ORIGINAL PAPER

Sedimentology, diagenesis, and reservoir quality assessment of the Upper Cretaceous sedimentary succession (Anambra Basin) in Inyi and environs, southeastern Nigeria

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Abstract

The Upper Cretaceous sedimentary facies in areas around Inyi and environs, southeastern Nigeria comprises Ajali and Nsukka formations. A total of 19 outcrops were mapped and logged. Interpretation was based on field facies analysis and laboratory tests which include granulometric and X-ray diffraction (XRD) analyses of the rock samples. The objective of the study was to reconstruct the environment of deposition as well as understand the textural attributes of the sand size sediments for reservoir quality assessment. Eleven lithofacies: conglomeritic sandstone facies (Gc), cross-bedded sandstone facies (Scb), pebbly sandstone facies (Sp), bioturbated sandstone facies (Sb), heterolithic facies (Sht), claystone facies (Cl), coal facies (Co), bioturbated shale facies (Shb), laminated siltstone facies (Stl), muddy sandstone facies (Sm), and black carbonaceous shale facies (Shcb), were identified with four sub-facies occurring within low- to high-energy environment. These lithofacies were grouped into four facies association (FA1, FA2, FA3, and FA4). FA1 is dominantly conglomerates and pebbly sandstone deposited as channel/alluvial fan deposits. FA2 are deposits in a swamp or lagoon setting consisting of coal and black carbonaceous shale. FA3 is characterized by bioturbated sandstone, muddy sandstone, and heteroliths deposited in a lower shoreface setting. The cross-bedded sandstones and the heterolithic facies belong to the FA4 deposited in an upper shoreface setting. Sieve analysis results show sediments that are medium to coarse grained in sizes, poorly to moderately sorted, dominantly very negatively skewed to symmetrical and mainly mesokurtic. These granulometric attributes are typical of shallow marine deposits influenced by fluvial processes under low- to high-energy conditions. Result of XRD analysis show the presence of clay and non-clay minerals in the sediments, with quartz as the most dominant. Diagenetic processes which include compaction, cementation, precipitation, and dissolution influenced the reservoir quality of the sands. Compaction significantly reduced the primary porosity, and the sand-size grains (quartz) created a self-supporting framework while the clay minerals, mainly kaolinite and dickite, occluded the pores spaces. Dissolution removed some detrital grains leaving obvious indications of few interconnecting and independent pores and moderately to poorly sorted sands. These clay minerals bridge the pore throat connectivity and cause reduction in pore radii, and consequently reducing the reservoir potentials of the sands. However, the sediments could serve as potential hydrocarbon reservoirs especially for gas. The coal seams and the black carbonaceous shale facies can serve as the source or seal rocks whereas the sandstone, siltstone, and heteroliths are possible reservoir rocks of the petroleum system in the study area.

Keywords Inyi · Lithofacies analysis · Ajali Formation · Nsukka Formation · Depositional environment · Reservoir quality

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Introduction

The study area, located within the Anambra Basin, is bounded by latitudes 6°5′00″N and 6°13′00″N and longitudes 7°13′00″E and 7°20′00″E (Fig. 1). It is bordered in the west by the Enugu metropolis and lies southwest of the N-S trending Enugu escarpment, southeast of Oji River, about 25 km from Oji River Power station.
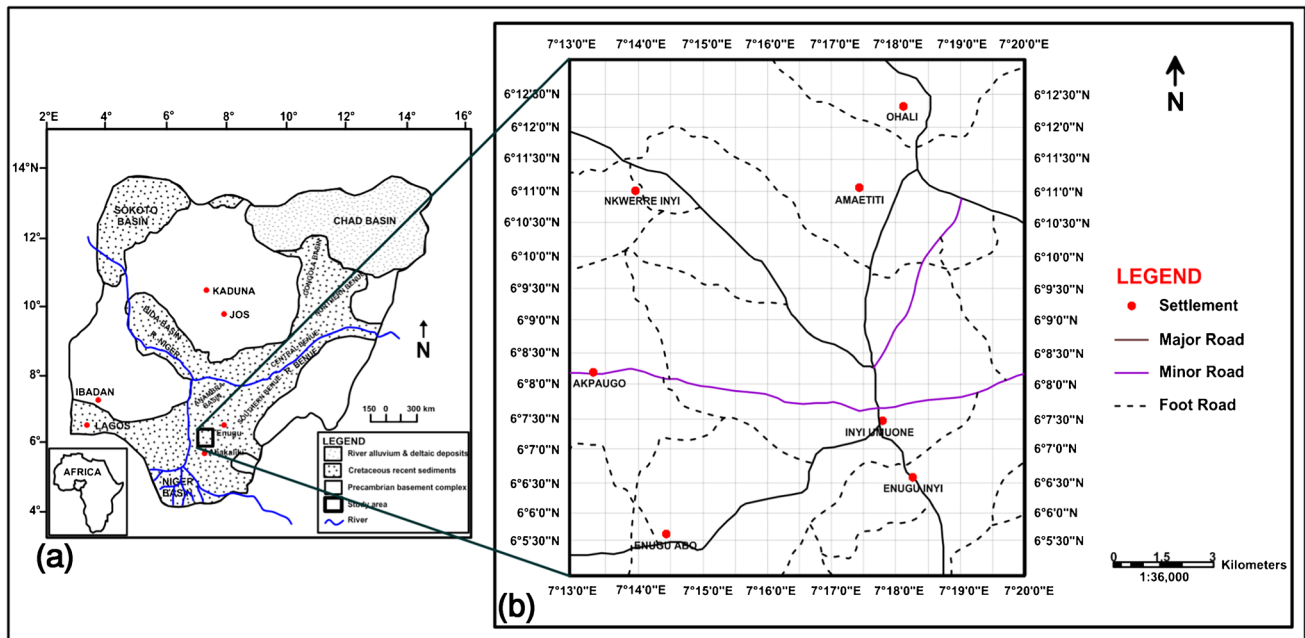
Fig. 1 **a** Generalized geologic map of Nigeria showing the Benue Trough and location of the study area (redrawn after Abraham et al. 2019). **b** Enlarged view of the study area showing various settlements within the Inyi locality

The Ajali and Nsukka formations, which are well exposed at Inyi and environs in southeastern Nigeria, make-up the uppermost Cretaceous sedimentary succession within the basin and has been described as holding economic potentials for hydrocarbon resources particularly natural gas (Ekweozor 2006). The sands within these formations are considered potential reservoirs for hydrocarbon fluids generated by the shales of the Nkporo Group. However, analysis of the stratigraphic framework, reservoir quality, and distribution are among major hydrocarbon exploration uncertainties encountered in the assessment of these sediments. These uncertainties result from diverse factors such as depositional environment, sediment package distribution, and post-depositional deformation. Since the Anambra Basin is considered a potential hydrocarbon area, there is a need for proper analysis of the lithofacies and evaluation of the reservoir attributes of the Ajali and Nsukka formations for better stratigraphic prediction, reservoir facies architecture, and reservoir quality assessment. A record of past literature in the Anambra Basin shows that extensive studies have been carried out on the maturity, organic richness, and kerogen types of the source rocks; paleoecology, sedimentary thickness, and geothermal gradients have been determined as well, and the hydrocarbon generative potential of the Nkporo Shale have been studied in details (Hoque and Ezepue 1977; Obaje et al. 2004; Nwajide 2005; Ekweozor 2006; Chiaghanam et al. 2013; Anyiam and Onuoha 2014; Dim et al. 2016). However, detailed studies on the sedimentology, diagenesis, depositional environment, and reservoir quality

of sediments of the Ajali and Nsukka formations in areas around Inyi, southeastern Nigeria are yet to be carried out. Geological and sedimentological analyses provide a platform for an outcrop-based evaluation of the petrophysical properties of sediments for their characterization as potential reservoirs. Facies analysis of the different formations using lithostratigraphic and structural data would reveal the spatial dispersal patterns of the formations within the study area.

This research presents findings of an integrated lithofacies analysis, paleodepositional environment, and outcrop-based reservoir quality assessment of the two formations relating to their potential as petroleum reservoir.

Regional geologic framework

The Anambra Basin is a structural depression situated at the southwestern edge of the Benue Trough that is exposed over a roughly triangular area, approximately 95,000 km^2 (Nwajide 2005). The basin is a northeast-southwest striking syncline located at the southwestern end of the Benue Trough. It is a component of the Central and West African Rift System which formed in response to the subsidence and stretching of crustal blocks during the Upper Jurassic to Lower Cretaceous break-up cycle of the Gondwana landmass (Chiaghanam et al. 2013). It is the oldest sedimentary basin in Nigeria that developed in the Early Cretaceous as the failed rift associated with the opening of the South Atlantic (Wright et al. 1985). Basin fills were controlled by

three mega-tectonic cycles. The first tectonic phase started in the Aptian-Albian time and was characterized by movements along the major NE-SW trending Benue Trough. The second major tectonic event, the Santonian compressional movements along the established NE-SW trend, caused a generalized folding which affected the Cretaceous sediments in the Benue Trough. This led to a series of NE-SW trending folds that resulted in the Abakaliki Anticlinorium, and the subsequent downwarping of the Anambra platform, to form the wide Anambra Basin, and the narrow Afikpo Synclinorium on the west and east of the anticlinorium, respectively (Mode et al. 2018). The depressions became the main depositional targets from Campanian to Maastrichtian. The final depositional phase commenced in the Eocene time and coincided with the formation of the Niger Delta Basin and further continued to the present (Hoque and Ezepue 1977; Obi 2000). The time of initiation of the Anambra Basin, therefore, corresponds to the period of subsidence in the southern part of the Benue Trough, which commenced during the Coniacian period and attained its peak at the Santonian thermo-tectonic event (Nwajide 2005). Hence, Santonian age represents the

phase when the trough experienced a tectonic episode that was associated with deformation, faulting, folding, and uplift of the pre-Santonian sediments resulting in the development of Anambra Basin which formed as a depression to the western side of the uplift (Benkhelil 1989). The basin became a Cretaceous depo-center that received Campanian to Maastrichtian sediments (Obi 2000). The stratigraphic succession of sediments within the Southern Benue Trough and Anambra Basin is shown in Fig. 2.

The oldest sedimentary deposit in the Anambra Basin is the Nkporo Group of the Late Campanian age, comprising Enugu Formation, Owelli Member, and Nkporo Formation (Kogbe 1989). The Nkporo Group is overlain by the sediments of Mamu Formation, which was deposited in the Early Maastrichtian (Nwajide 2013) (Fig. 2). It consists of a succession of shale, siltstone, sandstone, and coal seam (Mode and Odumodu 2014). The Ajali Formation (Late Campanian-Early Maastrichtian) overlies the Mamu Formation. It is composed mainly of white to pale grey, poorly sorted, unconsolidated sandstones that are sometimes stained yellow, brown, or red by iron oxides (Burke et al. 1972; Kogbe

Fig. 2 Stratigraphic chart of the Cretaceous–Paleogene sequence in southern Nigeria (redrawn after Ozioko et al. 2020)
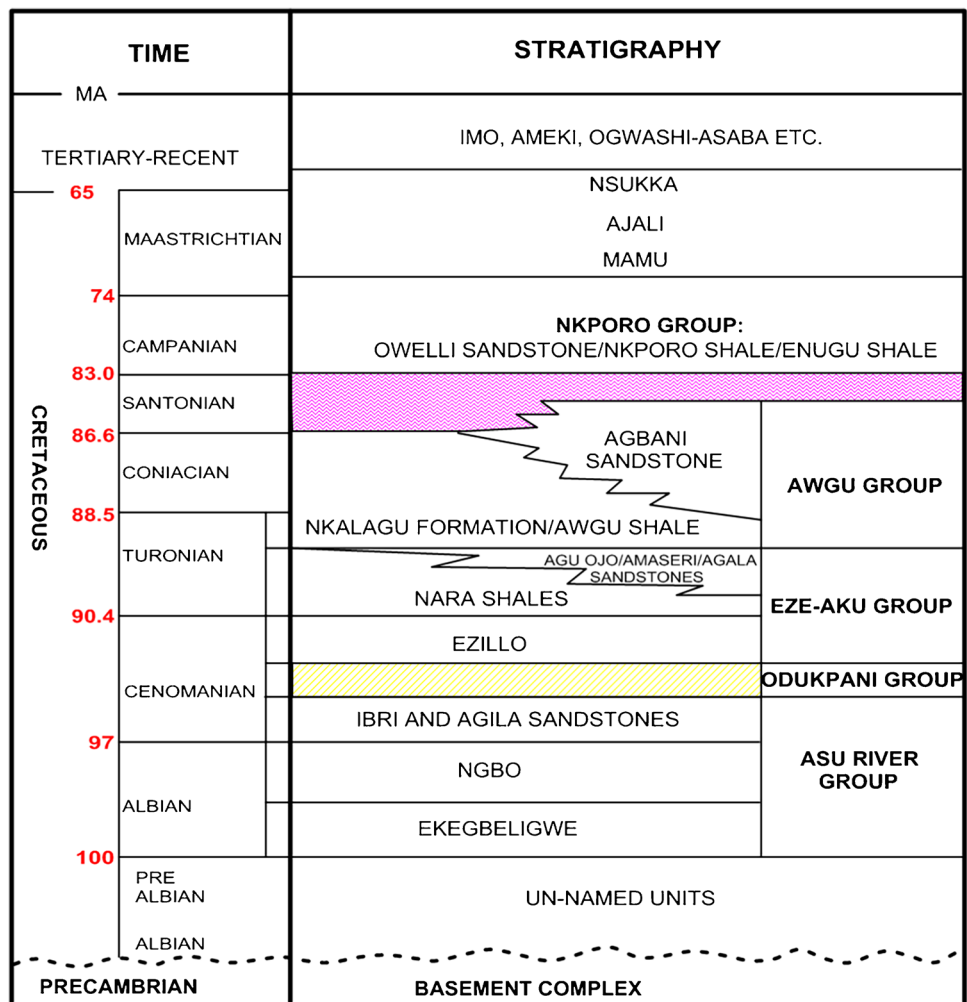
1989). The rocks are strongly cross-bedded on a large scale, with the foreset laminae making an angle of up to 20° with the major bedding planes. Thin units of whitish-grey shale have been observed at intervals and increases towards the base, where there is a gradual transition into the underlying Mamu Formation. The diachronous Nsukka Formation (Maastrichtian-Danian), also known as the "Upper Coal Measure" overlies the Ajali Formation (Nwajide and Reijers 1996; Obi 2000). It comprises predominantly of lateritic sands, coal seams, and little clayey shales with intermittent ironstone and thin sandstones in which carbonized plant remains may occur (Odumodu 2014) (Fig. 3).

