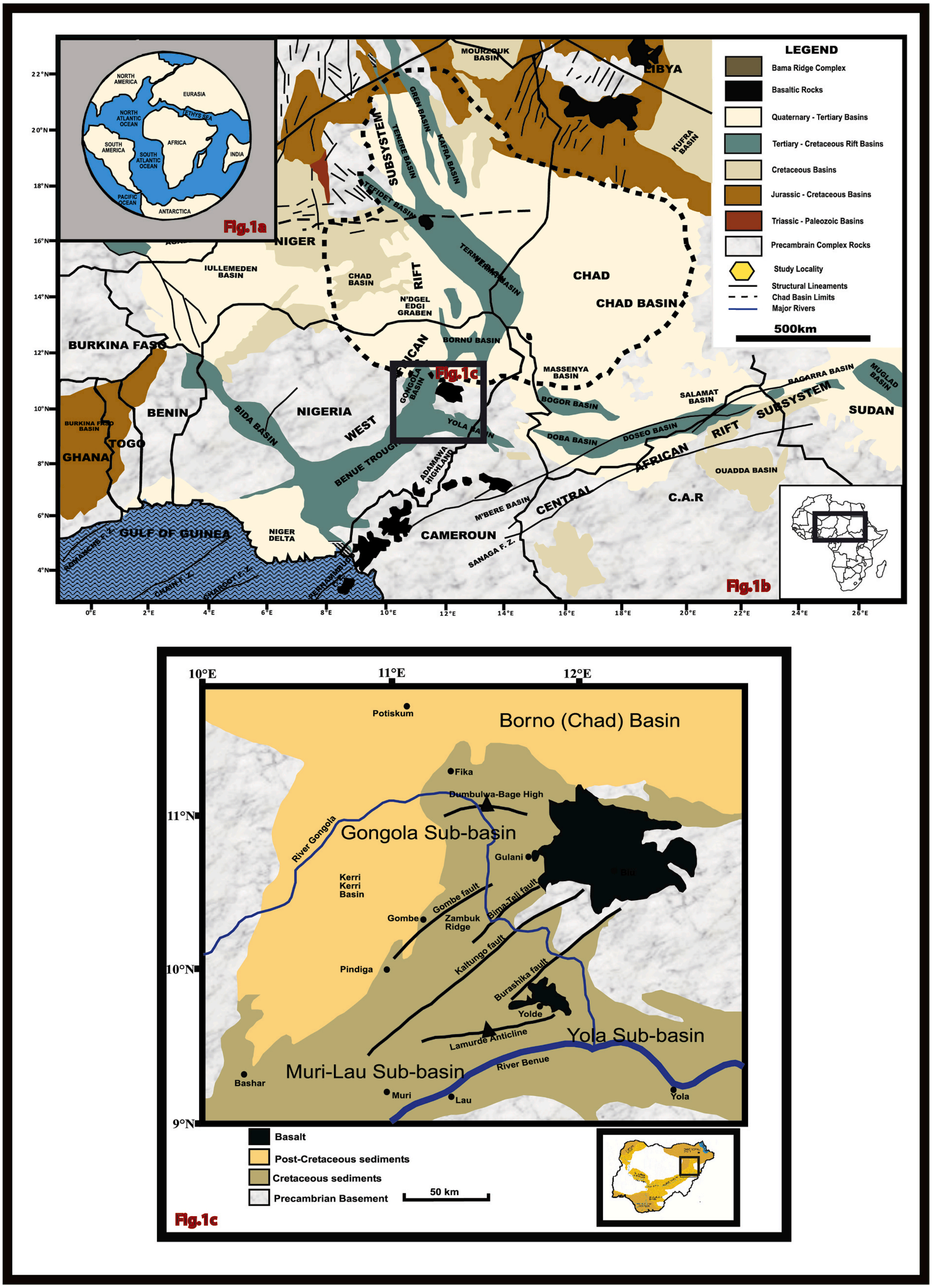

Fig. 1. Maps showing the location of the study area. (a) Global map showing lithospheric plates, (b) Map showing the West and Central African Rift System (adopted from Shettima et al., 2018), (c) Map showing the Northern Benue Trough.

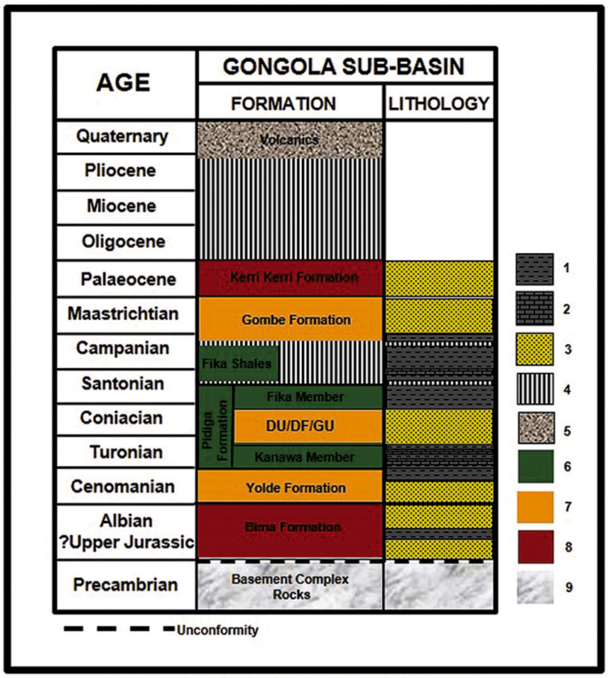

Fig. 2. Stratigraphy of the Gongola Sub-basin, Northern Benue Trough, Nigeria (modified from Zaborski et al., 1997). 1-Mudstone, 2-Limestone, 3-Sandstone, 4-Hiatus, 5-Basalt, 6-Marine sediments, 7-Transitional-marine sediments, 8-Continental sediments, 9-Basement Complex (DU-Dumbulwa Member, DF-Deba Fulani Member, GU-Gulani Member).

4. Results and interpretations

4.1. Facies and facies associations

Fourteen facies were identified from the lithologic sections of the Sandy Members of the Pindiga Formation within the study area (Fig. 3) on the basis of lithology and sedimentary structures (Table 1) (Fig. 4). These facies were grouped into nine facies associations that include: wave-storm dominated pro-delta to delta front facies association (FA1), wave-storm dominated shoreface to nearshore facies association (FA2), offshore to offshore transition facies association (FA3), tide-influenced fluvial facies association (FA4), tidal bar facies association (FA5), central estuary facies association (FA6), tidal channel facies association (FA7), bay-head delta facies association (FA8) and estuary mouth facies association (FA9) (Fig. 5). The temporal and spatial distribution of the facies and facies associations indicated a preferential

distribution where the FA1 – FA3 are typically restricted to the lower portion of the Sandy Members, commonly occurring below an erosional surface that marks a change in depositional trend from coarsening-up to fining-up facies associations (Fig. 5B, F, I, L). However, the FA2 and FA3 also occur at the uppermost part of the Sandy members in the very north of the study area (Fig. 5C). Field observation also indicated a general gradational contact between the Sandy members and the underlying Kanawa Member of the Pindiga Formation (Fig. 5A, C & L). Conversely, the upper boundary of the Sandy members was observed to be a marked angular unconformity. This unconformity surface is exposed in the southern part of the study area at numerous streams along the Gombe-Dampami-Kembu-Kumo road, with the best exposure seen at the Dampami stream section (Fig. 3).

4.1.1. Wave-storm dominated prodelta to delta front facies association (FA1)

4.1.1.1. Description. The wave-storm dominated pro-delta to delta front facies association (FA1) consists of interbedded facies of dark grey mudstones (S1), ripple laminated mudstones (S2), shell beds (S14), planar bedded sandstones (S6) as well as hummocky and swaley cross-stratified sandstone facies (S8, S9) (Fig. 5A and B; Fig. 6A, D). Stacked units of this association range between 3 and 6 m and form the lowest part of the Sandy Members in the northern part of the study area (Figs. 5A and 6A). Locally, abundant *Thalassinoides* and sporadically distributed *Chondrites*, *Skolithos*, *Rhizocorallium* and ?*Anconichnus* are common within this facies association (Fig. 6).

4.1.1.2. Interpretation. FA1 is interpreted as having been deposited in wave-storm dominated prodelta to delta front environment due to its distinctive coarsening and thickening upward character with the mudstones of facies S1 dominating at the base, passing through interbedded units of S2 and S6/S9 and capped by S8/S9 facies (Fig. 6). The coarsening up character, the abundant wave and storm formed sedimentary structures as well as the trace fossil content and distribution in this association suggests progradation of prodelta to delta front sediments into an offshore environment in a river mouth setting. Whereas the prodelta mudstones, shell beds and associated fine grained sandstones (S1 and S14 facies) reflect deposition from hyperpycnal flow during high storms, the delta front sediments (S6 and S8/S9) record deposition within proximal and distal parts of distributary mouth bar environment (e.g. Bhattacharya, 2010; Tye et al., 1999; Reading and Collinson, 1996; Chan and Dott, 1986). Wavy tops observed in the sandstones suggest wave reworking. Deposition in prodelta to delta front is further supported by the occurrence of *Chondrites*, *Thalassinoides* and *Rhizocorallium* of the Cruziana ichnofacies (Pemberton et al., 1992) in the lower part of the association. Also, the sporadic distribution of bioturbation towards the upper part of the association indicates stressed conditions that are known to occur in distributary delta front environments (Gingras et al., 2011). The stress here is commonly attributed to high sedimentation rates (e.g. Gringras et al., 2011). Cruziana ichnofacies are indicative of shallow bathymetry of about 30 m water depth (Seilacher, 2007), suggesting deposition in a shallow offshore Platform.

4.1.2. Wave dominated shoreface to nearshore facies association (FA2)

4.1.2.1. Description. FA2 Association is characterized by the prevalence of grey mudstones (S1), ripple laminated mudstones (S2), horizontal to low-angle stratified sandstones (S7), swaley cross stratified sandstones (S8), hummocky cross-stratified sandstones (S9), planar crossbedded sandstones (S11) and trough cross bedded sandstones (S12) facies (Fig. 5C, D, G, H, & K; Fig. 7). The association forms 2–7 m coarsening and thickening upward units with bases composed of S1/S2 facies, grading into interbedded units of S2 and S9 and terminating with S12 or S7 at the top where the sedimentary cycles are complete (Fig. 7). Most units end up with S9 especially at the lower stratigraphic level of the Sandy Members. The association ordinarily show upward decrease in bioturbation index within a cycle. Identified ichnogenera include *Ophiomorpha, Thalassinoides, Planolites, Skolithos, Palaeophycus, Diplocraterion* and *Terebellina* (Fig. 7).

4.1.2.2. Interpretation. Deposition above fair-weather wave base, where wave energy reworks sediments in open marine shoreface setting is recorded by the FA2 facies association. The hummocky cross stratified (S9) suggests deposition in the lower to middle shoreface with the swaley cross stratified (S8) units representing higher energy conditions (Nichol, 2009). The cross bedded units (S11 and S12) indicate deposition in the upper shoreface zone where longshore currents commonly form 2D and 3D dunes that produced the cross beds. The horizontal to low angle stratified units (S7) are inferred to record deposition in the foreshore environment (e.g. Nichol, 2009).

