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Trace Fossils and Paleoenvironments of the Turonian Amasiri (Afikpo Synclinorium) and Campanian Afikpo Sandstone Facies (Afikpo Sub-Basin), Southeastern Nigeria

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Abstract
This study evaluated trace fossils and lithofacies of the Turonian Amasiri (Afikpo Synclinorium) and Campanian Afikpo Sandstone facies (Afikpo Sub-basin), southeastern Nigeria. The lithofacies and ichnofossils, distribution, and ichnofabric index were used to interpret paleoenvironments of deposition for the sandstone units. The trace fossils recorded in the Amasiri Sandstone includes *Ophiomorpha irregulaire* of the *Skolithos* ichnofacies; *Thalassinoides, Planolites, Paraonis, Monocraterion, Palaeophycus* and *Arthrophycus* belonging to the *Cruziana* ichnofacies. The Afikpo Sandstone is characterised by *Skolithos, Arenicolites*, *Ophiomorpha nodosa*, and *Chondrites*, *Rosselia, Thalassinoides*, *Planolites* belonging to *Skolithos* and *Cruziana* ichnofacies respectively. The trace fossil assemblages of *Skolitho*s and *Cruziana* ichnofacies are characteristic ichnofacies of both lower and high energy conditions in shallow water sand environments. The ethological categorisation of the ichnofossils shows that feeding and dwelling traces occur in the sandstone facies. The facies include bioturbated sandstone, cross-bedded sandstone, laminated sandstone, thin-bedded sandstone, massive/ conglomeritic sandstone facies for the Amasiri Sandstone, while bioturbated sandstone, cross-bedded sandstone, bioturbated cross-bedded sandstone and sandy heterolith were recorded in the Afikpo Sandstone. The gross paleoenvironments of deposition deduced from the trace fossil assemblages and lithofacies/ association suggests that the Amasiri Sandstone facies were deposited in foreshore to offshore settings; while the Afikpo Sandstone facies were deposited in estuarine and foreshore environments. The general absence of *Zoophycos-Nereites* ichnofacies (deep water ichnofacies) in the sandstone facies indicates the Turonian and Campanian epeiric seas were shallow.

Keywords: *Ichnofossils; Sandstone facies, Paleoenvironments; Amasiri Sandstone; Afikpo Sandstone, Nigeria*

Introduction

The Turonian Amasiri Sandstone, a lithostratigraphic unit of the Eze-Aku Group in the Afikpo Synclinorium unconformably underlies the Campanian Afikpo Sandstone (Igwe and Okoro, 2016; Okoro and Igwe, 2018) (Table 1 and Fig. 1) of the adjoining Afikpo Sub-basin (Reijers et al., 1997). The ubiquitous angular unconformity which occurs in between the two sandstone units represents absence of Awgu Formation (Coniacian) probably due to non-deposition or intense erosion associated with Santonian Orogeny, a period of uplift, folding and widespread erosion in the southern Benue Trough of Nigeria. The Afikpo Synclinorium (Murat, 1972; Benkhelil, 1987) is a re-entrant between the Oban Massif and the Abakaliki Anticlinorium (Nwajide, 2013) in the southern Benue Trough (Fig. 2). The term "Syncline" connotes folding and tectonic deformation of the sedimentary fills. The synclinorium has been distinguished as a full-fledged basin by some workers (eg., Amajor, 1985, 1987). The Afikpo Sub-basin occurs as a synclinal depression in the eastern flank of Abakaliki Anticlinorium and its lithic fill postdates the Santonian folding event and is really not itself folded (Nwajide, 2013). The Afikpo Sandstone is the basal stratigraphic unit in the Afikpo Sub-basin, and unconformably overlies the Eze-Aku Group in the synclinorium.

Several palynological, lithological, lithofacies and granulometric analyses based on aspects of stratigraphy and paleoenvironmental studies have been carried out for the Amasiri and Afikpo sandstones in the Afikpo Synclinorium and the sub-basin respectively. These previous studies include those of Amajor (1987), Ojoh (1990), Odigi (2012), Okoro and Igwe (2014), Igwe and Okoro (2016) and Okoro et al. (2016) for the Amasiri Sandstone. Though some of the previous works identified some ichnofossils in the sandstone units, none of these researchers gave attention to detailed study of the trace fossils. The sandstone unit designated as the Afikpo Sandstone by Simpson (1954) has not received attention in the area of evaluation of its trace fossils for paleoenvironmental reconstruction. The only available published literature on ichnofossils and paleoenvironments for studied lithostragraphic units is the work done by Banerjee (1982) on the Amasiri Sandstone, while there is no published detailed work specifically on the ichnofossils and paleoenvironments for the Afikpo Sandstone. Mode (1993) and (1997) carried out studies on the ethology and ichnostratigraphy based on paleoenvironments for the

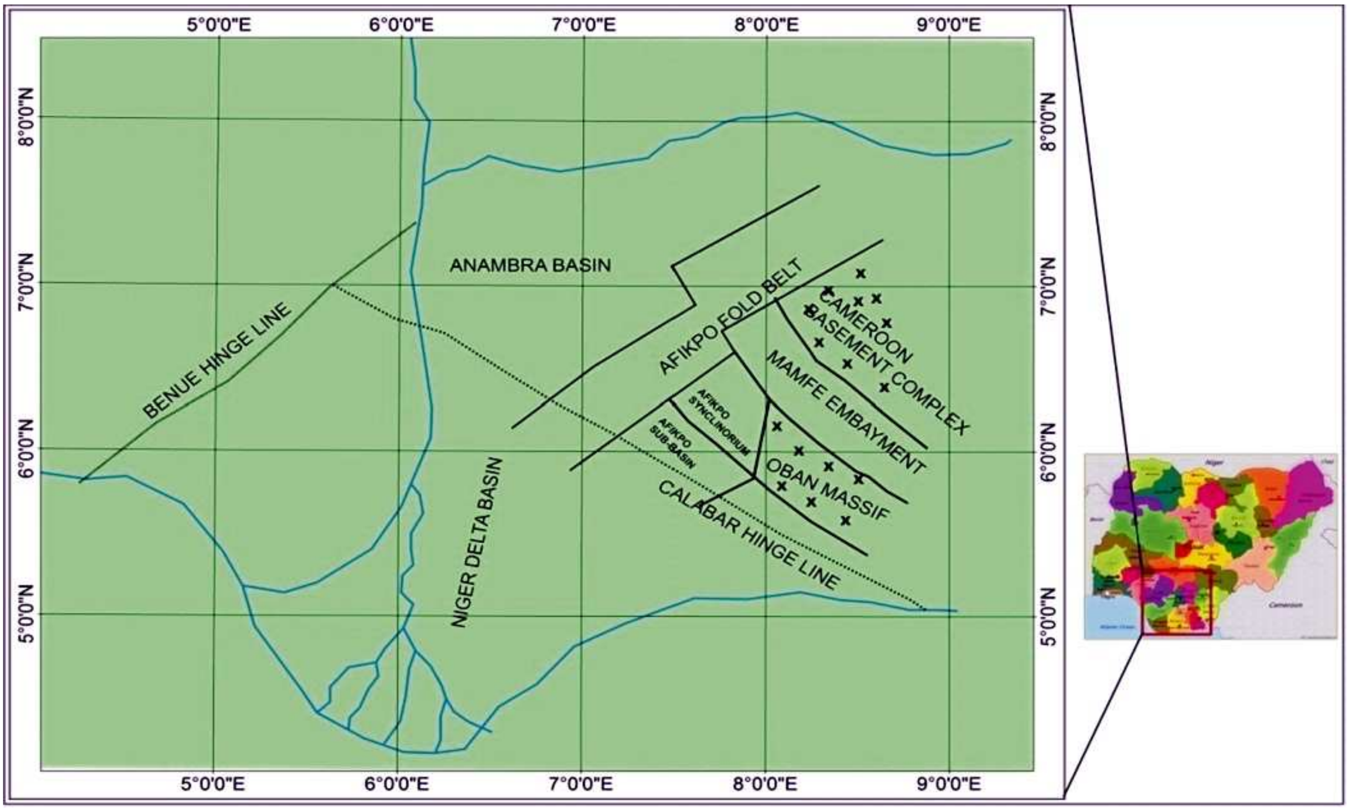

Fig. 2: Structural units of the southern Benue Trough Nigeria showing the Afikpo Synclinorium and Afikpo Sub-basin (Modified after Murat, 1972 cited in Okoro and Igwe, 2018)