Materials and methods

Field geological studies

Detailed geological field work was carried out in the Inyi area particularly in and around Inyi-Umuone, Akpaugo,

Oji-Arum, Amaetiti, Enugu Abo, and Ohali to locate, study, and describe various exposed lithologic units. Field studies involved careful lateral and vertical description of different lithologic units and their variations in thickness, texture, orientation, composition, fossil content, sedimentary structures, and discontinuity surfaces. At each outcrop, a systematic description of each lithologic unit was carried out. The results were plotted using the Sed Log Software and displayed as lithologic sections. Measurements of attitude of beds (strike, dip direction, and dip amount) of bed units were taken and shown on maps. Directional structures were measured with a Silva compass and structures of geologic significance photographed. A Garmin Global Positioning System (GPS) was used to record geographic coordinates of each outcrop location. The coordinates were then transferred onto a Minna geodetic datum georeferenced base map of Inyi and environs using MapInfo Geographical Information System (GIS) platform. Soil samples were put into sample bags and subjected to laboratory analysis.
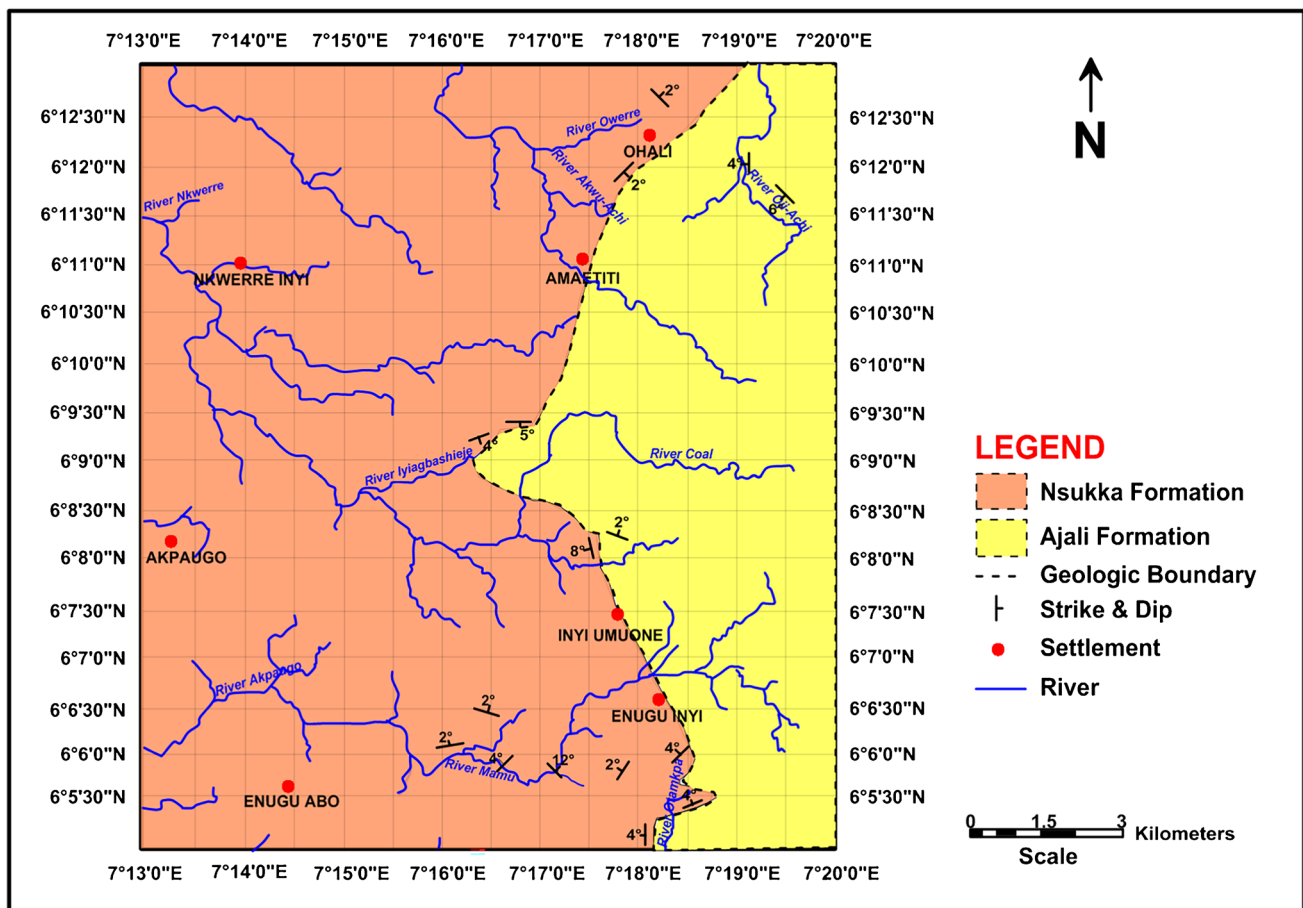

Fig. 3 Geological map of the study area

Sedimentological analysis

Lithofacies analysis

The description of outcrops was based on the various facies encountered in the field. At each outcrop, the bed units were described systematically to indicate their thickness, texture, fossil content, and sedimentary structures. This is to better understand the vertical variation in facies profile as a basis for identifying facies and facies assemblages.

The lithofacies recognized and described were grouped into facies associations in order to characterize and interpret environments of deposition. These facies were grouped into facies associations on the basis of stratigraphic succession, inter-related controls, and similar environmental significance.

Granulometric analysis

Samples collected in the field were subjected to sieve analysis. Twenty-five samples were analyzed. It was done to ascertain the percentage as well as the distribution of different sizes of grains in each sand sample. For this analysis, unconsolidated soil samples were utilized. The samples were dried under the heat of the sun, at room temperature (25 °C). A beam balance was used to weigh 50 g of disaggregated samples. Each sample is sieved for about 20 min on a Pascal sieve shaker that has meshes at intervals of 1 unit on the "phi" scale. Each retained sieve fraction is weighed to an accuracy of 0.001 g and recorded. This analysis was done at the Sedimentology Laboratory of the Department of Geology, University of Nigeria, Nsukka. The primary aim of this analysis is to determine the textural attributes and granulometric properties of the sand samples for reservoir quality evaluation.

Results of grain size analysis were plotted on log-probability charts and used in calculating the different grain-size statistical parameters (sorting (σ_I), mean size (Mz), kurtosis (K_σ), and skewness (Sk_I)) by applying the equations of Folk and Ward (1957). These statistical parameters were computed in order to better understand the role of the energy of the depositing medium in grain size distribution. Employing these textural parameters, bivariate analysis of each sample was carried out to discriminate between adjacent depositional environments, while multivariate analysis, which combines two or more statistical parameters from more than one depositional environment were used for their discrimination. The linear discriminate functions employed are: Y_2 (Beach, Shallow marine) $= 15.6534 \text{Mz} + 65.7091$ $\sigma_I^2 + 18.1071 \text{Sk}_I + 18.5043 K_\sigma$ and Y_3 (shallow marine, fluvial) $= 0.2852 \text{Mz} - 8.7064 \sigma_I^2 - 4.8932 \text{Sk}_I + 0.0482 K_\sigma$ (Sahu 1964) (Mz, σ_I, Sk$_I$, and K_σ are the values of mean size, sorting, skewness, and kurtosis, respectively).

Reservoir quality assessment

Porosity estimation Porosity is the percentage of the soil that has space, whether the pores are connected or not (North 1985). Porosity estimation is important because it determines the volume of a soil mass that can contain hydrocarbons. In this research, reservoir assessment of sands for porosity was done using the Coalson and Inden (1990) plot of permeability and grain size and porosity interpretation from North (1985).

Permeability estimation Permeability (K) is the property of a medium to allow fluids to pass through it without a change in the structure of the medium or displacement of its parts (North 1985). In this research, permeabilities for samples were obtained using empirical formula (Eq. 1). To calculate the permeability for the reservoir units, sieve data were plotted as cumulative curves on semi-log sheet for determining median diameter (d_{50}) in millimeters, and on probability paper for determining sorting ($\sigma\varnothing$) in phi units, then substituted into the Krumbein and Monks equation (Eq. 1) given below (Krumbein and Monk 1943):

$$K = 760 d^2_{50} \exp(-1.31 \sigma_D) \qquad (1)$$

where K is permeability given in millidarcies (mD), d_{50} is the geometric mean grain diameter (mm), and σ_D is the sorting of grain diameter in phi units.

X-ray diffraction analysis X-ray powder diffraction is commonly used to identify unknown crystalline materials (e.g., inorganic compounds and minerals). Identification of unknown solids is vital to sedimentological analysis for the recognition of crystalline substances, identification of clays, mixed layer clays, and oxide cements that are arduous to ascertain optically, and determination of the modal amounts of minerals (quantitative analysis) for reservoir quality evaluation.

X-ray diffraction analysis for eight samples was performed at the Nigerian Geological Research Laboratory (NGRL) of the Nigerian Geological Survey Agency (NGSA) in Kaduna State, Nigeria. The NGRL uses the Empyrean diffractometer with a copper anode material. The analyzed materials were ground into fine particles, homogenized, and the mean bulk composition measured. The sample preparation block was used to prepare the powered sample, which was then pressed onto a flat sample holder to form a smooth, flat surface that was later placed on the sample stage in the X-ray diffraction (XRD) chamber. The reflection-transmission spinner stage employing the Theta-Theta settings was used in sample analyses. Two-Theta end position was 75° and starts at 4° with a two-theta step of 0.026261 at 8.67 s per step. The tension was 45 VA and tube current

was 40 mA. A Gonio Scan and a Programmable Divergent Slit with a 5-mm width mask was used. As the sample and detector rotate through their respective angles, the intensity of diffracted X-rays is continuously recorded. A peak in intensity occurs when the mineral contains lattice planes with d-spacings appropriate to diffract X-rays at that value of θ. Although a peak comprises two different reflections ($K\alpha_2$ and $K\alpha_1$), at small values of 2θ the peak locations overlap with $K\alpha_1$ having $K\alpha_2$ on its side, which appears as a hump. Higher separation occurs at greater values of θ. Generally, these combined peaks are considered one. The 2λ position of the diffraction peak is typically measured as the center of the peak at 80% peak height.

Results and discussion

Sedimentary facies

Eleven facies were recognized from the sediments of the Ajali and Nsukka formations in the study area. These were based on lithology, grain sizes and texture, geometry, and sedimentary structures. Analysis of these facies provides a platform to distinguish relationship and infer a depositional environment for the sediments (Mode et al. 2018).

Conglomeritic sandstone facies

There are two types of conglomeritic facies identified in the study area assigned clast-supported conglomeritic units (Gcc) for clast-supported and Gcm for matrix-supported conglomeritic facies. These different conglomeritic units were observed at the upper parts of outcrop sections located in Inyi-Ubo and Oji-Arum, respectively (Fig. 4). At Inyi-Ubo, the Gcc was observed at the topmost part of the Inyi-Ubo section whereas the matrix-supported conglomeritic unit (Gcm) was observed at the uppermost part of the Oji-Arum outcrop section.

Gcc shows a light yellowish color and consists of very coarse sand to quartz pebbly grain size. The clasts are sub-rounded to rounded quartz pebbles with very coarse sand matrix. They are poorly sorted and are of the monomict type with bed thickness of about 1.5 m (Fig. 4a). The beds are structureless displaying a sharp contact. The clasts do not show imbrications (Fig. 4b).

Gcm are matrix-supported conglomerate since most of the clasts are completely surrounded by matrix with very

Fig. 4 Conglomeritic facies (Gc) observed in the Ajali Formation, exposed at a quarry site in Inyi-Ubo and Oji-Arum. **a** The clast-supported conglomeritic sub-facies (Gcc) exposed at the upper part of the Inyi-Ubo section. **b** A section of the clast-supported conglomeritic sandstones in (**a**). **c** The matrix-supported conglomeritic sub-facies (Gcm) encountered at the uppermost part of an outcrop in Oji-Arum

coarse material as the matrix (Fig. 4c). The para-con-
glomerates are poorly sorted with the clasts sub-rounded
to rounded. The matrix consists of very coarse sands and
form about 50% of the sediment make-up. The conglom-
erate shows yellow to light brown color with bed thick-
ness that ranges from 50 cm to 1 m. It has sharp contact
with no structure and imbrications (Fig. 4c).

Interpretation Absence of definite clasts orientation is com-
monly associated with subaqueous debris-flow conglomer-
ates (Reineck and Singh 1980). This is suggestive of a more
viscous debris-flow deposit (Boggs 2009). Gcc occur as lag,
erosive current winnowed gravelly sands, taking other sand
grains into suspension or saltation (Collinson et al. 2006),
representing a sieve deposit. The pebbles are then left behind
and concentrated as a thin layer. The clasts may be trans-
ported via traction current under conditions of lower flow
regime (Ghazi and Mountney 2009). The rounded clasts
were probably as a result of abrasion during cyclic sediment
transport and storage (Uba et al. 2005). The conglomerate
deposits are not meandering stream deposits because such
deposits are made up of mainly sands, silt, and clay (Nichols
and Hirst 1998).

