



Influence of depositional environment on coal quality in Jangwa-Shankodi and Lafia-Obi areas, Central Benue Trough, north-central Nigeria

Johnson Ogonna Amobi¹ · Itohowo Moses Ekpo¹ · Ogechi Clementina Ekwenye¹ · Ifeanyi Andrew Oha¹ · Chidubem Okwudiri Emedo^{1,2}

Received: 26 July 2021 / Accepted: 10 November 2021 / Published online: 24 November 2021

© Saudi Society for Geosciences 2021

Abstract

The environment of deposition of coal-bearing strata not only controls the accumulation of coal seams but also determines the quality of coal deposits. In this study, the thickness and quality parameters of Jangwa-Shankodi and Lafia-Obi coal seams have been investigated and linked to the depositional palaeoenvironmental features. Lithofacies analysis was carried out to deduce the nature of the depositional environment of the coal-bearing strata. Geochemical characterization was performed on eight samples to determine the coal qualities using proximate and ultimate analysis. Nine lithofacies were identified and grouped into two facies associations (FA 1 and FA 2). FA 1 represents several repeated inclined and fining upward units and cycles, with erosional bases and trough cross-stratification, indicating a fluvial regime (meandering river setting). FA 2 consists of thicker deposits of laminated shales and coal seams in a swamp/lagoonal environment. Diminished seam thicknesses in the Jangwa-Shankodi area are due to early termination of peat growth and channel abandonment, whereas relatively thick seam development in the Lafia-Obi area is attributed to regular nutrient supply caused by persistent water coverage as well as high compaction rates of the underlying shaly sediments. The Jangwa-Shankodi and Lafia-Obi coal zones are high volatile C bituminous coal resources with ash, moisture, fixed carbon and volatile matter yield that range between 7.99–8.64% and 7.83–8.34%, 2.33–2.50% and 2.28–2.40%, 55.97–56.14% and 56.18–56.31% and 29.99–30.34% and 29.98–30.22%, respectively. Following the same order, the percentage ranges of elemental carbon and hydrogen are 52.92–53.19% and 53.99–54.52% and 4.47–4.55% and 3.89–4.06%, respectively. Sulphur content was lower in the Lafia-Obi coals (0.08–0.13%). Unlike the Lafia-Obi coals, the close proximity of the Jangwa-Shankodi area to channel and marine influences resulted in a higher sulphur content and ash yield of the coal-bearing strata. This translates to a lesser heating value and coking ability. Better peat growth and preservation points to a higher fixed carbon and better quality for the Lafia-Obi coals. Higher carbon and lower ash yield improve coal reservoir porosity and correlates positively with greater methane absorption capacity. The Lafia-Obi coal field is, therefore, of better quality compared to its Jangwa-Shankodi counterpart.

Keywords Jangwa-Shankodi · Lafia-Obi · Central Benue Trough · Proximate analysis · Ultimate analysis · Lithofacies

Introduction

Nigeria is home to one of the most widely distributed coal deposits in sub-Saharan Africa. These coal seams have been observed within the Benue Trough and Anambra Basin in areas such as Tai, Maiganga, Jangwa-Shankodi, Lafia-Obi, Enugu, Okaba, Inyi, Agbogugu, Ehandiagu and Eha-Alumona. In the past, with the exception of coal bed methane production, the Enugu coal deposits propelled the advancement of several industrial and domestic ventures that have become stagnant today. Efforts to revive the coal industry in Nigeria have all proved abortive. Besides

Responsible Editor: Domenico M. Doronzo

✉ Chidubem Okwudiri Emedo
chidubem.emedo.pg.80047@unn.edu.ng;
ecogeogranite@gmail.com

¹ Department of Geology, University of Nigeria,
Nsukka 410001, Nigeria

² Department of Geology, Federal University of Technology,
Owerri 460114, Nigeria

quality, the paucity of geological exploration data has resulted in the non-utilization of coal resources in other parts of the country despite holding large coals reserves, estimated to be at least 2 Gt (Ministry of Mines and Steel 2008; Chukwu et al. 2016). Insufficient data regarding the geology and quality of the coals has adversely affected their exploration. As a result, these abundant coal resources have been underexploited, in particular, the Jangwa-Shankodi and Lafia-Obi coals (Onoduku 2014b; Ryemshak et al. 2016).

In recent times, it has become necessary to support coal-prospection activities with palaeodepositional environmental studies (Galloway and Hobday 1983). These are carried out in order to show the relationship between the sedimentological attributes of the palaeoenvironment of the coal deposits and the coal distribution and quality parameters. From these, zones of different mining feasibility and variable economic seam quality can be identified within a particular coalfield (Hagelskamp et al., 1988). Studies of ancient and recent coal-forming environments show that coals develop under different environmental conditions, namely lagoonal, deltaic, back-barrier, alluvial fan and fluvial settings (Heward 1978; Horne et al. 1978; Flores 1983; Fielding 1985). These depositional environments exert diverse effects on coal quality and coal seam geometry.

Facies analysis which involves the observations of lithologic units, sedimentary structures and fossil contents of bed units is known to provide information on the environment(s) of deposition of coals (Okolo et al. 2020). The rank and quality of coals is commonly determined from its proximate and ultimate characteristics as well as other parameters such as fuel ratio and heating value. Proximate analysis gives the percentages (in weight) of the four parts in which coal is normally split: ash content, fixed carbon, moisture content and volatile matter (ASTM 2010). These four components constitute 100% of all chemical constituent of a coal. Ultimate analysis provides the elemental concentrations mainly for the purpose of computing the quantity of air needed for the total combustion of a coal: carbon, nitrogen, hydrogen, sulphur and oxygen (Seidle 2011). These geochemical constituents are being used for the determination of coal quality, rank and maturity (Green et al. 2019).

Although scanty data exist on the proximate and ultimate characteristics of the Jangwa-Shankodi and Lafia-Obi coals, data related to environment of deposition of the Jangwa-Shankodi coals are absent in previous literature. Past studies on coal deposits in these areas have, so far, mainly focused on the stratigraphy, proximate, ultimate, thermal, rank and petrographic characteristics of the coals (Akande et al. 1992; Obaje and Ligouis 1996; Onoduku 2014a; Adekunle et al. 2015; Ryemshak et al. 2016; Ezeh and Okeke 2016; Akinyemi et al. 2020). Their environment of deposition has received little or no attention. More so, no study has been

conducted to link the quality of the coals to their palaeoenvironmental history.

The aim of this study is to interpret and relate the palaeodepositional environment of sediments in Jangwa-Shankodi and Lafia-Obi (Central Benue Trough, Nigeria) areas to the quality of coal deposits. Firstly, a palaeoenvironmental model of the coals in Jangwa-Shankodi and Lafia-Obi will be established. Afterward, the distribution and properties of the coal seams will be tied to the depositional model. This will indicate the effect that the depositional environment has on the coal types and hence on the economic worth of the seam. This tie between coal parameters and depositional model should ultimately result in a reduction in exploration risk and possibly serve as a panacea to the limited exploitation of the coal deposits.

Geological setting

The Benue Trough is an aborted extensional (pull-apart) intracratonic rift basin situated within the Central African mobile belt (Chaboureaux et al. 2012). This mobile belt is bounded to the east by the Congo craton and to the west by the West African craton. The trough is about 1200 km in length and 40–170 km in width and stretches obliquely (SW-NE) from the northeastern end of the Niger Delta Basin to Lake Chad (Fig. 1). It is arbitrarily divided into the Southern, Central and Northern Benue Trough. This sub-division is based on structural, sedimentary and palaeontological characteristics of the underlying sediments (Benkhelil

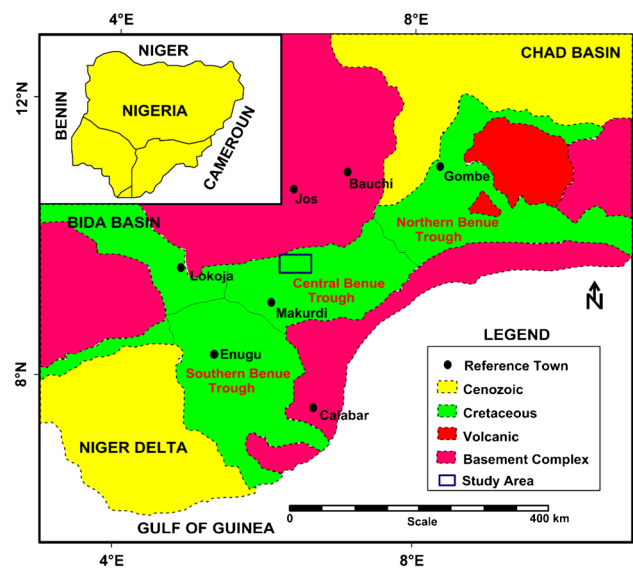


Fig. 1 Outline geological map of southeastern, north-central and northeastern Nigeria showing the location of the central Benue Trough and study area (modified after Okolo et al. 2020)

1989). The Jangwa-Shankodi and Lafia-Obi areas are situated within the central part of the Benue Trough.

The sedimentation cycles within the Central Benue Trough are subdivided into four stages: middle Albian to middle Cenomanian, upper Cenomanian to middle Turonian, upper Turonian to Coniacian and upper Campanian to Maastrichtian (Farrington 1952) (Fig. 2). The middle to late Albian period was characterized by the deposition of the Arufu, Uomba and Awe formations, which comprise mainly of siltstones, dark shales, limestones and fine-grained sandstones. Suitable well-preserved exposures of these formations have been observed in Jangwa, at the northeastern part of Keana, where they unconformably overlie the crystalline basement complex rocks (Ehinola et al. 2002) (Fig. 3). These sediments are unconformably overlain by the Keana Sandstone of Eze-Aku Group. These sands, deposited in middle Cenomanian period, are moderately to poorly sorted, coarse grained, usually pebbly and frequently feldspathic in occurrence (Obaje 2009; Obaje et al. 2020). They are overlain by the shale members of the Eze-Aku Group which were deposited between the upper Cenomanian and middle Turonian depositional cycle (Fig. 3). They are composed of light grey shales that are severely fractured and jointed. The shales in turn are overlain by the well-bedded shales of the Awgu Formation of Turonian to Coniacian age. These shales, which are mainly light to dark or bluish-grey in colour, are characterized by intercalations of coal seams of varying lengths

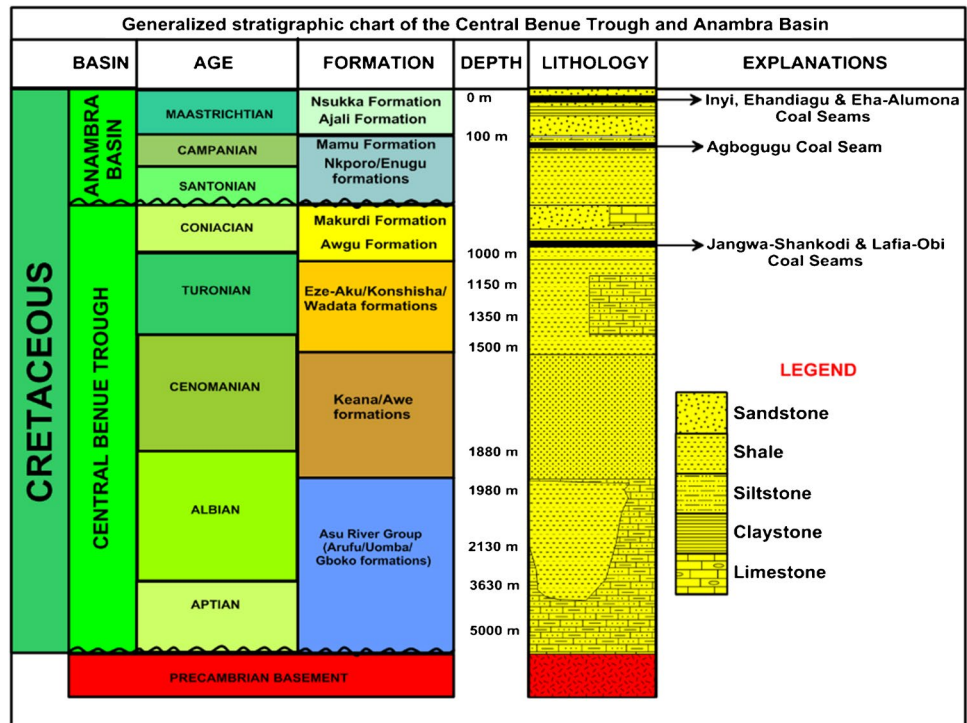
and thicknesses (Ryemshak et al. 2016) (Figs. 2 and 3). The seams have been observed along river banks and road cuts mainly in Jangwa-Shankodi and Lafia-Obi areas. The National Steel Raw Materials Exploration Agency (NSRMEA) in Nigeria has drilled several wells that penetrated a number of coal seams within these areas. The seam numbers and recoverable thickness ranges of some coal seams encountered during drilling in the Lafia-Obi coal field is shown in Table 1.

The Lafia-Wukari Formation, the youngest formation in the study area, unconformably overlies the coal-bearing Awgu Formation. It belongs to the upper Campanian to Maastrichtian depositional phase and consists of creamy yellow to white, moderately sorted and coarse-grained sandstones (Ehinola et al. 2002). Igneous intrusive rocks such as trachytes and basalts have also been reported in some parts of Keana and Jangwa (Farrington 1952).