Table 1: Stratigraphic sequence for the Afikpo Synclinorium and Afikpo Sub-basin of southeastern Nigeria (Modified from Okoro and Igwe, 2018)

Age	Lithostratigraphic Unit		Basin
	Formation	Subunits	
Upper Maastrichtian	Nsukka Formation		**Afikpo Sub-Basin**
Middle Maastrichtian	Ajali Formation		
Lower Maastrichtian	Mamu Formation		
Campanian	Nkporo Formation		Amaiyi Shale Owutu Sandstone Asaga Shale
	Afikpo Sandstone		
Santonian			Afikpo Synclinorium (Southern Benue Trough)
Upper Cenomanian - Turonian	Eze-Aku Group	Amasiri Sandstone Eze-Aku Shale	

upper Benue Trough and Benue Trough of Nigeria respectively. An increasing intensity in the ichnologic research recently has given rise to the development of trace fossil analysis as a significant contributor to a wide range of fields, including paleobiology, paleoecology, biostratigraphy, paleobathymetry and sedimentology (Egbu et al., 2009; Nagy et al., 2016). In sedimentology, trace fossil associations have been used to assess paleoenvironments mainly based on the adaptation of trace fossils to particular paleoecological and depositional conditions (Nagy et al., 2016). Trace fossils have been used significantly in the paleoenvironmental reconstruction (eg., Seilacher, 1967; Ekdale et al., 1984; Pemberton et al., 1992, 2001;

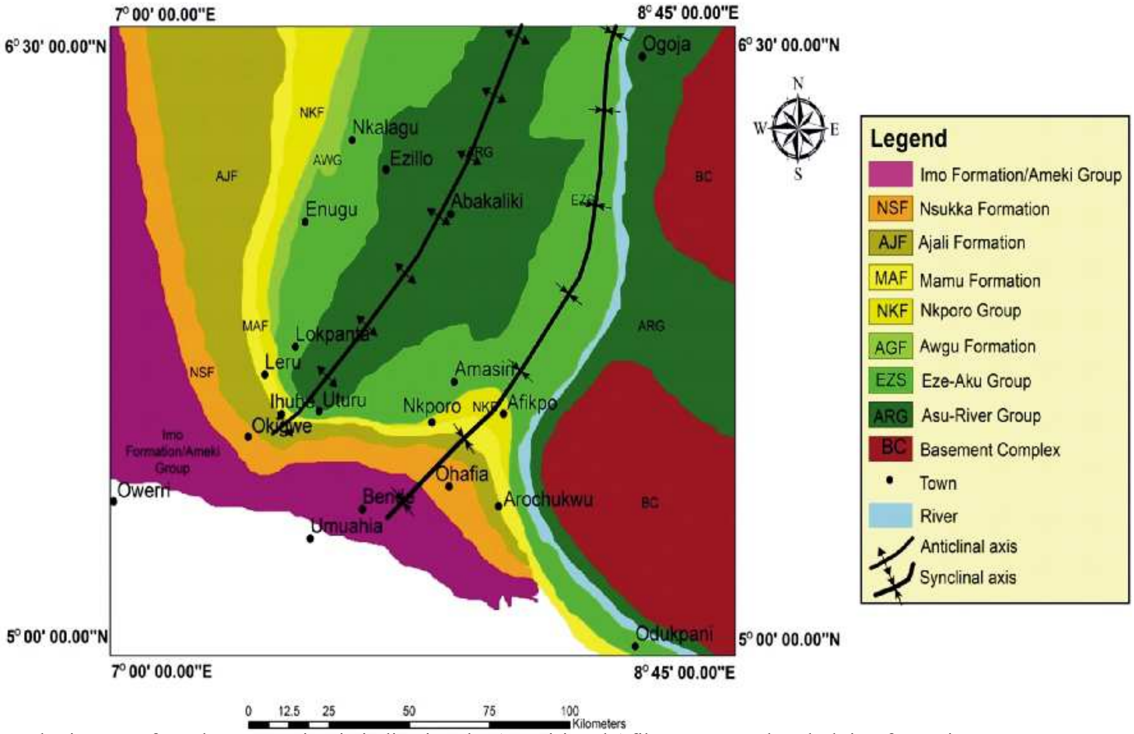

Fig. 1: The geologic map of southeastern Nigeria indicating the Amasiri and Afikpo areas and underlying formations.

Bromley, 1996, Buatois and Mangano, 2011; Mangano et al., 2012).

Previous study by Banerjee (1982) that utilised ichnofossils in the paleoenvironmental analysis of the Amasiri Sandstone in the study area is grossly inadequate; while no attempt has been specifically made on the evaluation of ichnofossils abound in the Afikpo Sandstone. The interpretations of paleoenvironments of deposition for the Amasiri and Afikpo Sandstone have been based largely on the lithofacies and granulometric analyses of the sandstones. However, previous authors (eg., Okoro and Igwe, 2014; Igwe and Okoro, 2016; Okoro and Igwe, 2018) mentioned few ichnofossils while describing lithofacies in these sandstone units as no known online published information on the ichnofossils and paleoenvironments of the Afikpo Sandstone is available. Hence there is need to assess the paleoenvironments of the sandstone facies based on its trace fossils suite. This study will provide useful information on the ichnofabric index (II), ichnofossils, ethology, and paleoenvironments of the Amasiri and Afikpo Sandstone facies. The expected ichnological contribution is the first of its kind for the Afikpo Sandstone while the only available online published information particularly on ichnofossils for the Amasiri Sandstone provided by Banerjee (1982) will be expanded.

Geologic Setting

Benkhelil (1989) and Nwajide (2013) described the Benue Trough as aggregation of pull-apart sub-basins or grabens developed from sinistral strike-slip displacements inherited from pre-existing transcurrent fault zones in the Pan African mobile belt. The trough regarded as part of the much larger West and Central African Rift System (Fairhead, 1988; Genik, 1993) which resulted from the breakup of the Gondwana supercontinent and subsequent opening up of the southern Atlantic and Indian Oceans in the Jurassic (Burke et al., 1972; Benkhelil, 1982, 1989; Fairhead, 1988; Gebhardt et al., 2019). Murat (1972) suggested that the geologic history of southeastern Nigeria have been controlled by three major tectonic phases. He noted that as result of these phases, the axis of the main basin has been displaced giving rise to three successive basins: the Abakaliki- Benue Trough, the Anambra Basin, and the Niger Delta Basin.

Regional compression associated with the Santonian Orogeny led to folding and uplift of the Abakaliki - Benue Trough sediments and subsidence of the Anambra Basin to the northwest and the smaller Afikpo Sub-Basin, southeast of the Abakaliki Anticlinorium. The re-entrant between the Oban Massif and the Abakaliki Anticlinorium in the southern Benue Trough is Afikpo Synclinorium (Murat, (1972; Benkhelil, 1987;

Nwajide, 2013) (Fig. 2). The synclinorium has been distinguished as a full-fledged basin by some workers (Amajor, 1985, 1987) and represents parts of the subsided basin which its sediments are folded. The Amasiri Sandstone in the Afikpo Synclinorium is bounded above and below by Santonian unconformity at Afikpo and late Albian – middle Cenomanian unconformity at Abaomege respectively (Igwe and Okoro, 2016). The top of the Turonian Amasiri Sandstone in the synclinorium is marked by the unconformity which separates it from the overlying Campanian Afikpo Sandstone in the sub-basin (Nwajide, 2013; Igwe and Okoro, 2016). The Santonian angular unconformity accounts for the missingness of the Coniacian Awgu Formation in the Afikpo Sub-basin (Nwajide, 2013). He noted that the sediment-fills in the Afikpo Sub-basin postdates the Santonian folding event and is really not folded (late Campanian – Maastrichtian sediments) (Murat, 1972; Hoque, 1977). The sedimentary succession in the Afikpo Sub-basin comprises the Afikpo Sandstone, Nkporo, Mamu, Ajali and Nsukka formations (Simpson, 1954; Reyment, 1965, Okoro and Igwe, 2018). Table 1 is the stratigraphic succession for the Afikpo Synclinorium and Afikpo Sub-basin showing the position of the Amasiri and Afikpo sandstones.