Cross-bedded sandstone facies

The cross-bedded sandstone facies (Scb) is sub-divided into
two sub-facies (1) trough cross-bedded sandstone facies
(Stcb) and (2) planar cross-bedded sandstone facies (Spcb).

The Stcb comprise massive white to yellowish-white
or brown, coarse to pebbly, semi-consolidated, and poorly
sorted to moderately sorted sandstone. This sub-facies were
observed at the topmost part of the Oji-Achi section and at
the middle and basal portions of the Inyi-Ubo outcrop sec-
tion (Fig. 5a). In some cases, mud clasts were observed at
the top contact with the overlying bed (Fig. 5b). The sand-
stone units are generally void of burrows with a thickness
that ranges from 1.5 to 3 m. At the basal part of the Inyi-
Ubo section, the trough cross-beds occur together with her-
ringbone structure (Fig. 5c). The large-scale trough sets at
the central part of the outcrop have sharp tangential basal
contacts and sharp tops (Fig. 5d).

The Spcb is the most extensive sub-facies within the
study area. They are present at the upper, middle, and basal
sections of outcrops located at Inyi-Ubo, Mamu, Umu-
one, Ngwara, Oji-Achi, Akwu-Achi Amaetiti, and Ohali
(Fig. 5e–i). They are characterized by planar foresets with
angular bases and asymptotic (tangential) or concave toe-
sets and are bounded at the top and base by sharp contacts
(Fig. 5e, f). This facies comprises fine to pebbly, moderately

Fig. 5 a Trough cross-bedded
sandstone sub-facies (Stcb)
occurring with herringbone
cross-beds encountered at the
basal part of the outcrop sec-
tion at Inyi-Ubo. **b** Mud clasts
observed at the top contact with
the overlying bed. **c** Enlarged
view of the herringbone cross-
beds. **d** Large-scale trough
cross-beds showing tangential
basal contacts observed at the
middle part of the outcrop. **e**
Spcb sub-facies (Spcb) occur-
ring with thin bands of clay at
the Mamu outcrop section. **f**
Planar forests with a sharp top
contact seen at the surface of
a weathered sandstone unit in
Amaetiti. **g** A section of the
outcrop at Oji-Achi showing the
bioturbated planar cross-bedded
sands. **h** A close view the Spcb
facies showing *Ophiomorpha*
burrows occurring along the
forest trends. **i** Spcb encoun-
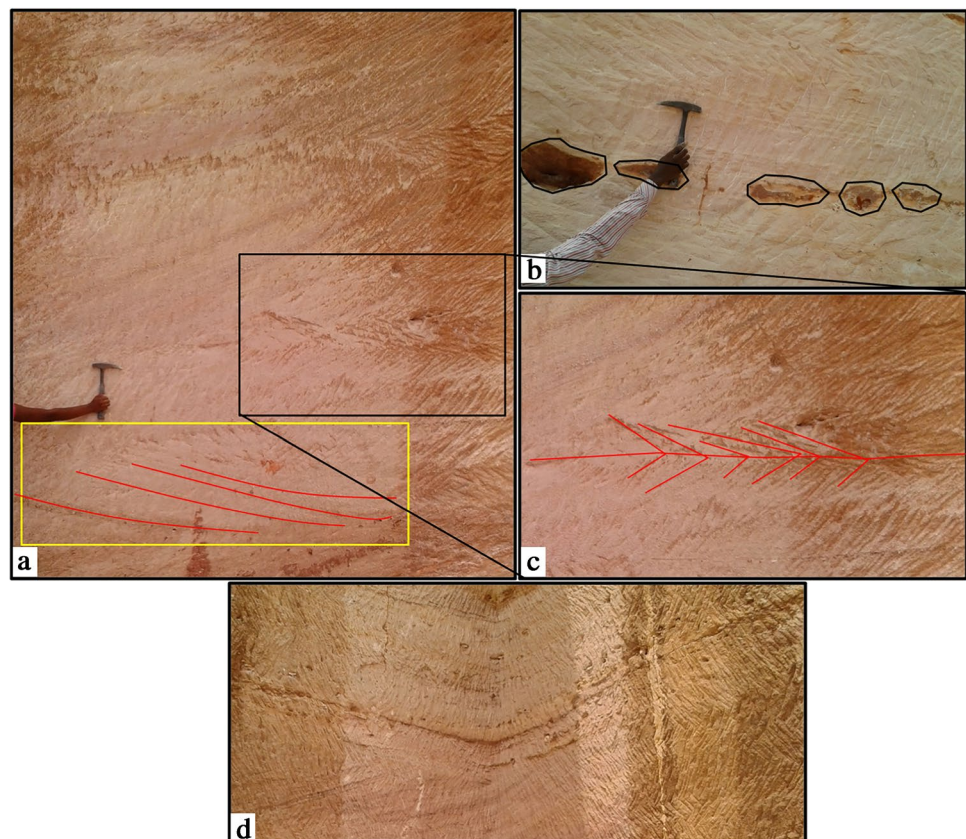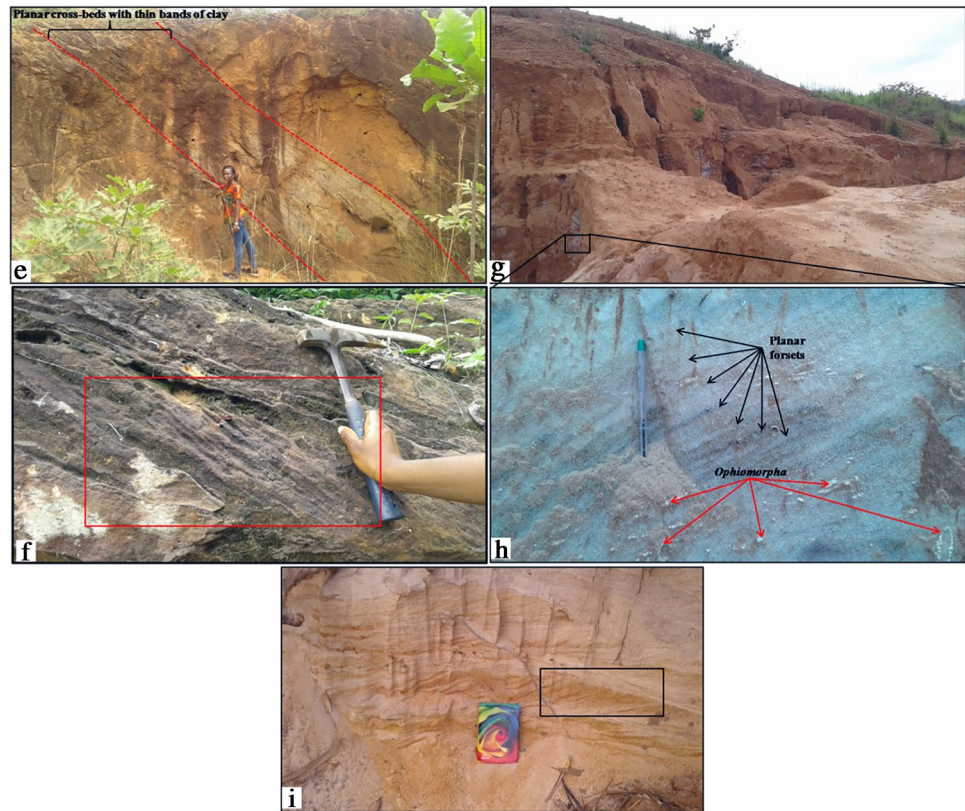tered at the lower parts of an
outcrop in Oji-Achi

Fig. 5 (continued)

to well-sorted sandstone with small-scale bioturbations consisting of *Ophiomorpha* burrows (Fig. 5g, h). Together with the Mamu section, this facies has thin bands of clay marking the bedding planes (Fig. 5e). The sediments are mainly whitish-yellow to light brown/yellowish-brown with the exception of the ferrugenized, reddish-brown sandstones which outcrop at Oji-Achi, Akwu-Achi Amaetiti, and Ohali. Mud clasts and extraformational clasts occur in the Inyi-Ubo and Umuone sections, respectively. In some outcrop sections, the mud clasts occur locally along the foreset planes (Fig. 13a). Bed thickness ranges from a few millimeters to several centimeters thick.

Interpretation The presence of trough cross-stratification indicates migration of sinuous crested or lunate bedform, at a higher and deeper velocity flow than straight-crested dunes (Collinson et al. 2006). Variation in grain size is determined by variation in sorting which is due to fluctuation in the energy of flow. The occurrence of mud balls/clasts on the foresets is an indication of suspension sediment fallout at slack water periods. The presence of thick mud balls on trough foresets is controlled by quick flocculation and is often associated with tidally influenced environments (McIlroy 2004).

The Spcb depicts the migration of straight-crested bedforms, usually in the middle part of the lower flow regime. Intensity of flow over the crest can strongly influence the

foreset shapes. Weak flows form angular forests whereas, strong flows generate tangential forests, as observed in the Inyi-Ubo outcrop section (Collinson et al. 2006). Full vortex stage of dune migration is accompanied with rising velocities leading to the formation of tangential, concave-shaped, and angular cross-beds. Small-scale foresets indicate migration of small-scale bedforms with low relief. Mud clasts present on planar foreset planes were formed during slack water conditions in response to semi-diurnal tidal fluctuation (Shanley et al. 1992). The presence of iron mineral noticed in the ferrugenized units of the facies at Oji-Achi, Akwu-Achi Amaetiti, and Ohali suggests post-depositional effect caused by sub-aerial exposure in an oxidizing environment.

Pebbly sandstone facies

The pebbly sandstone facies (Sp) is characterized by reddish-brown and yellowish-brown to light yellow, moderately to poorly sorted, semi-consolidated to consolidated, very coarse to pebbly sandstone unit. They are seen at the top part of outcrop exposures located at Inyi-Ubo, Ngene, Umuchime, Ngwara, and Oji-Achi (Fig. 6a, b). With the exception of the Oji-Achi section, this lithofacies occurred at the southernmost part of the study area. At Umuchime, the pebbly sandstone unit was observed to be slightly bioturbated with *Ophiomorpha* burrows particularly at the
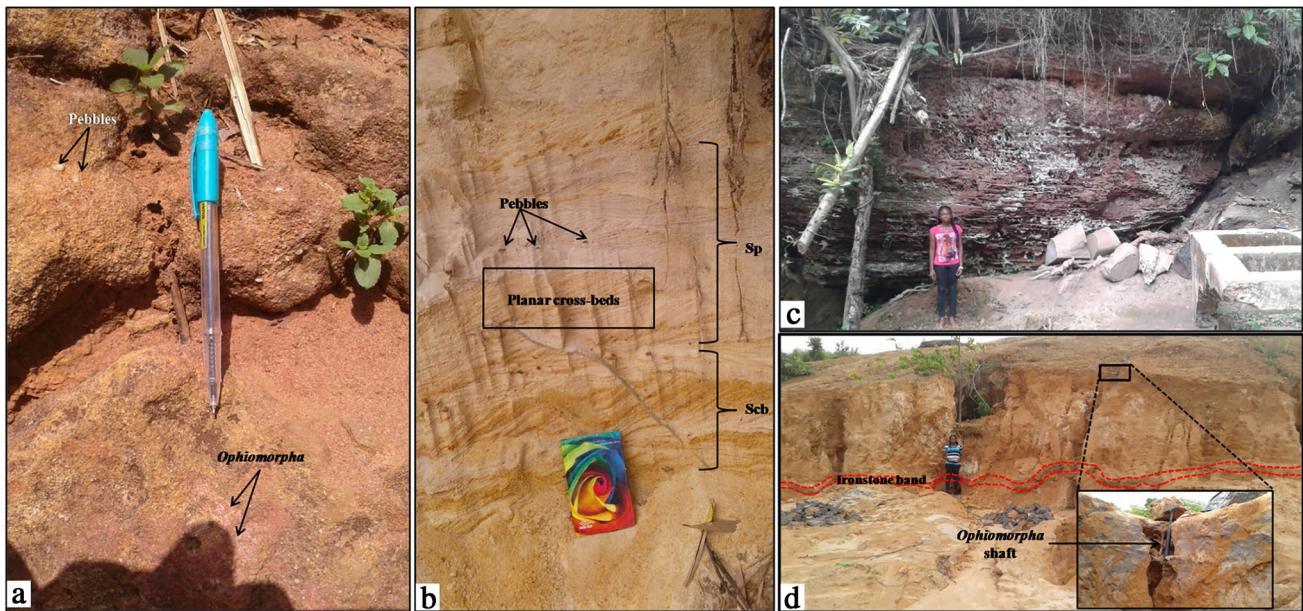
Fig. 6 a Slightly bioturbated pebbly sandstone facies (Sp) encountered at the uppermost part of the outcrop located in Umuchime. **b** Pebbly sandstone facies (Sp) observed at the middle section of the exposure at Oji-Achi and underlain by the cross-bedded sandstone facies (Scb). **c** Bioturbated sandstone facies (Sb) observed near a spring in Ohale. The sands are intensely bioturbated and consolidated. **d** Sb with band of ironstone encountered at the Umuone. An *Ophimorpha* shaft is seen exposed at the upper part of the bioturbated sands

uppermost part of the bed (Fig. 6a). At Ngwara and Oji-Achi, this facies was characterized by trough and planar cross-stratification, respectively and is directly underlain by the Scb) (Fig. 6b. Bed thickness varies from 10 cm to 1 m.