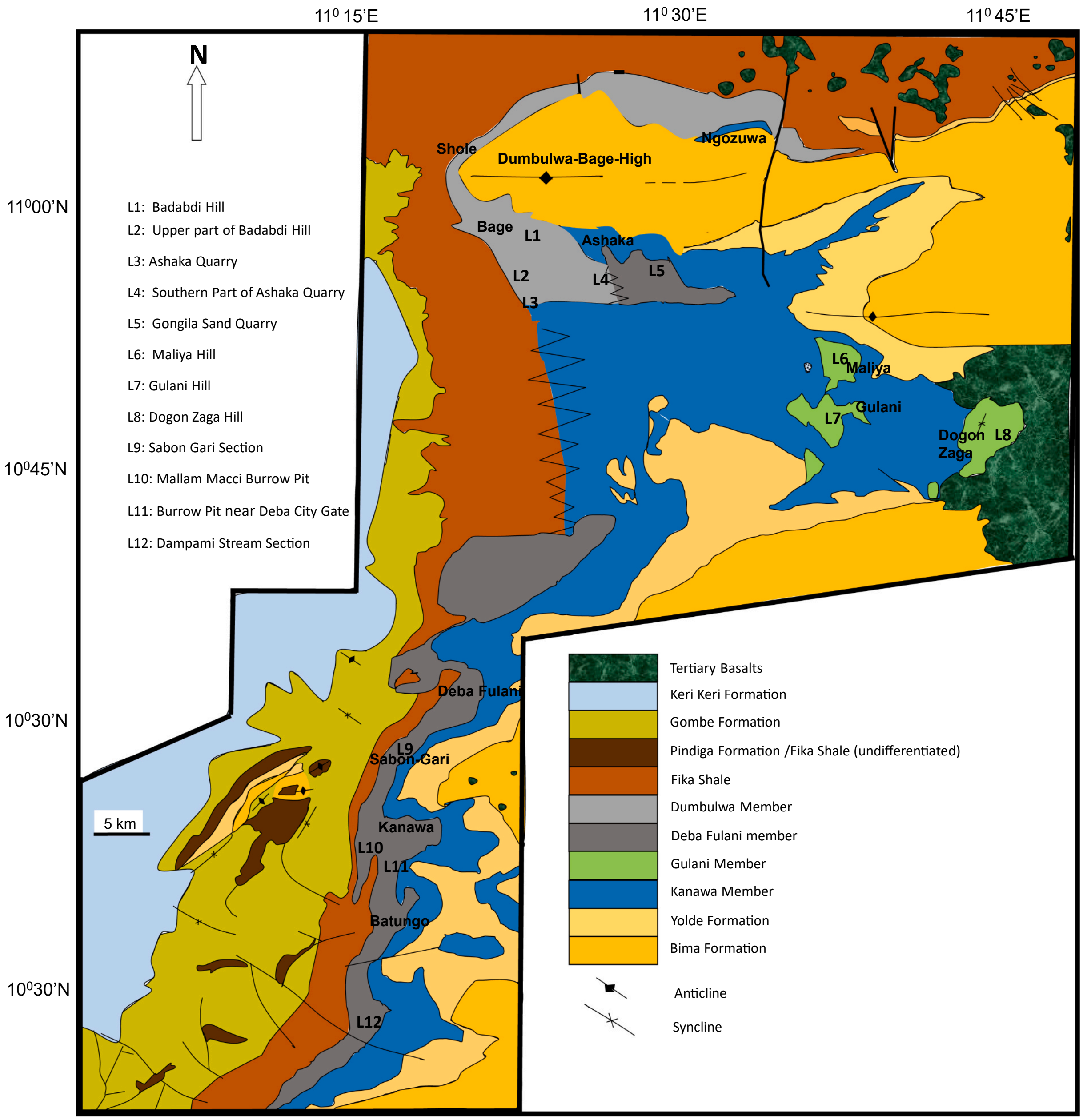

Fig. 3. Geological map of the Gongola Sub-basin (modified from Zaborski et al., 1997) showing approximate positions of the logged sections in the study area (L1 to L12).

4.1.3. Offshore to offshore transition facies association (FA3)

4.1.3.1. Description. FA3 comprises predominantly of grey mudstone (S1) and ripple laminated mudstones (S2) with lesser amount of bioturbated units of hummocky cross-stratified sandstones (S9). The S9 facies occur as thin to relatively thick bedded units within the mudstones. Thick units of this facies association (7–12 m) mainly occur at the transition between the Kanawa Member and the Sandy Members especially in the east and southern part of the study area (e.g. Fig. 5G, H, K). This facies association also occur as thin units interbedded with the wave-storm dominated shoreface to nearshore (FA2).

4.1.3.2. Interpretation. The interbedded nature of this FA suggests deposition largely from suspension settling below fair-weather wave base, but above storm-wave base. The mudstones record fair weather periods while the sandstones represent intermittent storms and their bioturbated nature is indicative of the generally low energy offshore environment of deposition (e.g. Reading, 1996; Nichol, 2009).

4.1.4. Tide influenced fluvial channel facies association (FA4)

4.1.4.1. Description. FA4 consists of conglomerate facies (S13), planar and trough cross bedded sandstone facies (S11, S12), planar bedded sandstone facies (S6), heterolithic sandstone facies (S4) and herringbone sandstone facies (S10). Where complete, this association is up to 6 m thick and comprises of fining upward association with basal scour surfaces composed of conglomerate facies (S13) transiting into planar and/or trough cross bedded sandstones of (S11 and S12) that fines upwards to either planar bedded fine grained sandstones of S6 facies or heterolithic sandstone facies (S4) (Fig. 5B, G, H, I, J, K). Individual cycles range between 1 and 6 m and form multistory packages of about 10 m at Dampami section (Fig. 5K) and over 30 m at Dogon Zaga (Fig. 5G). Stacked units of this association are typically underlain by a disconformity surface defined by thin coarse lag layer. This surface is of regional

Table 1
Summary of sedimentary facies within the Sandy Members of the Pindiga Formation, Gongola Sub-Basin, Northern Benue Trough, Nigeria.

Facies	Lithology	Sedimentary structures	Trace fossils	Interpretation
S1 Grey mudstone facies	Grey mudstones, as well as silty and sandy mudstones	Parallel lamination, fissile, some intervals appear massive	Most beds are bioturbated, BI is variable ranging between 2–and 5, some units are apparently non-bioturbated. iIdentified ichnogenera include *Planolites, Thalassinoides, Terebellina, Palaeophycus, Skolithos*	Suspension settling in low energy environment
S2 Ripple laminated mudstone facies	Grey mudstones, siltstones and very fine sandstones	Lenticular ripple lamination, wavy ripple lamination	Sporadic occurrences of *Thalassinoides*, *Chondrites* and *Rhizocorallium* ichnogenera	Fair weather deposition with fluctuating energies
S3 Laminated siltstone facies	Siltstones, mudstones and very fine sandstones	Parallel lamination, massive, some may show brecciated texture	Individual trace fossils not distinct but colour mottles showing grey, brown, reddish brown, cream and reddish purple colours is common	Suspension settling in low energy environment
S4 Heterolithic sandstone facies	Very fine to fine grained sandstone, siltstone and mudstone	Flaser and wavy ripple lamination	Bioturbation is sporadic. *Skolithos* occur in sandy parts while *Thalassinoides* are confined to the muddy parts	Alternating traction current and slack water suspension settling
S5 Cross laminated sandstone facies	Very fine to fine grained sandstone	Trough cross lamination, cross lamina-sets are 5–12 cm thick, cosets may reach 1.5 m, very thin to thin mud partings may separate the sets or cosets	Bioturbation is absent to sparse, locally common ichnogenera includes *Skolithos*, BI = 0-1	Migration of small subaqueous dunes due to waning flow condition
S6 Planar bedded sandstone facies	Fine to medium grained sandstones	Horizontal lamination	Bioturbation is absent	High energy upper plane-bed phase lamination
S7 Horizontal to low- angle stratified sandstone facies	Moderately well sorted fine to medium grained sandstones	Low-angle planar cross lamination	Non to sparse bioturbation	Deposition by high energy wave swash and/or backwash
S8 Swaley cross stratified sandstone facies	Moderately well sorted fine to medium grained sandstone	Swaley cross stratification, appear as amalgamated 10–60 cm thick beds	Bioturbation is absent	High energy storm deposition
S9 Hummocky cross stratified sandstone facies	Fine to coarse grained sandstone, some units are micaceous	Hummocky cross lamination, usually amalgamated thin to medium beds, bed tops may be wavy commonly marked by symmetrical or combined flow ripples	Bioturbation intensity varies from 0 to 4. Identified ichnogenera include *Skolithos, Ophiomorpha, Planolites and Thalassinoides.*	Storm deposition
S10 Herringbone cross bedded sandstone facies	Very fine to fine grained sandstone, micaceous	Herringbone cross bedding (bipolar cross bedding)	Non-bioturbated	Migration of opposing dunes formed by tidal current reversal
S11 Planar cross bedded sandstone facies	Medium to very coarse grained sandstones and gravels	Tabular cross bedding, grading of the foreset laminae, cross bed sets are commonly large-scale (1–4 m) thick.	Bioturbation is absent to sparse.	Migration of straight-crested subaqueous 2D dunes
S12 Trough cross bedded sandstone facies	Fine to medium grained sandstone to granulestones, may be bioturbated and pedogenically altered,	Trough cross bedding, Cross bed sets are mostly 0.1–1 m but may be up to 4 m thick locally, mud drapes on some foreset laminae and between cross bed sets, fining upward grain size, show both bipolar and unidirectional paleocurrent pattern, alternating coarse and finer laminae on foresets of cross beds, clinoform units separated by thin mud drapes.	Bioturbation is absent to sporadic, impoverished *Skolithos, Ophiomorpha, Arenicultes* are present	Migration of curve-crested subaqueous 3D dunes
S13 Conglomerate facies	Gravel and pebble conglomerate, pebbly sandstone, mud clast conglomerates, phosphatic nodules, fish and vertebrate spines and bones	3–50 cm thick beds, flat to irregular lower contacts, commonly internally massive.	Bioturbation is absent to sparse	High energy unidirectional traction current
S14 Shell-bed facies	Predominantly whole shell fragments, some broken shells of molluscs, some contain sandy matrix	Wavy tabular bedding 3–7 cm thick, wavy shell beds may be amalgamated to form up to 20 cm thick units.	BI = 2–4, *Thalassinoides* on bed undersurfaces	Winnowed storm sediments

extent and cut through FA1, FA2 and FA3 sediments (Fig. 5B, G, K) across several localities in the study area, displaying dissimilar coarse lag characteristics. The lag deposits consists of thin 5–10 cm thick mud rip-up clasts rich unit at Dogon Zaga locality in the east (Fig. 5G), whereas at Sabon Gari locality in the south (Fig. 5H), it comprises of very coarse grained, gravelly sandstones about 10–20 cm thick and at Dampami locality (Figs. 4N; 5K), the lag unit is characterized by concentration of 5–20 cm thick pebbly phosphatic nodules and vertebrate