Materials and methods

The materials used for this study include field geological mapping data from outcrops, drill hole data (excluding the drill cores) acquired from the National Steel Raw Materials Exploration Agency (NSRMEA) and geochemical data. These datasets were analysed and integrated to achieve the already outlined objectives of this work.

Fig. 2 Stratigraphic succession showing the sediments and coal seams of the Central Benue Trough and Anambra Basin (redrawn and modified after Petters and Ekweozor 1982; Petters 1983, 1991)



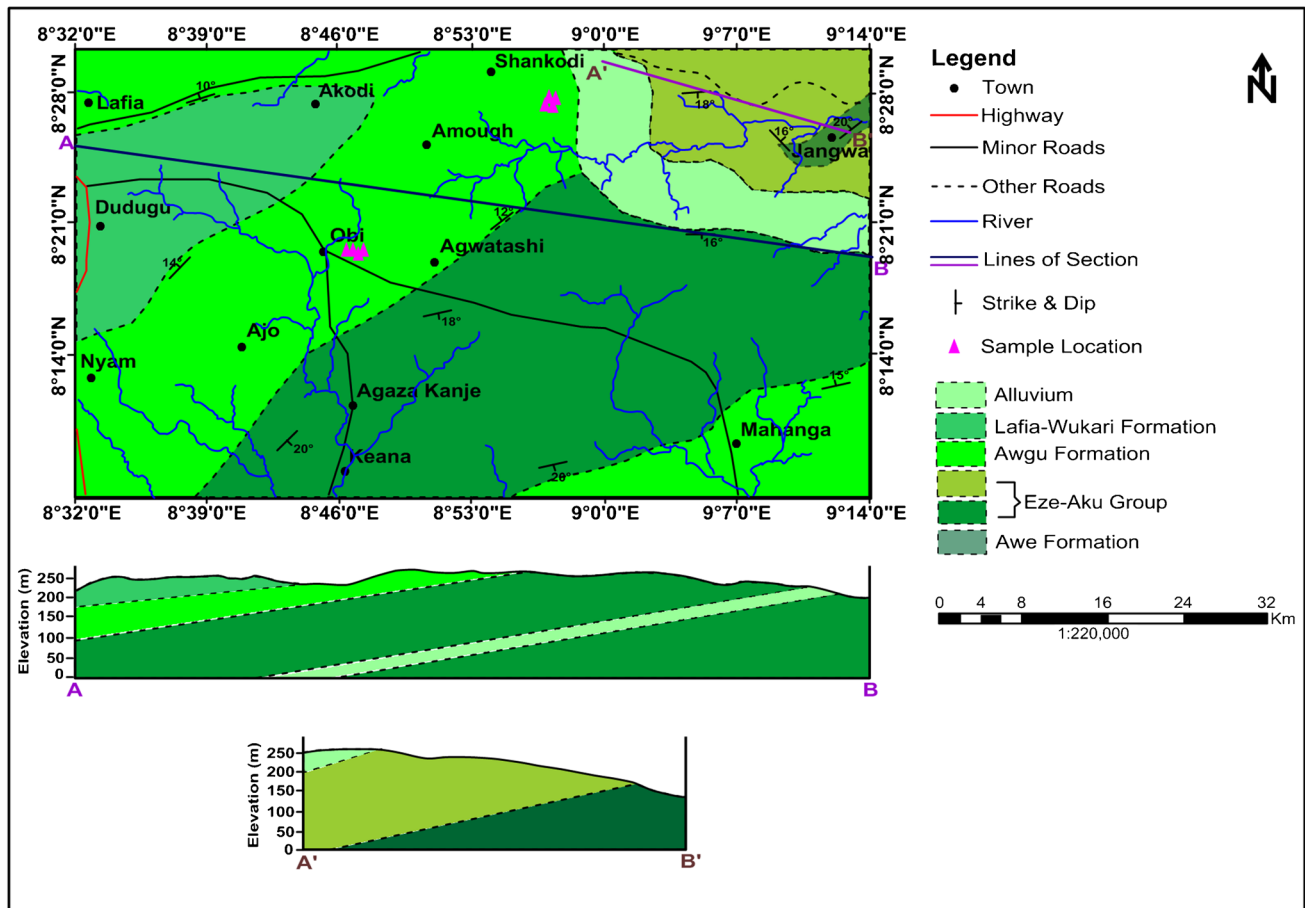


Fig. 3 Geological map of the study area showing various outcrop locations and coal sample collection points within the Awgu Formation

Geological field study

Detailed geological field mapping was conducted in the Jangwa-Shankodi and Lafia-Obi areas of Nasarawa State, north-central Nigeria. Field studies involved systematic lateral and vertical description of lithologic units and their variabilities in terms of orientation, strata thickness, composition, texture, fossil content, discontinuity surfaces and sedimentary structures. The exposed sections were carefully logged, and fresh representative coal samples were carefully collected with the aid of a geological hammer, labelled and packaged for further laboratory studies. The description of outcrops was based on the various facies encountered in the field. A Silva compass clinometer (model 15 T) was used to measure directional attributes, and structures of geologic significance were photographed. The geographic coordinates of each outcrop location were recorded with a Garmin GPS (model 76TM). The coordinates were then put into a Minna geodetic datum georeferenced base map of the Central Benue Trough using Map-Info (version 8.0) GIS platform.

Sedimentological analysis

Lithofacies analysis

The description of outcrops was based on the various facies encountered in the field. Beds at each outcrop were carefully logged to show their thickness, texture, and sedimentary structures. This is to provide information on the vertical variation in facies profile as a basis for recognizing lithofacies and facies assemblages.

The lithofacies recognized and analysed were grouped into lithofacies associations in order to define and interpret depositional environments. These facies associations are classified on the basis of sedimentary structures, lithology, texture, lateral and vertical succession of lithologic units.

Coal chemistry

The eight coal samples analysed in this study were obtained from Nasarawa State in the Central Benue Trough of Nigeria. Four samples each were collected at different points

Table 1 Excerpt from the report of coal exploration in the Lafia-Obi area. For proprietary reasons, the maximum and minimum thicknesses of eight coal seams (1, 3, 4, 7, 24, 27 and 29) were omitted from the data provided (Source: National Steel Raw Materials Exploration Agency (NSRMEA))

| Seam number | Recoverable thickness range | |
|-------------|-----------------------------|-----------------------|
| | Minimum thickness (m) | Maximum thickness (m) |
| Seam 2 | 0.10 | 0.10 |
| Seam 5 | 0.20 | 0.20 |
| Seam 8 | 0.15 | 1.20 |
| Seam 9 | 0.10 | 0.55 |
| Seam 10 | 0.05 | 0.40 |
| Seam 11 | 0.05 | 0.55 |
| Seam 12 | 0.85 | 4.20 |
| Seam 13 | 2.40 | 3.70 |
| Seam 14 | 0.05 | 1.67 |
| Seam 15 | 0.10 | 0.50 |
| Seam 16 | 0.05 | 0.40 |
| Seam 17 | 0.03 | 0.60 |
| Seam 18 | 0.05 | 0.71 |
| Seam 19 | 0.03 | 0.55 |
| Seam 20 | 0.03 | 0.60 |
| Seam 21 | 0.03 | 1.50 |
| Seam 22 | 0.02 | 0.40 |
| Seam 23 | 0.05 | 0.40 |
| Seam 25 | 0.10 | 0.45 |
| Seam 26 | 0.10 | 0.30 |
| Seam 28 | 0.10 | 0.25 |
| Seam 30 | 0.05 | 0.20 |
| Seam 31 | 0.15 | 1.14 |
| Seam 32 | 0.05 | 0.25 |
| Seam 33 | 0.15 | 0.50 |
| Seam 34 | 0.60 | 1.61 |

from the Jangwa-Shankodi and Lafia-Obi coal seams, both in the Obi Local Government Area of the state. The coals were subsequently labelled: JSK, Jangwa-Shankodi coal and LAF, Lafia-Obi coal. Thereafter, the samples were air-dried to eliminate the free moisture and then crushed into small particles. The pulverized coal samples were then sifted with the aid of an analytical sieve (250- μ m mesh) to obtain homogeneous particles for chemical characterization.

Proximate analysis, heating value and fuel ratio determination

The volatile matter yield, ash yield, moisture contents and heating value of the coal samples were ascertained in accordance with the specifications of the American Society for Testing and Materials (ASTM) D3175, ASTM D3174,

ASTM 3173 and ASTM 3286, respectively. The percentages of volatile matter yield, ash yield and moisture were subtracted from 100 to obtain the percentage of fixed carbon. For convenience, the heating values were converted to the British thermal unit per pound (Btu/lb). These were done to determine the coal quality, rank and utilization potential. The fuel ratio, which indicates the ease of ignition and burn out of a coal sample, was computed as the ratio of fixed carbon and volatile matter yield.

Ultimate analysis

Analyses for elemental composition (hydrogen, carbon, sulphur and nitrogen in weight percent) of the coal samples were performed at the National Geosciences Research Laboratory (NGRL) of the Nigerian Geological Survey Agency (NGSA), Kaduna state, Nigeria according to American Society for Testing and Materials (ASTM) methods and procedures (ASTM D3178, ASTM D3179 and ASTM D3177).

The sum of the percentages of sulphur, nitrogen, hydrogen and carbon were subtracted from 100 to obtain the oxygen content (Chukwu et al. 2016).

Results and discussion

Sedimentary facies

Nine sedimentary facies were recognized from sediments that underlie the study area on the basis of sedimentary structure, lithology and texture. Lithofacies analysis provides a means to distinguish relationship and suggest a depositional environment for the coal deposits (Miall 2000).

Epsilon cross-stratified sandstone facies (Sf)

The epsilon cross-stratified sandstone facies sequences are characterized mainly by the fine-grained sandstone with inclined surfaces (Fig. 4a). These surfaces consist of finer grains such as clayey siltstone. The sandstone is moderately sorted and light brown in colour. Sf are dominant and are widely distributed within the study area particularly at Jangwa and Keana. At Keana (06, 07 and 08), they constitute the only lithological unit, while at Gidan Obunde, this facies is present at the lowermost part of the outcrop section and display basal erosional surfaces and a multi-storied succession of fining upward sequences (Fig. 4b and c). It occurs at the lower, middle and upper sections of the Gidan Soja outcrop where they are demarcated by the siltstone facies (St). They are generally creamy white and light brown to light yellow in colour, indurated and well sorted with a thickness that ranges from 0.3 to 2 m. At Keana (07), they are characterized by several quartz veinlets that are parallel to each

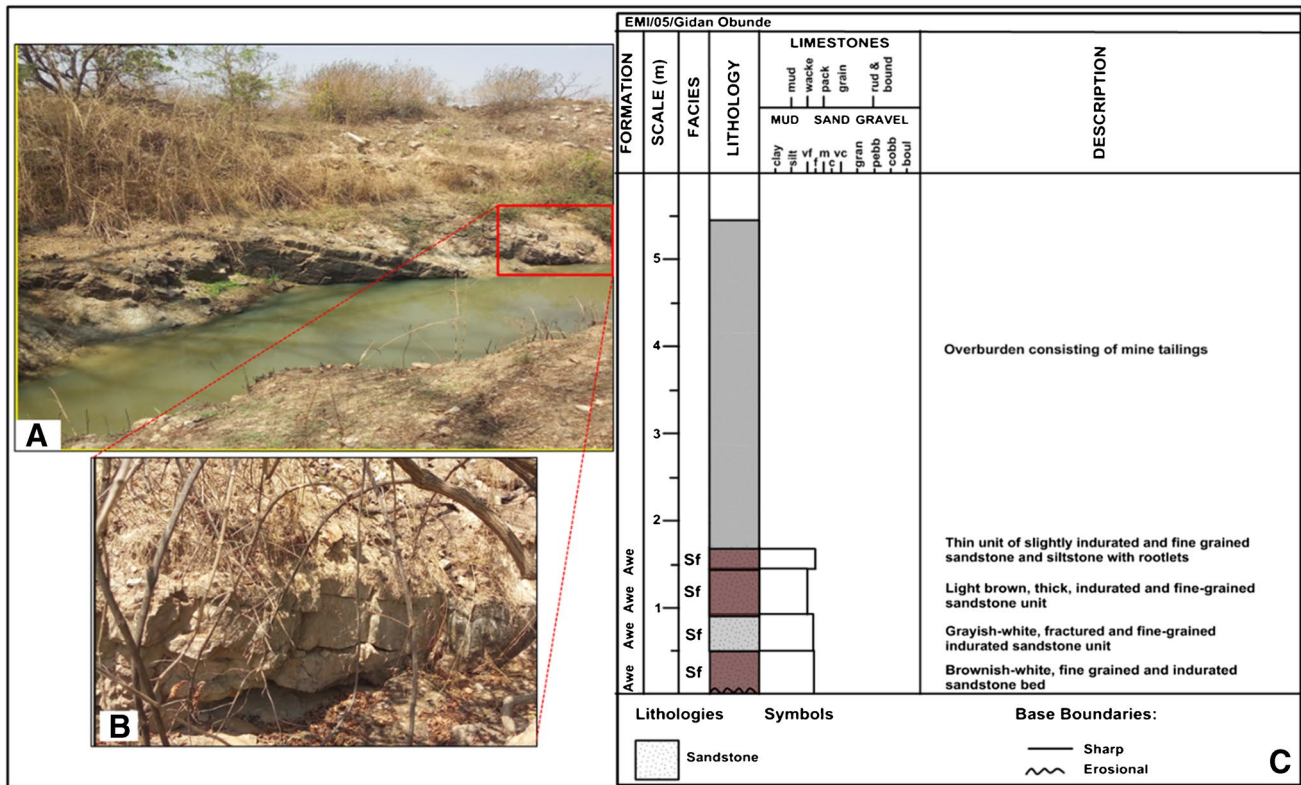


Fig. 4 a Outcrop photograph showing laterally accreted sandstone consisting of epsilon sandstone facies encountered in Gidan Obunde, Jangwa. b Inset showing the inclined and indurated sandstones. c Stratigraphic profile of the outcrop section.

other, while at Keana (08), they comprise numerous joints and fractures and appear to be inclined with low-angle cross-stratification (dips range from 3 to 15°) (Fig. 5).