Interpretation The presence of pebbles suggests a high energy environment and high velocity of the transporting agent, hence, the coarse nature of the grain sizes. The rounded and sub-rounded nature of the pebbles implies that the sediments could have travelled a relatively long distance. The pebbles do not show any form of imbrications. Sp is structureless in most of the outcrops where they occur except at Umuchime where they are slightly bioturbated and at Ngwara and Oji-Achi where they are characterized by trough and planar cross-beds. The minor bioturbations could have occurred after sediment deposition during a much quieter period.

Bioturbated sandstone facies

This lithofacies occur as thick or thin, intensely to slightly bioturbated, fine to pebbly, well to moderately sorted, white to yellowish-white, and light brown-colored sandstone. Some ferrogenized surfaces are reddish, reddish-brown, or dark brown. Bed thickness ranges from 10 cm to 5 m with sharp contacts at the top and base. They are mainly observed at Ohali (Fig. 6e), Inyi-Ubo, Mamu, Umuone, Ugwu-Odu, Akpaugo-Eze, Oji-Arum, Umuchime, Ngwara,

and Oji-Achi. At Mamu, this lithofacies are overlain and underlain by the claystone facies (Cl). In some cases, there is complete absence of observable sedimentary structures, probably due to the intensity of bioturbations within the units. This was particularly observed at the middle part of the Ohali outcrop section. A band of bioturbated irontone (30 cm thick) was observed at the middle part of this lithofacies exposed in Umuone (Fig. 6f). Dominant ichofacies burrow is *Ophiomorpha* (Fig. 6f).

Interpretation *Ophiomorpha* are formed by suspension-feeder dwelling burrows that reflect high-energy environments typical of shallow subtidal to intertidal deposits (Dam 1990). The dominance of *Ophiomorpha* burrows indicates condition of high- and moderate-energy sedimentation and predominance of the vertical shafts suggest that sedimentation was periodic causing a successive upward extension of shafts (Howard and Frey 1984). Complete bioturbation resulting in concealment of original sedimentary structures indicates periods of bottom stability (Mode et al. 2018). The high intensity of bioturbations at the topmost part of the beds of this facies indicates post-storm domination by trace markers.

Heterolithic facies

The heterolithic lithofacies (Sht) are widespread and occur at the top part of outcrop sections at Umuone, Umuagu-Inyi,

Ugwu-Odu, Otamkpa (Fig. 7a, b), Iyi-agbashieje, and Umuchime, the middle part of outcrop sections at Mamu and Oji-Arum, and the basal portion of the outcrop section at Akpaugo-eze. At Ngene, the heterolithic facies occur at the top of the outcrop section (Fig. 7a). In most places where they occur, they were observed to be directly overlain and underlain by the Sb or siltstone facies. Sht consists predominantly of sandstone and clay. In some cases, the facies comprises siltstone with intercalations of black carbonaceous shale or sandstone. Some of the heterolithic units are moderately to intensely bioturbated and exhibits parallel lamination (Fig. 7b). This is commonly observed at Oji-Arum, Umuchime, Iyi-agbashieje, and Ngene. Bed thickness ranges from 30 cm to 6 m. Dominant ichnofacies is *Ophiomorpha*.

Interpretation The occurrence of parallel laminations and heterolithic facies suggests alternating low- and high-energy conditions (Kvale 2006). The parallel lamination is usually formed during lower flow regime conditions. The rhythmic pattern of the heterolithic facies depict cyclic deposition of vertically accreted sediments known as tidal rhythmites (Reineck and Singh 1980). The resultant ichnofabric represents a response to sedimentary events that demonstrates the heterolithic beds reflect seasonal or annual cyclicity. These deposits are possibly tidally influenced and accumulated in a brackish water setting. It is also possible that the seasonal fluctuations could have altered the depositional and biological processes.

Claystone facies

The claystone facies comprises thin bands of reddish or reddish brown to dark grey clay that are slightly bioturbated and commonly mark the top and/or base contact of the Sb that outcrop at Inyi-Ubo, Mamu (Fig. 7c), Umuone, and Akpaugo-eze. At Umuchime, this facies alternate with the black carbonaceous shale facies (Shcb) that is considerably thicker than the claystone units (Fig. 7d). Bed units have thickness that ranges from 6 mm to 30 cm. Dominant ichnofacies observed in this facies is *Ophiomorpha*. Apart from the Inyi-Ubo and Akpaugo-eze sections, they are observed to be intensely bioturbated.

Interpretation The claystone facies owe their red color to pervasive hematite-grown coatings and crystals intergrown with clay. Reddening occurred both by ageing of hydrous ferric oxides plus by staining of grains by hematite pigment formed by oxidation of detrital iron oxide grains due to subaerial exposure. The bioturbated claystone facies suggest a low- to high-energy depositional system within floodplain. The presence of *Ophiomorpha* suggests a marine floodplain environment.

Coal facies

This facies is made up of black coal units that are located in Ogba, Oji-Arum, Umuchime, and Obune area (Fig. 8a–c). The thickness of the coal seam ranges from 0.5 m to 1.3 m and are laterally continuous in some locations and discontinuous in others. The seams are characterized by medium to high vitreous luster on cleat surfaces (Fig. 8b). The upper and lower contacts are sharp with overlying black carbonaceous shale, except in Ogba area, where it is overlain by reddish-brown indurated sandstone (Fig. 8a). The coal seams at Obune, Umuchime, and Ogba are underlain by grey

Fig. 7 **a** Heterolith of black shale and siltstone exposed at a spring in Ngene. The heterolithic facies overlies the intensely bioturbated black carbonaceous shale facies (Shb). **b** Heterolith of siltstone and clay present at the topmost part of an outcrop in Otamkpa. The heterolithic unit is underlain by the laminated siltstone facies (Stl). **c** Cl marking the top contact of the bioturbated sandstone facies (Sb) in Mamu. **d** Claystone facies (Cl) (yellow dotted lines) alternating with black carbonaceous shale facies (Shcb) at a spring in Umuchime
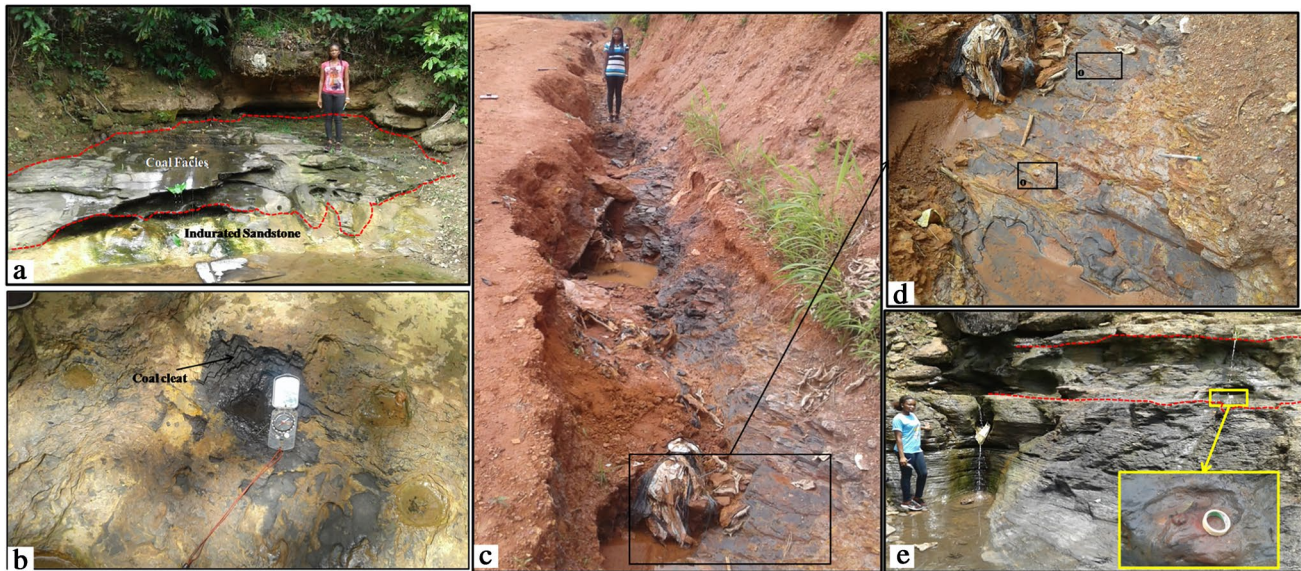
Fig. 8 **a** Coal facies (Co) overlain and underlain by grey to reddish-brown indurated and weathered sandstone unit at a spring in Ogba. **b** Coal cleats exposed beside a river channel in Obune. **c** Road cut section showing the light grey and slightly bioturbated shale facies (Shb) overlain by the heterolithic facies (Sht) encountered at Iyi-agbashieje. **d** Closure showing the bioturbations on the shales (o = *Ophiomorpha*). **e** Iron concretion seen within the bioturbated shale facies (Shb) in Ngene. Shb is also directly overlain by the heterolithic facies (Sht)

indurated sandstone and weathered sandstone. This facies is structureless, and no rootlets were observed.

Interpretation The coal facies are depositional processes formed by peat, accumulation, burial, and coalification. This is evidenced by its high organic content, lamination, as well as its compacted nature. At Ogba, the coal seam was sharply underlain by non-rooted 80-cm-thick grey indurated sandstone unit. This possibly might have been eroded and transported from a nearby peat-forming environment and are genetically related to the underlying sediments (Mc Cabe et al. 1987).

Coal beds are thin occurring with sandstone and mudstone units in marsh/swamp environment formed on the lagoonal margins (Reinson 1992). They generally represent floodplain and swamp deposition that is characterized by shale, coal seams and sandstone.

Bioturbated shale facies

This facies comprises thick lightly grey to black, very fine grained, sparsely to intensely bioturbated shale unit with sharp contacts at the top and base. They are found exposed at outcrop sections located at Iyi-agbashieje (Fig. 8c, d), Ngene (Fig. 8e), and Obune-Inyi, where they form the only lithologic unit of the outcrop. At Iyi-agbashieje and Ngene, the bioturbated shale facies are directly overlain by the heterolithic facies (Sht) (Fig. 8c, e). Iron concretions

were observed within this lithofacies unit at Ngene (Fig. 8e). Dominant trace fossil is the *Ophiomorpha* burrows.

Interpretation The black color, very fine-grained composition, and iron concretion structure of this facies suggest deposition by suspension sediment fallout in an anoxic, low-energy, offshore marine environment. The occurrence of plant debris/matters at the Iyi-agbashieje section indicates sub-aerial or supratidal conditions. The iron concretions are of early diagenetic origin but may be concentrated at the surface due to winnowing or low net accumulation rates (Reading and Levell 1996). Marine conditions are indicated by *Ophiomorpha* burrows and by concretion formation.

Laminated siltstone facies

Laminated siltstone facies (Stl) is less abundant and consists of light to dark grey units of laminated siltstone that are moderately to highly consolidated (Fig. 9a, b). They occur in Oji-Arum, Otamkpa, and Umuchime. At Oji-Arum, this facies was micaceous and appear to be enclosed in clay-like pipes that are broken at intervals (Fig. 9a). At Umuchime, they were observed to be slightly to moderately bioturbated (Fig. 9b). Bed thickness ranges from 10 cm to 3 m.

Interpretation Stl are suspension fallouts that represent deposits of waning stage flood deposition, mainly in overbank areas (Hjellbakk 1997), with most of the deposition occurring from suspension settling and with only limited

Fig. 9 a Horizontally laminated siltstone facies (Stl) observed along a vertically extensive exposure in Oji-Arum. Stl are micaceous and occur within clay-like pipes. **b** Stl facies with bioturbations occurring at middle part of the outcrop section in Umuchime. **c** Muddy sandstone facies (Sm) with bioturbations encountered at the center of a thick sandstone unit in Umuone. **d** Black carbonaceous shale facies (Shcb) observed at the base of the river section in Oji-Arum. The Shcb here is directly underlain and overlain by the laminated siltstone facies (Stl) and coal facies (Co), respectively

bed-load transport via weak currents. The undulating lamination indicates reworking by strong wave action in shallow water.

Muddy sandstone facies

Muddy sandstone facies (Sm) are poorly exposed within the study area. They consist of thick white to brown, fine to coarse-grained, moderately to poorly sorted, thickly bioturbated muddy sandstone unit characterized by sharp contacts at the top and base (Fig. 9c). They are present at the middle section of outcrops exposed at Umuone and Ogba. At Umuone, the lithofacies unit was intensely bioturbated with *Opiomorpha* burrows (Fig. 9c).

Interpretation Sm is indicative of an alternating high- and low-energy condition. The presence of mud within the sands suggests period of low-energy conditions where the muds are deposited by episodic sedimentation, suspension settling, and/or fallout during one or several slack-water periods. The sands constitute traction load during transportation. The occurrence of heavy bioturbation of *Ophiomorpha* burrows suggests an increase in energy level.

Black carbonaceous shale facies)

Shcb comprises dark grey to black carbonaceous shale with thickness ranging from 20 cm to 2 m. This facies are

low land exposures of spring sections at Ngene, Obune, Oji-Arum (Fig. 9d), and Umuchime. They are mostly found at the basal section of the outcrops with the exception of the Umuchime section where they were exposed at the basal and middle intervals. At Obune and Umuchime, the facies is underlain by the coal facies unit and the Stl and bioturbated claystone band facies, while at Obune, it is overlain by lateritic fronts of boulders. In Oji-Arum, this facies is overlain and underlain by the coal facies (Co) and Stl, respectively (Fig. 9d). There is absence of sedimentary structures and trace fossils or plant remains.

Interpretation The black color, non-calcareous nature and fine-grained composition of this facies is a result of the high organic content present in the shales. This suggests deposition by suspension sediment fallout in an anoxic, low-energy, offshore marine environment (Miall 2000). The absence of macroscopic plant debris is an indication of offshore conditions where the portion of organic debris that is deposited is broken down and not preserved.