Materials and Methods

The Amasiri Sandstone outcropping on NE-SW parallel ridges and the Afikpo Sandstone (Fig. 3) on the Macgregor hills, and surrounding Afikpo areas in the sub-basin were described and systematically logged. The detailed study involved lithological characteristics, description of physical sedimentary structures, textures and trace fossil types, distribution and index of bioturbations as well as the ethology. These are critical parameters of lithofacies and trace fossil analyses for the interpretation of the paleoenvironments of deposition. The sandstone outcrops were described on road-cuts, hills, quarries and slopes of the sandstone ridges. Measurements of bed thicknesses and contact types were noted. The identified and interpreted facies were grouped into related facies associations (subenvironments). Two vertical profiles showing composite representation of the facies in the Amasiri Sandstone and the litholog of Afikpo sandstone on the Macgregor Hills (Figs. 4 and 5), and field photographs for the important sedimentological features were presented.

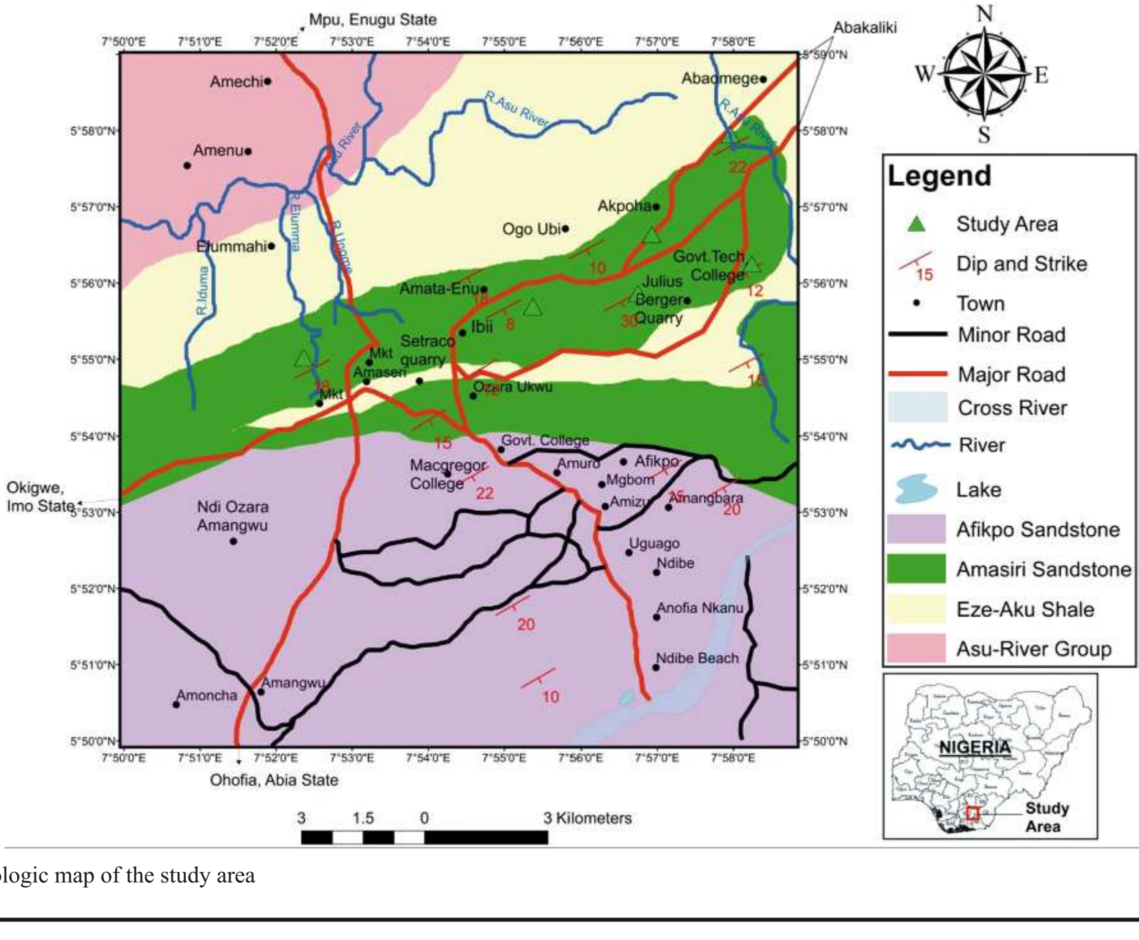

Fig. 3: Geologic map of the study area

Table 2: Summary of the lithofacies, ichnofossils, ethology, ichnofabric index (II), lithofacies association/ environments in the Amasiri and Afikpo Sandstone facies

Formation/ Age	Lithofacies/ Ichnofabric Index (II)	Ichnofossil Assemblage	Ethology Seilacher (1964) and Frey (1978)	Ichnofacies	Facies Association
	Thin-bedded sandstone, II = 1	No trace fossil	-	-	Prodelta facies
Amasiri Sandstone (Turonian)	Bioturbated sandstone, II = 3 – 4	*Orphiomorpha irregulaire* *Arthrophycus* *Monocraterion*	Domichinia	*Skolithos*	
	Laminated sandstone, II = 2 Massive/conglomeritic sandstone, II = 1 Cross-bedded sandstone, II = 2	*Thalassinoides* *Palaeophycus* *Paraonis*	Fodinichinia	*Cruziana*	Distal delta front facies
		Monocraterion *Palaeophycus*			
		No trace fossil	Fodinichinia	*Cruziana*	Proximal delta front facies
			-	-	
		Planolites	*Fodinichinia*	*Cruziana*	Foreshore facies
	Bioturbated sandstone, II = 4 – 5	*Ophiomorpha nodosa* *Planolites*	Domichinia	*Skolithos*	Estuarine bayhead delta facies
	Cross-bedded sandstone, II = 3 Sandy heterolith, II = 2 – 3	*Thalassinoides*	Fodinichinia	*Cruziana*	
Afikpo Sandstone (Campanian)	Bioturbated cross-bedded sandstone, II = 3 – 4	*Ophiomorpha nodosa* *Rosselia*		*Skolithos*	Estuarine bayhead delta and Subtidal sand ridge/ foreshore facies
			Domichinia		
		Ophiomorpha nodosa *Skolithos* *Chondrites*		*Cruziana*	Central estuarine delta facies
		Arenicolites	Domichinia	*Skolithos*	
			Fodinichinia	*Cruziana*	
			Domichinia	*Skolithos*	Subtidal sand ridge/ foreshore facies

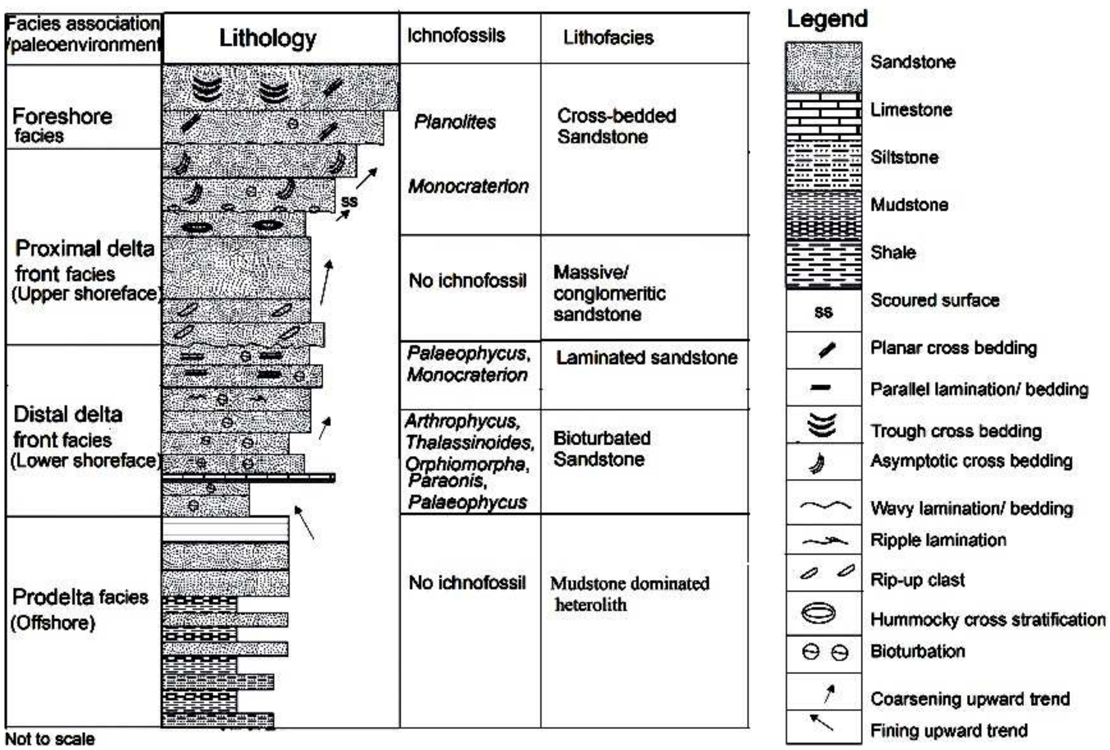

Fig. 4: Composite representation of the lithofacies in the Amasiri Sandstone in a vertical profile. The log indicates observed ichnofossils, facies associations, and paleoenvironment. See text results and discussion for the descriptions of facies, trace fossils as well as interpretation of paleoenvironments