Interpretation The quartz veins could have formed through precipitation of the aqueous solution during sediment transportation. The fine-grained sandstone represents deposition by vertical accretion on the top of channel sand bars during lower flow conditions (Rust 1975). The trough cross-beds, erosional bases and inclined sandstone sequence may be attributed to down current migration of sand dunes and sand waves (Miall 1996).

Coal facies (Co)

This facies consists of black to dark brown, hard and compacted coal units that are located in Lafia-Obi and Shankodi (Fig. 6). The coal seams appear to be laterally continuous in some locations and discontinuous in others with a thickness ranging from 0.5 to 1.5 m (Figs. 6 and 7). They occur at the middle and lower parts of the outcrop sections located in Lafia-Obi and Shankodi (03), respectively. At Shankodi (01), this facies is present at the middle and lowermost portions of the outcrop sections (Fig. 7b). They are intercalated with carbonaceous

siltstone at Shankodi (03) where they are overlain by the dark brown shale facies (Shb) (Fig. 7). They are characterized by high to medium vitreous luster on cleat surfaces. They are generally structureless with no rootlets.

Interpretation The compacted nature of the coals as well as its high organic carbon content is evidence that this material is a product of depositional processes that include peat formation, burial and coalification. At Shankodi (01), the coal seam occurs with patches of indurated sandstone. The indurated sands might have possibly been eroded and transported from a nearby peat forming environment (Ehinola et al. 2002).

Silty sandstone facies (Sst)

This facies is less abundant and comprises yellow to brown units of silty sandstone. The sandstones in this facies are also fine grained and show a fining upward sequence. They are observed at the uppermost parts of outcrop sections that are exposed in Shankodi (01) (see Fig. 6) and Lafia-Obi (Fig. 8). Bed thickness ranges from 0.2 to 2.5 m. At Lafia-Obi, this facies is observed to be intercalated with siltstone beds (Fig. 8b).

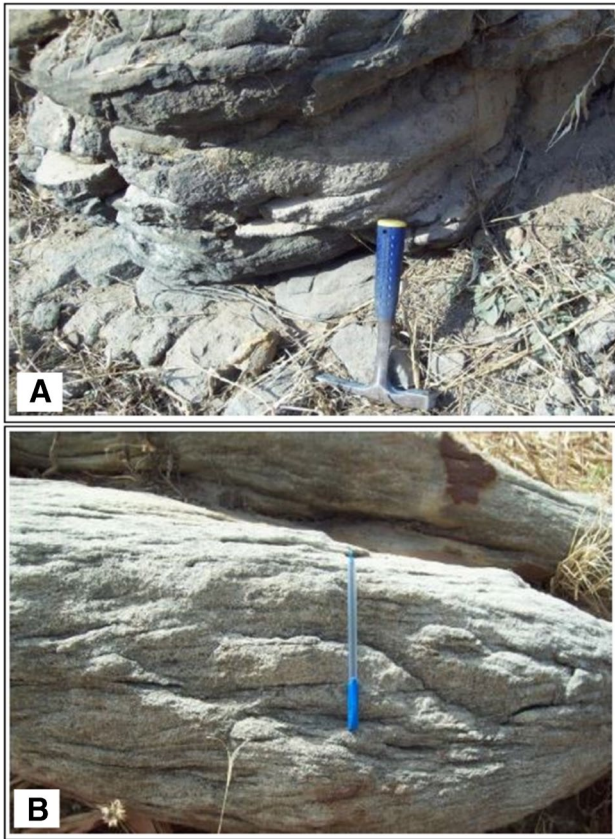


Fig. 5 **a** Laterally accreted sandstone encountered at Bayanlabo, Jangwa. **b** Cross-trough stratified sandstone observed at Akondo, Keana.

Interpretation Sst are suspension fallouts that represents deposits of waning stage flood deposition, with most of the deposition occurring from suspension settling and with only limited bed-load transport via weak currents. The presence of thick wood, stream bank erosion and densely vegetated areas as well as coal supports this assertion.

Carbonaceous shale facies (Shcb)

Shcb consists of light to dark grey, fissile and carbonaceous shale with thickness that ranges from 2 to 6 m. They are low land exposures of river sections at Lafia-Obi (Fig. 9) and Agwatashi. Shcb are mainly found at the middle sections of outcrops at Agwatashi and Lafia-Obi, where they also occur at the basal part as the only lithological unit (Fig. 9b). At Agwatashi, they are separated by a thin unit of indurated shale that is light grey in colour. Generally, Shcb are horizontally laminated, and there is absence of trace fossils.

Interpretation The light to dark colour and slightly calcareous nature of this deposit is the result of the moderate to high organic carbon content present in the shales. This suggests

deposition by suspension sediment fallout in a low-energy, anoxic environment. The horizontal lamination is the result of slow settling of the fine shale sediment due to a fall in velocity of flow (Okolo et al. 2020).

Dark grey shale facies (Shg)

Shg is not well exposed in the study area and consists of medium to dark grey shales. It occurs at the basal portion of the outcrop section encountered at Lafia-Obi where it has a thickness of about 3 m (see Fig. 8). The shales are fissile and calcareous. Sedimentary structures are not well pronounced and include thin (1–2 mm) to very thin (< 1 mm) parallel or horizontal laminae. This facies has a sharp upper contact with the overlying coal facies (Co). Body fossils are rare and plant debris range from absent to abundant.

Interpretation The dark colour and very fine-grained composition of this facies represent anoxic coastal environment. Thin, parallel or horizontal laminae without re-activation surfaces reflect suspension sediment fallout without traction currents. The dark grey shales indicate suspended sediment fall-out and periodic low-energy currents in a slightly restricted basin or a coastal, moderate-depth setting.

Dark brown shale facies (Shb)

Similarly, Shb does not occur extensively in the study area. It is present in Shankodi (03), at the middle part of an outcrop section that is exposed along River Dep where it is underlain by the coal facies (Co) (see Fig. 7). It is characterized by thick, massive, fissile (almost structureless) bed of shale. The shales are dark brown, carbonaceous, calcareous and contain sandy silty sediments, sometimes forming continuous and discontinuous parallel laminations. Bed thickness is 3 m.

Interpretation The colour and thickness of this facies suggest that they were deposited during a fairly long period of wet season in a low energy setting. The presence of continuous and discontinuous parallel laminations also indicates a low-energy regime (Hjellbakk 1997).

Siltstone facies (St)

St is poorly exposed, weathered and less abundant. It is noticeable at the basal and middle part of a river section located in Gidan Soja (Fig. 10). This facies consists of a light yellow or whitish grey to light grey weathered siltstone unit that is slightly fractured with a bed thickness of 1 m. St is moderate to highly consolidated and alternates with the sandstone facies (Sf), which are the only facies occurring in this outcrop section. Sedimentary features

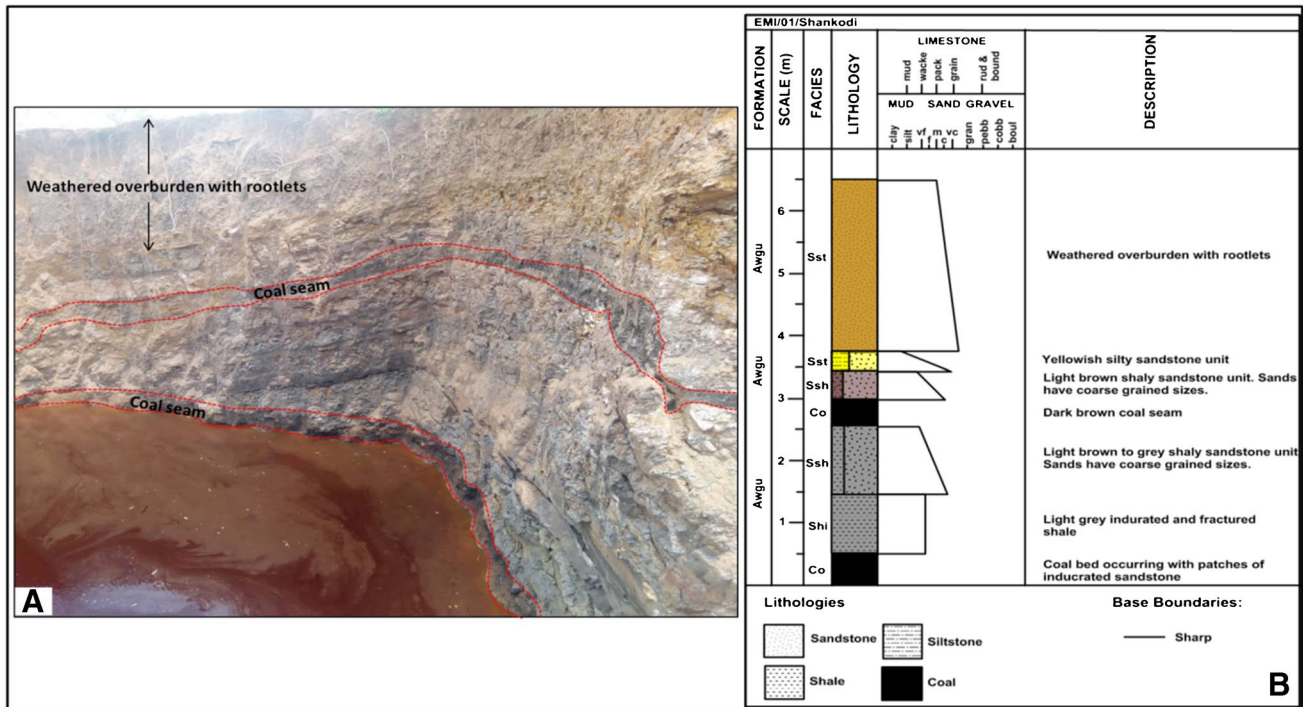


Fig. 6 a Outcrop photograph showing coal facies observed at a mining site in Shankodi. b Stratigraphic profile of the logged units.

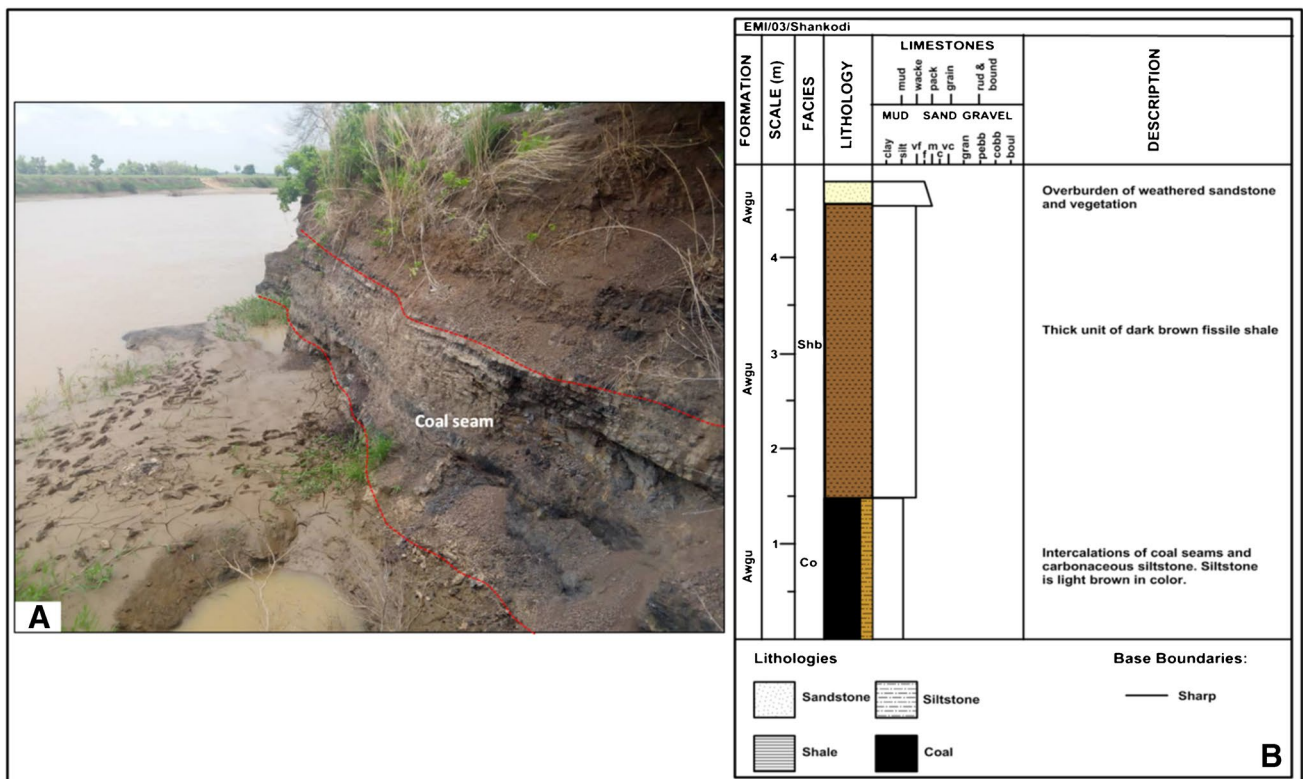


Fig. 7 a Outcrop photograph showing coal facies encountered along River Dep in Shankodi. b Stratigraphic profile of the logged units.