Facies association

Similar or closely related sedimentary facies were classified into assemblages of genetically related facies, known as facies association (FA). The description and interpretation of the facies association and their inferred environments of deposition are given below and summed up in Table 1.

Table 1 Facies description and interpretation of depositional environment

| Lithofacies	Lithofacies association	Sedimentary structures	Depositional environment
1. Conglomeritic sandstone facies (Gc) 2. Pebbly sandstone facies (Sp)	FA1	Conglomeritic sand are clast and matrixes supported and do not exhibit imbrication. Pebbly sandstones are characterized by planar and trough cross-beds with the presence of *Ophiomorpha* burrow in some cases. Pebbles are sub-rounded to sub-angular	Channel/alluvial fan deposit
3. Coal facies (Co) 4. Black carbonaceous shale facies (Shcb) 5. Heterolithic facies (Sht) 6. Claystone facies	FA2	Coal seams are intercalated with black carbonaceous shales and are characterized by medium to high vitreous luster on cleat surfaces. Shales are dark grey to black and structureless. Heteroliths are predominantly sandstone and clay, moderately to intensely bioturbated and exhibits parallel laminations. Claystone bands are slightly to intensely bioturbated	Lagoonal/swamp deposit
7. Bioturbated sandstone facies (Sb) 8. Muddy sandstone facies (Sm) 9. Laminated siltstone facies (Stl) 10. Heterolithic facies (Sht)	FA3	*Ophiomorpha* burrows are common. Siltstones are laminated, micaceous, slightly consolidated and slightly to moderately bioturbated. Hetrolithic facies are non-bioturbated	Lower shoreface deposit
11. Bioturbated sandstone facies (Sb) 12. Cross-bedded sandstone facies (Scb) 13. Heterolithic facies (Sht)	FA4	Large- and small-scale planar and trough cross-stratifications with mud and extraformational clasts. Variation in intensity of bioturbations. In some cases, intense bioturbations result in concealment of sedimentary structures. Dominant ichnofacies is *Ophiomorpha*	Upper shoreface deposit

Facies association 1: channel/alluvial fan deposit

Facies association 1 (FA1) (Fig. 10) is characterized by conglomeritic sandstone facies (Gc) and Sp (Table 1). The conglomerates (clast supported and matrix supported) have varying thickness of about 10 cm to 7.5 m, with colors ranging from yellowish-white to light brown (Fig. 11a). They comprise very coarse to quartz pebbly grains, predominantly sub-rounded. On the other hand, the pebbly sandstone facies is characterized by bed thickness of 10 cm to 1 m with its color ranging from reddish brown to yellowish-brown. They are rounded to sub-rounded in shape. FA1 is observed in Inyi-Ubo, Oji-Arum, Ngene, Umuchime, Ngwara, and Oji-Achi, respectively.

The clast-supported conglomeritic units are interpreted to have been deposited as small bodies of channel lag or longitudinal braided bars of low sinuous streams. The matrix-supported conglomeritic unit suggests debris-flow deposits. The conglomerates are monomict and texturally sub-mature. These conglomerates are likely to be alluvial

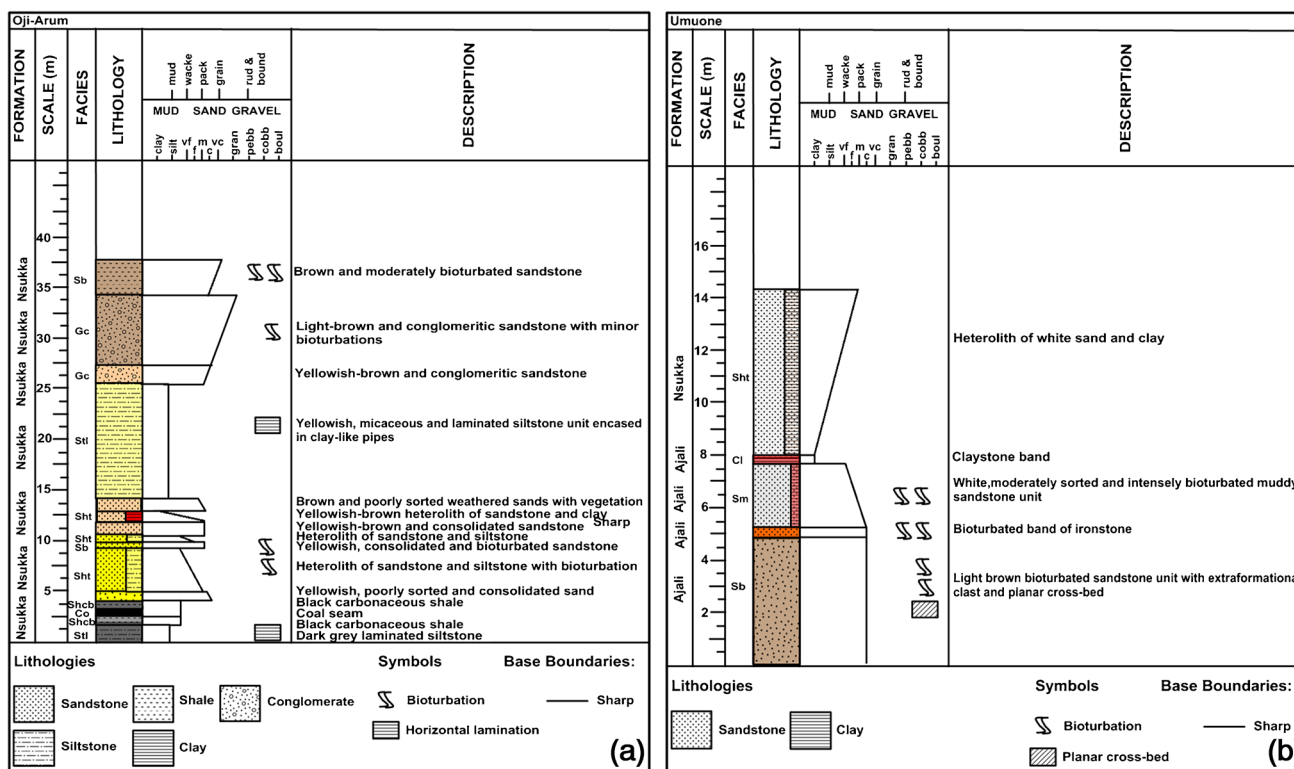**Fig. 10** Conceptual facies depositional model of the study area
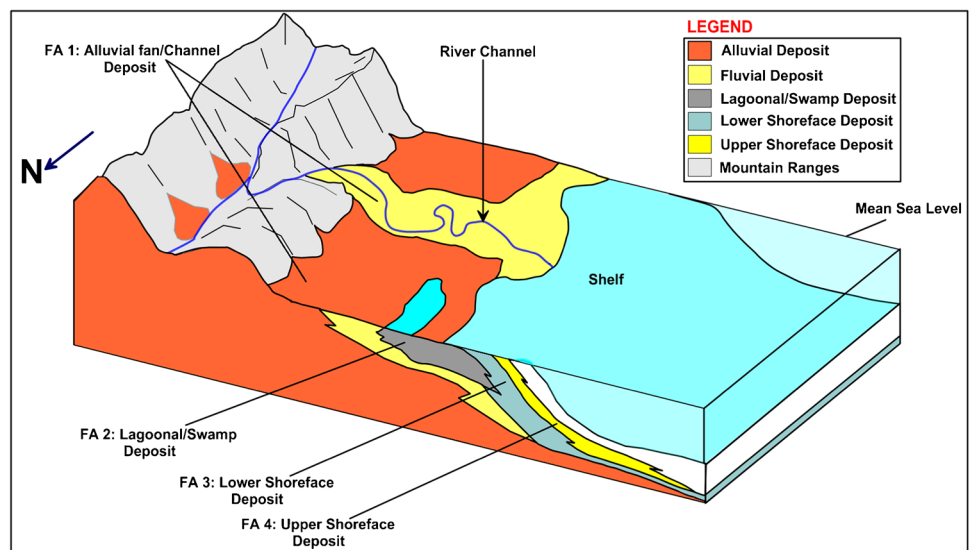
Fig. 11 Representative lithologic profiles of **a** Oji-Arum and **b** Umuone showing the distribution of the various lithofacies across the outcrop sections

fan accumulation in response to uplift along faulted margins. FA1 is dominantly alluvial and braided fluvial channels.

Facies association 2: lagoonal/swamp deposit

Facies association 2 (FA2) comprises mainly of coal facies, black carbonaceous shale facies, and heterolithic facies (Table 1). The coal facies is commonly interbedded with the black carbonaceous shales facies. The thickness of FA2 ranges from 20 cm to 1.3 m. Facies association 2 is observed at different locations of Obune, Oji-Arum, Umuchime, and Ogba, respectively.

FA2 is interpreted to depict back swamp and flood plain deposits due to the occurrence of relatively thin coal seams or abundance of preserved organic materials. Carbonaceous shale is observed as part of a facies progression capping many flood plain pond successions. Based on their high carbon content, the dull, dark gray colors of the carbonaceous shales suggest occurrence within a well-vegetated and wet paleoenvironment. It is possibly linked with the lower reaches of a fluvial stream system. The coal beds are thin, occurring with sandstone and mudstone units in marsh/swamp environments (Reinson 1992).

Facies association 3: lower shoreface deposit

Facies association 3 (FA3) comprises bioturbated sandstone, muddy sandstone, laminated siltstone, and non-bioturbated heterolithic units. This facies association is characterized by very fine to pebbly grained, white to light brown sandstone with bed thickness that ranges from 10 cm to 6 m. Bioturbations within this facies association are generally moderate to intense. However, there is the absence of sedimentary structures in certain areas particularly at Ogba and Ohali.

The heterolithic units, which consist of siltstone laminae, sand, and clay, suggest fluctuation in energy at some periods. The absence of sedimentary structures could possibly be due to intense bioturbations. The fine and laminated nature of the heteroliths depicts deposition in a low-energy setting (Dim et al. 2016; Nichols et al. 2016). This association is interpreted as lower shoreface deposits (Table 1).

Facies association 4: upper shoreface deposit

This facies association is the most extensive in the study area. Facies association 4 (FA4) consists of cross-bedded sandstones, bioturbated sandstone, and heterolithic facies (Table 1). It ranges in thickness from 30 cm to 6 m with average thickness of about 1 m. It is observed mainly in

Umuone, Ugwu-Odu, Otamkpa, Umuagu-Inyi, Iyi-agbashieje, Akpaugo-Eze, Umuchime, and Ngene (Fig. 11a, b). They also occur in Inyi-Ubo, Oji-Achi, Mamu, Oji-Arum, Ngwara, Akwu-Achi Amaetiti, and Ohali. FA4 comprises yellowish-white to brown, very fine to coarse and pebbly sandstone. Bioturbations are moderate to intense.

Planar and cross-stratified sandstone beds record migration of two- and three-dimensional subaqueous dunes produced by strong unidirectional currents in a high-energy, storm-wave-dominated, upper shoreface setting. The general scarcity of trace fossils within the cross-stratified sandstones further supports high-energy conditions that were unfavorable for invertebrate activity. The *Ophiomorpha* ichnofacies portray high energy environments that occurs both in the shoreface and foreshore sequences. The heterolithic units depict energy fluctuation and could represent the products of shoreface deposition under storm conditions of varying severity. Associated bioturbated sandstones represent periods of fair weather reworking of sands by biological activity within subaqueous environments (c.f. Clifton et al. 2006; Hampson 2010).

The black color, non-calcareous nature and fine-grained composition of this facies is a result of the high organic content present in the shales. This suggests deposition by suspension sediment fallout in oxygen-deficient, low-energy, offshore marine environment. The absence of macroscopic plant debris is an indication of offshore conditions where the portion of organic debris that is deposited is broken down and not preserved. Figure 10 shows the conceptual facies depositional model of the study area.

Granulometric analysis

Log-probability graphs were generated for twenty-five samples (Inyi-ubo/bed 1 to 17, Mamu/bed 1, Mamu/bed 3, Mamu/bed 7, Umuone/bed 4, Oji-Achi/bed 1, Oji-Achi/bed 3, Umuagu-Inyi/bed 1, and Umuagu-Inyi/bed 3) collected at five different locations (Inyi-Ubo, Mamu, Umuone, Oji-Achi, and Umuagu-Inyi).

Log-probability curves

The sands were transported by suspension, saltation, and traction mechanisms (Fig. 12a, b). Samples collected from bed 4 in Umuone, beds 1 and 2 in Oji-Achi and Umuagu-Inyi, and bed 1 in Mamu showed traction, saltation, and suspension sub-populations whereas sand samples collected from beds 3 and 7 in Mamu had saltation and suspension loads. With the exceptions of samples collected from beds 5, 6, 10, 11, 12, 14, and 15, which had saltation and suspension loads, all the other samples (beds 1 to 4, 7 to 9, 13, 16, and 17) collected at the outcrop exposure in Inyi-Ubo showed traction, saltation, and suspension sub-populations.

Results of univariate grain size parameters

The computed mean grain size values in the sand samples ranged between 0.68 (coarse sand) and 1.95 (medium sand) with an average value of 1.28 (Table 2). The standard deviation varies from 0.53 (moderately well sorted) to 1.36 (poorly sorted). An average standard deviation of 0.91 implies that most of the samples are moderately sorted except samples from some localities (Inyi-Ubo/bed 9, Inyi-Ub/bed 10, Inyi-Ubo/bed 13, Inyi-Ub/bed 14, Umuagu-Inyi/bed 1, Mamu/bed 1, Mamu/bed 3, and Oji-Achi/bed 1) which are poorly sorted (1.02 to 1.36). Grain size distribution of most of the samples is symmetrical (Table 2). In terms of skewness, the distribution of grain sizes of the samples are very negatively or negatively skewed except samples Inyi-Ubo/bed 11, Inyi-Ubo/bed 12, Inyi-Ubo/bed 16, Mamu/bed 3, and Mamu/bed 7, which belonged to the less-abundant positive and very positively skewed class. According to the kurtosis scale, 17 samples have mesokurtic curves of distribution while four samples each have platykurtic (Inyi-Ubo/bed 1, Inyi-Ubo/bed 14, Mamu/bed 1, and Mamu/bed 3) and leptokurtic curves (Inyi-Ubo/bed 4, Inyi-Ubo/bed 5, Inyi-Ubo/bed 8, and Umuagu-Inyi/ bed 3) (Table 2).