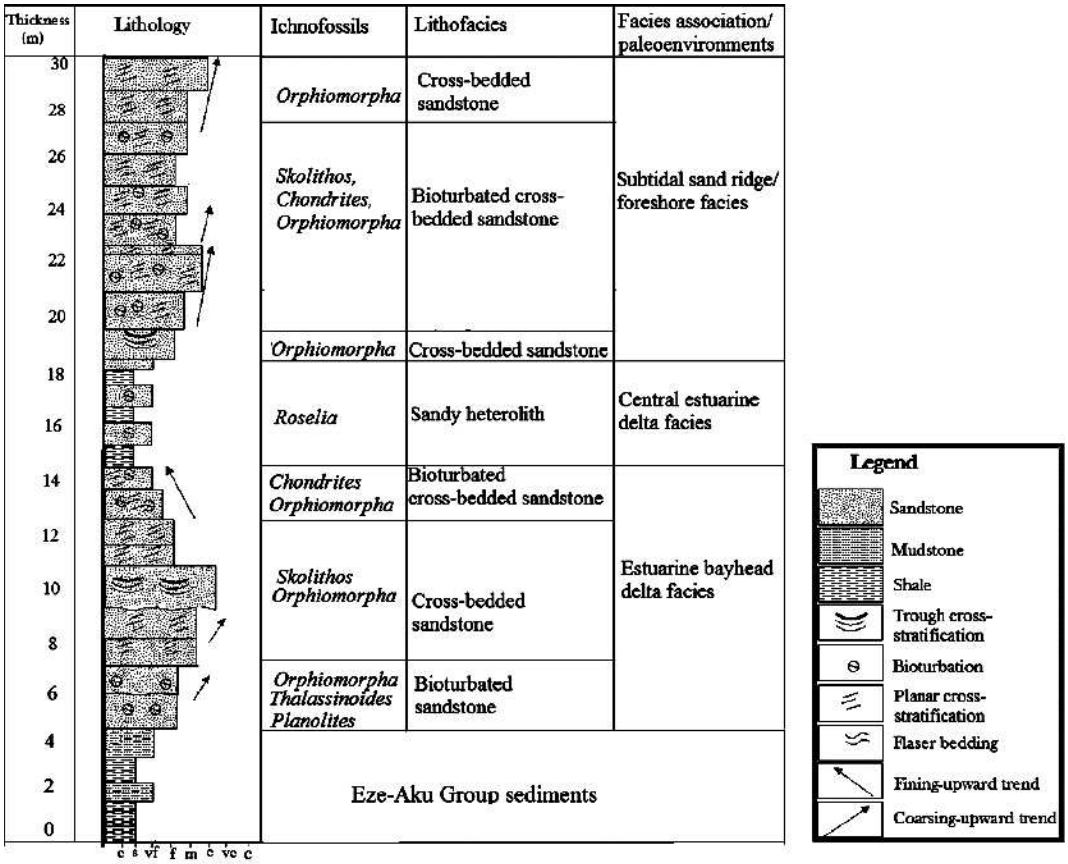

Fig. 5: Vertical profile of the Afikpo Sandstone. The log indicates observed lithofacies, ichnofossils, facies associations, and paleoenvironment. See text results and discussion for the descriptions of facies, trace fossils as well as interpretation of paleoenvironments

For the trace fossils, the description and identification of ichnogenera, ethological classes and ichnofacies followed the methods of Seilacher (1963, 1964, 1967), Mode (1997), Nagy et al. (2016) and Odumodu and Mode (2014). Measurement of ichnofabric index (II) which explains semi-qualitative determination of extent of the ichnofabric index (II), following the methods of Droser and Bottjer (1986, 1993) .They categorized the extent of bioturbation into six classes used in this study: II = 1 indicates no bioturbation, II = 2 represents less than 10%, II = 3 represents 10 – 40 %, II = 4 denotes 40 – 60%, II = 5 indicates 60 – 100 % and II = 6 shows complete homogenisation. The trace fossils and sandstone lithofacies data provided information used for the paleoenvironmental reconstructions for the depositional sandstone.

Results and Discussion

Systematic Ichnology

The ichnofossils observed in this study are *Arenicolites*, *Arthrophycus*, *Chondrites*, *Monocraterion*, *Ophiomorpha irregulaire*, *Ophiomorpha nodosa*, *Palaeophycus*, *Paraonis*, *Planolites Rosselia*, *Skolithos*, and *Thalassinoides*. Field images of the ichnofossils in the study area are shown in Figs. 6 and 7. Ichnological descriptions of the ichnofossils are systematically presented as follows:

Thalassinoides Ehrenberg, 1944

This ichnofossil exhibit irregular networks of tunnels, usually branched (3-D horizontal branching networks) (Figs. 6a and 7h) with variable diameters ranging from 2.8 – 5. 5 cm, considerably swelling joints especially at points of branching and occur parallel to the sandstone bedding planes. *Thalassinoides* occur in firm ground (Benton and Harper 1997) in wide range of environment. They occasionally contain scratch marks and remains of the burrowing animals such as crustaceans, crabs, lobsters, shrimps and stomatopods (Frey et al., 1990). The firm ground may also develop in varying energy situations such as those of mud bars of high intertidal flats or in shallow marine environments where erosion has removed superficial unconsolidated layers of sediment (Seilacher, 1967).

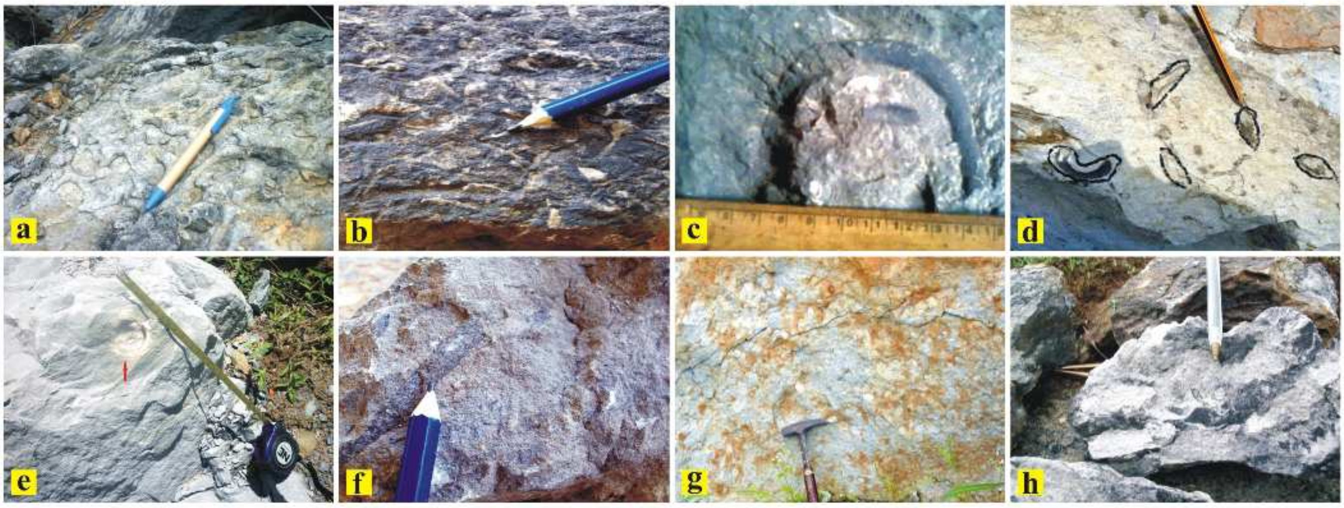

Fig. 6: Outcrop photographs showing trace fossils in the Amasiri Sandstone (a) *Thalassinoides* associated with the bioturbated facies at Ibii Junction; (b) *Palaeophycus* in the laminated sandstone lithofacies behind Government college, Akpoha (Okoro and Igwe 2014); (c and d) *Orphiomorpha irregulaire* in the bioturbated sandstone at Ibii Junction; (e) *Paraonis* in the bioturbated sandstone facies at Julius Berger Quarry, Akpoha; (f) *Arthrophycus* in the bioturbated sandstone Outcrop at Ibii Junction; (g) *Planolites montanus* in the cross-bedded sandstone at Ozaraukwu; (h) *Monocraterion* in the laminated sandstone at Crushed Stone Quarry, Amasiri