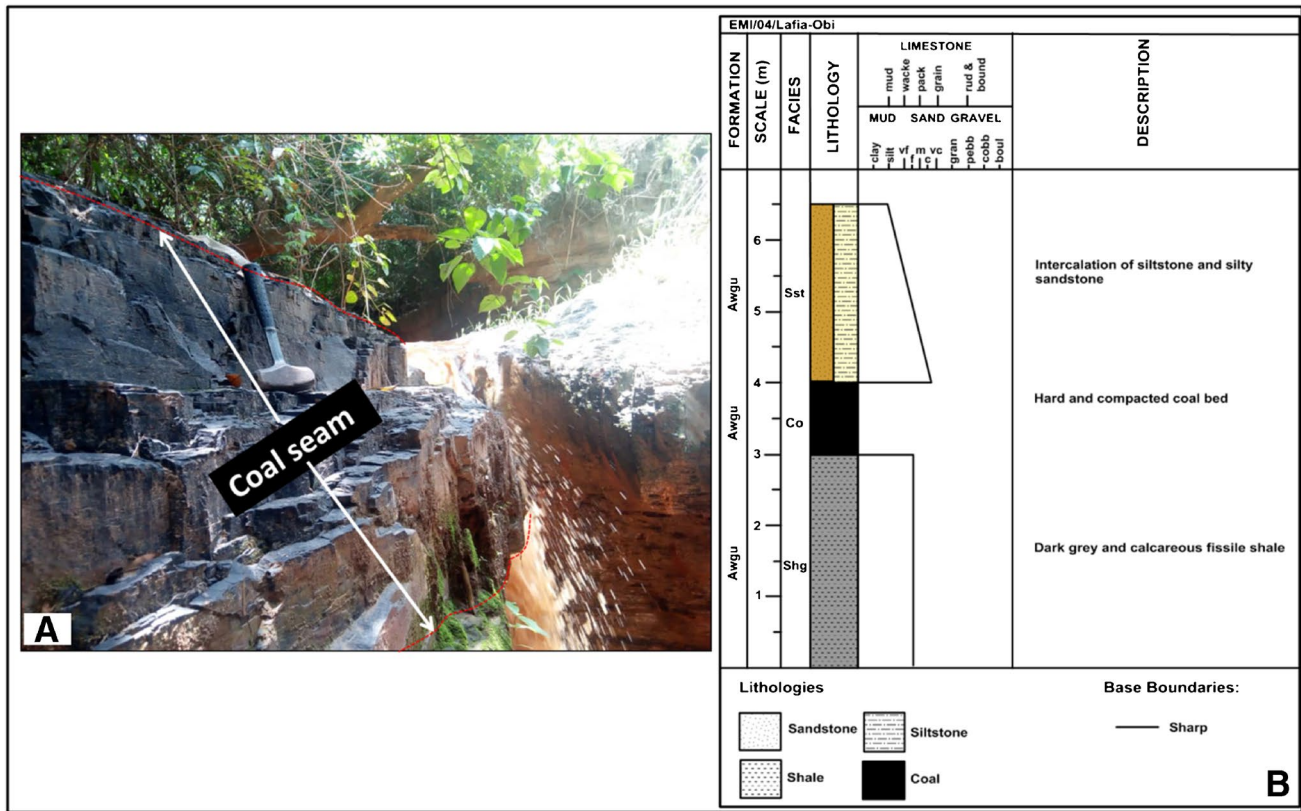


Fig. 8 a Outcrop photograph showing silty sandstone facies associated with a coal seam in Lafia-Obi. b Lithologic section of the logged units.

include thick (3–10 mm), thin (1–3 mm), to very thin (< 1 mm), to horizontal silt laminae, interlaminated with thick to thin silty sandstone laminae.

Interpretation St are suspension fallouts that represents deposits of waning stage flood deposition, mainly on over-bank areas (Hjellbakk 1997), with most of the deposition occurring from suspension settling and with only limited bed-load transport via weak currents. The laminations indicate reworking by strong current action in shallow water.

Shaly sandstone facies (Ssh)

Ssh are also poorly exposed in the study area. Ssh occur at two intervals and are demarcated by the coal facies (Co) in an outcrop exposure located at Shankodi (01) (see Fig. 6). It is also present in Lafia-Obi, at the uppermost part of the basal unit (see Fig. 9). It comprises light brown to grey, fine to coarse and moderately sorted shaly sandstone. The shales are horizontally laminated, while majority of the sands have a coarse grain texture and are characterized by a sharp contact at the top and base. Bed thickness ranges from 0.3 to 1 m.

Interpretation Ssh suggest an alternating high and low energy condition. The presence of shales within the sands indicates periods of low energy conditions where shales are deposited by episodic sedimentation and/or fallout during one or several slack-water periods (Mode et al. 2018). The coarse sands constitute traction load during transportation in a fluvial system. They also represent wash-over deposits comprising thin layers of sand that are deposited by storms and may be intercalated with shales (Learning Geology 2015; Davies-Vollum et al. 2019).

Indurated shale facies (Shi)

This facies is extensive and well exposed within the study area. Shi is observed in outcrop sections that were encountered in Shankodi (01), Agwatashi and Keana (Figs. 11 and 12). It forms the basal unit at these locations with a thickness that ranges from 0.5 to 5 m. This facies consists of light to dark grey, thin and/or thick unit of indurated shales that are sometimes carbonaceous. At Shankodi (01) and Keana, these facies were observed to be highly fractured and weathered. The presence of fractures is partly due to the ongoing mining activities

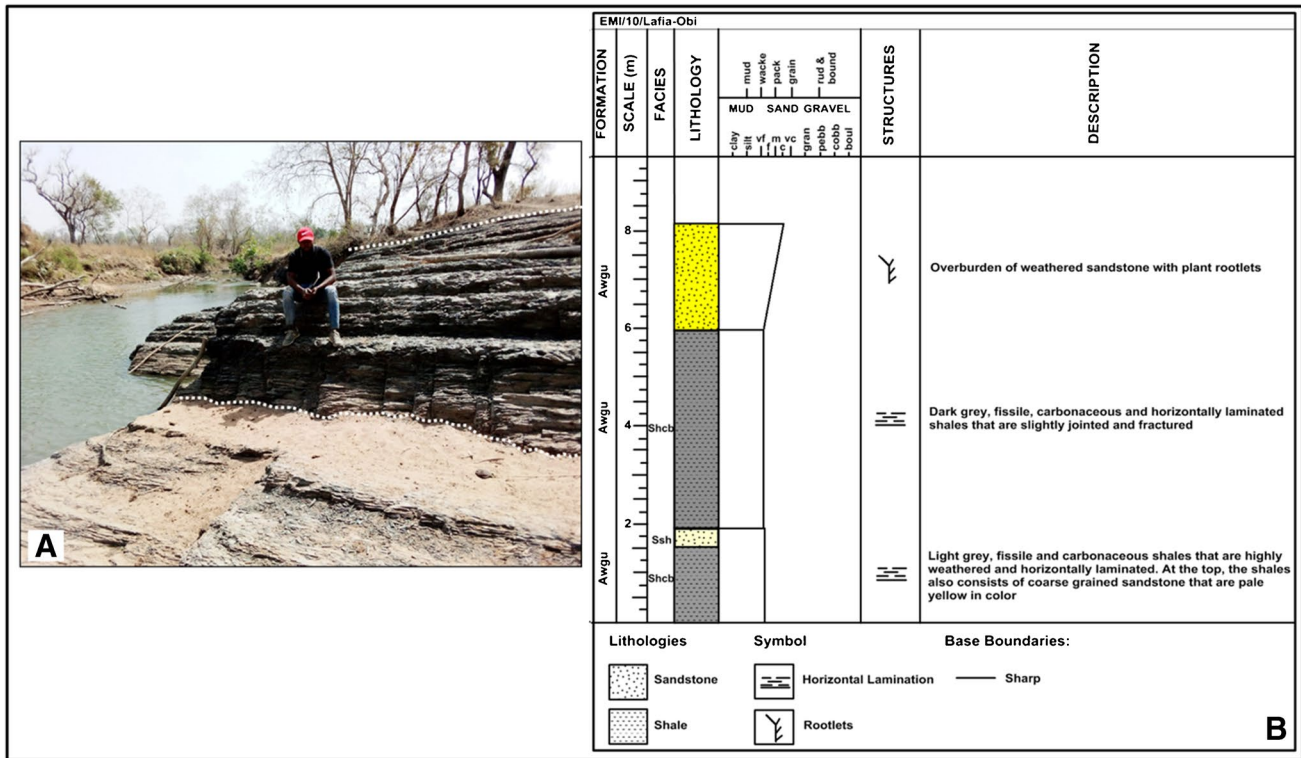


Fig. 9 a Outcrop section showing massive carbonaceous shale facies and shaly sandstone facies observed along a river in Lafia-Obi. b Lithologic profile of the logged units (scale: sitting human = 1.00 m).

within the area. In Agwatashi, this facies appears slightly carbonaceous and is underlain and overlain by the carbonaceous shale facies (Shcb) (Fig. 11).

Interpretation The carbonaceous nature of the shales suggests high organic matter content of the shales, while the weathering effect is due to sub-aerial exposure. The reddish-brown, medium to coarse grained sands overlying this facies in Keana is probably a palaeosol. The reddish-brown colour is due to long sub-aerial exposure. The presence of fractures could be attributed to stress suggesting that the shales could have been affected by deformative force or stress that affected the area in geologic history. The highly indurated nature of the shales is a consequence of burial and tectonic deformation (Anyiam et al. 2017).

Facies association

The facies are grouped into two associations (FA 1 and FA 2). The description and interpretation of the facies associations and their inferred depositional environments are shown in Table 2.

Facies association 1 (FA 1): fluvial deposit

FA 1 comprises epsilon cross-stratified sandstone facies (Sf), siltstone facies (St), coal facies (Co), shaly sandstone facies (Ssh) and silty sandstone facies (Sst). This facies association is characterized by yellowish brown to white and light grey, very fine, fine and medium grained sandstones and silt (Fig. 13). The fine and medium grained sands appear cross-laminated and inclined with erosional bases. They are composed of stacked cyclic patterns of fining upward successions. Coarse grained sands are present but rare. It varies in thickness from 0.2 to 2 m with an average thickness of about 1.1 m. They are moderate to highly indurated and consist of quartz veins, joints and fractures. Bioturbations are absent. Coal seams are intercalated with the shaly sandstones facies. FA 1 is observed mainly in Gidan Soja, Shankodi, Lafia-Obi, Jangwa and Keana.

Interpretation The fine-grained sands and silts are interpreted as deposits of point bars of highly sinuous streams. The inclined, low-angle surfaces represent the point bar surfaces of a meandering fluvial channel (Nichols, 2009). Also, the amalgamated cross-stratified sandstones are also

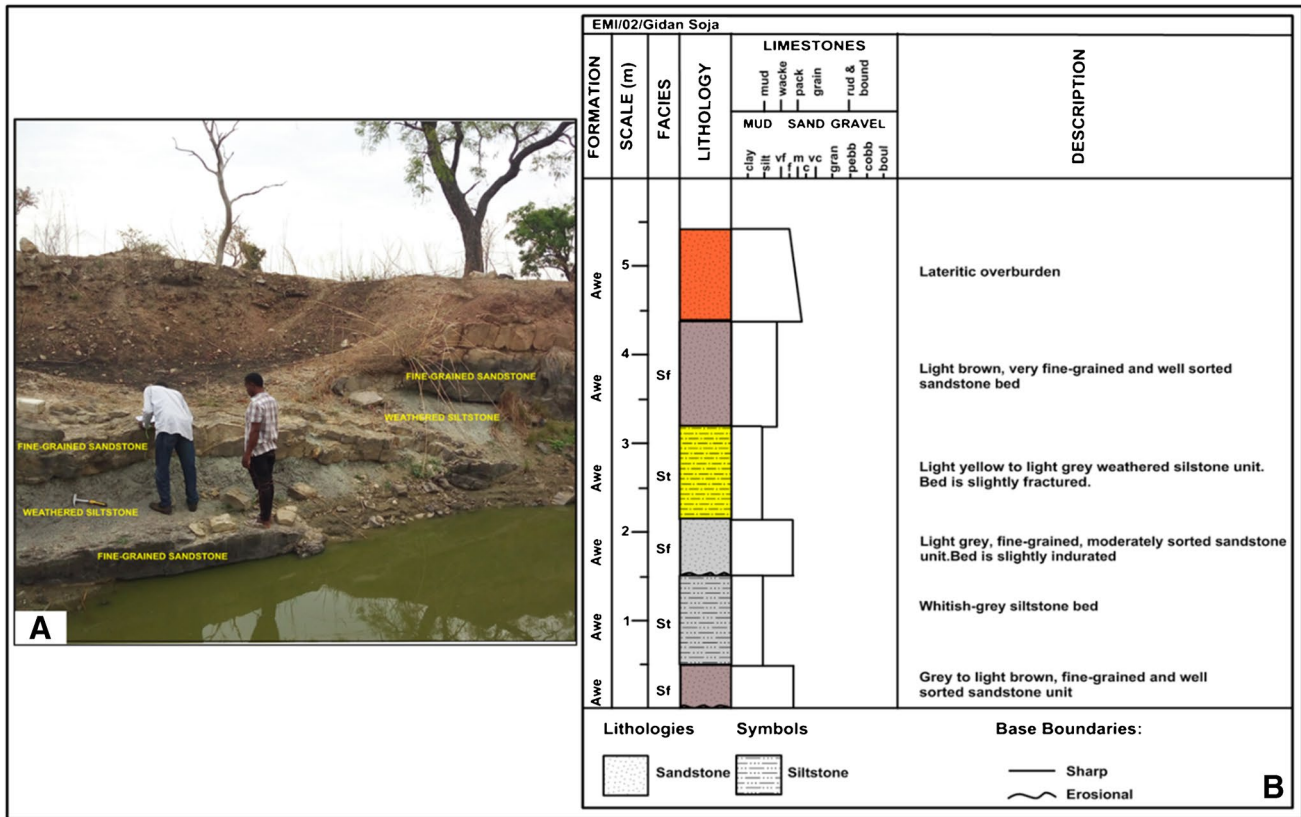


Fig. 10 a Outcrop section showing siltstone facies alternating with fine grained sandstone facies seen at Gidan Soja. b Lithologic profile of the logged units (scale: stooping human = 1.30 m).

regarded as the record of stacked, lateral-accretionary point bars deposits of high sinuous streams. The silts and silty sands could be the result of sedimentation on backswamps and flood plains probably due to periodical floods, mainly in overbank areas (Hjellbakk 1997; Cook 2015). FA 1 is dominantly meandering river deposits.