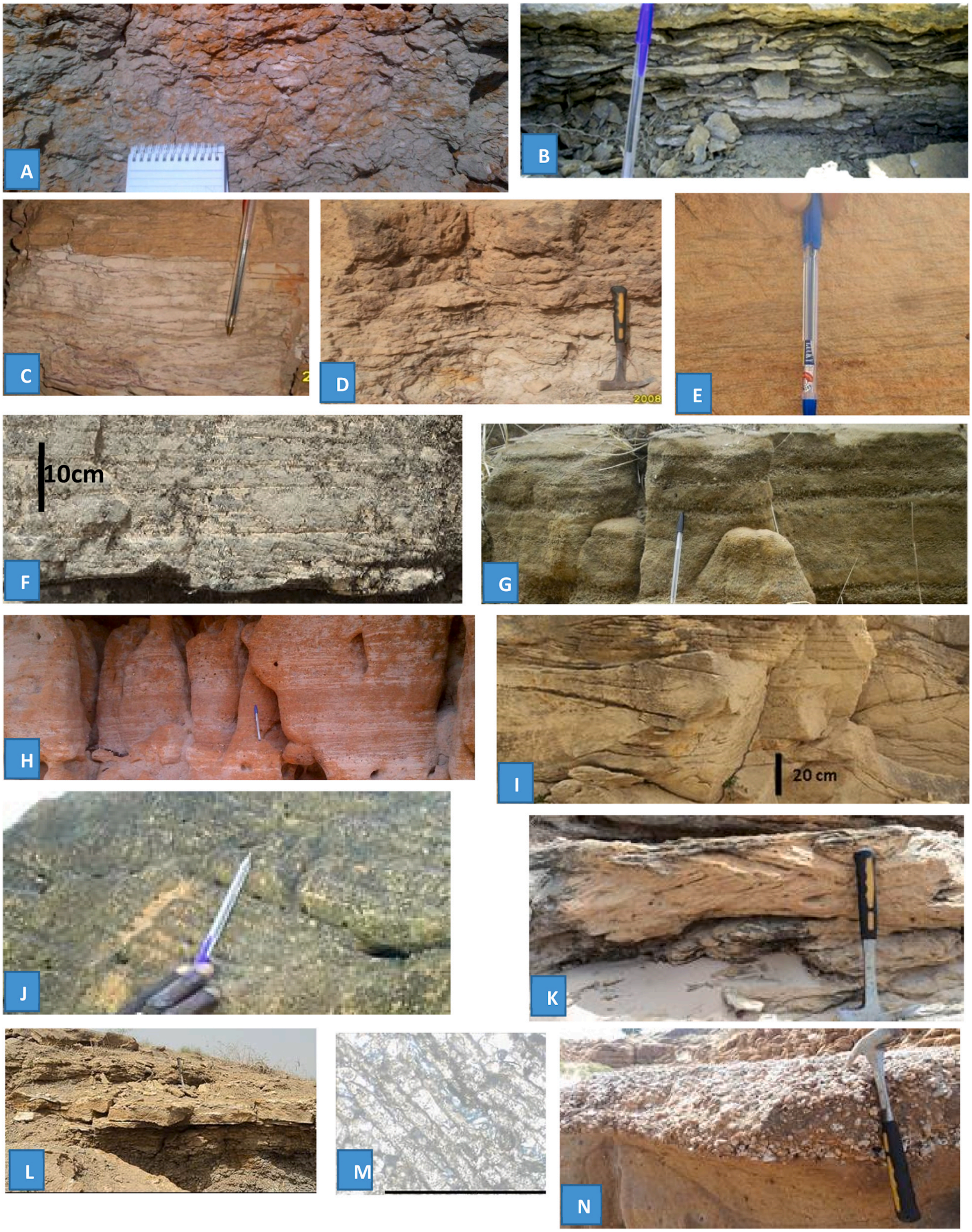

Fig. 4. Representative photographs of the Sandy members lithofacies. [A] Grey mudstone (S1). [B] Ripple laminated mudstone (S2). [C] Laminated siltstone (S3). [D - E] Heterolithic sandstone (S4). [F] Cross laminated sandstone (S5). [G] Planar bedded sandstone (S6). [H] Horizontal to low angle stratified sandstone (S7). [I] Swaley/Hummocky cross stratified sandstone (S8/S9). [J] Trough cross bedded sandstone (S12). [K] Herringbone cross bedded sandstone (S10). [L] Shell bed (S14). [M] Photomicrograph of shell bed. [N] Conglomerate facies (S13) overlying a sharp erosional boundary.

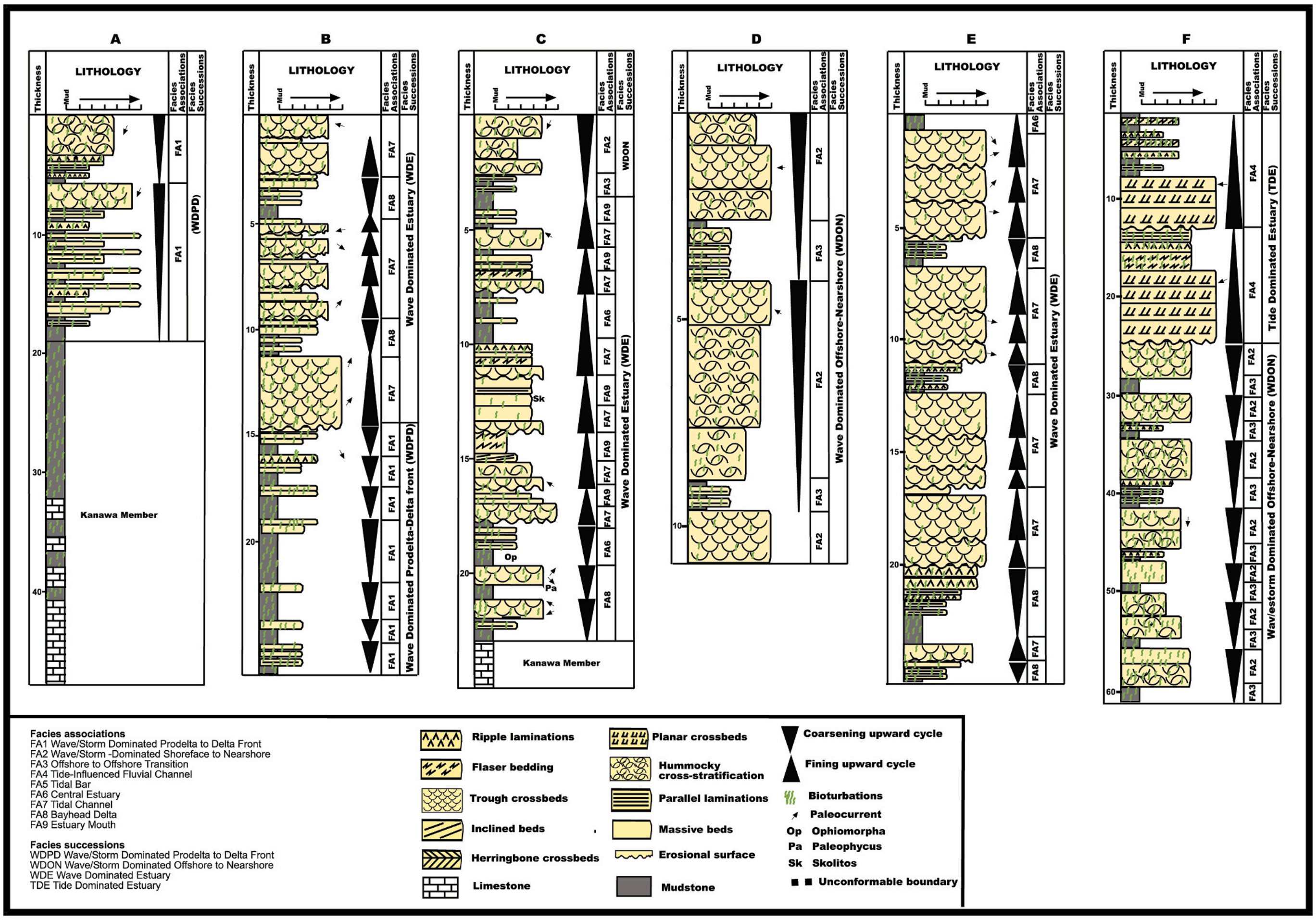

Fig. 5. Sedimentary graphic logs showing facies associations and facies successions of the Sandy members of the Pindiga Formation, Gongola Sub-basin Northern Benue Trough. [A] Ashaka Quarry, [B] Southern part of Ashaka Quarry, [C] Badabdi Hill, [D] upper part of Badabdi Hill, [E] Gongila Quarry Section, [F] Sabon Gari, [G] Deba City Gate, [H] Mallam Macci, [I] Dampami Section, [J] Maliya, [K] Gulani, [L] Dogon Zaga. Note: the approximate position of these locations are plotted on Fig. 3.

bones mixed with ferruginised matrix. The crossbeds of the FA4 locally display both unidirectional and bipolar paleocurrent direction, but on a regional scale, a bipolar paleoflow trend is revealed. Trace fossils are sporadic with typically diminutive sizes of *Skolithos, Arenicullites* and *Thalassinoides* (Fig. 8F and G).

4.1.4.2. Interpretation. The FA4 facies association displays typical features of deposition within mixed tide and fluvial influenced environment (Dalrymple, 1992; Dalrymple and Choi, 2007). The sharp lower contact, basal lag units, large scale cross bedding and fining-up grain size trend displayed within S11 and S12 facies as well as fining up from S11/S12 at the base and S4 at the top all point to deposition due to waning flows within channels and there flanking flood plainsor tidal flats. Furthermore, the regional bipolar paleoflow trend, mud draped trough cross bedded cosets and the sparse trace fossil assemblage represented by impoverished *Skolithos* suggests deposition in marginal marine, tide influenced environment (Dalrymple, 1992; Dalrymple and Choi, 2007; Reading and Collinson, 1996). The small-scale coarsening-up cycles displayed by fine grained heterolithic sandstones (S4) at the upper parts of this association record seaward progradation of tidal flat in a tide-dominated shoreline (e.g. Mangano and Buatois, 2004).

4.1.5. Tidal bar facies association (FA5)

4.1.5.1. Description. FA5 is up to 8 m thick. It is dominated by large-scale units of planar and trough crossbedded sandstone facies (S11, S12) which is commonly overlain by fining-up planar bedded fine grained sandstone facies (S6) facies, heterolithic sandstones (S4) or laminated siltstone facies (S3) (Fig. 5E, F, K). Occasionally, very thin coarse lag conglomerates (S13) occurs at the bases of the association. The association is characterized by abundant reactivation surfaces, mud drapes on foresets of cross beddings and flaser bedding towards its tops. The cross bed sets are commonly large-scale up to 4 m. This association is well exposed in Maliya and Gulani areas (Fig. 3; Fig. 8) to the east of the study area. Identified ichnogenera include impoverished *Ophiomorpha* within the S12 facies. This facies association marks the topmost part of the Sandy Members around the east and southern part of the study area where it is directly and unconformably overlain by a thick (about 4 m) paleosol unit in the Dampami area (Fig. 5K).