Interpretation of grain size parameters

The mean size (Mz) represents the overall average size of the sand samples that is influenced by mode of transportation, sample source, and depositional environment. Most of the samples are medium-grained sand (Table 2). This suggests that the sediments were deposited under a moderately high-energy condition, as sediments usually become coarser with increasing energy of the transporting medium.

The sorting is a measure of the uniformity of grain size distribution within the samples. It relies on the size range in the source rock, distance of the transportation, extent of weathering and the energy variation of the depositing medium. About 68% of the samples are moderately sorted (Table 2). This suggests that little grain selection have taken place during deposition or transport. This could have resulted from a slightly variable and unidirectional energy of flow.

Eighty percent of the samples are coarse or very coarse-skewed. Thus, indicating the dominance of coarser fraction in the sediments. Most of the sediments from the collected samples are symmetrical and negatively skewed, and mesokurtic with few samples being platykurtic. This suggests the dominance of a sand population with the presence of a subordinate population of coarse-grained particles.

The mesokurtic nature of the samples implies that the sediments are likely derived from multiple sources (Akaegbobi and Boboye 1999). The dominant mesokurtic and less-dominant platykurtic and leptokurtic nature of the
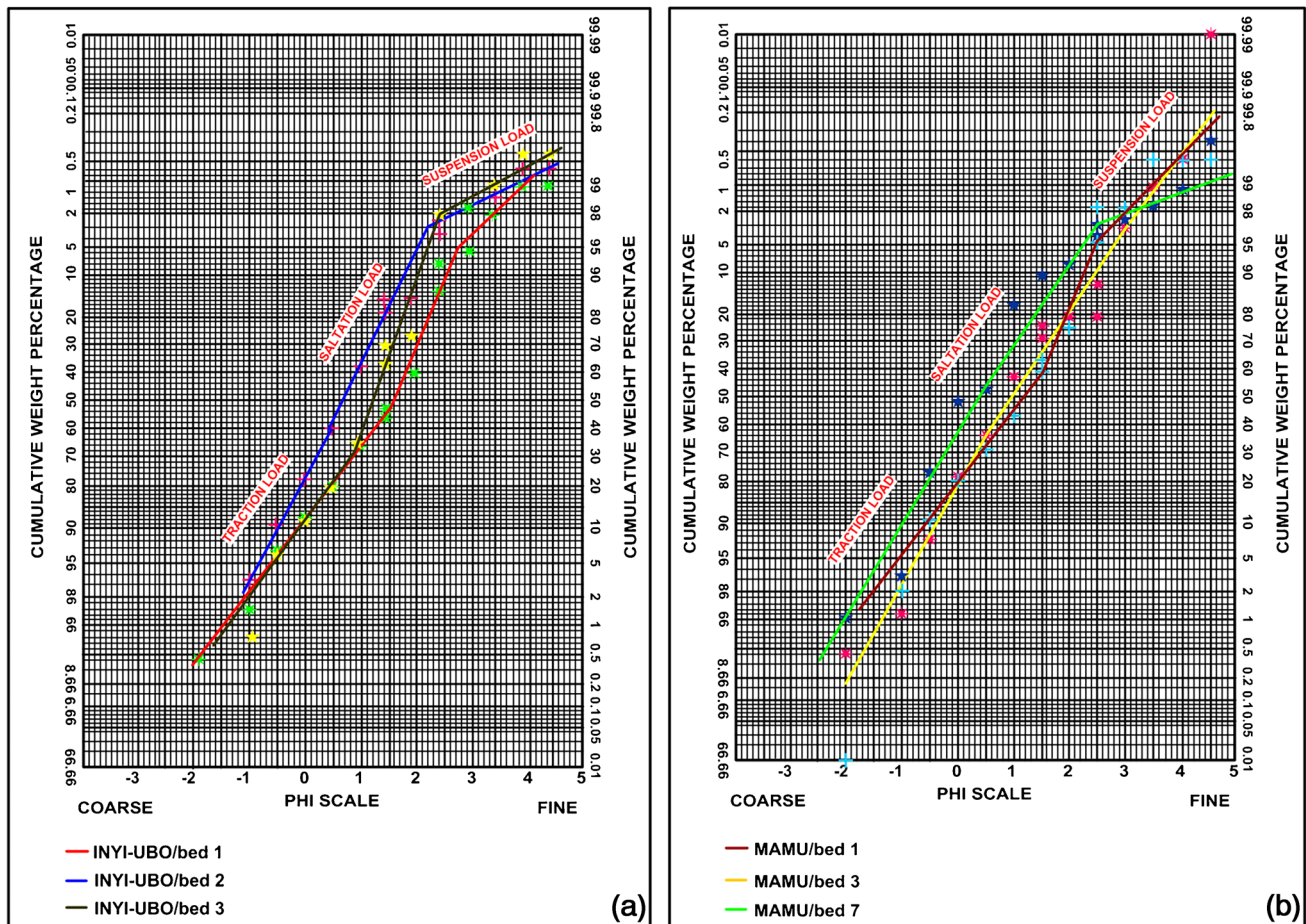
Fig. 12 Representative log probability plots of sand samples of **a** beds 1, 2, and 3 collected at Inyi-Ubo and **b** beds 1, 3, and 7 collected at Mamu showing their mechanisms of transportation during deposition

sediments is also an indication of a moderate to high energy of deposition.

Bivariate scatter graphs of grain size parameters Bivariate plots show the relationship between the univariate parameters and can be used to differentiate between fluvial, dune, and beach environment. Four plots are presented in this work; two of which are sector plots showing the relationships between sorting (σ_I) and mean size (Mz) and between kurtosis (K_σ) and skewness (Sk_I).

The relationship between sorting and mean grain size of the sand samples is displayed in Fig. 12a. Majority of the samples are mostly of medium sand range with a few samples within the coarse sand range. Specifically, 19 samples fall within the medium sand range while six samples fall within the coarse sand range, respectively (Fig. 13a). This is in agreement with the result of univariate analysis. Eight samples lie in the range of very poorly sorted sediments out of which all except one are medium sands. In line with the result of univariate analysis, 17 sand samples fell within

the moderately sorted range (Fig. 13a). Of these, only five samples are coarse in grain size while the others indicate medium grain sizes.

The plotting relationship between kurtosis and skewness shows that nine of the sand samples lie within the negatively skewed class (Fig. 13b). Only six and ten samples fall within the positively skewed and symmetrical range, respectively. In all, 21 samples lie within the kurtosis field of mesokurtic and leptokurtic while four samples occupy the platykurtic kurtosis field (Fig. 13b). The dominance of the mesokurtic and leptokurtic range supports sand- and mud-dominant sediment (Saeed and Abdi 2016). Skewness is environmentally sensitive whereas kurtosis is not diagnostic of depositional environment. River sands are generally symmetrical or positively skewed as is the case with majority of the sand samples (Friedman 1961) (Fig. 13b). River transportation results from unidirectional flow and may be responsible for the skewness of the river sands.

A plot of mean grain size and sorting is commonly used to distinguish river sands from dune sands. All except two

Table 2 Summary of grain size characteristics of collected samples with interpretations

Sample number	Mean size (Mz)	Sorting (σ_I)	Skewness (Sk_I)	Kurtosis (K_σ)
Inyi-Ubo/bed 1	1.38 (medium sand)	0.55 (moderately sorted)	−0.31 (very negatively skewed)	0.83 (platykurkic)
Inyi-Ubo/bed 2	0.68 (coarse sand)	0.53 (moderately sorted)	−0.04 (symmetrical)	0.97 (mesokurtic)
Inyi-Ubo/bed 3	1.08 (medium sand)	0.83 (moderately sorted)	−0.24 (negatively skewed)	1.07 (mesokurtic)
Inyi-Ubo/bed 4	1.32 (medium sand)	0.99 (moderately sorted)	−0.23 (negatively skewed)	1.32 (leptokurtic)
Inyi-Ubo/bed 5	0.70 (coarse sand)	0.63 (moderately sorted)	0.09 (positively skewed)	1.13 (leptokurtic)
Inyi-Ubo/bed 6	1.10 (medium sand)	0.88 (moderately sorted)	−0.01 (symmetrical)	0.93 (mesokurtic)
Inyi-Ubo/ bed 7	1.60 (medium sand)	0.80 (moderately sorted)	−0.05 (symmetrical)	0.99 (mesokurtic)
Inyi-Ubo/bed 8	1.77 (medium sand)	0.87 (moderately sorted)	−0.17 (negatively skewed)	1.27 (leptokurtic)
Inyi-Ubo/bed 9	1.07 (medium sand)	1.36 (poorly sorted)	−0.47 (very negatively skewed)	1.02 (mesokurtic)
Inyi-Ubo/ bed 10	1.83 (medium sand)	1.07 (poorly sorted)	−1.42 (very negatively skewed)	0.93 (mesokurtic)
Inyi-Ubo/ bed 11	1.37 (medium sand)	0.85 (moderately sorted)	0.04 (positively skewed)	1.04 (mesokurtic)
Inyi-Ubo/bed 12	1.15 (medium sand)	0.96 (moderately sorted)	0.50 (very positively skewed)	1.01 (mesokurtic)
Inyi-Ubo/bed 13	1.30 (medium sand)	1.02 (poorly sorted)	−0.03 (symmetrical)	1.07 (mesokurtic)
Inyi-Ubo/bed 14	1.27 (medium sand)	1.19 (poorly sorted)	−0.09 (symmetrical)	0.89 (platykurtic)
Inyi-Ubo/bed 15	0.88 (coarse sand)	0.81 (moderately sorted)	−0.02 (symmetrical)	0.97 (mesokurtic)
Inyi-Ubo/bed 16	1.68 (medium sand)	0.93 (moderately sorted)	0.03 (positively skewed)	0.98 (mesokurtic)
Inyi-Ubo/bed 17	1.60 (medium sand)	0.89 (moderately sorted)	−0.05 (symmetrical)	0.99 (mesokurtic)
Umuagu-Inyi/bed 1	1.15 (medium sand)	1.24 (poorly sorted)	−0.13 (negatively skewed)	0.94 (mesokurtic)
Umuagu-Inyi/bed 3	0.25 (coarse sand)	0.94 (moderately sorted)	−0.04 (symmetrical)	1.52 (very lepkurtic)
Mamu/bed 1	0.98 (coarse sand)	1.09 (poorly sorted)	−0.19 (negatively skewed)	0.86 (platykurtic)
Mamu/bed 3	1.03 (medium sand)	1.11 (poorly sorted)	0.04 (very positively skewed)	0.89 (platykurtic)
Mamu/bed 7	0.60 (coarse sand)	0.99 (moderately sorted)	0.19 (positively skewed)	0.92 (mesokurtic)
Umuone/bed 4	1.58 (medium sand)	0.58 (moderately sorted)	−0.07 (symmetrical)	1.04 (mesokurtic)
Oji-Achi/bed 1	1.55 (medium sand)	1.21 (poorly sorted)	−0.26 (negatively skewed)	1.02 (mesokurtic)
Oji-Achi/bed 3	1.98 (medium sand)	0.53 (moderately sorted)	−0.01 (symmetrical)	0.96 (mesokurtic)

samples indicate sorting values that are greater than 0.5 which suggest that the sands are river deposited (Fig. 13c). According to Friedman (1961), most coastal, barrier bar, and lake dune sands have a sorting of less than 0.4 and many desert and inland dune sands do not exceed 0.5, whereas most river sands have a sorting in excess of 0.5. The generally moderately sorted and poorly sorted nature of the sediments strengthen the argument that the sands are fluvially
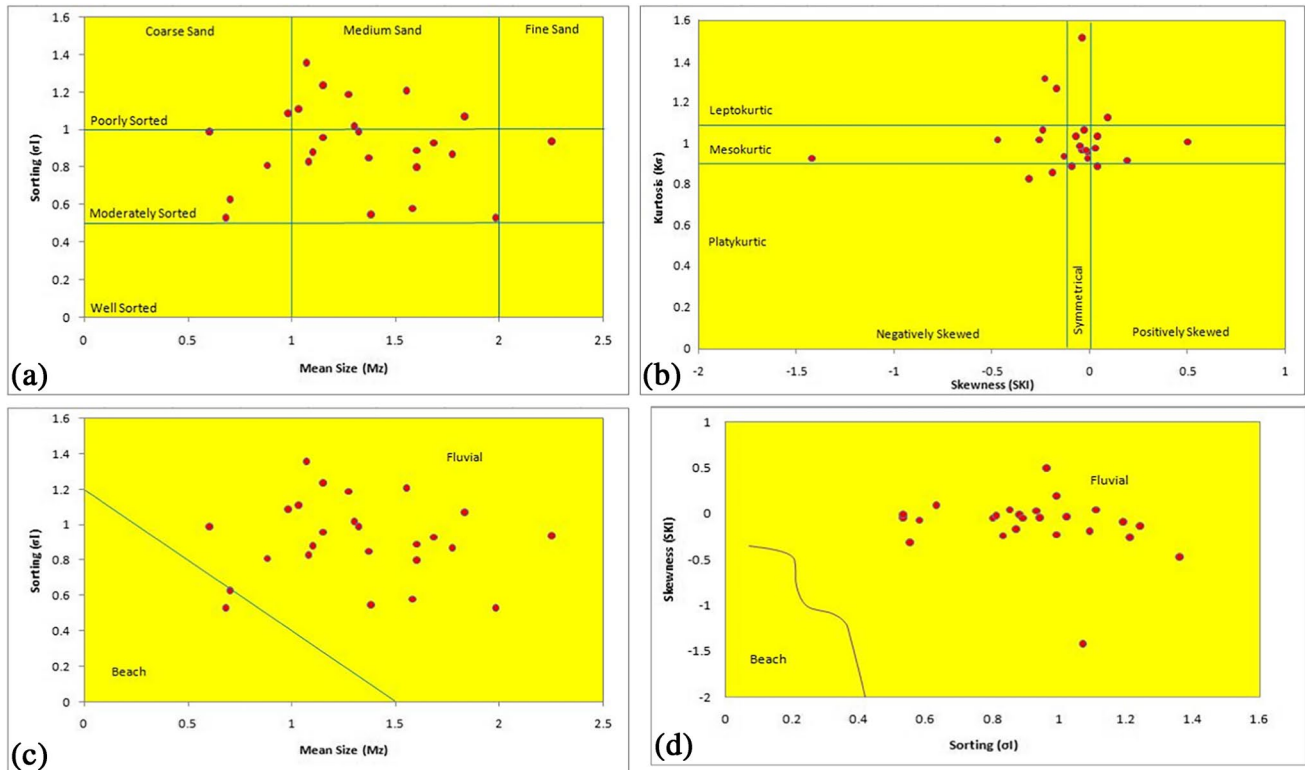
Fig. 13 a Sector plot showing the bivariate relationship between sorting (σ_I) and mean size (Mz) (adapted from Miola and Weiser 1977). **b** Sector plot showing the bivariate relationship between kurtosis (Kσ) and skewness (SkI) (adapted from Friedman 1961). **c** Plotting relationship between graphic mean and sorting showing inferred depositional environment (adapted from Friedman 1961) (d) Sector plot showing the bivariate relationship between Kσ and SkI (adapted from Friedman 1961)