Facies association 2 (FA 2): swamp/lagoonal deposit

FA 2 consists mainly of coal facies (Co), dark brown shale facies (Shb), dark grey shale facies (Shg), carbonaceous shale facies (Shcb), shaly sandstone facies (Ssh) and indurated shale facies (Shi) (Fig. 13). The thickness of this facies varies between 2 and 6 m. FA 2 comprises dark brown, grey to dark grey and light brown, carbonaceous, thick to thin and sometimes calcareous fissile shales and appears fractured and horizontally laminated in some areas. The sand members of this facies are pale yellow and coarse in grain size (see Fig. 9). It is also made up of hard and compact coals with vertical cleats. FA 2 occurs extensively in the study area and was observed at different locations such as Shankodi, Lafia-Obi, Agwatashi and Keana.

Interpretation The presence of relatively thick coal seams and abundance of preserved organic matter suggests that FA 2 represents swamp or lagoonal deposits. The light and dark carbonaceous shales are probably part of a facies progression capping many pond successions. Exposure to high temperature and pressure conditions are responsible for indurated nature of some of the shales. On the basis of their high carbon content, the dull, dark colours of the shales depict occurrence in a well-vegetated and wet palaeoenvironment. It is possibly connected to the lower reaches of a fluvial system. The calcareous non-fossiliferous brown-coloured shales as well as the presence of macroscopic plant debris suggest palaeosol or supratidal conditions and deposition proximal to continental or shallow marine environments (Reading and Levell 1996; Hampson 2010)). The presence of coal facies (Co) is indicative of swamp or lagoonal environment. According to Reinson (1992), thin coal beds occurring with sandstones and mudstone units in swamp/marsh environments are formed on lagoonal margins. They mainly depict swamp and flood plain deposition that is characterized by shale, coals and sandstone. The coarse sands entered the lagoon when storms washed sediments over the barrier as wash-over deposits, which are thin layers of sand reworked by waves. The FA 2, therefore, represents a lagoonal or

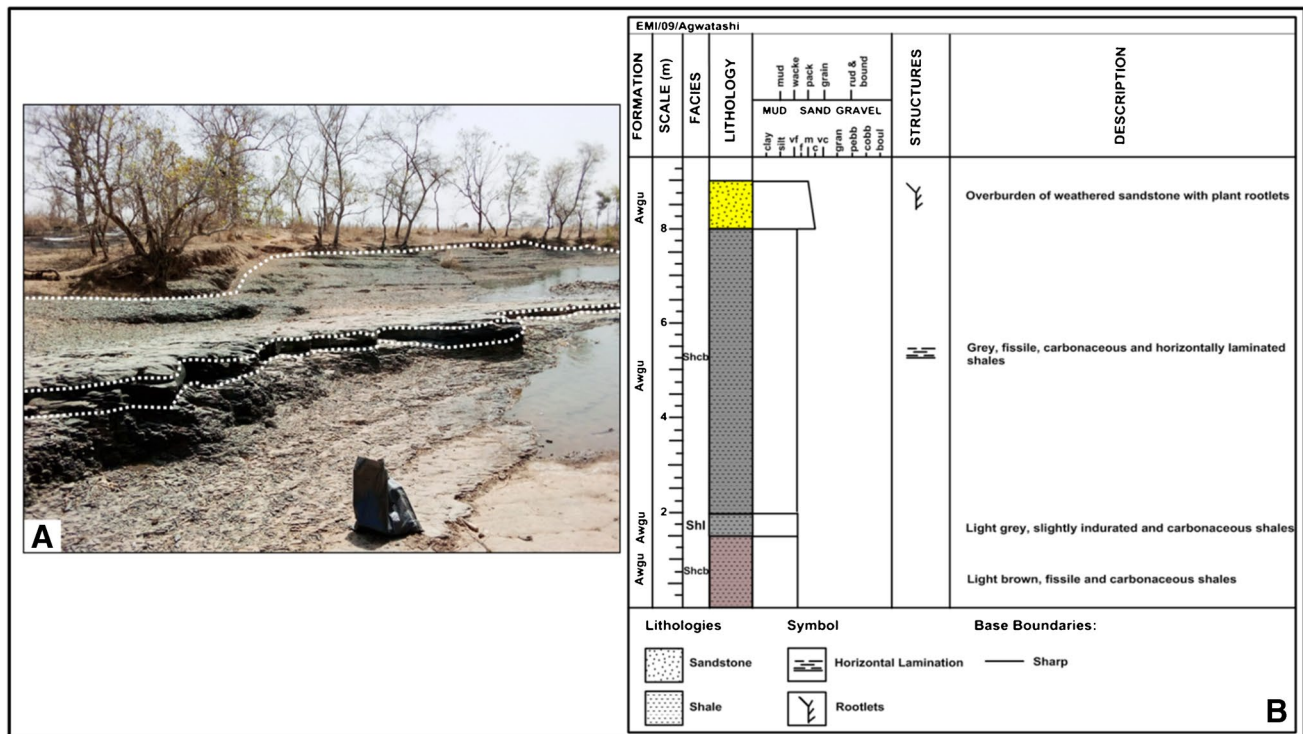


Fig. 11 a Outcrop section showing indurated shale facies overlain and underlain by carbonaceous shale facies in Agwatashi. b Lithologic profile of the logged units (scale: polythene bag in the centre foreground=0.5 m).

swamp environment, which is in agreement with the petrographic studies of Obaje and Ligouis (1996).

Result of proximate analysis

The results of proximate analysis of the coals are shown in Table 3. JSK and LAF are mnemonics used to refer to Jangwa-Shankodi and Lafia-Obi coal samples, respectively.

The moisture contents range from 2.28 to 2.56%. JSK 3 had the highest moisture content of 2.56%, followed by LAF 3 and then LAF 2 with 2.48% and 2.45%, respectively. There is no significant difference between the volatile matter yields of JSK (29.99–30.34%) and LAF (29.98–30.22%). However, the Lafia-Obi coals appear to have lesser volatile matter yields. LAF 2 had the lowest volatile matter content (29.98%). The highest fixed carbon contents of 56.30%, 56.21% and 56.20% were recorded in Lafia-Obi. Conversely, the lowest value of fixed carbon was seen in JSK 4 (55.97%). Generally, the Jangwa-Shankodi coal samples had higher ash yields that ranged from 7.99 to 8.64%. The least value of ash yield was reported in LAF 1 (7.83%) (Table 3).

The moisture content of coal depends on the degree of maturity. LAF 1 has the lowest moisture content (2.28).

The Jangwa-Shankodi and Lafia-Obi coal samples, with a volatile matter yield that ranges from 29.98 to 30.34%, fall within the range of medium volatile coals (Table 3) (Obaje

1997; Chukwu et al. 2016). Although the ash yields in all the coal samples are lower than the 10% specified for a good coal (Obaje 1997), Lafia-Obi coal samples recorded lower values of ash yield (7.83–8.34%) compared to their Jangwa-Shankodi counterparts (7.99–8.64%).

Analysis of the fixed carbon contents suggest that the Lafia-Obi coal samples with the highest values (56.18–56.30%) are of better quality compared to the Jangwa-Shankodi coal samples.

Analyses of fuel ratio

The fuel ratio computed for each coal sample is shown in Fig. 14. LAF 2, LAF 3 and JSK 3 had the highest fuel ratios of 1.87 followed by LAF 1 and LAF 4 coal samples (1.86). These are closely followed by JSK 1 and JSK 4 samples with a value of 1.85 each. The least fuel ratio was recorded by JSK 2 coal sample. Generally, the values of fuel ratios indicated by all the coal samples are low. However, the higher values of ratio of fixed carbon to volatile matter yield indicated by LAF 2, LAF 3 and JSK 3 indicate their ease of ignition and burn out (Fig. 14). The lower values of volatile matter yield exhibited by these samples means that they would easily ignite when compared with other samples. The expectation is that ammonia as a hydrogen-energy carrier would improve the ignition

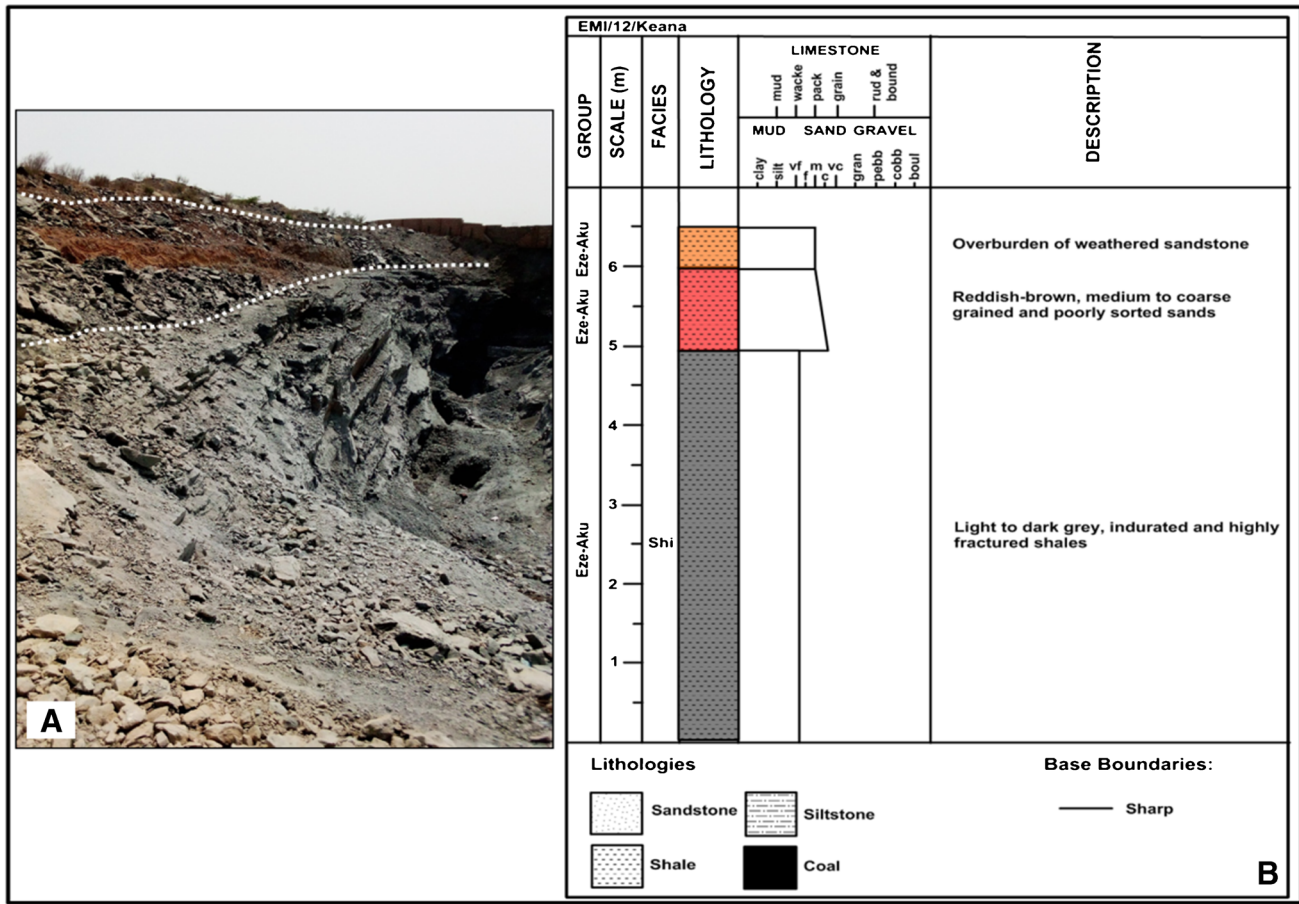


Fig. 12 a Outcrop photograph showing a thick unit of indurated shale facies observed at a mining site in Keana. b Stratigraphic profile of the logged units.