4.1.5.2. Interpretation. The lower scour surfaces, moderate to well sorted coarse to gravelly grains, the large scale gradded and crossbedings, as well as the flaser beddings, mud drapes on beddings, abundant reactivation surfaces and common associaton with laterally restricted fine grained facies all suggest deposition of the FA5 by tidal activities. These attributes are representative of tidal bar deposits and flanking

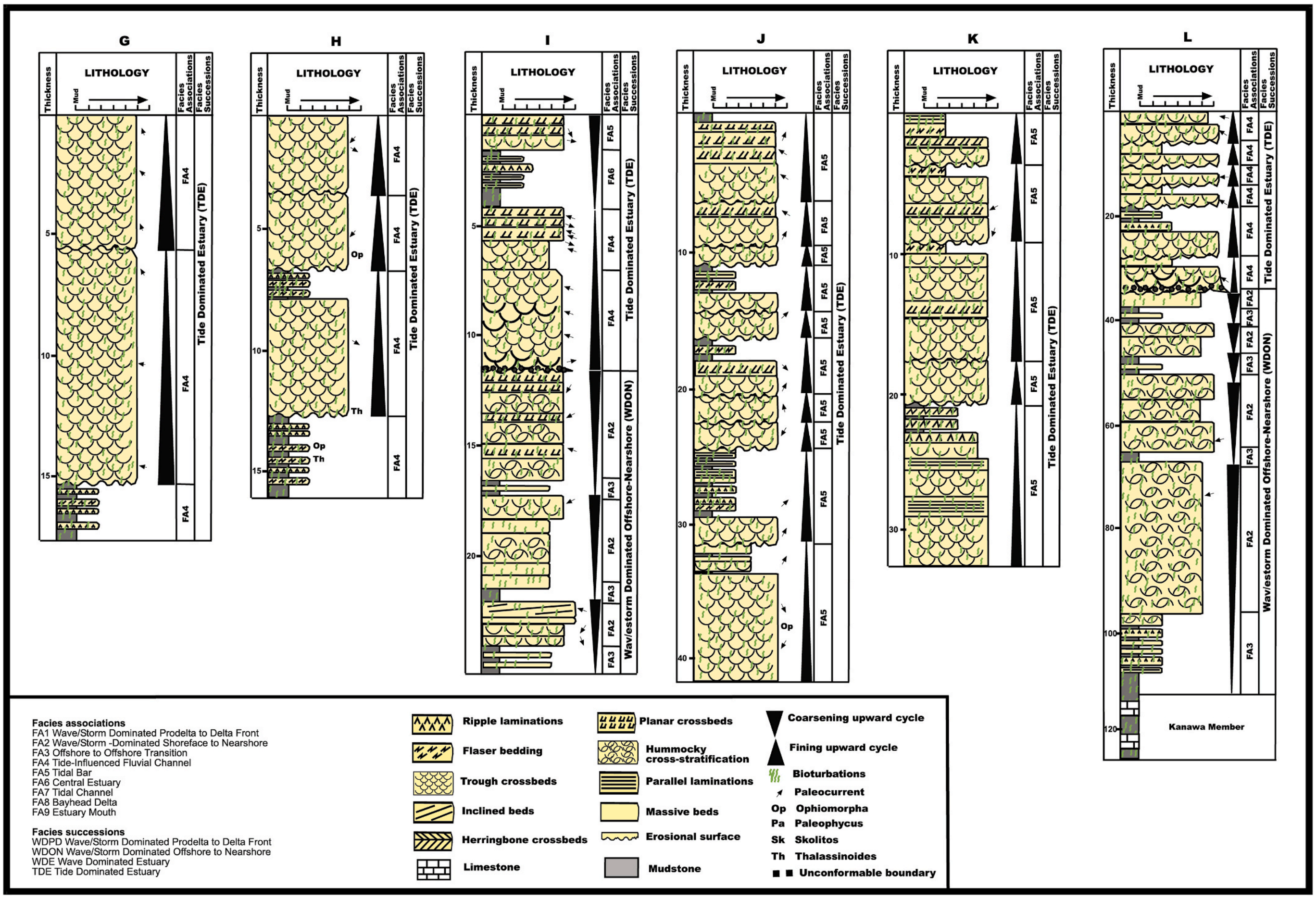

Fig. 5. (*continued*).

tidal flats which are indices to the high energy outer portion of tide dominated estuaries (Shanmugam et al., 2000; Dalrymple and Choi, 2007; Boyd, 2010).

4.1.6. Central estuary facies association (FA6)

4.1.6.1. Description. FA6 consists predominantly of grey mudstones of S1 and ripple laminated mudstones of S2. The association is generally mottled and bioturbated with variable intensities ranging from sparse to abundant. Individual trace fossils are usually not discernible but *Ophiomorpha* are identifiable in some units. This FA is intricately associated with the tidal channel (FA7), bay-head delta (FA8) and estuary mouth (FA11) (Fig. 5C; Fig. 9) in the northern part of the study area.

4.1.6.2. Interpretation. The FA6 is inferred to be deposited in the central estuary bay portion, owing to its fine grained nature and its association with bayhead deltas and tidal channels as well as estuary mouth facies associations (e.g. Dalrymple et al., 1992; Buatois et al., 1999; Boyd, 2010). The grey mudstones (S1) indicates suspension sedimentation in low energy environment while the ripple lamination displayed by facies S2 records fine grained sand deposition as a result of tidal currents (Buatois et al., 1999).

4.1.7. Tidal channel facies association (FA7)

4.1.7.1. Description. The tidal channel facies association (FA7) consists of trough crossbedded sandstone facies (S12), conglomerate facies (S13) and heterolithic sandstone facies (S4). The association forms fining-up packages with the S13 facies directly overlying concave-up erosional base, followed by the S12.

Facies and capped by S4 facies unit (Fig. 9). The upper heterolithic sandstone units are generally laterally restricted disappearing within 1–10 m. The association may occur as thick (>5 m) stacked units of trough cross bedded sandstone facies devoid of finer grained heterolithic units. Foresets of some of the trough crossbeds are commonly smeared with mud-drapes, whereas some unit show contorted bedding. The association display sparse to moderate bioturbation with *Palaeophycus* and rare *Skolithos* ichnogenera identifiable. This association typically occurs together with the bay-head delta facie association (FA8), central estuary facies association (FA6) and the estuary mouth facies association (FA9) in the middle part of the Sandy Members at the northern part of the study area.

4.1.7.2. Interpretation. The close association of FA7 with bayhead delta, estuary mouth and central bay facies associations suggests deposition in tidal channels. The concave-up sharp bases, coarse lag conglomerates, the fining-up grain size profile, trough cross bedding, and mud drapes on foreset or coset laminae in the FA7 indicate deposition in tidal channel sub-environments of wave dominated estuary (Buatois et al., 1999; Boyd, 2010). Whereas the associated laterally restricted heterolithic units (S4) suggest deposition on tidal flats or flood plains.

4.1.8. Bay-head delta facies association (FA8)

4.1.8.1. Description. FA8 consists of coarsening upwards sedimentary packages of 1–4 m thick that comprises of grey mudstone (S1) and ripple laminated mudstone (S2) at its lower parts and planar bedded sandstone facies (S6) dominated upper parts (Fig. 5). The association is restricted

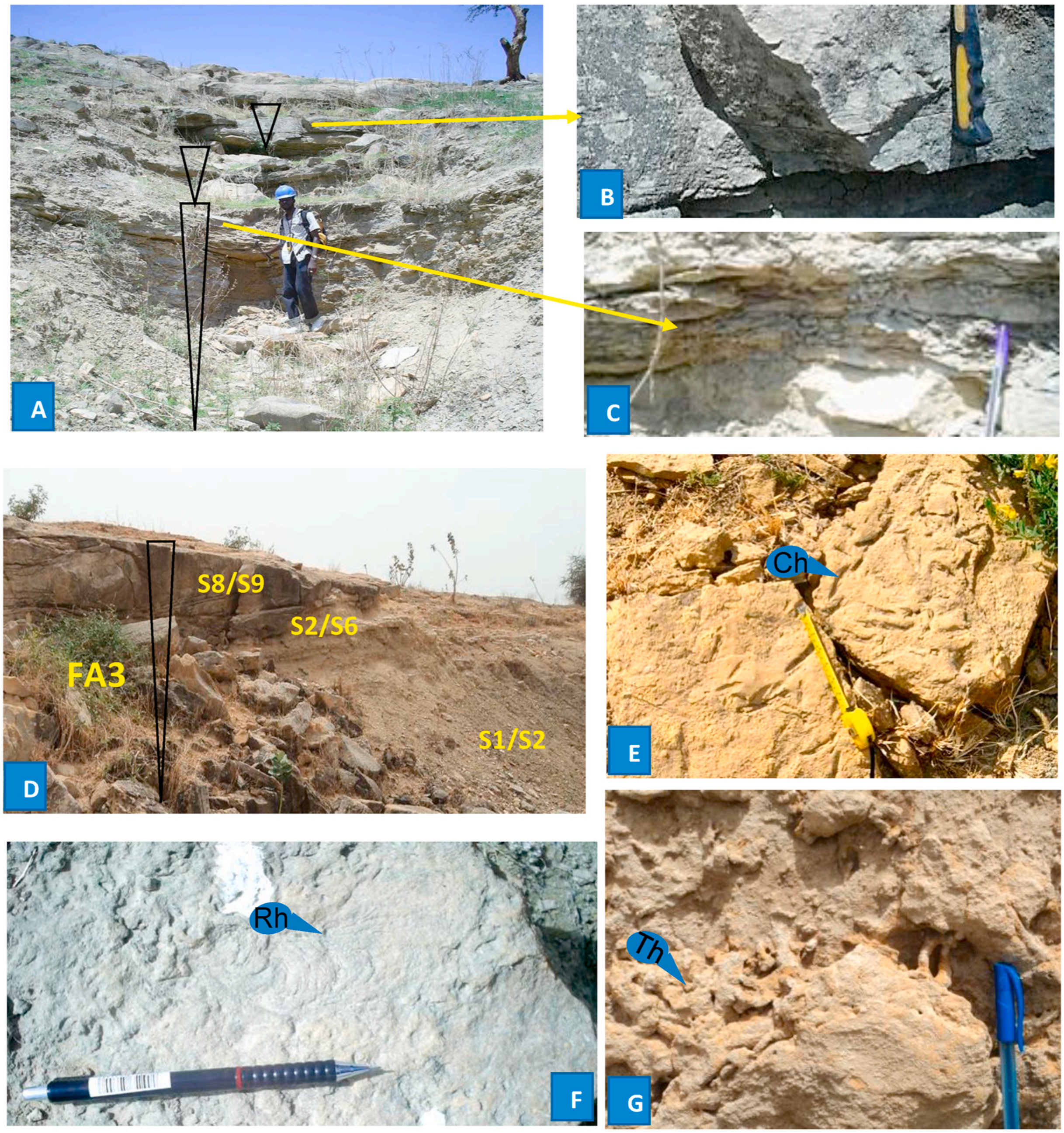

Fig. 6. Typical features of the wave-storm dominated prodelta to delta front facies association (FA1). [A] a succession of three coarsening-up cycles formed by FA1, Ashaka; [B &C] close-up views of the upper parts of the topmost and lowermost cycles displayed in (A); [D] coarsening and thickening-up in FA1, Ashaka. [E] Chondrites ichnofabrics (Ch), Ashaka; [F] Rhizocorallium ichnofabrics (Rh), Ashaka. [G] Thalassinoides ichnofabrics (Th), Ashaka.

to the northern part of the study area where it is associated with tidal channel facies association (FA6) (Fig. 5B; Fig. 9A–C). The association is typically, erosionally overlain by the FA6 (Fig. 5B; Fig. 9A–C).