derived since dune sands tend to be better sorted than river sands.

The plot of skewness against sorting, a measure of the standard deviation is used to discriminate beach and river sands (Fig. 13d). The degree of sorting is helpful in distinguishing beach from river sands. Sands from both environments usually show grain sizes that are larger than 0.5 mm (Keller 1945). However, river sands have a high numerical value for sorting and are mostly characterized by symmetrical and positive skewness (Friedman 1961) as indicated in Fig. 13d. Hence, on the basis of the high numerical value for the sorting and the predominantly symmetrical nature of the sand samples, we conclude that the sands are river deposited. This assertion is in agreement with the results of other bivariate plots that have been discussed earlier (Fig. 13a–c).

Multivariate scatter graphs of grain size parameters Table 3 shows the various values of the linear discriminating functions (Y_2 and Y_3) for each sample. After computing the linear discriminating functions for the Inyi sediments, it was determined that the values for Y_2 and Y_3 range from 47.01 to 149.719 and -13.550 to -0.699, respectively. Based on the Y_2 values, all the samples fall in the shallow marine

environment except Inyi-Ubo beds 1 and 2, which indicate beach deposition (Table 3). According to Sahu (1964), if $Y_2 > -63.3650$, the environment of deposition of the sand sediments is shallow marine. With reference to the Y_3 values, the Inyi sand samples are fluvial (deltaic) and shallow marine deposits. Samples with $Y_3 < -7.4190$ indicate fluvial (deltaic) deposition (Baiyegunhi et al. 2017). Of all the samples, those collected from Inyi-Ubo and Umuone indicate shallow marine deposition with the exception of four samples (Inyi-Ubo/bed 9, Inyu-Ubo/bed12, Inyi-Ubo/bed 13, Inyi-Ubo/bed 14), which indicate fluvial (deltaic) deposition (Table 3). One sample each from Umuagu-Inyi and Oji-Achi show shallow marine deposition whereas all the samples from Mamu indicate fluvial (deltaic) deposition. The binary plot of Y_2 versus Y_3 indicates that all the samples from the study area fall in the shallow agitated waters/shallow marine (Fig. 14).

Permeability and porosity of the sediments

Permeability values computed for the collected samples ranges from 6.41 to 168.29 mD (Table 4). Interpretation of the permeability and porosity values of the sand samples

Table 3 Computed values of discriminating functions Y_2 and Y_3 showing environment of deposition

| Sample number	Beach: shallow marine (Y_2 value and interpretation)	Shallow marine: fluvial (deltaic) (Y_3 value and interpretation)
Inyi-Ubo/bed 1	52.61 (beach)	−0.699 (shallow marine)
Inyi-Ubo/bed 2	47.01 (beach)	−2.024 (shallow marine)
Inyi-Ubo/bed 3	78.707 (shallow marine)	−4.501 (shallow marine)
Inyi-Ubo/bed 4	106.644 (shallow marine)	−7.021 (shallow marine)
Inyi-Ubo/bed 5	60.274 (beach)	−3.664 (shallow marine)
Inyi-Ubo/bed 6	86.232 (shallow marine)	−5.776 (shallow marine)
Inyi-Ubo/bed 7	86.113 (shallow marine)	−4.858 (shallow marine)
Inyi-Ubo/bed 8	99.633 (shallow marine)	−5.233 (shallow marine)
Inyi-Ubo/bed 9	149.719 (shallow marine)	−13.550 (fluvial)
Inyi-Ubo/bed 10	97.203 (shallow marine)	−2.514 (shallow marine)
Inyi-Ubo/bed11	90.258 (shallow marine)	−6.084 (shallow marine)
Inyi-Ubo/bed 12	107.451 (shallow marine)	−10.144 (fluvial)
Inyi-Ubo/bed 13	109.268 (shallow marine)	−8.839 (fluvial)
Inyi-Ubo/bed 14	129.04 (shallow marine)	−11.561 (fluvial)
Inyi-Ubo/bed 15	75.354 (shallow marine)	−5.352 (shallow marine)
Inyi-Ubo/bed 16	103.487 (shallow marine)	−7.198 (shallow marine)
Inyi-Ubo/bed 17	96.107 (shallow marine)	−6.190 (shallow marine)
Umuagu-Inyi/bed 1	135.225 (shallow marine)	−12.460 (fluvial)
Umuagu-Inyi/bed 3	122.934 (shallow marine)	−6.830 (shallow marine)
Mamu/bed 1	106.863 (shallow marine)	−9.188 (fluvial)
Mamu/bed 3	115.306 (shallow marine)	−10.653 (fluvial)
Mamu/bed 7	94.857 (shallow marine)	−9.300 (fluvial)
Umuone/bed 4	66.392 (shallow marine)	−2.103 (shallow marine)
Oji-Achi 1/bed 1	136.184 (shallow marine)	−11.063 (fluvial)
Oji-Achi/bed 3	69.015 (shallow marine)	−1.806 (shallow marine)
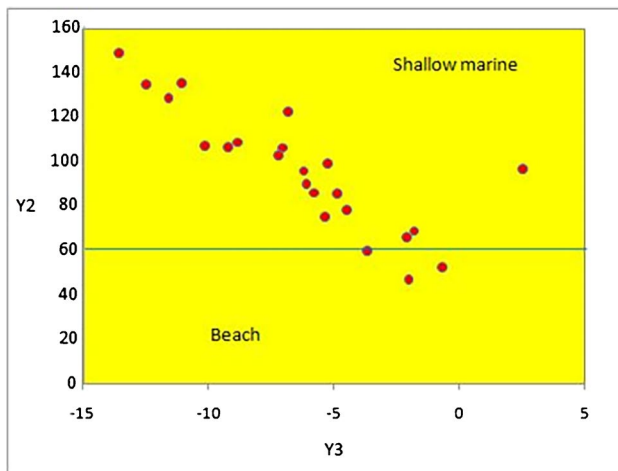
Fig. 14 Plotting relationship between Y_2 and Y_3 showing inferred depositional environment (adapted from Baiyegunchi et al. 2017)

was based on the criteria established by North (1985). Qualitative assessment of calculated permeabilities shows that they vary from poor to good. Majority of the samples (16) reveal moderate permeabilities. This constitutes about 64% of the total samples collected. They have permeability values that range from 15.68 to 45.73 mD. Six samples (Inyi-Ubo/bed 1, Inyi-Ubo/bed 3, Inyi-Ubo/bed 5, Inyi-Ubo/bed 15, Mamu/bed 3, and Mamu/bed 7) fall within the class of good permeability (51.88–168.29 mD). Only three samples (Inyi-Ubo/bed 10, Umuone/bed 4, and Umuagu-Inyi/bed 3) show permeability values that are poor to fair (6.41–14.22 mD).

Twenty-one sandstone samples, representing about 84% of the total collected sand samples show porosities that vary from 5 to 9.50% (Fig. 15; Table 4). Three samples (Mamu/bed 1, Oji-Achi/bed 1, and Umuagu-Inyi/bed 3) have negligible porosities (4 to 4.8%) (little or no pore spaces) and hence, very low permeabilities (6.41 to 36.91 mD). One sample (Inyi-Ubo/bed 1) show fair porosity value (11%). Comparing these values with the values for most currently productive reservoirs, these units may be classified as poor reservoir sands (North 1985; Baker Hughes 1996). The grain size characteristics (medium grained size and moderate to poor sorting) of majority of the samples could have adversely affected the porosities of the sediments (Fig. 15).

Table 4 Estimated permeabilities and porosities of the sand samples based on grain size

S/n	Locations	Permeability (mD)	Porosity (%)
1	Inyi-Ubo/bed 1	156.22	11.00
2	Inyi-Ubo/bed 2	34.16	5.00
3	Inyi-Ubo/bed 3	51.88	8.00
4	Inyi-Ubo/bed 4	25.45	6.50
5	Inyi-Ubo/bed 5	123.89	8.00
6	Inyi-Ubo/bed 6	38.39	6.80
7	Inyi-Ubo/bed 7	23.98	6.00
8	Inyi-Ubo/bed 8	16.44	5.80
9	Inyi-Ubo/bed 9	15.68	5.50
10	Inyi-Ubo/bed 10	10.78	5.20
11	Inyi-Ubo/bed 11	39.93	7.00
12	Inyi-Ubo/bed 12	45.73	7.50
13	Inyi-Ubo/bed 13	35.24	6.70
14	Inyi-Ubo/bed 14	26.88	6.60
15	Inyi-Ubo/bed 15	76.69	9.50
16	Inyi-Ubo/bed 16	18.90	5.90
17	Inyi-Ubo/bed 17	29.01	6.50
18	Mamu/bed 1	36.91	4.80
19	Mamu/bed 3	59.73	9.00
20	Mamu/bed 7	168.29	8.00
21	Umuone/bed 4	14.22	5.50
22	Oji-Achi/bed 1	36.08	4.70
23	Oji-Achi/bed 3	23.72	6.00
24	Umuagu-Inyi/bed 1	28.99	6.40
25	Umuagu-Inyi/bed 3	6.41	4.00

Fig. 15 Effect of grain size on the permeability and porosity of the collected sand samples (adapted after Coalson et al. 1990)

Sandstone diagenesis from X-ray diffraction analysis

Eight sandstone samples from different locations within the study area (Inyi-Ubo, Mamu, Umuone, and Oji-Achi, respectively) were sampled and subjected to analysis using this method. The result of the analysis shows the presence of 11 minerals that are contained in the sandstone samples (Table 5).

The principal minerals (non-clay minerals) contained in the samples include quartz, birnessite, and goethite in their different percentage concentrations. The clay minerals present are amesite, kaolinite, and dickite while quartz, birnessite, and pseudoeucryptite are the major non-clay mineral present in the sandstones (Table 5). Other minerals present include tridymite, berlinite, and moissanite. Among these, some occur as oxides while others as phyllosilicates. Quartz, goethite, birnessite, tridymite, and pseudoeucryptite make up the framework grains while kaolinite and dickite occur as cements. Amesite, berlinite, moissanite, and moraesite constitute the accessory minerals (Table 5).

The results show variations in the mineral composition across the locations. Quartz, a detrital mineral is the most dominant mineral present with its highest concentrations (82.2%) at Oji-Achi location. Goethite (6.9%) and dickite (5.1%) concentrations are relatively very low in Mamu/bed 3 and Inyi-Ubo/bed 3 samples, respectively (Table 5). The occurrence of quartz was not observed in two samples (Inyi-Ubo/bed 2 and Inyi-Ubo/bed 3); however, they both consist of tridymite and berlinite, respectively (Table 5). Tridymite and berlinite are high-temperature minerals. Their occurrence in the analyzed samples is indicative of a volcanic and metamorphic source. This suggests that the sediments are of volcanic and metamorphic origin (Onac and White 2003).

The combined effect of burial, compaction, and chemical reaction between rocks and fluid are collectively known as diagenesis. These processes pose a major influence on the reservoir quality of sediments.