Table 2 Facies classification and interpretation of depositional processes and environment

| Lithofacies | Lithofacies association | Sedimentary structures | Depositional environment |
|---|-------------------------|--|------------------------------------|
| 1. Epsilon cross-stratified sandstone facies (Sf) 2. Siltstone facies (St) 3. Silty sandstone facies (Sst) 4. Coal facies (Co) 5. Shaly sandstone facies (Ssh) | FA 1 | The fine-grained sands are inclined, low-angled and cross-stratified with erosional bases. They consist of stacked cyclic patterns of fining upward successions. The siltstone facies are slightly fractured with very thin to thick horizontal silt laminae, and interlaminated with thin to thick silty sandstone laminae. Coal seams are thin and intercalated with shaly sandstone | Fluvial (meandering river) deposit |
| 6. Coal facies (Co) 7. Dark brown shale facies (Shb) 8. Dark grey shale facies (Shg) 9. Carbonaceous shale facies (Shcb) 10. Shaly sandstone facies (Ssh) 11. Indurated shale facies (Shi) | FA 2 | Coal seams are associated with dark grey and dark brown shales, and are characterized by high to medium vitreous luster on cleat surfaces. Shales are light to dark grey, thick and laminated, and sometimes highly indurated. Thin coarse grained sands occur within laminated shales | Swamp/lagoonal deposit |

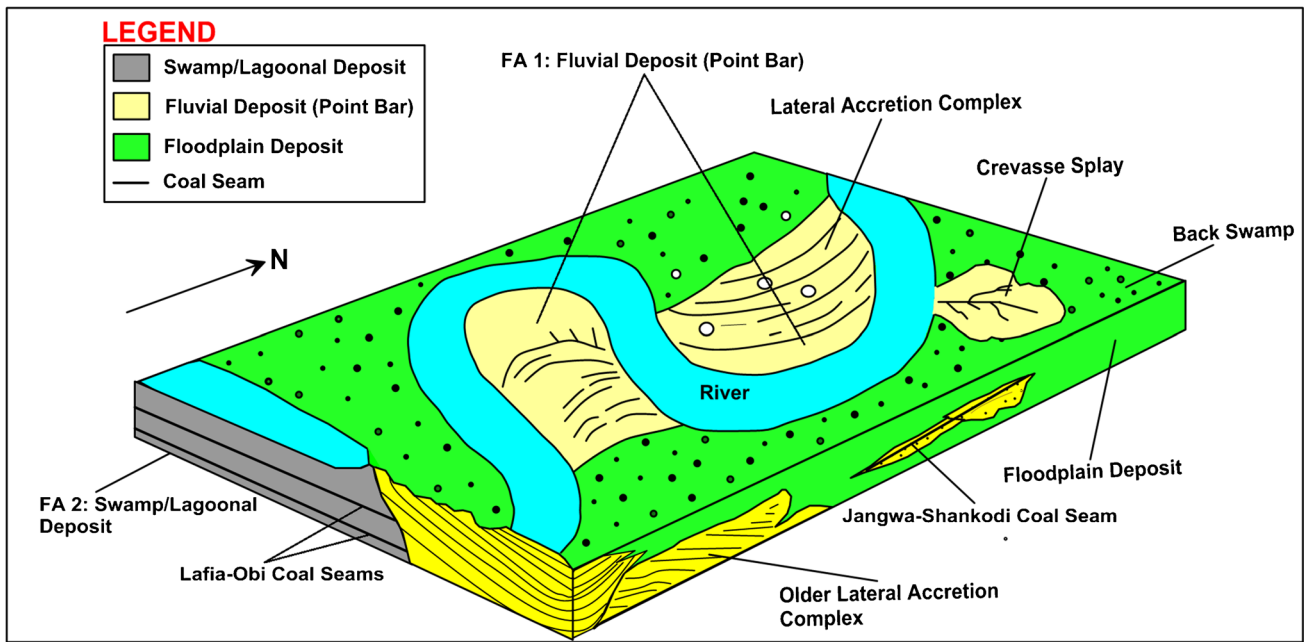
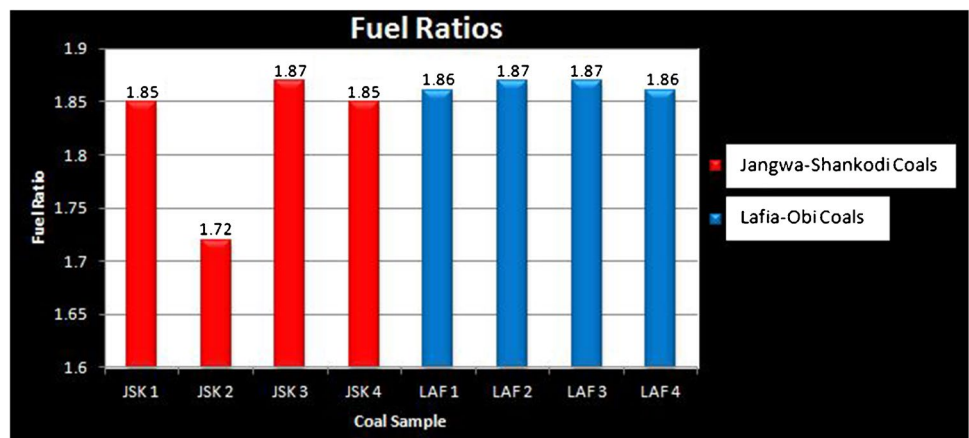


Fig. 13 Facies depositional model of the study area

Table 3 Results of proximate analysis (air dried basis) of the coals studied

| Parameter | Coal sample | | | | | | | |
|--|-------------|-------|-------|-------|-------|-------|-------|-------|
| | JSK 1 | JSK 2 | JSK 3 | JSK 4 | LAF 1 | LAF 2 | LAF 3 | LAF 4 |
| Moisture content (%) | 2.34 | 2.37 | 2.56 | 2.33 | 2.28 | 2.45 | 2.48 | 2.39 |
| Ash yield (%) (dry basis) | 8.64 | 8.48 | 7.99 | 8.49 | 7.83 | 8.34 | 7.94 | 8.29 |
| Volatile matter yield (%) (dry ash-free basis) | 30.26 | 30.34 | 29.99 | 30.21 | 30.20 | 29.98 | 30.00 | 30.22 |
| Fixed carbon (%) | 56.09 | 56.08 | 56.14 | 55.97 | 56.20 | 56.18 | 56.21 | 56.30 |

Fig. 14 Bar graph showing the calculated fuel ratios of the coal samples



capability of the coal particles. However, because low volatile matter yield results in higher NO_x formation, such coals could have lower flame stability when compared to other coal samples.

Analyses of heating value

The heating values of Lafia-Obi and Jangwa-Shankodi coals ranges from 12,341.0 to 12,366.8 Btu/lb and 12,319.5 to

Fig. 15 Bar graph showing the calculated heating values of the coal samples

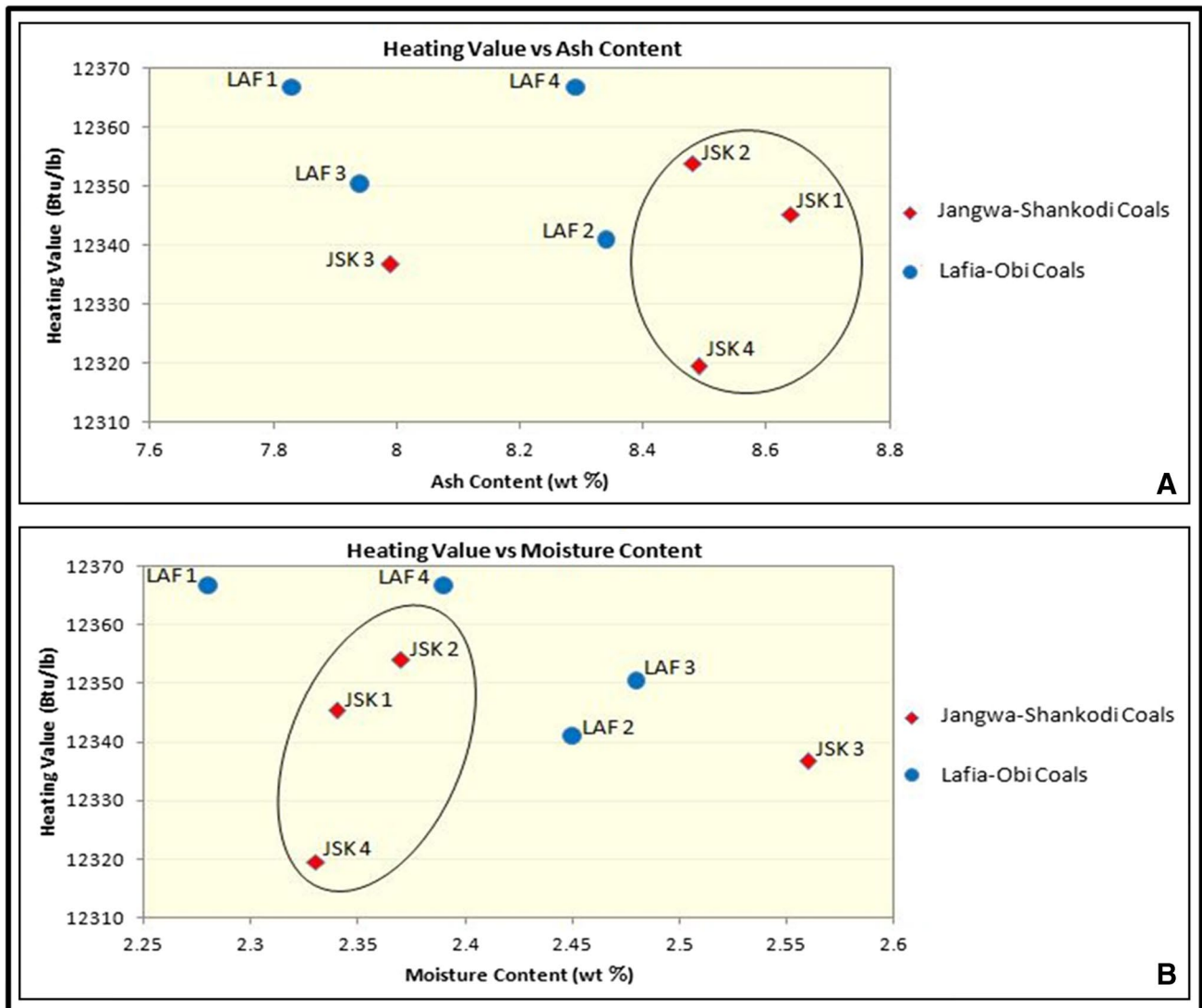
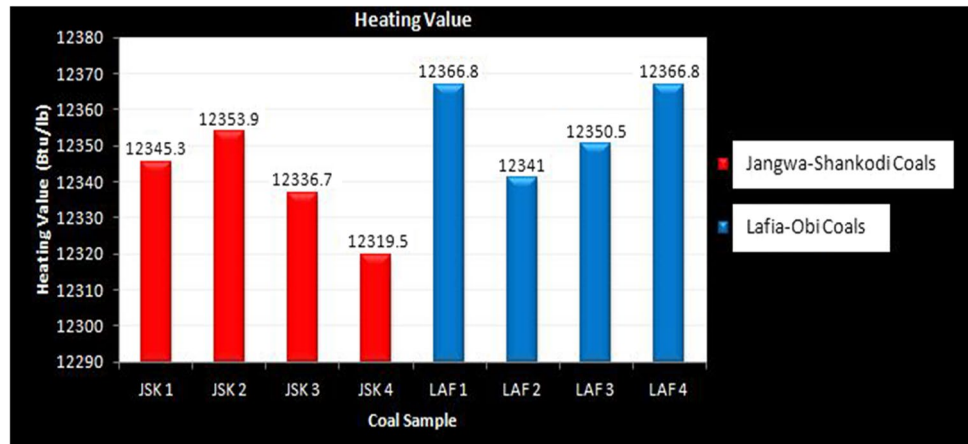


Fig. 16 Scatter plot showing the relationship between heating value and (a) ash content and (b) moisture content

12,353.9 Btu/lb, respectively (Fig. 15). These values indicate the heat of combustion of the coals. It is a measure of the energy or heat released when the coals are combusted in the presence of oxygen. The Lafia-Obi coal samples, LAF 1 and LAF 4, with the highest heating value of 12,366.8 Btu/lb, are best for heat generation (Fig. 15). JSK 3 and JSK 4, which have the least heating values, will produce the lowest heat on combustion.

The heating value of coal samples is mainly affected by their ash yields and moisture contents (Jauro and Chukwu 2011). The plot of heating values of the coal samples against their respective ash contents is shown in Fig. 16. The lower ash contents of the coals tallied with higher heating values and vice versa. Lafia-Obi coals are generally characterized by relatively lower ash yields; hence, they possess higher heating values (Fig. 16a). Thus, the lower the ash yield, the better the quality of the coal. On the hand, the comparatively higher ash yield of the Jangwa-Shankodi coals resulted in the reduction of their heating values with the exception of JSK 3 (Fig. 16a).