4.1.8.2. Interpretation. The coarsening and thickening-up in the FA8 record progradation of bayhead delta into central estuary bay mudstones (Boyd, 2010). While the lower parts (represented by S1 and S2 facies mudstones with subordinate planar beds of S6) are interpreted as bayhead delta prodelta sediments, the upper parts that are dominated by the sand prone facies S6 suggests bayhead delta front and distributary mouth bars (Boyd, 2010).

4.1.9. Estuary mouth facies association (FA9)

4.1.9.1. Description. FA9 comprises mainly of the planar bedded sandstone facies (S6) and horizontal to low angle stratified sandstone facies (S7) with associated trough crossbedded sandstone facies (S12), grey mudstone (S1) and ripple laminated mudstone (S2) facies. The sandstone beds are rarely thick, occurring in thin grades of 3–15 cm. The association may show thickening up character similar to the bay-head delta facies association or may be represented by beds of S6 or S7 that are locally associated with small-scale cross bedded units. The units are commonly bioturbated with ichnogenera of *Thalassinoides, Skolithos, Palaeophycus, and Planolites*. This association occurs together with the tidal channel facies association (FA7) and central estuary facies association (FA6) in the northern part of the study area (Fig. 5C; Fig. 9D–F).

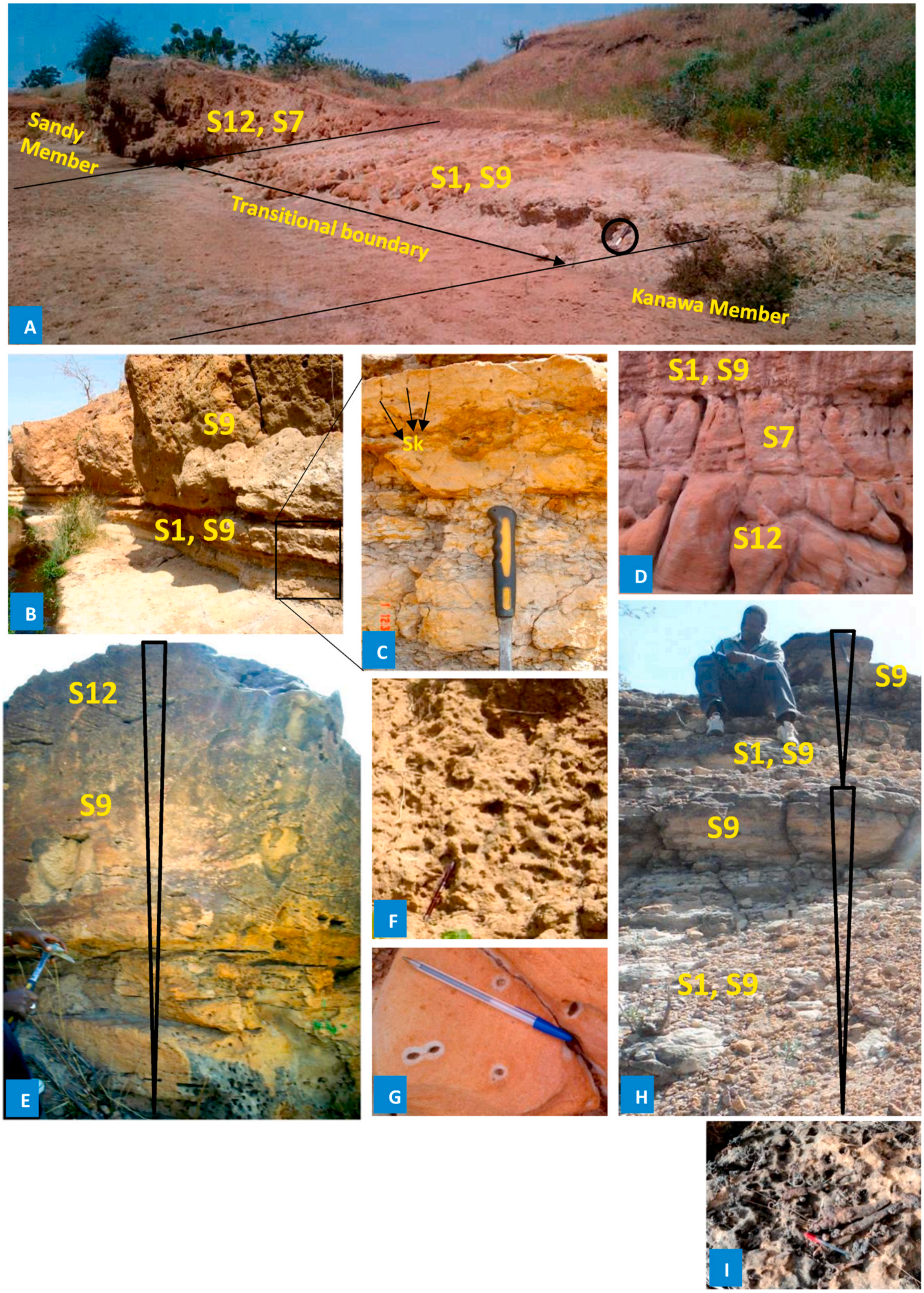

Fig. 7. Outcrop pictures showing typical features of the wave-storm dominated shoreface to nearshore facies association (FA2) and the offshore to offshore transition facies association (FA3): [A] transitional boundary between the Kanawa Member and the Sandy Members, Dampami; [B] upward coarsening and thickening from interbedded S1/S9 to S9, Sabon Gari; [C] close-up view of part of (B) showing *Skolithos* ichnofabrics (Sk) in S9; (D) trough crossbedded sandstone (S12) overlain by horizontal to low angle stratified sandstone (S7) forming upper part of coarsening-up cycle; Dampami [E] a typical coarsening-upward unit formed by FA2, Badabdi; (F) *Thalassinoides* burrows in FA2, Dogon Zaga; (G) *Diplocraterion* ichnofabric in S9, Dampami; [H] two coarsening and thickening upward cycles of FA4, Badabdi; [I] abundant *Ophiomorpha* in FA2, Dogon Zaga.

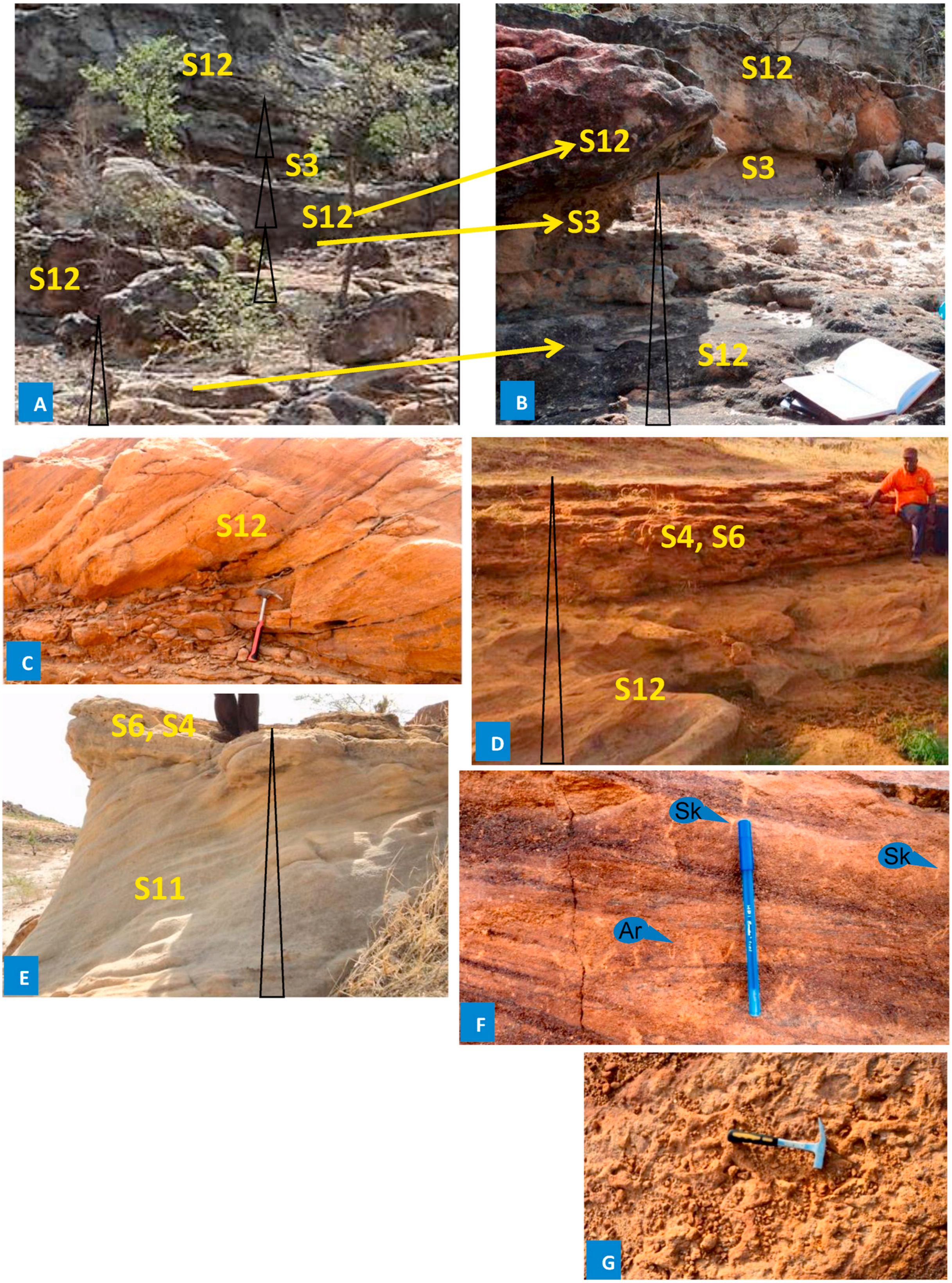

Fig. 8. Features of the tide-influenced fluvial channel facies association (FA4) and tidal bar facies association (FA5): [A] stacked fining-up units consisting of the FA4; [B] closer view of part of (A) showing upward fining from S12 to S3; [C] mud-drapes between large-scale cross bed sets in FA4; [D] fining-up grain size profile in FA5; [E] fining-up character typical of FA5; [F] diminuted *Skolithos* and *Areniculites* ichnofabrics in FA4; [G] sporadically abundant *Ophiomorpha* in FA5.