Palaeophycus Hall 1847

This trace fossil ichnogenus (Fig. 6b) is essentially cylindrical, branched or unbranched, lined burrows, predominantly horizontal taces of varying diameter with filling being massive (structureless) with similar lithology as the parent rock. There are also irregular bifurcations. *Palaeophycus* is generally regarded as open burrows generated by polychaete worms (Pemberton and Frey, 1982).

Ophiomorpha irregulaire Frey et al., 1978

Orphiomorpha irregulaire is a thick burrow characterized by meandering shape, most times coiled, subcircular and sinuous forms. Some of the forms show an upward-bending subconical (Fig. 6c and d) initial projection which apparently formed a vertical or inclined shaft probably of short extent. Most of them observed are subhorizontal, lying parallel to the bedding planes. The sand and clay fillings of the tunnels show an irregular knobby and bumpy surface wall lining are covered by dark substances in non-weathered specimens. The tunnels are elliptical to subelliptical with varying diameter sizes ranging from 3.2 – 6.5 cm. Following the intial description of *Ophiomorpha irregulaire* by Frey et al. (1978); Bromley and Ekdale (1998) described geometry of *Orphiomorpha irregulaire* as predominantly horizontal system giving rise to a meander maze composed of smoothly curved internodal tunnels.

Paraonis Rhoder 1971

The *Paraonis* fulgens observed in this study makes well defined spiral and meandering burrow system within the sediment. This trace fossil ichnogenus is calcified in the Amasiri Sandstone where it was observed (Fig. 6e) while moving through the sediment for feeding (Reineck and Sigh, 1980). *Paraonis fulgens* feeds on diatoms buried on bedding planes within the sediment and produces spiral traces 2 – 3cm diameter. The *Paraonis* spirals inhabit sandy littoral and sub-littoral sediments though have superficial resemblance to other spiral traces such as spiroraphe, found at abyssal depths.

Arthrophycus Hall 1852

The *Arthrophycus* ichnogenus consists of elongate (Fig. 6f), oblique or horizontal, cross-cutting and branching burrows (Donovan, 2010). The traces are parallel or sub-parallel sided, sometimes with tapering ends. Burrows are sometimes bilobed longitudinally and display transverse annulations. *Arthrophycus* is regarded as the burrows of annelids and anthropods (Frey and Howard, 1970)

Planolites Nicholson 1873

The trace fossil ichnogenus is simply unlined, unbranched, straight to sinuous cylindrical, infilled burrows (Figs. 6g and 7b), commonly sand-filled with unlined smooth walls. They may also be irregular, gently curved with varying dimensions and differing lithology from parent rock. *Planolites* are usually attributed to the burrowing activities of deposit-feeding vemiforms organisms (Pemberton and Frey, 1982) and various invertebrate burrowing organisms.

Monocraterion Torell 1870

This trace fossil ichnogenus is characterised by funnel–like negative epirelief with a projected knob (Fig. 6h). The knob is usually continuous with short vertical, located centrally to the tubular structure. *Monocraterion* is essentially horizontal, small, non-branched, sometimes lined or tubular with the smooth outer surface projecting out from the knob (Fig. 6h). *Monocraterion* are usually attributed to the burrowing activities of polychaete worms or phoronids (Hantzschel, 1962).

Ophiomorpha nodosa Lundgren 1891

Ophiomorpha nodosa represents vertical, slightly oblique and rarely bending shafts (Fig. 7a). The interior wall lining of *Orphiomorpha nodosa* is smooth and swells at points of bifurcation, characterised by clayey and knobby walls. The exterior of its shafts is covered by irregularly spaced low subconical to spike-like projections (visible at the burrow-to sediment-contact) regarded as deformed pellets (Nagy et al., 2016). Elsewhere, *Orphiomorpha nodosa* has been described as structures of vertical shafts and branching tunnels forming a horizontal meander maze (e.g., Pickett et al., 1971; Frey, 1975; Bromley and Pedersen, 2008). The branched and horizontal tunnels type did not occur in the studied sandstone units

Chondrites Von Sternberg 1833

This trace fossil ichnogenus consists of infilled, complex dendritic rootlike burrows with branching shafts (Fig. 7c and d) and branching angles ranging from 30 – 40^0 and varying shaft diameter of 1.8 – 5 mm. The maximum observed length of the *Chondrites* burrow is 26 mm. This burrow occurs in the lower beds of the Afikpo Sandstone on the Macgregor Hill. *Skolithos* and *Orphiomorpha* ichnogenera occur in the middle and upper sections of the sandstone outcrops with clay as fill sediment different the parent rock.

Rosselia Dahmer 1937

Rosselia socialis recorded in this study is a conical to irregularly funnel shaped sand filled burrow structure which turns horizontal, consists of other small central burrows surrounded by conical, concentric sand-clay laminae. The laminae spreite-like helicod swirls round concentrically tapering downwards towards the central tube.

Skolithos Haldeman 1840

Skolithos are unbranched, single, vertical to steeply inclined burrows and have smooth walls; cylindrical or subcylindrical, lined or unlined and elongated in shape (Fig. 7e), normally perpendicular to the surface of the host sediments. They consists of tunnel uniform diameters about 5 cm and reach lengths of up to 30 cm. The mineralogical composition of *Skolithos* in the sandstone is same as the surrounding rock matrix which allow for homogeneous deformation with the parent rock. The funnel-shaped apertures of this trace fossil are direct characteristics of its filter- and suspension-feeding behavioral attributes. *Skolithos* are generated by variety of organisms in shallow water such as polychaetes and phoronids and resemble linear features in sedimentary rocks (Desjardins et al., 2010)

Arenicolites Salter 1857

Arenicolites (Fig. 7f) represents straight cylindrical, unbranched burrow having slightly oblique U- tubes shaped without spreiten, perpendicular to the sandstone bedding planes. The tubes are cylindrical; commonly smooth walled and can have flared openings or funnel – shaped apertures Hantzschel (1962) identified *Arenicolites* occur in fine grained sandstone. *Arenicolites* is commonly produced by deposit-feeding worms such as polychaetes (Bromley, 1996).