Figure 16b illustrates a relatively poor correlation between heating value and moisture content. However, as expected, some coals of higher heating values (LAF 1 and LAF 4) possess lower values of ash yield, as well as relatively lower moisture content. Although the Lafia-Obi coals display lower ash yields, the effect of moisture on its heating value was more compared to their Jangwa-Shankodi counterparts. Therefore, the role of ash in reducing the heating value of the Jangwa-Shankodi coals was greater compared to the effect of moisture on the heating value of the Lafia-Obi coals.

Rank of the coals based on proximate properties

The fixed carbon content along with the heating values and fuel ratios of the Jangwa-Shankodi and Lafia-Obi coals indicate medium rank, high volatile C bituminous coals according to the ASTM D388 classification (ASTM 2002), which agrees with the bituminous classification reported in previous literature (Obaje 2009; Ryemshak and Jauro 2013; Nyakuma 2016). Coals that fall under this category have heating values that range from 11,500 to 13,000 Btu/lb with fuel ratios that are greater than 1.5. Volatile matter yield

was excluded in the ranking and classification of the coals on dry bases following ASTM guidelines since the analysed samples contain sufficient volatile matter yields.

Result of ultimate analysis

The elemental composition of hydrogen, carbon, sulphur, oxygen and nitrogen in the coal samples are displayed in Table 4. The percentage ranges of the elemental carbon and hydrogen of the Jangwa-Shankodi and Lafia-Obi coals are as follows: 52.92 to 53.19% and 53.99 to 54.52% and 4.47 to 4.55% and 3.89 to 4.06%, respectively. There is a slight significant difference between the hydrogen and carbon contents of the coal samples. LAF 1 and LAF 2 had low sulphur contents of 0.08 and 0.09%, respectively, while JSK 2 had the highest value of 0.14%. The oxygen contents of the coal samples range between 3.67 and 6.92%. JSK 1 had the least oxygen content of 3.67%, followed by JSK 3 and JSK 2 with 3.68% and 3.80%, respectively. LAF 2 had the highest nitrogen content of 1.40%, followed by LAF 4 with 1.38%, while JSK 4 had the lowest value of 1.19%.

Hydrogen and carbon are the main combustible components of coal, and both of them are high in the coal samples (Table 4). A good coal sample should have high amount of carbon (and hence, a high heating value) with lower amount of hydrogen as is the case with the Lafia-Obi coals.

Oxygen and nitrogen have no heating value, but low amount of nitrogen is required in coal because it reduces oxidation. The typical acceptable range for nitrogen in coal is < 2% to avoid the risk of NO_x emissions (Thomas 2002). All the coal samples fall within the acceptable range (1.19–1.4%) for elemental nitrogen. Also, a good-quality coal should have low oxygen content, as observed in all the coal samples.

The Lafia-Obi coals possess lower sulphur content values compared to the Jangwa-Shankodi coals and are better quality coals (Table 4). The lower sulphur values are attributed to less marine influence. The barrier island could have shielded the lagoon from much sea water invasion.

Figure 17 showed good correlation between the elemental carbon content and other ultimate properties of the studied coals. Generally, the elemental carbon content of Lafia-Obi coals varies inversely with the hydrogen content (Fig. 17a).

Table 4 Results of ultimate analysis (air dried basis) of the coals studied

| Coal sample | | | | | | | | |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Parameter | JSK 1 | JSK 2 | JSK 3 | JSK 4 | LAF 1 | LAF 2 | LAF 3 | LAF 4 |
| Carbon (%) | 53.17 | 53.19 | 52.92 | 53.16 | 54.30 | 54.35 | 54.52 | 53.99 |
| Hydrogen (%) | 4.55 | 4.49 | 4.47 | 4.53 | 4.06 | 3.89 | 3.95 | 3.90 |
| Oxygen (%) | 3.07 | 3.80 | 3.68 | 3.81 | 6.87 | 6.79 | 6.90 | 6.92 |
| Nitrogen (%) | 1.23 | 1.22 | 1.20 | 1.19 | 1.34 | 1.40 | 1.36 | 1.38 |
| Sulphur (%) | 0.11 | 0.14 | 0.11 | 0.12 | 0.08 | 0.09 | 0.13 | 0.10 |

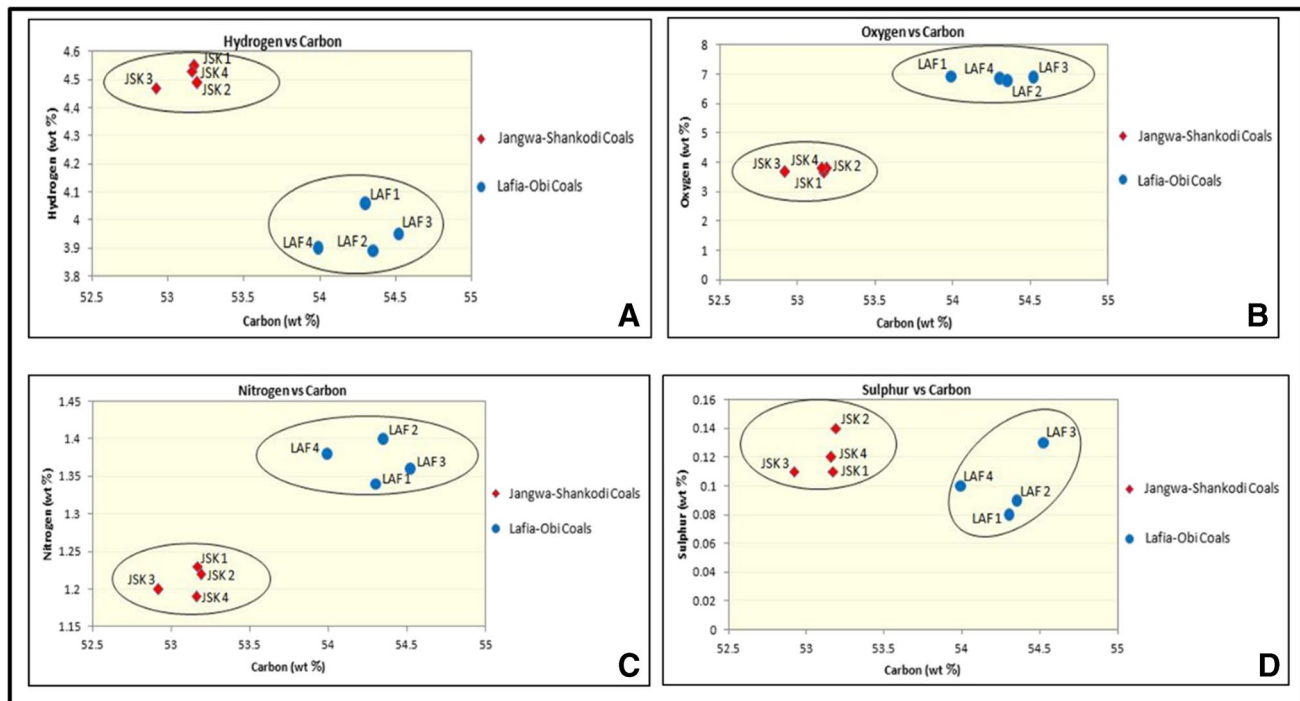


Fig. 17 Scatter plot showing the relationship between elemental carbon and (a) elemental hydrogen, (b) elemental oxygen, (c) elemental nitrogen and (d) elemental sulphur

This implies that on heating, the coals are likely to produce less additional moisture when the hydrogen particles react with atmospheric oxygen unlike the Jangwa-Shankodi coals. Despite the relatively higher elemental oxygen in these coals (Fig. 17b), their lesser elemental sulphur value means they are unlikely to produce harmful SO_x gas emissions although CO_x and NO_x emissions could occur due to slightly higher values of elemental carbon and nitrogen compared to Jangwa-Shankodi coals (Fig. 17c and d). Moisture production and SO_x gas emissions will likely be higher on heating the Jangwa-Shankodi coals. This is due to their higher elemental hydrogen, relatively high elemental oxygen and higher sulphur content, which reduces their quality.

Effect of depositional environment on coal seam thickness

The complex vertical facies changes, including both fining upward and coarsening upward sequences, are attributed to a meandering river system (Flores 1983), where the sandy sediments indicate point bar deposits as well as crevasse splays. The siltstones (and partly silty sandstones and shaly sandstones) and associated coal seams represent flood plain and backswamp deposits. The thick laminated shales and coal seams represents lagoonal or swamp deposits. A meandering river system is therefore more likely than a braided river setting due to the generally high proportion

of suspended load clastics (Reading 1982); the latter setting would have produced an almost entirely sandy succession.

Drilling data obtained from the National Steel Raw Materials Exploration Agency (NSRMEA) revealed several coal seams in the Lafia-Obi area with their recoverable thickness range (see Table 1). The data was acquired to investigate the beneficiation and coking capacity of the coals. A total of 34 coal seams and lenses from 180 drill holes were encountered in Lafia-Obi within the 400 m thick upper Cretaceous sediments. Seam 22 recorded the least thickness (0.02 m), while Seam 12 reported the highest thickness value (4.20 m). Only seams 8, 12, 13, 14, 21, 31 and 34 had thicknesses exceeding 1.0 m.

It is widely known that the Lafia-Obi coals are generally thicker than the Jangwa-Shankodi coals (Obaje 2009). According to Obaje (2009) and Obaje et al. (2020), the major outcrop of the coal bearing Awgu Formation is at the bank of River Dep in Shankodi, 7 km to the west of the village of Jangwa. Along the bank of this river, the coal seams can be traced laterally for about 500 m with the thickest seam about 1.5 m.

The presence of much thinner coal seams in Jangwa-Shankodi represents widespread and long lasting backswamp conditions (Stach et al. 1982). This suggests that a meandering river environment prevailed during this period; nonetheless, at different periods, either backswamp and floodplain conditions or channel processes controlled the deposition

in the coalfield. A dominance of mixed-coal lithotypes (see Figs. 6, 7 and 10) indicates relatively inferior peat preservation conditions, due to contact with oxygen-rich waters (Stach et al. 1982). Peat is thinly developed here due to lower nutrient supply and lesser water coverage. Also, the proximity of an actively shifting channel belt could have been indicated by the thin coals; these reflect late abandonment of the active channels in the initial phase, early termination of the peat growth and erosional activity by a reactivated meander channel during the final stage of the backswamp, i.e. post-swamp erosional activity, attributed to shifting channel, also caused diminished seam thicknesses. Any thick seam encountered here could have been the result of frequent crevasse from the nearby channel belt, which provided ample nutrient supply to improve peat growth. The parting between the two coal seams in Shankodi (see Fig. 6) may represent an interfingering of channel and crevasse deposition with steady floodplain deposition.

The fining upward characteristics of the sediments (between 3.5 and 6.5 m (see Fig. 6b)) into the mainly silty and shaly roof rocks of the upper coal seam can be attributed to a gradual cessation of channel activity and a re-occupation of the study area by quiescent floodplain conditions (see Fig. 7). Thickly developed shales and shaly sandstones in the floor rocks outline ox-bow lakes of a meandering river system, preceding the peat growth.

On the other hand, the Lafia-Obi coals were deposited in lagoonal environment consisting predominantly of relatively thick coal seams and horizontally laminated shales. This is in agreement with the petrographic study carried out by Obaje and Ligouis (1996). Bioturbations, however, were not observed. Lagoonal environments are quiet and are characterized by high biological activity with sufficient water coverage. These environmental factors promote peat growth by regular nutrient supply due to persistent water coverage to allow the peat to be preserved (Hagelskamp et al. 1988), thus, leading to the formation of thicker coal seams, as is the case with the Lafia-Obi coals. It is possible that water depth slowly increased to form extensive lagoons where shales accumulated. The coal seam observed at an outcrop in Lafia-Obi (see Fig. 8) is relatively thickly developed due to high compaction rates of the thick shaly sediments beneath. The thin coal seams could have resulted from periods of low sediment supply and reduced subsidence within the swamp environment (Holm and Bell 2013).

Effect of depositional environment on coal quality parameters

The ash yield of the Jangwa-Shankodi coals is generally about 7.99–8.64% on an air-dry basis. The relatively high ash yield could be attributed to their close proximity to channel influences or margins of underlying major

crevasse deposits (Hagelskamp et al. 1988). Peats formed on the floodplain are occasionally flooded by sediment-bearing water. Because peat accumulation is slow, the rare flood events become important in increasing the peat's ash yield due to the influx of clastic sediments and oxidative peat degradation during dry periods. The relatively lower ash yields of the Lafia-Obi coals (7.83–8.34%) suggest that the coals may have deposited in an area nearly void of clastic sediments. The slightly high acidity of swamps, which will cause leaching of the minerals, may also be a factor in causing these slightly lower ash yields (McCabe 1985). The volatile matter yields of both the Jangwa-Shankodi and Lafia-Obi coals are at best moderate. The moderate values of the Jangwa-Shankodi coals are associated with underlying crevasse and channel deposits, which allowed a fairly high plant community to grow, due to nutrient supply and a more stable rooting ground (Harvey and Dillon 1985). This would have resulted in the accumulation and preservation of peat that have a moderate to relatively high volatile matter yield (Stach et al. 1982). This is corroborated by the works of Jauro et al. (2008) and Obaje and Ligouis (1996). Lafia-Obi coals possess higher fixed carbon content compared to Jangwa-Shankodi coals as earlier stated. This is due to better peat growth and preservation (in a much quieter lagoonal environment) caused by sufficient water coverage and higher nutrient supply.