Generally, the sands of the Ajali Formation are deposited with mixture of minerals that vary with local rock source (clay minerals, non-clay minerals and accessory minerals) (Fig. 16a, b). At the time of deposition, sand-sized grains (quartz, pseudoeucryptite, birnessite, and moraesite) created a self-supporting framework. Finer particles such as clays (kaolinite and dickite) formed the detrital matrix and the remaining volume was pore space. Kaolinite occurs as a result of chemical weathering from lateritic soil formation and granitic source rocks. These clay minerals suggest terrestrial influence in a shallow marine environment. The constituent minerals (goethite, amesite, and moissanite) of this assemblage were formed under a specific range of temperature, pressure, and oxidation state unique to each mineral which had a bearing on the physiochemical stability
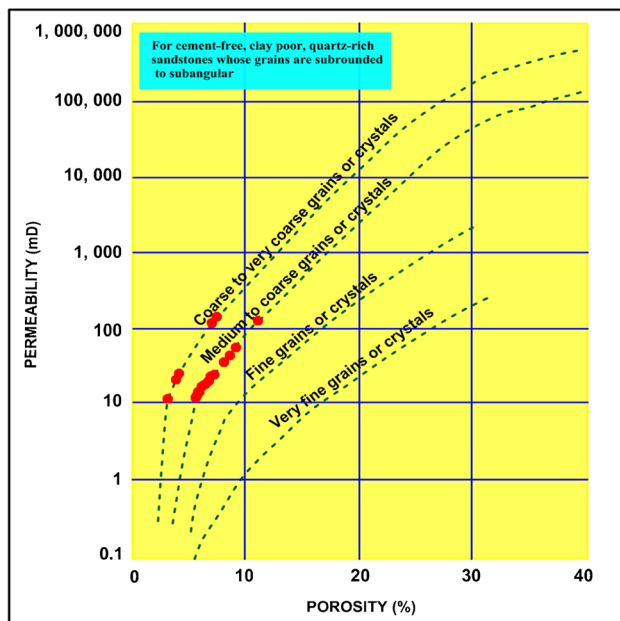
Table 5 Results of X-ray diffraction (XRD) analysis of the sand samples showing mineral percentages

Mineral composition	Inyi-Ubo/bed 1 (%)	Inyi-Ubo/bed 2 (%)	Inyi-Ubo/bed 3 (%)	Inyi-Ubo/bed 4 (%)	Mamu/bed 3 (%)	Umuone/bed 4 (%)	Oji-Achi/bed 1 (%)	Oji-Achi/bed 2 (%)
Quartz	19.2	–	–	30.2	66.3	26.0	82.2	65.0
Pseudoeucryptite	38.4	–	–	–	–	–	4.0	26.0
Moraesite	42.4	–	–	–	–	–	–	–
Tridymite	–	50.0	–	–	8.0	–	–	–
Kaolinite	–	32.0	–	23.2	–	–	–	–
Moissanite	–	18.0	–	–	–	–	–	–
Goethite	–	–	11.0	–	6.9	74.0	–	–
Dickite	–	–	5.1	–	18.8	–	–	–
Amesite	–	–	6.1	–	–	–	–	–
Berlinite	–	–	78.5	–	–	–	–	–
Birnessite	–	–	–	46.5	–	–	13.8	9.0

of the mineral assemblage. Diagenetic processes were initiated at the interface between depositional medium and the previous layers of sediments which were modified as the rock layers became buried beneath sedimentary overburden. With time, the sands responded to change in pressure and temperature. The occurrence of tridymite as a high-temperature polymorph of silica is an evidence of terrestrial environment commonly associated with silica volcanism (Fig. 16a). After lithification, mechanical compaction, alteration of framework grains, cementation, precipitation, and dissolution ensued. During compaction, mechanically stable grains (quartz) compacted faster than unstable grains (clays). Compaction mechanisms include grain re-arrangement and pressure dissolution. During precipitation, authigenic minerals such as quartz and its likes developed into overgrowths, which served as cements and in most cases bridge the pore throat connectivity. Dissolution removed some detrital grains leaving obvious indications of few interconnecting and independent pores and clay minerals such as kaolinite and dickite (Fig. 16a, b). These clay minerals also act as cements within the Ajali sandstone and were probably formed through recrystallization of fine matrix and dissolution of K-feldspar. Kaolinite occurs in open environment with high acidic content and represents warm and humid conditions and high leaching environment (Aoki and Kohyama 1991). It acts as pore-filling and pore lining rim cement. Dickite is formed by solution, either involving growth during diagenesis or as hydrothermal replacement and bridges the pore throat thereby causing drastic reduction in porosity and permeability.

Variation in soil components of the Nsukka and Ajali formations means that their diagenetic processes are different. These variations in mineral composition are related to climatic conditions, rate of subsidence, source terrains, and sedimentation.

The primary diagenetic processes that may have strongly affected the sandstones of the Nsukka Formation in the study area are mechanical compaction, chemical compaction, precipitation, and cementation. Cementation is an important process that results in disaggregated sediments forming a cohesive rock, thus leading to porosity reduction. The main cements identified in the sandstones of the Nsukka Formation are quartz cement and iron oxide cement (geothite) (Table 5). Quartz cements exist in the rocks as a result of precipitation of silica into the pore spaces between grains. They could occur as both overgrowths and pore filling. This type of cement was formed early in the shallow marine diagenetic environment and in the early diagenetic stage. Goethite is inferred to wet periods with base level. It is favored by cooler, wetter, and less seasonal climatic conditions, when soil saturation becomes more likely (Kwetche et al. 2018). During the initial stages where diagenesis took place under oxidizing pore waters, mechanical compaction starts to influence the soft sediments when it was buried by overloading deposits. The higher the overburden, the more intense is the compaction. The overburden pressure results in bed thinning of the rocks, expelling the intergranular fluids (dewatering), closely packing the grains and thus, resulting in porosity reduction. The sandstones of the Nsukka Formation exposed in the study area seem to have been subjected to intense-moderate chemical and physical compaction during their progressive burial. Progressive burial resulted in increasing compaction and porosity loss either by grain slippage or rotation, resulting in eventual fracturing of resistant minerals. This explains the high percentage of goethite (74%) in the Umuone/bed 4 sample as it serves as a binder during compaction thereby bridging the pore spaces (Table 5). This resulted in porosity loss within the Nsukka Formation.
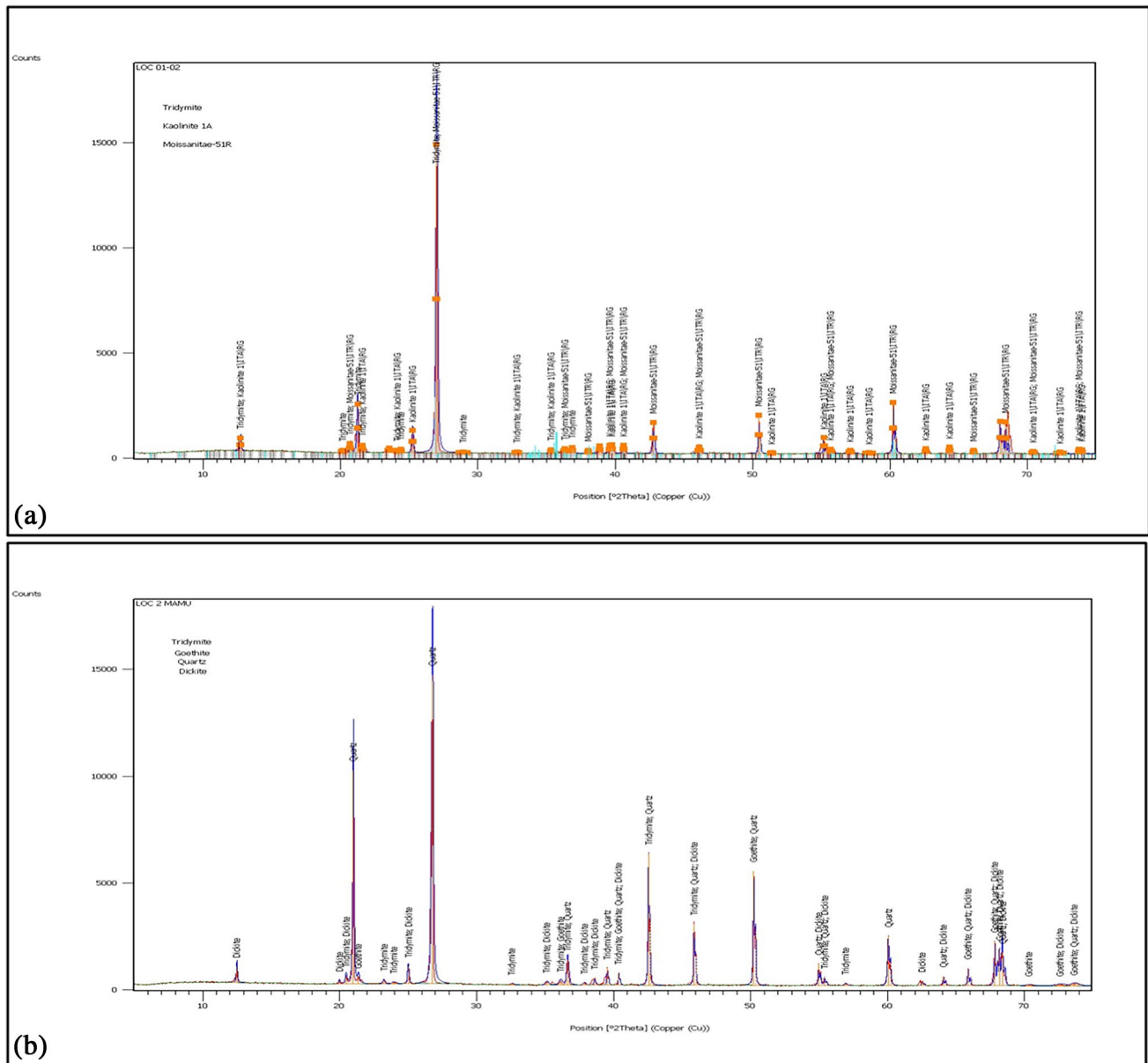
Fig. 16 Representative XRD graphical chart showing mineral composition in **a** Inyi-Ubo/bed 2 and **b** Mamu/bed 3 sand samples

Reservoir Quality Assessment

Integration of field and sedimentological data defines the geometry, distribution of physical properties, and flow characteristics of reservoir sands, which provides a reliable means for reservoir quality assessment and characterization. This is because the sedimentary facies has a significant effect on the composition and texture of the sediments; thus, it can influence subsequent diagenesis and affect the reservoir quality. The clastic sediments at Inyi-Ubo and Mamu predominantly comprise the conglomeritic, bioturbated, and cross-bedded sandstone facies with numerous mud balls and little clay deposited in a moderate- to high-energy

environment. This means that the sediments have characteristics of medium to coarse grains and a predominant moderately sorted texture. With the exception of one sample (Inyi-Ubo/bed 10), these sandstones had moderate to good permeability (15.68 to 168.29 mD). They probably experienced weak compaction; thus, their initial permeability was relatively preserved. The relatively high quartz content (19.2 to 78.5%) implies that the sands are better able to resist compaction. However, the porosities were poor (excluding Inyi-Ubo/bed 1). The poor porosity values observed in the sand samples could be attributed to the presence of clay minerals (kaolinite, dickite and amesite) of a structural type resulting in a reduction in sediment porosity. Also, the presence

of birnessite (oxide cement) in high proportion (46.5%) as observed in Inyi-Ubo/bed 4 could have adversely affected the porosity of the sediments. At Umuone, the sands consist mainly of the heterolithic and muddy sandstone facies deposited in a low- to moderate-energy environment with fine-grained and clay/mud-rich sediments. They are medium grained, with high matrix content. Cementation tends to occur in reservoirs that form in such environments. Here, the major cements are the oxide cements (Geothite), which show 74.0% in Umuone/bed 4. The occurrence of this cement in large amounts resulted in the poor porosity and permeability of the sediments. The occurrence of this cement in large amounts led to the poor porosity and permeability values obtained. Sediments at Oji-Achi were characterized by the pebbly, cross-bedded, and bioturbated sandstone lithofacies deposited in high-energy environment. Despite their high quartz content (81 to 86%) and low debris content, their permeabilities and porosities were moderate and poor, respectively. The presence of oxide cement (birnessite) in considerable quantity (9 to 13.8%) as well as quartz overgrowth could be responsible for this. During precipitation, authigenic minerals such as quartz, precipitate silica and develop into overgrowths. This in some cases bridge the pore throat connectivity and cause reduction in pore radii and consequently reducing porosity and permeability.

The sandstone of the Ajali and Nsukka formations in areas around Inyi are therefore of poor reservoir quality. However, they could serve as potential reservoirs for natural gas with the black carbonaceous shales, coal, and heterolithics, serving as source rocks and seal, respectively.

Conclusion

Detailed depositional facies interpretation, granulometric and X-ray diffraction analyses were integrated to analyze the textural attributes, reservoir potential, and paleodepositional environment of the sediments around Inyi, Anambra Basin, southeastern Nigeria. Two formations were encountered in the study area; Ajali and Nsukka formations. Eleven depositional lithofacies of conglomeritic facies, cross-bedded sandstone facies, coal facies, black carbonaceous shale facies, biorturbated shale facies, muddy sandstone facies, laminated siltstone facies, claystone facies, pebbly sandstone facies, heterolithic facies, and bioturbated sandstone facies were grouped into four facies association (FA1, FA2, FA3, and FA4). These lithofacies association reveals sediment packages deposited in channel/alluvial fan, lagoons and swamps, and lower to upper shoreface environments. These reflect characteristics of sediments deposited in low- to high-energy environment during transgression and regression events. This confirms the results of the granulometric analyses which also suggested shallow marine setting. The presence

of kaolinite from the X-ray diffraction analysis shows terrestrial influence in a shallow marine environment. These lithofacies are potential source, reservoir, and seal rocks. The permeability results range from 6.41 mD to 156.22 mD; an indication of poor to fair, moderate to good reservoir. The porosities are poor to fair, with values ranging from 4.0 to 11.0%. The presence of some clay minerals may have adversely affected the porosity and permeability characteristics of the sediments thereby making them poor reservoir sands especially for crude oil.

Author contribution Okwudiri Aloysius Anyiam conceptualized and supervised the study. Nkem Judith Odu, Chidubem Okwudiri Emedo, Kachikwulu Kingsley Okeke, and Ngozi Augustina Ulasi participated in field work, laboratory studies, and data analysis. Chidubem Okwudiri Emedo drafted the manuscript.

Data availability Data used in this research can be obtained from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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