The Sandstone Facies

The sandstone facies were differentiated based on lithological and sedimentological characteristics such as distinct assemblages of sedimentary structures (physical and biogenic) which allow the identification of major facies of the Amasiri and Afikpo sandstones. Representative logs of the Amasiri and Afikpo sandstones are presented in vertical profiles (see Figs. 4 and 5)

Amasiri Sandstone Facies

Five major sandstone facies occur in the Amasiri Sandstone (see Fig. 4) namely; mudstone dominated heterolith facies (prodelta facies association); bioturbated sandstone facies, laminated sandstone facies, massive/ conglomeritic sandstone facies

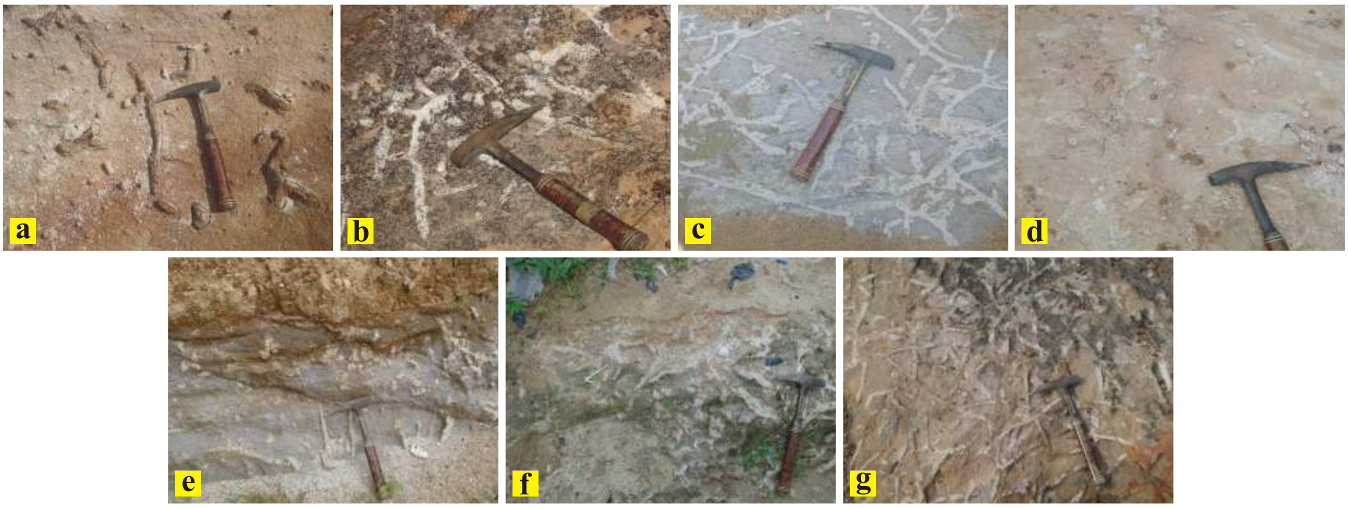

Fig. 7: Outcrop photographs of trace fossils in the Afikpo Sandstone (a) *Ophiomorpha nodosa* associated with the bioturbated facies outcropping at the Government College junction, Afikpo; (b) *Planolites* observed in the outcrop of bioturbated sandstone facies at the Macgregor Hill block industry; (c) *Chondrites bollensis* in the bioturbated cross-bedded sandstone facies at Macgregor Hill beside Mechanic village; (d) *Skolithos* and *Chondrites* in the bioturbated cross-bedded facies at Ozizza, Afikpo; (e) *Skolithos* and *Orphiomorpha* in the bioturbated cross-bedded sandstone facies at the Ebonyi Hotel Junction, Afikpo; (f) *Arenicolites* in the bioturbated cross-bedded sandstone facies at Mechanic village, Afikpo; (g) *Thalassinoides* in the bioturbated facies, 800 m from Mater Hospital along Afikpo – Ozizza Road .

belonging to delta front facies association, and cross-bedded sandstone facies (foreshore facies association).

Mudstone Dominated Heterolith Facies

The mudstone dominated heterolith (Fig. 8a) consists of siltstone, very fine grained sequence of thin-bedded sandstones interbedding with mudstones with cryptic bioturbations and occasional plant/wood fragments. This facies is interpreted as prodelta facies association (Mutti et al., 2003; Ponciano Luiza and Della Favera, 2009).

Bioturbated Sandstone Facies

The bioturbated sandstone facies is comprises of fine grained sandstone characterised by bioturbations, burrows, and a distortion of physical sedimentary structures and fabrics due to strong bioturbation (Fig. 8b); with occasional cryptic bioturbation in some places. The fine grained bioturbated sandstone facies show moderate to well sorting. Trace fossils recorded in this sandstone facies include *Skolithos* and *Cruziana* ichnofacies. The bioturbated sandstone facies is interpreted as distal delta front facies association (Ponciano Luiza and Della Favera, 2009).

Laminated Sandstone Facies

The laminated sandstone facies comprises of very fine to fine grained, moderately to well sorted, by planar, parallel and wavy/ripple laminated sandstones (Figs 8c and d). This sandstone facies consists of horizontal laminations, wavy/ ripple laminations, ripples, flaser beddings, and burrows of *Arthrophycus* ichnospecies. This facies is interpreted proximal delta front facies (Mutti et al., 2003; Ponciano Luiza and Della Favera, 2009; Puigdomenech et al., 2014).

Massive/ Conglomeritic Sandstone Facies

The massive/ conglomeritic sandstone facies consists of massive bedded, calcareous and conglomeritic sandstone with irregular-shaped extrabasinal limestone rip-up clasts (Fig. 8e) ranging from 8 to 30 cm in diameter. It consists of massive, medium to fine grained, very poorly sorted, calcareous sandstones. This facies are interpreted as proximal delta front facies (Puigdomenech et al., 2014; Ponciano Luiza and Della Favera, 2009) representing proximal channelised bedload facies (Zavala and Pan, 2018).

Cross-bedded Sandstone Facies

The cross-bedded sandstone facies (Fig. 8f) comprises of light grey to dirty white, medium to very coarse grained cross-bedded sandstone which is predominantly characterized by large scale planar, trough and asymptotic cross-beddings. This facies is also characterised by mud draped foresets and clay chips, and erosional bedding planes. The asymptotic cross-bedded sandstone with cross-beddings and limestone clasts at lower parts denotes bedload materials transported by shear and frictional drag forces influenced by the overpassing sustained turbulent flows (Zavala et al., 2008; Zavala et al., 2011). The cross-bedded sandstone with large scale planar and trough cross-beddings is interpreted as deposits of deltaic foreshore environments (Banerjee 1980; Okoro and Igwe, 2014; Okoro et al., 2016).

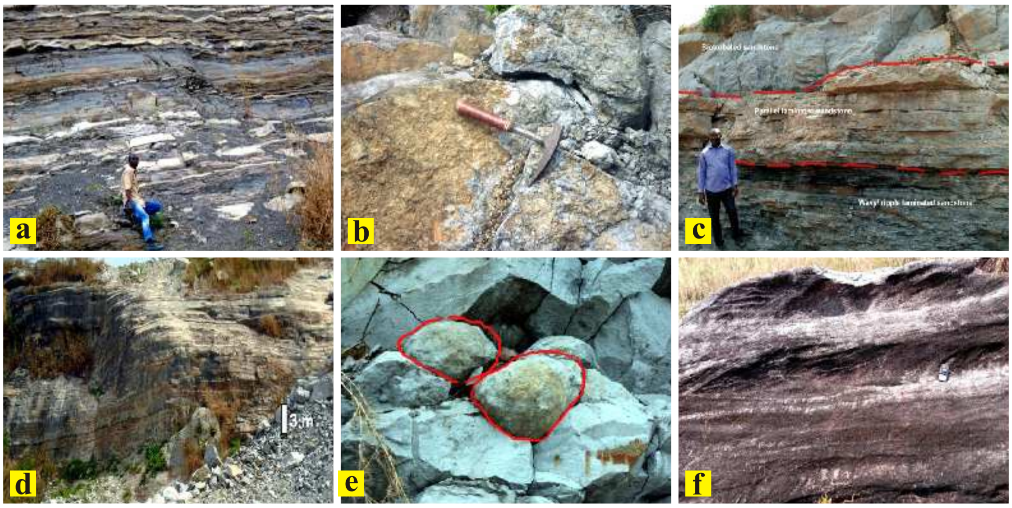

Fig. 8: Field photographs of lithofacies in the Amasiri Sandstone (a) Mudstone dominated heterolith facies at Setraco Quarry, Asaga-Amasiri; (b) Bioturbated sandstone lithofacies at Ibii junction; (c and d) Laminated sandstone facies at Julius Berger Quarry, Akpoha and Setraco Quarry, Asaga-Amasiri respectively; (e) Massive/ conglomeritic sandstone facies at Ibii junction; (f) Cross-bedded sandstone facies behind Government College, Afikpo.

Afikpo Sandstone Facies

Four sandstone facies occur in the Afikpo Sandstone namely; bioturbated sandstone facies, cross-bedded sandstone facies, sandy heterolith facies, bioturbated cross-bedded sandstone facies, (see Fig. 5 and Table 2). The bioturbated sandstone facies consists of light grey to light brown, very fine to fine grained poor to moderately sorted with obliterated sediment fabric and absence or distorted physiogenic sedimentary structures due to intense bioturbation and burrowing.