The carbon and hydrogen content largely control the heating values (Snyman et al. 1983) and is mainly the result of rank. As especially the later factor does not, under normal coalification, change significantly over the size of an area, such as investigated here, its effects on spatial changes in heating value will not be considerable. Therefore, components that diminish the heating value, such as the ash yield in the coal, will have a much higher effect. The comparatively higher heating values of the Lafia-Obi coals is tied to its lower ash yield since the coals are deposited in swamps that received little clastic sediments. On the other hands, the lower heating values of the Jangwa-Shankodi coals (see JSK 1, JSK 3 and JSK 4) is related to their relatively higher ash yields caused by their proximity to clastic sediments from the meandering river. Thus, the heating value of the coals is inversely proportional to the ash yield (Hagelskamp et al. 1988) (see LAF 1, LAF 3 and LAF 4). However, there are little divergences from this relation, in that the heating value appears too high in comparison to the given ash content, such as in JSK 1. This is attributed to its comparatively higher volatile matter yield. In comparison with other Lafia-Obi coal samples, the lower heating value of LAF 2 is credited to its higher ash yield, which could have resulted from wash-over clastics that entered the lagoon from the top of the barrier island.

Conclusion

The quality parameters and coal seam thicknesses of the Jangwa-Shankodi and Lafia-Obi coal fields have been analysed from a palaeoenvironmental stand point. Nine depositional facies of epsilon cross-stratified sandstone (Sf), siltstone (St), silty sandstone (Sst), coal (Co), shaly sandstone (Ssh), dark brown shale (Shb), dark grey shale (Shg), carbonaceous shale (Shcb) and indurated shale (Shi) were recorded suggesting deposition in fluvial (meandering) and lagoonal (swamp) environments. Coal seam thickness was controlled by fluvial, floodplain and backswamp depositional and erosional processes, as well as compaction and water coverage. Coal parameters (ash, fixed carbon, volatile matter and heating value) and rank showed significant correspondence with depositional features. Consequently, the Lafia-Obi coals, which was found to be of better quality, is characterized by thicker coal seams, higher fixed carbon, lower ash yield and lesser sulphur content. Major changes in coal thickness and quality parameters, and thus in the economic value of the seams, can be expected in the vicinity of abandoned channels previously characterized by less floods and crevasse splaying.

Acknowledgements The second author wishes to thank the entire academic personnel of the Department of Geology, University of Nigeria, Nsukka, particularly Prof. O. Igwe, Prof. A.W. Mode, Prof. O.A. Anyiam and Dr. O.S. Onwuka, for their support and encouragement during the course of this study. Our sincere appreciation also goes to Prof. Usman Onoduku of the Department of Geology, Federal University of Technology, Minna, for providing guidance and technical input that improved the quality of the final thesis. The National Steel Raw Materials Exploration Agency is acknowledged for the provision of drilling data that aided the analysis of this work.

Author contribution Itohowo Moses Ekpo and Johnson Ogonna Amobi conceptualized the project and, along with Chidubem Okwudiri Emedo, participated in data curation, formal analysis, data interpretation and manuscript drafting. Clementina Ogechi Ekwenye and Ifeanyi Andrew Oha provided immense technical support.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

- Adekunle JO, Ibrahim JS, Kucha EI (2015) Proximate and ultimate analysis of bio-coal briquettes of Nigerian's Ogboyaga and Okaba sub-bituminous coal. *Br J Appl Sci Technol* 7:114–123
- Akande S, Hoffknecht A, Erdtmann BD (1992) Rank and petrographic composition of selected Upper Cretaceous and Tertiary coals of Southern Nigeria. *Int J Coal Geol* 20:209–223
- Akinyemi SA, Adebayo OF, Nyakuma BB, Adegoke AK, Aturamu OA, OlaOlorun OA, Adetunji A, Hower JC, Hood MM, Jauro A (2020) Petrology, physicochemical and thermal analyses of selected Cretaceous coals from the Benue Trough Basin in Nigeria. *International Journal of Coal Science and Technology* 7:26–42
- Anyiam OA, Onuorah LC, Okwara IC (2017) Depositional framework and stratigraphy of the Koshisha area, southern Benue Trough. *Glob J Geol Sci* 15:41–55
- ASTM C618 (1992) Manual on drilling, sampling, and analysis of coal. www.astm.org. Accessed 21th Jan 2021
- ASTM D3178–89 (2002) Standard testing method for carbon and hydrogen in the analysis of the sample of Coal and Coke. www.astm.org. Accessed 19th Jan 2021
- ASTM D5142 (2010) Standard testing method for proximate analysis of the sample of coal and coke by instrumental procedures. www.astm.org. Accessed 20th Jan 2021.
- ASTM D7582–15 (2015) Standard test method for gross calorific value of coal and coke by the Adiabatic Bomb Calorimeter. www.astm.org. Accessed 20th Jan 2021.
- Benkhelil J (1989) The origin and evolution of the Cretaceous Benue Trough (Nigeria). *J Afr Earth Sc* 8:251–282
- Chaboureau AC, Donnadieu Y, Sepulchre P, Robin C, Guillocheau F, Rohais S (2012) The Aptian evaporites of the South Atlantic: a climatic paradox? *Climate of the past* 8:1047–1058
- Chukwu M, Folayan CO, Pam GY, Obada DO (2016) Characterization of some Nigerian coals for power generation. *J Combustion* 16:972–982
- Cook JM (2015) Stratigraphy, depositional environments, and reservoir characteristics of the Tussy (Desmoinesian) sandstones, southeast Joiner Cityfield, Love and Carter Counties, Oklahoma. Search and Discovery Article No. 20317
- Davies-Vollum KS, Zhang Z, Agyekumhene A (2019) Impacts of lagoon opening and implications for coastal management: case study from Muni-Pomadze lagoon, Ghana. *J Coast Conserv* 23:293–301
- Ehinola OA, Ekweozor CM, Oros DR, Simoneit BRT (2002) Geology, geochemistry and biomarker evaluation of Lafia-Obi coal, Benue Trough, Nigeria. *Fuel* 81:219–233
- Ezeh E, Okeke O (2016) Proximate and elemental analysis of some Nigerian coal deposits. *British Journal of Environmental Sciences* 4:34–38
- Farrington JL (1952) A preliminary description of the Nigerian lead-zinc field. *Econ Geol* 47(583):608
- Fielding CR (1985) Coal depositional models and the distinction between alluvial and delta plain environments. *Sediment Geol* 42:41–48
- Flores RM (1983) Basin facies analysis of coal-rich Tertiary fluvial deposits, Northern Powder River Basin, Montana and Wyoming. *Mod Anc Fluv Syst* 7:499–515
- Galloway WE, Hobday DK (1983) Terrigenous clastic depositional systems: applications to petroleum, coal, and uranium exploration. Springer-Verlag, Netherlands
- Green I, Ugoji K, Igbere B (2019) Economic analysis of natural gas reserves addition from coal bed methane in Nigeria. *Eur J Eng Technol Res* 4:31–34
- Hagelskamp HB, Eriksson PG, Synman CP (1988) The effect of depositional environment on coal distribution and quality parameters in a portion of the Highveld Coalfield, South Africa. *Int J Coal Geol* 10:51–77
- Hampson GJ (2010) Sediment dispersal and quantitative stratigraphy architecture across an ancient shelf. *Sedimentology* 57:96–141
- Harvey RD, Dillon JW (1985) Maceral distributions in Illinois coals and their palaeoenvironmental implications. *International Journal of Coal Geology* 5:141–168
- Heward AP (1978) Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Cinera-Matallana and Sabero) Coalfields, Northern Spain. *Sedimentology* 25:451–488
- Hjellbakk A (1997) Facies and fluvial architecture of a high-energy braided river: The Upper Proterozoic Segloddan Member,

- Varanger Peninsula, northern Norway. *Sedimentary Geology* 114:131–161
- Holm R, Bell DH (2013) Sedimentology and structure of the Malvern Hills Coal Mine, Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics* 56:39–52
- Horne JC, Ferm JC, Caruccio FT, Baganz BP (1978) Depositional models in coal exploration and mine planning in Appalachian region. *American Association of Petroleum Geologists' Bulletin* 62:2379–2411
- Jauro A, Agho MO, Abayeh OJ, Obaje NG, Abubakar MB (2008) Petrographic studies and coking properties of Lamza, Chikila and Lafia–Obi Coals of the Benue Trough. *Journal of Mining and Geology* 44:37–47
- Jauro A, Chukwu CJ (2011) Production of formed coke from Nigerian coals. *Petrol Coal* 53:22–25
- Learning Geology (2015) Barrier and Lagoon Systems: Learning Geology. <http://geologylearn.blogspot.com/2015/07/barrier-and-lagoon-systems>. Accessed 7 Oct 2021.
- McCabe PJ (1985) Depositional environments of coal and coal-bearing strata. *Sedimentology of Coal and Coal Bearing Sequences* 11:21–42
- Miall AD (1996) The geology of fluvial deposits - sedimentary facies, basin analysis, and petroleum geology. Springer Verlag, Berlin
- Miall AD (2000) Principles of sedimentary basin analysis. Springer-Verlag, Berlin
- Ministry of Mines and Steel. (2008). Ministry of solid minerals investment brochure. www.minesandsteel.gov.ng/wp-content/uploads/2017/10/. Accessed 2nd Feb 2021
- Mode AW, Anyiam OA, Okara ES (2018) The use of cross plots in lithology delineation and petrophysical evaluation of some wells in the western Coastal Swamp, Niger Delta. *J Petrol Explor Prod Technol* 8:61–71
- Nichols G (2009) Sedimentology and stratigraphy. John Wiley and Sons, London
- NSRMEA (1976) Report on prospection and exploration of Lafia coal deposits in Obi area. Exploration Report-Contact 1717. National Steel Development Authority, Nigeria
- Nyakuma BB (2016) Physicochemical characterization and thermal analysis of newly discovered Nigerian coals. *Bul Chem Commun* 48:746–752
- Obaje NG, Ligouis B (1996) Petrographic evaluation of the depositional environments of the Cretaceous Obi/Lafia coal deposits in the Benue Trough of Nigeria. *J Afr Earth Sci* 22:159–171
- Obaje NG (1997) Petrographic evaluation of the coking potentials of the Cretaceous Lafia-Obi coal deposits in the Benue Trough of Nigeria. *J Min Geol* 43:103–116
- Obaje NG (2009) Geology and mineral resources of Nigeria. Springer, Heidelberg, Netherland
- Obaje NG, Umar UM, Aweda AK, Ozoji TM (2020) Nigerian Cretaceous coal deposits and their petroleum source rock characteristics. *Int J Petrol Gas Explor Manage* 4:1–14
- Okolo GC, Emedo CO, Obumselu AC, Madukwe FC, Ulasi AN (2020) Lithofacies, particle size analysis and paleodepositional environment of the Eze-Aku Group (Cenomanian-Turonian) in the Itigidi-Ediba area, Afikpo Synclinorium, southeastern Nigeria. *J Sediment Environ* 5:375–398
- Onoduku US (2014a) Chemistry of Maiganga coal deposit, upper Benue Trough, Northeastern Nigeria. *J Geosci Geomat* 2:80–84
- Onoduku US (2014b) Geochemistry of Okaba coal deposit, Anambra Basin, Nigeria. *Res J Sci Inf Technol Manage* 3:11–16
- Petters SW, Ekweozor CM (1982) Petroleum geology of Benue Trough and southeastern Chad basin, Nigeria. *Am Asso Petrol Geol Bull* 66:1141–1149
- Petters SW (1983) Gulf of Guinea planktonic foraminiferal biochronology and geological history of the South Atlantic. *J Foramin Res* 13:32–59
- Petters SW (1991) Regional geology of Africa. Springer Verlag, Berlin
- Reading HG (1982) Sedimentary Environments and Facies. Blackwell Science, London
- Reading HG, Levell BK (1996) Sedimentary environments: processes, facies and stratigraphy. Blackwell Science, London
- Reinson GE (1992) Transgressive barrier island estuarine systems. In: Walker RG, James NP (eds) Facies Models Response to Sea Level Change, Geotext, Canada, pp. 179–194
- Rust IC (1975) Tectonic and sedimentary framework of Godwana Basins in southern Africa. In: Campbell KS (ed) Godwana Geology. Australian National University Press, Australia, pp 537–564
- Ryemshak SA, Jauro A, Putshaka JD, Sori RM (2016) Ultimate analysis of some Nigerian coal: ranking and suitable application. *Int J Eng Appl Sci* 3:31–35
- Ryemshak SA, Jauro A (2013) Proximate analysis, rheological properties and technological applications of some Nigerian coals. *Int J Ind Chem* 4:1–7
- Seidle J (2011) Fundamentals of coalbed methane reservoir engineering. Pennwell Books, London
- Snyman CP, Vna Vuuren MCJ, Barnard JK (1983) Chemical and physical characteristics of South African coal and a suggested classification system. NICR Report-079882799.
- Stach E, Mackowsky M, Teichmuller, M, Taylor GF, Chandra G, Teichmuller R (1982) Stach's Textbook of Coal Petrology. Gebrüder Borntraeger, Germany
- Thomas L (2002) Coal geology and use. Wiley Publishing, London