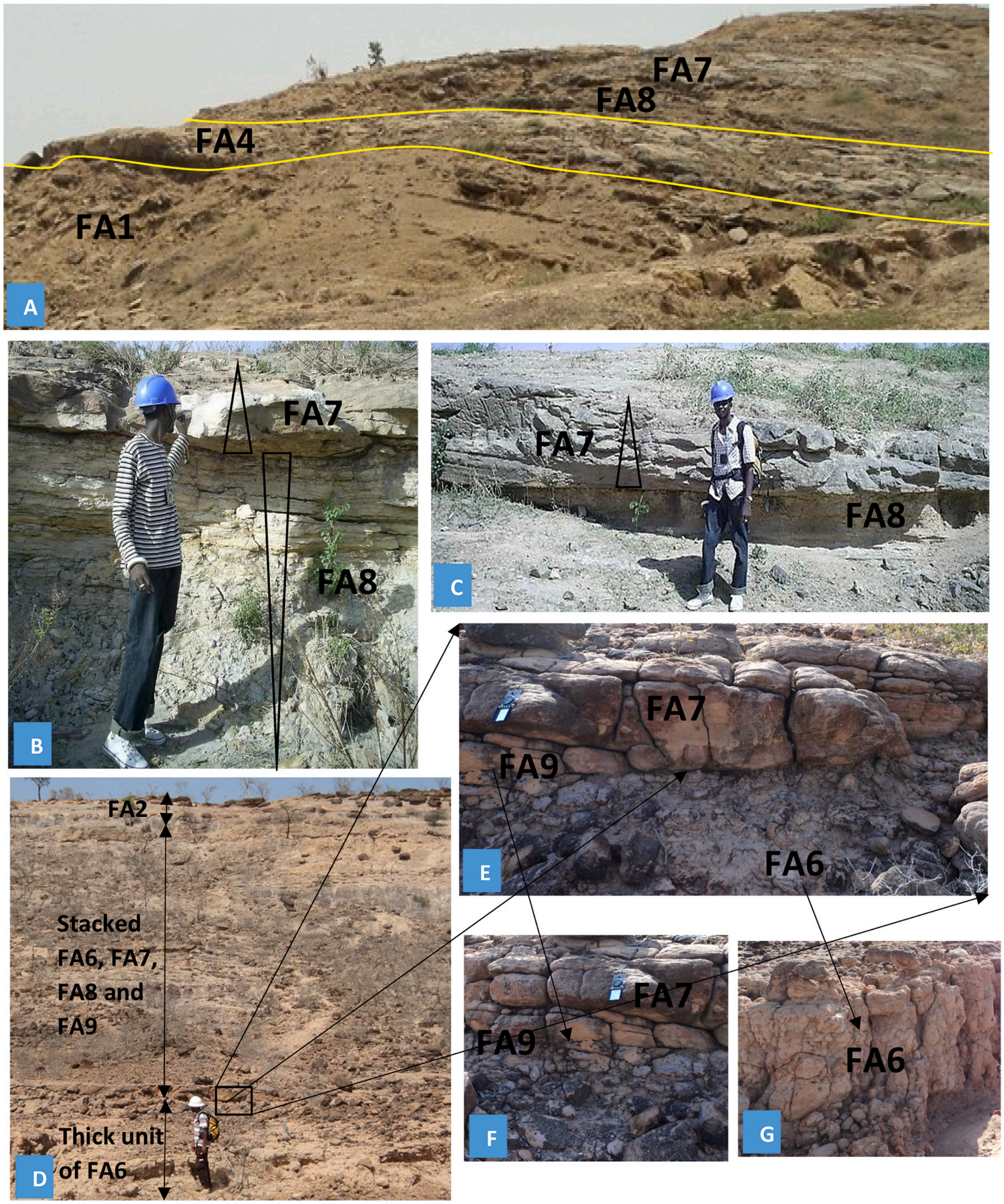

Fig. 9. Photographs illustrating characteristics of the Central estuary (FA6), Tidal channel (FA7), Bayhead delta (FA8) and the Estuary mouth facies associations (FA9). [A] field relation of FA1, FA4, FA7 & FA8, note the erosional contact between FA1 and FA4; Ashaka; [B] coarsening and thickening upward character of the FA8 as well as erosional base and fining-up character of FA7; [C] FA7 overlying FA8, note the sharp, erosional concave-up base of FA7, Ashaka; [D] succession of FA6, FA7, FA8 & FA9, note a change to FA2 towards the upper part of the exposure; Badabdi; [E, F, G] close-up views of part of (D, boxed area) showing the relationship between FA6, FA7 and FA9.

However, at Badabdi area (Fig. 9D), the FA6 grades directly into the FA9 facies association.

4.1.9.2. Interpretation. FA9 is thought to represent sediments deposited at the seaward portion of wave dominated estuary based on its close association with central estuary fines (FA6) and tidal channels (FA7) (e.g. Boyd, 2010). The deposits generally represent different sub-environments but the ones described from the present study show typical features of tidal delta and washover deposits (Dalrymple et al., 1992; Catuneanu, 2006; Nichols, 2009; Boyd, 2010). Buatois et al. (1999) in a similar study interpreted the thicker sandstone units as tidal delta deposits while the thinner units as washover deposits and the mudstones (S1 and S2) as quieter environments where sand deposition is minimal.

4.2. Facies successions and depositional environments

4.2.1. Wave-storm-dominated prodelta to delta front facies succession

This succession comprises stacked units of wave-storm-dominated prodelta to delta front facies association (FA1) and is restricted in occurrence to the northern part of the study area around Ashaka, Badabdi, and Bage axis (Fig. 5A and B). The lower part of the succession is characterized by mud prone FA1 units while the upper part is more sand prone. It conformably overlies the limestones and shales of the Kanawa Member of the Pindiga Formation (Fig. 5B) and is disconformably overlain by the wave-dominated estuary facies succession (Fig. 5B). Laterally the succession inter-fingers with the wave-storm dominated offshore-nearshore facies succession.

The interpretation of this facies succession is based on the generally mud-prone nature of the interval, coarsening upward facies associations, the prevalence of wave generated sedimentary structures and typically lower bioturbation levels than the laterally correlatable non-deltaic offshore to nearshore facies succession (e.g. Bhattacharya, 2010; Mangano and Buatois, 2004). In addition, the absence of distributary channels and the laterally restricted occurrence of the succession lends further support for this interpretation. The sparse and variable bioturbation indices recorded in the lower part of this succession indicates brackish water conditions that are commonly associated with variable sedimentation rates or hyperpycnal flows in prodelta environments (Bhattacharya, 2010). Within the prodelta intervals, the preservation of laminations in the siltstones to fine grained sandstones indicate deposition by river floods suggesting proximity of a river mouth while the presence of shell beds (calcareous beds) especially at the lower part of the succession indicates merging of the prodelta with the basin floor (Bhattacharya, 2010).

4.2.2. *Wave-storm dominated offshore to nearshore facies succession*

This facies succession consists of the wave-storm-dominated shoreface to nearshore facies associations (FA2) and the offshore to offshore transition facies association (FA3). Stacked coarsening and thickening-up sub-units produced by FA3 at the lower parts and FA2 tops, make-up the bulk of this succession. Up section, the FA2 dominates the succession with corresponding decrease or absence of the FA3 association (e.g. Fig. 5I). This succession occupies two stratigraphic positions in the Sandy members: lower and upper units. The lower unit comprises the lower portion of the Sandy Members especially in the east and southern parts of the study area where it conformably overlies the Kanawa Member and is disconformably overlain by the tide dominated estuary facies succession (Fig. 5G, H, K). The upper units occurs at the uppermost portion of the Sandy Members in the northern part of the study area (Fig. 5C–D). Here it overlies the wave dominated estuary facies succession and it is overlain directly by the Fika Shale.

The wave-storm dominated offshore to nearshore facies succession is interpreted to record the deposition of a wave-storm dominated shoreline into an offshore environment typical of storm dominated shallow clastic sea or shelf (e.g. Reading, 1996; Nichol, 2009). The general coarsening-up character of the succession indicates a progressive upward increase in the wave and currents as the shoreline prograded (Plint, 2010). The dominance and amalgamation of the FA2 towards the upper part of this succession indicates higher sedimentation rates than accommodation, a condition commonly created during normal regression (Catuneanu, 2006).

The observed trace fossil assemblage further supports deposition in wave-dominated open marine (non-deltaic) nearshore to shoreface environment. Generally, the sediments display two trace fossil assemblages that can be related to Skolithos and Cruziana ichnofacies. The muddier FA3 association with ichnogenera (*Thalassinoides*, *Planolites*, *Palaeophycus*, *Skolithos* and occasional *Terebellina* (Table 1) are indicative of Cruziana ichnofacies (Pemberton et al., 1992). The prevalence of the *Skolithos, Ophiomorpha, and Planolites* ichnogenera is depictive of the Skolithos ichnofacies in the middle to upper shoreface (FA2). This setting is naturally akin to higher energy conditions (Reinson, 1986; Boyd et al., 2006) and this is captured herein by the vertical borrows of *Skolithos* that are usually indicative of stressed environment, in this case, owing to physical energy associated with wave and storm deposition (Pemberton et al., 1992).

4.2.3. *Wave-dominated estuary facies succession*

This facies succession is restricted to the northwestern part of the study area (Fig. 5B and C). It consists of bayhead delta (FA8), central estuary (FA6), tidal channel (FA7) and estuary mouth (FA9) facies associations. The succession overlies a deeply erosional, disconformity surface that separates it from the underlying prodelta to delta front facies succession (Fig. 10F); it also inter-fingers at its upper boundary with the wave-storm dominated offshore to nearshore facies succession (Fig. 5C).

The relative temporal and spatial disposition of the facies associations in this succession demonstrate a paleogeomorphic framework definitive of a wave dominated estuary (e.g. Dalrymple and Choi, 2007).

The vertical facies associations of this succession have been depicted in the stratigraphic log of the northern part of the study area around Badabdi (Fig. 5C). The profile exhibits large scale fining upwards character of the succession from predominantly bayhead delta (FA8) facies association at the base to central estuary and then to a complex formed by central estuary (FA6), estuary mouth (FA9) and tidal channel (FA7) facies associations. This complex is overlain by an erosional surface which in-turn is overlain by offshore to offshore transition facies association. This vertical progression indicates overall transgressive pattern commonly seen in wave dominated estuary successions (Dalrymple et al., 1992; Dalrymple, 2010).

The close association of FA6, FA7 and FA8 at the basal part of the succession suggests progradation of bayhead delta into central estuary mudstones which represents the lowest energy part of the succession (Dalrymple et al., 1992). The interfingering of the coarsening-up estuary mouth with the central estuary fines at the middle part of the succession represents the progradation of either washover or flood tidal delta into the low energy central estuary while the associated tidal channels have been interpreted to represent tidal inlet deposit.