Cross-bedded Sandstone Facies

The cross-bedded sandstone facies comprises fine – very coarse grained but dominantly coarse, poorly sorted sandstone with graded foreset laminae, dispersed pebbles, planar and trough cross-beddings (Fig. 9a). The thickness of beds is in the range of 0.4 – 1.0 m. The planar foresets may vary from 8^{0} to 24, with highest angle of 28^{0} in few places. They are occasionally rippled or contorted. The sandstone facies is characterised by conglomerate subfacies (Fig. 9b). The cross-bedded sandstone and bioturbated sandstone facies are interpreted as estuarine bayhead delta facies association (Allen, 1991; Dalrymple et al., 1992; Shanmugam et al., 2000).

Sandy Heterolith Facies

The sandy heterolith comprises of brownish to dirty white sandstone, very fine grained, interbedded with claystone and siltstone with distinct laminations (Fig. 9c). The thicknesses of the beds range from 30 – 80 cm. Physical sedimentary structures such as wavy/ ripple laminations and flaser beddings and biogenic structures occur in this facies. This facies is interpreted as central estuarine delta facies association dominated by intertidal bayfill and lagoonal muddy deposits (Dalrymple et al., 1992).

Bioturbated Cross-bedded Sandstone Facies

The bioturbated cross-bedded sandstone facies (Fig. 9d) comprises dominantly of coarse grained, poorly sorted sandstone with abundant clay matrix, biogenic structures, and planar cross-bedded bedsets, occasional herringbone structures and ripples (ripple bedforms and mega ripples. This facies is characterized by bioturbated sandstone subfacies (Fig. 9e and f). The planar cross-stratifiactions sometimes occur as bipolar orientation of foresets beds. This facies is interpreted as subtidal sand ridge/ foreshore environment (Miall, 2000; Shanmugam et al., 2000; Catuneanu, 2006; Nichols, 2009). Generally, the Afikpo Sandstone lithofacies occur as estuarine bayhead delta, central estuarine delta and subtidal sand ridge/ foreshore facies associations.

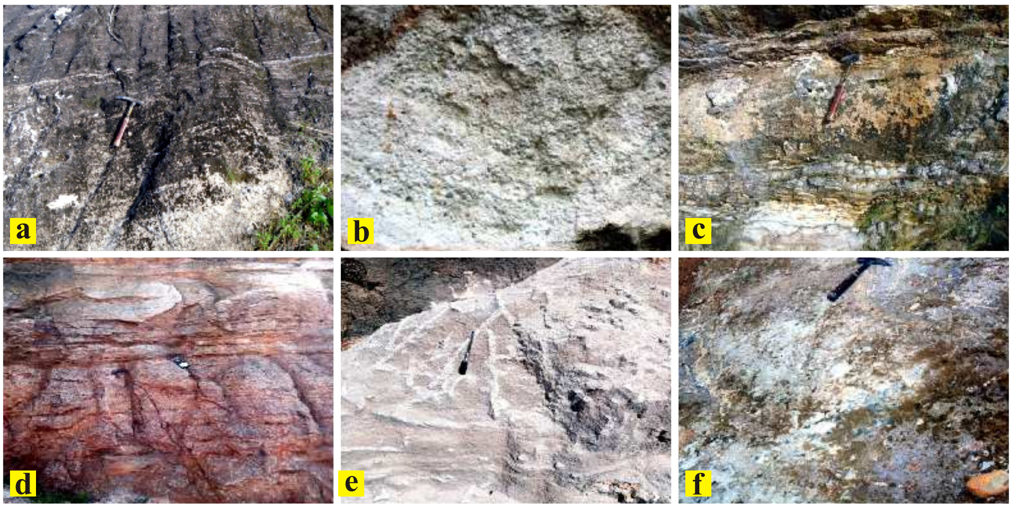

Fig. 9: Field photographs of the Afikpo Sandstone facies (a) The cross bedded facies outcropping at Macgregor Hill, Afikpo; (b) Conglomerate subfacies at the Macgregor Hill, Afikpo; (c) Sandy heterolith facies at Mechanic village, Afikpo; (d) Bioturbated cross bedded sandstone facies in Afikpo Sandstone at Macgrego Hill, Afikpo; (e) Bioturbated Sandstone facies in the outcrop at the Ebonyi Hotels Junction, Afikpo.

Ichnofossils Occurrence and Ichnofabric Index

There are different extents of obliteration and distortion of sediment fabrics, textures and physical sedimentary structures in the sandstone facies of the Amasiri and Afikpo sandstones. The bioturbation appears cryptic in few places within the Amasiri Sandstone at Julius Berger Quarry, Akpoha. The extent of bioturbations in the sandstone facies gave rise to serious distortion of the sedimentary structures (both physical and biogenic) making it difficult to identify and describe the distinctive trace fossils abound in the units. However quarrying activities and road construction ongoing in the area exposed the sandstone facies for easier identification of the trace fossils. The following ichnofossils were recorded in the sandstone facies (see Table 2 and Fig. 4): *Ophiomorpha irregulaire*, *Ophiomorpha nodosa*, *Skolithos, Arenicolites* (*Skolith*os ichnofacies) and *Chondrites*, *Monocraterion*, *Paraonis, Palaeophycus*, *Arthrophycus*, *Rosselia*, *Thalassinoides*, *Planolites* (*Cruziana* ichnofacies). Mode (1993, 1997) reported some of these trace fossil ichnogenera in the Benue Trough of Nigeria. In the Amasiri Sandstone, *Monocraterion* occurs in a low bioturbated sandstone and laminated sandstone facies (inchnofabric index (II) = 2) at Crushed Stone Quarry, Amasiri. The bioturbated Sandstone facies shows fairly bioturbation (II = 2 – 3) with occurrence of *Ophiomorpha irregulaire* and *Arthrophycu*s. *Planolites* was recorded in the cross-bedded sandstone facies of the Amasiri Sandstone at Ozaraukwu with low bioturbation (II = 2). *Thalassinoides* occur in the bioturbated facies of the Amasiri Sandstone with moderate to high bioturbation (II = 3 – 4) at Ibii quarry. The laminated sandstone facies, moderately bioturbated (II = 3 – 4) at sandstone ridge behind Akpoha Government College recorded *Paleophycus*. *Paraonis* was identified in the cryptic bioturbated sandstone facies outcropping along 350 m from Julius Berger quarry along Akpoha – Afikpo Road.

In the Afikpo Sandstone, the bioturbated sandstone and bioturbated cross-bedded sandstone lithofacies on the Macgregor Hills, Ebonyi Hotels, Afikpo and Government College Roundabout recorded high abundance of *Ophiomorpha nodosa*, *Planolites* and *Skolithos* with moderate bioturbation (II = 3 – 4). The bioturbated sandstone facies at the premises of Macgregor Hill Block Industry is moderately bioturbated (II = 3 – 4) and has *Planolites.* Sandy heterolith outcropping at Ozizza is fairly bioturbated (II = 2 – 3) and recorded *Rosselia*. *Chondrites*, *Arenicolites* and *Orphiomorpha* isp occur in the bioturabted cross-bedded sandstone and bioturbated sandstone facies, moderately bioturbated (II = 3 – 4). The bioturbated facies outcropping 800 m from Mater Hospital along Afikpo – Ozizza Road is moderately to highly bioturbated (II = 4 – 5) dominated by *Thalassinoides*. In overall, the lithofacies of the Afikpo Sandstone depict a description of moderately to highly bioturbated facies, intermittently spread trace fossils suites belonging to *Skolithos* and *Cruziana* assemblages.

Ethology

Ethology involves the classification of trace fossils based on their adaptations, behavioural patterns or activities. The ethological classes recognized by Seilacher (1964) and Frey (1978) are domichnia (dwelling traces), repichnia (crawling traces), cubichnia (resting traces), pasichnia (grazing trails) and fodinichnia (feeding burrows traces). There are other categories that occur in sediments such as escape structures (fugichnia and praedichnia (predation traces). The ichnofossils identified in this study belong mainly to two ethological categories (see Table 2) viz: Domichinia (dwelling traces) and Fodinichina (feeding traces). Similar ichnofossils have been identified in the other portions of Benue Trough including Niger Delta and Anambra Basin (Mode, 1997; Odumodu and Mode, 2014).

These trace fossils or structures are produced by sessile and semi-sessile subsurface (endobenthic) organisms such as suspension feeders, certain predators/ scavengers. The fodinichinia are typical feeding traces or structures which are formed as a result of extensive subsurface foraging by non vagile deposit-feeding organisms (Bromley 1996) disturbing the sediment in their search for foods. The endobenthic organisms systematically mine sediments for foods both feed and dwell within the excavation; usually feeding activities are justification for the burrows. In the Amasiri Sandstone, the distal delta front (lower shoreface) facies association which consists of fine grained bioturbted sandstone facies outcropping in Akpoha, Amoha, Ibii and Amasiri areas is associated with both dwelling traces (*Ophiomorpha irregulaire*) and feeding traces (*Monocraterion*, *Paraonis*, *Palaeophycus*, *Arthrophycus*, *Thalassinoides*). The proximal delta front facies association which comprises fine grained laminated sandstone facies is associated with feeding burrow (*Monocraterion*) while the cross-bedded sandstone of the foreshore facies association hosts feeding traces (*Planolites*). There is no clear trace fossil observed in the Prodelta sandstone facies.

In the Afikpo Sandstone, the estuarine bayhead delta facies association is associated with dwelling traces of suspension feeders (*Ophiomorpha nodosa*, *Skolithos, Arenicolites*) and feeding burrows (*Thalassinoides*, *Planolites*, *Chondrites*) in the bioturbated cross-bedded sandstone and bioturbated sandstone facies. The cross-bedded sandstone and bioturbated cross-bedded sandstone where they are associated with subtidal sand ridges/ foreshore showed occurrence of dwelling traces (*Ophiomorpha nodosa*, *Skolithos*). Dwelling burrow (*Rosselia*) is associated with sandy heterolith of the central estuarine facies association.

Paleoenvironments

Trace fossil is useful in determining the paleonvironment in which the organism lived, and sedimentation rate. It has proved to be useful in the recognition of sedimentary facies and water depth (Pettijohn, 1975). Generally, the vertical and subvertical trace fossils are common in shallow water, whilst patterned and horizontal ichnospecies are commonly found in deeper water (Seilacher, 1967). While food and substrate, oxygen, salinity, sedimentation rate, food and substrate are controlling bioturbation; food and substrate appear to be the major contributing parameters for occurrence of ichnological signatures considering that shallow water ichnofossils have been identified in deep water sediments. For instance, some ichnospecies of *Cruziana* may occur in brackish-water settings, extending the environmental range of application of *Cruziana* in ichnological studies (Mangano and Buatois, 2003) beyond its more typical shallow-marine application (Mangano et al., 2012). In the case of delta deposits, the limiting factors use to be sedimentation rate, salinity and energy (Tonkin, 2012). The application of trace fossils as paleobathymetric indicators have been de-emphasised in recent works (eg., MacEachern et al., 2012). This observation is more evident in instances where trace fossils are used in isolation in the interpretation of paleobathymetry. This study utilised lithofacies and ichnofossil assemblages (see Figs. 4 and 5, Table 2) which are in contemporaneous and represents a fine resolution for the paleoenvironments of deposition for the sandstone units.

The Turonian Amasiri (Afikpo Synclinorium) and Campanian Afikpo Sandstone facies (Afikpo Sub-basin) are characterised by ichnospecies of *Skolithos* and *Cruziana* trace suites (shallower water ichnofacies) (Table 2). Notwithstanding, there is prevalence of subvertical and vertical ichnospecies (*Skolithos* trace suites) when compared to the horizontal ichnospecies (*Cruziana* trace suites) in the Afikpo Sandstone suggesting moderate to high energy environmental conditions. Zonneveld et al. (2001), Savary and Gaillard (2004) and Mapals et al. (2005) attributed occurrence of *Skolithos* ichnofacies to areas of high sediment influx, which denotes high energy shallow shelf paleoenvironmental setting (Pemberton and Maceachern, 2005; Catuneanu, 2006; Nichols, 2009). The index of bioturbation of the bioturbated sandstone and bioturbated cross-bedded sandstone facies (II = 4 – 5) of the Afikpo Sandstone supports shallow water paleoenvironmental conditions in which *Skolithos* burrows formed shortly after deposition of the sandstone beds (Wilkinson et al., 1975). The *Cruziana* ichnofacies in the Afikpo Sandstone which is represented by *Planolites, Chondrites* and *Thalassinoides* supports presence of moderate energy condition. Horizontal ichnofossils belonging to *Cruziana* ichnofacies which suggest less agitated shallow shelf setting dominated the Amasiri Sandstone. Banerjee (1982) noted earlier that the trace fossil assemblages from the Amasiri Sandstone (Turonian) in the Afikpo Synclinorium are dominated by horizontal ichnofossil assemblages. These horizontal trace fossils occur dominantly in the bioturbated sandstone facies (II = 3 – 4) of the distal delta front facies association. There is absence of current or wave structures (Mode, 1997) in the bioturbated sandstone facies which gives credence to this finding. In addition, the presence of *Paraonis fulgens* (see Fig. 6e) in the outcrop of the bioturbated sandstone facies near Julius Berger at Akpoha, supports the interpretation of low energy shallow shelf conditions for the unit. Elsewhere, the *Paraonis fulgens* inhabited sublittoral sandstones of the northern Gulf of Mexico and U.S East Coast (Gaston et al., 1992)

Specifically, the bioturbated lithofacies of the Amasiri Sandstone at Akpoha bearing the Ophiomorphid species (*Skolithos* ichnofacies) and associated lithofacies characteristics suggest delta front environmental setting for the lithofacies in the area which is in accordance with the environments of modern analogues (Nagy et al., 2016), and estuarine bayhead deltaic setting for the Afikpo Sandstone facies. *Ophiomorpha nodosa* in the Afikpo Sandstone displaying a dominance of vertical shafts (see Fig 7a.) characterise higher energy (stressed) environmental conditions; while the *Ophiomorpha irregulaire* (see Fig. 6d) observed in the fine grained bioturbated facies of the Amasiri Sandstone which composed mainly of horizontal mazes denotes lower energy conditions (Frey, 1975; Mude, 2011; Nagy et al., 2016). Nagy et al. (2016) and Miller et al. (1998) noted that *Ophiomorpha nodosa* colonized tidal and estuarine channel deposits where it occurs both in the Miocene marginal and axial channel strata of Delaware. *Ophiomorpha nodosa* is known to be globally widespread with high abundance in marginal marine and shallow marine sand environments (Nagy et al., 2016). Elsewhere in the southern Benue Trough, Umeji (1988) noted that the *Skolithos – Cruziana* is probably indicative of near shore to offshore setting which is in agreement with the outcome of this study.

The general absence of *Zoophycos*-*Nereites* ichnofacies (deep water ichnofacies) in the sandstone facies indicates the Turonian and Campanian epeiric seas were shallow. However, the shallowing of the sea in the Afikpo Synclinorium was also attributed to the growth of offshore bars (Banerjee, 1982). Okoro (1986) noted that the Campanian lithofacies in the Leru area represent low to high energy conditions in shallowing sea. Generally, estuarine deltaic and foreshore setting are suggested for the Afikpo Sandstone, while foreshore and shoreface paleoenvironmental settings are interpreted for the Amasiri Sandstone

Conclusion

This study identified trace fossils suite and lithofacies/ associations in the Amasiri and Afikpo sandstones. The outcome of this study shows that Amasiri Sandstone was deposited in foreshore to offshore environments. The Afikpo Sandstone was deposited in estuarine delta and foreshore settings. The trace fossil assemblages showed low to moderate diversity with fair to high inchnofabric index (II), sporadically distributed, represented by shallow water ichnofacies (*Skolithos* and *Cruziana* ichnofacies). The *Skolithos* ichnofacies is represented by *Orphiomorpha* irregulaire, *Arenicolites*, *Ophiomorpha nodosa, Skolithos,* while the Cruziana ichnofacies occur as *Thalassinoides, Planolites, Paraonis, Monocraterion, Palaeophycus*, *Arthrophycus* and *Chondrites*, *Rosselia, Thalassinoides*. Ethologically, the traces belong to two classes of domichinia and fodinichinia. The ichnofossils in the sediments are characteristic of both lower and high energy conditions in shallow water sand environments.

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