Towards the upper part of the succession, the erosional surface at the top of the complex comprising the estuary mouth, central estuary and tidal channels represents a wave ravinement surface created due to shoreface retreat during transgression. The offshore facies association overlying this surface represents the remaining part of the shoreface to offshore that was not removed by the erosion. However, the offshore to nearshore facies succession overlying the wave dominated estuary succession represents a progradational condition that ensured after the deposition of the wave dominated estuary succession.

4.2.4. *Tide-dominated estuary facies succession*

The tide dominated estuary facies succession forms the upper portion of the Sandy Members in the eastern and southern parts of the study area. The succession consists of stacked units of tide influenced fluvial channel facies association (FA4) at its lower part and the tidal bar facies association (FA5) at its upper part (Fig. 5E, F, G, & K). The succession is underlain and overlain by sharp, erosional surfaces (Fig. 5K). The basal boundary (disconformity) is well exposed in Dogon Zaga, Sabon Gari and Dampami areas (Fig. 5G, H & K; Fig. 6; Fig. 10A–C) where it is observed to cut into the underlying wave-storm-dominated offshore to nearshore facies succession. The first few meters of the FA4 associations that directly overlie this disconformity at Dampami and Dogon Zagga (Figs. 3 and 5I, L) areas are characterized by trough cross bedding and numerous internal concave-up erosional surfaces most of which are mantled with coarse particles. Within these units, trough cross beds with opposing paleocurrent direction were recorded. However, at Sabon Gari (Figs. 3 and 5F), the laterally equivalent FA4 associations are coarser and contains large-scale unidirectional planar cross beddings. The upper erosional boundary is an angular unconformity that is well exposed in the Dampami section, this surface is in turn overlain by the Fika Shales (Fig. 5K; 10D & E). This unconformity may represent the mid-Santonian unconformity in the sub-basin (M. B. Abubakar, pers. comm).

The sedimentary structures, the vertical and lateral relationships of the facies associations within this succession as well as the trace fossil characteristics all point to deposition in a tide-dominated estuary.

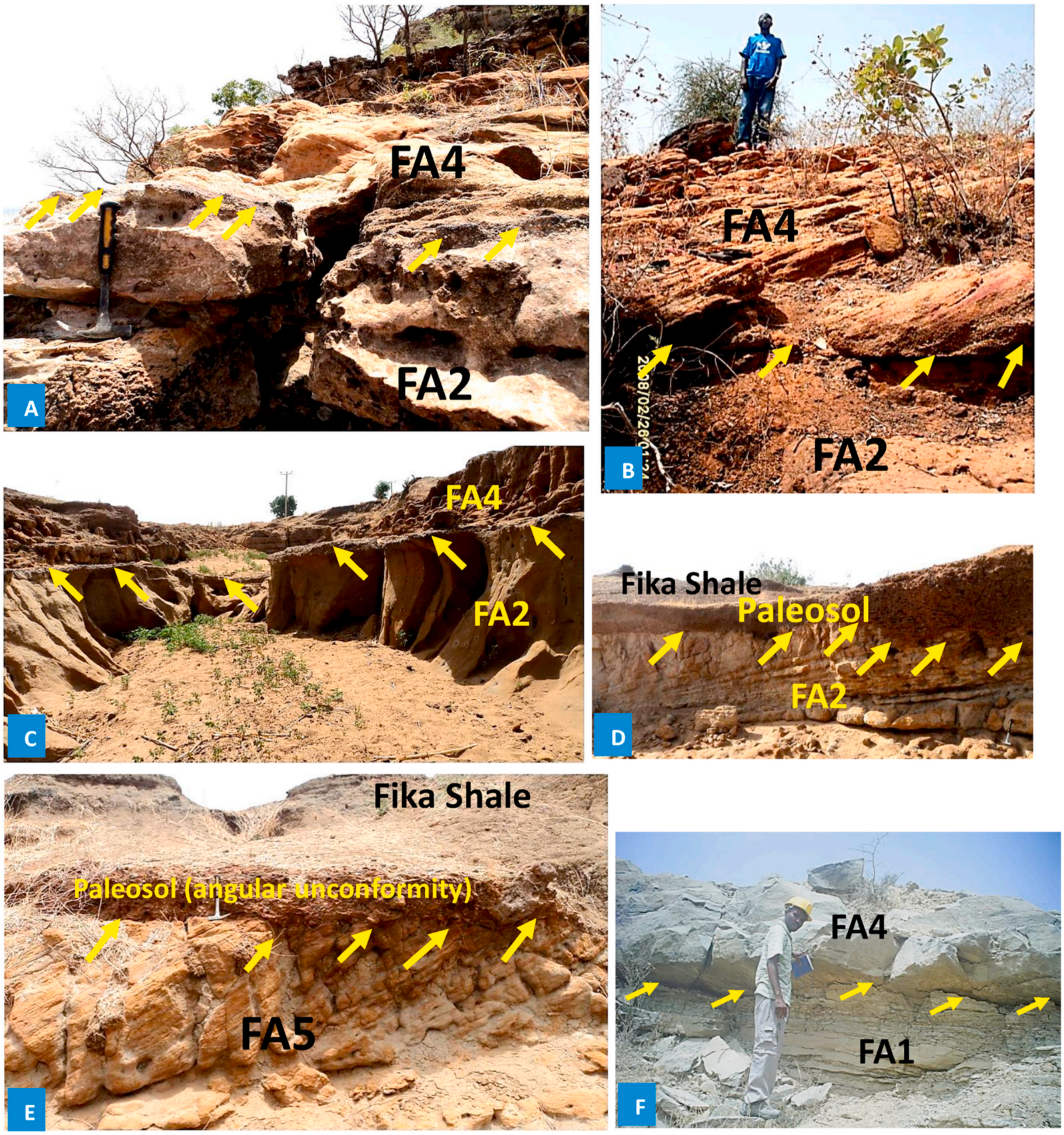

Fig. 10. Field expressions of unconformities at the middle part and at the upper bounding surface of the Sandy members. [A, B, C] disconformity surface separating the lower and upper parts of the Sandy members, exposed at Dogon Zaga, Sabon Gari and Dampami localities respectively. [D, E] angular unconformity separating the Sandy members from the overlying Fika Shale exposed at Dampami stream. [F] disconformity surface between the lower and upper portions of the Sandy members, exposed at Ashaka locality. Note: truncations at unconformities are indicated by arrows.

Although various descriptions are available on the predictable nature of facies and facies associations within tide dominated estuaries, gaps still exist in details of the facies to be encountered (Dalrymple et al., 2012). The interpretation herein is made based on the dominance of coarse sand-to gravel-sized tide influenced fluvial facies association (FA4) at the lower part of the succession, the occurrence of finer grained sandstones in the middle part and the dominance of medium grained sand to gravel sized large-scale tidal bar facies association (FA5) at the upper part of the succession. This reflects broadly the coarse-fine-coarse tripartite division envisaged in tide dominated estuaries.

The vertical progression of this succession is depicted in Dogon Zagga, Gulani and Maliya localities (Fig. 5 L, K, J) in the eastern part of the study area and in Dampami, Malam Macci and Deba in the south (Fig. 5 I, H, G). Overlying the bounding basal erosional surface of the succession, the stacked FA4 units are inferred to reflect the fluvial to tidal-fluvial zone of the inner estuary (Dalrymple et al., 1992; Dalrymple and Choi, 2007). Amalgamation of the fluvial channels is reflected by the numerous concave-up erosion surfaces displayed by some of the FA4 in Dampami and Dogon Zagga localities. This suggests deposition in low accommodation setting (Dalrymple, 2010). Whereas the less amalgamation and the occurrence of tidal flats in the FA4 at Sabon Gari locality reflects higher accommodation.

The from dominantly FA4 at the base to dominantly FA5 at the upper part of the succession records a deepening-up trend (transgression) from a basal disconformity surface to stacked tide influenced fluvial deposits to open marine tidal bar deposits. The FA5 therefore represents the deposits of outer estuary. The sedimentary structures ranging from small to large scale cross bedding displayed by the FA5 reflect the different bed-forms that are commonly encountered in the outer estuary complex (Dalrymple et al., 2012). Simple 2D and 3D dunes are recorded by the planar and trough-cross bedded units while compound dunes are reflected where the crossbed are more complexly arranged. For example, a typical compound dune within the Sandy members has been described from the Dampami section (Mohammed et al., 2019).

The generally sandy nature of the succession suggests deposition within incised valley system during transgression (Dalrymple et al., 1990, 1991). Due to the landwards erosion (tidal ravinement) that commonly occurs during transgressions, the preservation of thick tidal-fluvial and outer estuary facies associations in the study interval indicates that the shoreline trajectory was steeply rising (Plink-Bjorklund, 2005). This is opposed to situations where the outer estuary facies associations were eroded due to shoreline migration with nearly flat trajectory. Well documented tide dominated estuary with similar facies associations are recorded in the Cobequid Bay-Salmon-River system in the Bay of Fundy (e.g. Dalrymple et al., 1990, 1991).

4.3. Depositional model

The spatial and temporal distribution of the facies and facies associations of the Sandy members are depicted in composite sedimentary logs and models in Fig. 11. Open marine offshore, shoreface to nearshore and coastal environments are indicated by the facies successions. Considering the proportion of the wave (FA1, FA2, FA3), tide (FA, FA7) and fluvial (FA4, FA8) dominated facies associations, the Sandy members indicate mixed energy coastal system based on the ternary process-based classification of coastal systems (Dalrymple et al., 1992; Reading and Collinson, 1996, Ainsworth et al., 2011) (Fig. 11A). The lower part of these successions are interpreted to record open marine environment represented by progradation of wave-storm dominated offshore to nearshore facies succession in open shoreline areas and wave-storm dominated prodelta to delta front in river mouth areas (Fig. 11D, E, F). Their progradational character is indicated by the overall coarsening and thickening-up units. The occurrence of prodelta to delta front facies succession in the northern part of the study area suggests the presence of river mouth whose sediments prograded in to a shallow clastic sea (Catuneanu, 2006) in the early phase of the stratigraphic development of the Sandy members (Fig. 11E). The spatial disposition of these environments is suggestive of varying coastal physiography with probably highly elevated northern basin margin, supporting the development of deltaic depositional system due to significant fluvial discharge and sediment flux (Coleman and Prior, 1992; Einsele, 2000; Mellere et al., 2002; Helland-Hansen, 2010). Whereas the preferential build-up of offshore to nearshore facies succession in the east and south may be attributable to low relief hinterland flanking the.

Eastern and southern reaches of the Turonian coastline of the Gongola Sub-basin. Similar occurrences have been documented in the modern wave dominated Rhine delta having shoreface lying adjacent of wave dominated mouth-bars (Berendsen, 1998).

The lower facies successions (i.e. wave-storm-dominated prodelta to delta front and offshore to nearshore facies successions) were

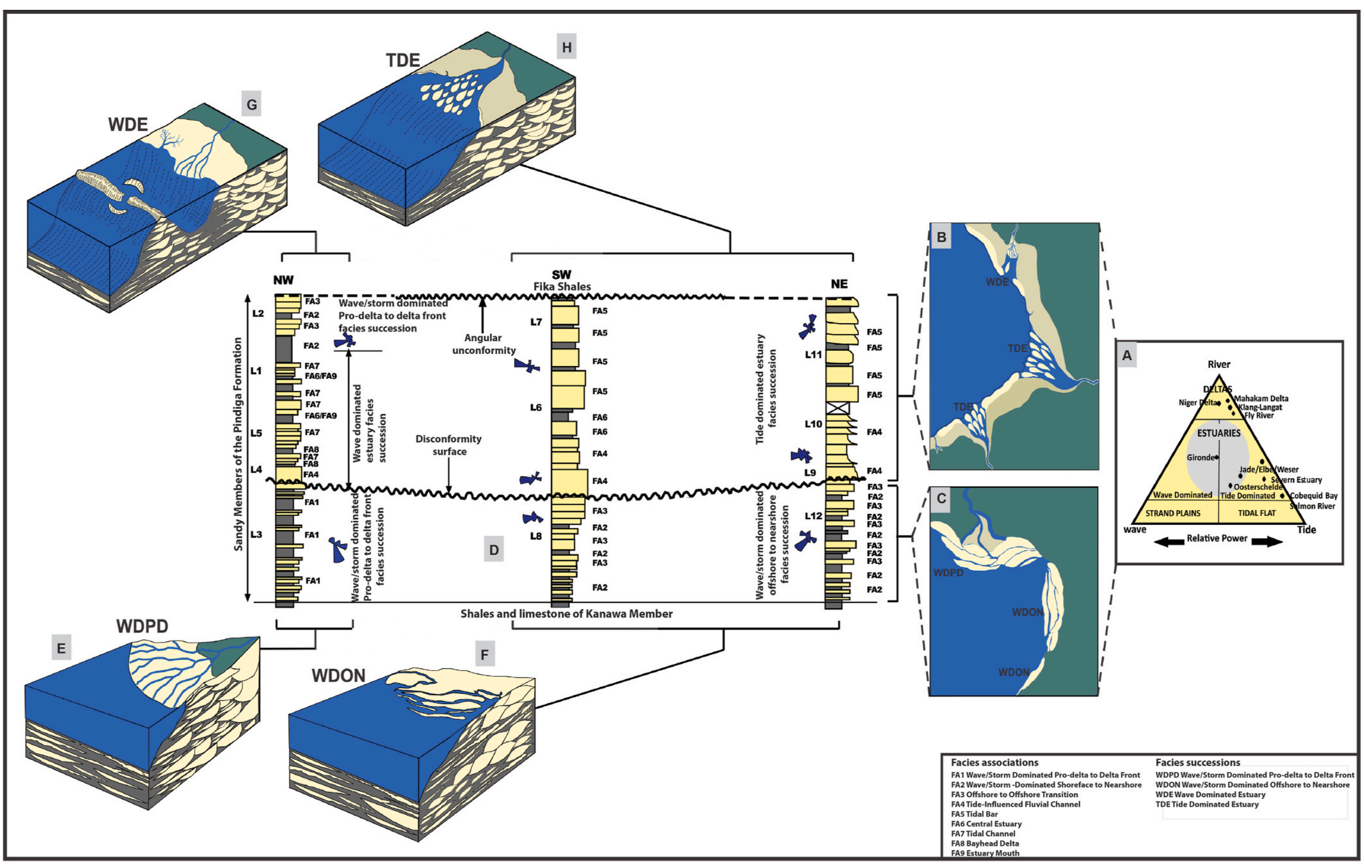

Fig. 11. Depositional model for the Sandy Members of the Pindiga Formation, Gongola Sub-basin, Northern Benue Trough. (A) Position (shaded grey) on the ternary process-based classification of coastal systems (Dalrymple et al., 1992) showing the range of possible environments for the mixed-energy coastal system. (B and C) Depositional models for the upper (tide and wave dominated estuary systems) and lower (wave-storm dominated shoreface and delta system) portions of the sandy members. (D) Composite logs illustrating vertical partitioning and distribution of sedimentary facies, associations and successions (not drawn to scale). (E, F, G, H) Schematic block diagrams showing three-dimensional views of wave dominated prodelta to delta front, wave dominated offshore to nearshore, wave dominated estuary and tide dominated estuary respectively. Note: the locations of L1- L12 are shown on Fig. 3.

subsequently partly eroded; dividing the Sandy members into two parts (Fig. 11D). This widely spread disconformity surface is overlain by sedimentary strata deposited in coastal environments (upper half of the Sandy members) represented by the tide-dominated estuary facies succession in the east and south (Fig. 11B, D, H) and wave-dominated estuary facies succession in the northern part of the study area (Fig. 11B, D, G). The occurrence of wave and tide dominated estuaries at this stratigraphic level records deepening up sedimentary facies trend which indicates that the shoreline was transgressive during their deposition.

Facies and facies associations having similar distribution and interpretations with the eastern and southern parts presented in this paper have been documented in the Cenomanian Twowells Tongue of the Dakota Sandstone, Acoma Basin, New Mexico (Mellere, 1994) and the early Permian Pebbly Beach Formation, in the southern Sydney basin, Australia (Bann et al., 2004). In the study area (eastern and southern parts), the tide dominated coastal successions are directly overlain by the Fika Shale separated by an angular unconformity making them the youngest part of the Sandy members. However, in the northern part, the re-establishment of the offshore to nearshore facies succession towards the top of the Sandy members indicates the replacement of the restricted, probably incised valley fill (wave-dominated estuary) by more extensive open marine sedimentation. This upper unit is here interpreted as barrier bar complex based on stratigraphic position and associated facies (Fig. 11B, D).

5. Discussion

Discriminating between offshore, shoreface and other inshore sand bodies is often a difficult task in ancient shallow clastic seas. However, analysis of both modern and ancient deposits show that sand-prone tide and storm dominated types as well as mud dominated end members are recognised (e.g. McCave, 1984; Johnson and Baldwin, 1996). The characteristics of shoreface successions as well as their trace fossil attributes have been detailed in many publications (e.g. MacEachern and Pemberton, 1992; Pemberton et al., 1992; Boggs, 2006; Nichol, 2009). The morphology of wave and tide dominated estuary deposits are also extensively documented in the literature (e.g. Buatois et al., 1999; Dalrymple et al., 1992; Kvale and Barnhill, 1994; Zaitlin et al., 1994; Dalrymple and Choi, 2007).

The stacked fining-up large scale cross bedded, gravely, coarse grained sandstones together with their intervening finer grained facies of the Sandy members outcropping in the Gulani area (Fig. 3 L5, 6, 7) were previously interpreted as fluvial deposits based on fining upward cyclotherms (Zarboski et al., 1997). This interpretation is however seen as inadequate due to the existence of a number of marine indicators such as tidal sedimentary structures and the trace fossil assemblage. Tidal effects in this interval are suggested in the large scale trough cross bedded sandstones (FA5) by abundant reactivation surfaces and bidirectional paleocurrent patterns as well as abundant flaser bedding in the finer grained facies. This corroborates the interpretation of a tidal depositional system (Dalrymple, 2010). The sporadic distribution of a low diversity ichnofauna assemblage dominated by *Ophiomorpha* also indicates a stressed marine environment consistent with brackish estuary environment of deposition (Pemberton and Wightman, 1992; Frey and Howard, 1986).

Unlike previous studies that suggested fluviatile environment of deposition for the sediments of the Dumbulwa Member of the Pindiga Formation at Dumbulwa and Bage areas (Fig. 3 L1, 2, 3) in the northern part of the study area (Zarboski et al., 1997), the present study proposes deposition in a wave dominated estuary. Starting from the lowermost part of this sandy member (best exposed in the southern part of Ashaka quarry, L4), the vertical stacking of the facies are interpreted to represent deposition in wave dominated prodelta to delta front environment erosionally overlain by wave dominated estuary deposits. This interpretation is supported by the lithofacies analysis; abundant wave generated sedimentary structures such as hummocky cross stratifications and wavy bedding, and the ichnofauna assemblage. The tripartite coarse-fine-coarse facies distribution typical of transgressive wave dominated coasts (Boyd, 2010) is also evident in the area.

Zaborski et al. (1997) inferred a coastal and shallow littoral environment with little fluvial input for the Deba Fulani Member without giving details of the sub-environments and their spatio-temporal disposition. This work demonstrates that the Deba Fulani Member around Sabon Gari and Dampami localities (near the type locality) consists of a lower part comprising of a regressive wave-storm dominated offshore to nearshore succession and an upper part comprising transgressive tide dominated succession separated by a disconformity surface. However, in the Ashaka-Bage areas in the north, the Deba Fulani Member of Zaborski et al. (1997) consists of a complex of tide-influenced fluvial, bayhead delta, central estuary and tidal channel facies associations while the Dumbulwa Member is here interpreted as barrier-bar complex comprising of central estuary, estuary mouth and shoreface associations. This indicates that the Dumbulwa Member is stratigraphically above the Deba Fulani Member in the Ashaka area. Therefore, the regional pelogeographic framework of the Gongola sub-basin during the deposition of the Sandy members is characterized by superposed succession of a repeatedly broad coastal to shallow marine setting with varying topographic morphology of high and low relief landscapes and competing hydro-dynamic processes, imposing cycles of progradation and retrogradation.

Regarding the upper boundary of the Sandy members, the field demonstration of the presence of an angular unconformity between the Sandy members and the Fika Shale clearly shows that the two deposits are separated by a long time of non-deposition, uplift and erosion. This may question previous notions (Zaborski et al., 1997; Zaborski, 1998) that they are products of continuous deposition. Nonetheless, accurate age determination may shed more light on these.

6. Conclusions

The stratigraphic succession and facies distribution of the Sandy Members of the Pindiga Formation in the Gongola Sub-basin, Northern Benue Trough, Nigeria, indicates a strong partition between a basal succession composed of regressive wave-storm dominated marine to shoreline deposits and an upper horizon consisting of transgressive tide and wave dominated coastal deposits. The basal stratigraphic successions display stacked coarsening upward cycles of wave-storm dominated facies succession recording progradation of shoreface-nearshore and delta front sands into open marine offshore environment and prodelta. The geomorphic framework of these assemblage accounts for an open coastal shoreline with wave dominated current system and relatively elevated hinterland, supporting a basin-wards sediment flux. The upper, transgressive successions represented by tide and wave dominated estuaries unconformably overlies the progradational deposits, signalling a variable coastal morphology with a net landward trajectory regime. The sedimentological architecture of the Sandy Members is also reflected in its ichnology, demonstrating abundance and high diversity of Skolithos and Cruziana ichnofacies in the lower, wave-storm dominated successions, which dissipates to impoverished assemblages with growing tidal disturbances in the upper transgressive succession. The lower bounding surface of the Sandy members is transitional. Within the Sandy members, the surface that separates the shoreface and the estuary successions is a disconformity surface, while the upper bounding surface is an angular unconformity that might represent a Santonian compressional event in the Northern Benue Trough.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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