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ORIGINAL PAPER

Lithofacies and environments of deposition within the Middle–Upper Cretaceous successions of Southeastern Nigeria

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Abstract This paper presents findings from detailed geologic mapping of the Cenomanian–Campanian sediment package of southern Benue Trough, outcropping in Afikpo area of Southeastern Nigeria. The aim was to integrate outcrop and sedimentological log data with lithofacies analyses to better understand prevalent depositional processes and environments of deposition, across the Amaseri–Ngodo outcrop sections. Ten lithofacies with their associated subordinate lithofacies were identified and grouped into five facies associations (FA 1–5) to aid depositional environment interpretation. FA 1 consists of silty-shale and shales of the mudstone (MS) lithofacies deposited within an oxygenated offshore/open shelf setting, probably below fair-weather and storm wave base. FA 2 comprises medium–coarse-grained sandstone (MCS), hummocky cross-bedded sandstone (sub-lithofacies 4 of CBS), bioturbated sandstone (BSs) facies, bioturbated siltstone (BSt) and planar parallel-laminated sandstone (PPLS) lithofacies, interpreted to be storm wave-dominated shelf deposits. FA 3 consists of tabular/planar and trough cross-bedded sandstones (sub-lithofacies 1 and 2 of CBS) and wave ripple-laminated sandstones (RLS) lithofacies interpreted as shorefaces deposits above fair-weather wave base. Herringbone cross-bedded sandstones (sub-lithofacies 3 of CBS) and bioclastic limestone (BcL) lithofacies constitute FA 4, interpreted as tidal inlet/lagoonal deposits. FA 5 is characterized by conglomeritic sandstone (CS) lithofacies, as well as CBS, PPLS, RLS lithofacies, deposited within fluvial channels. Furthermore, vertical stacking patterns reveal the occurrence of two facies successions: the fining-upwards/thinning-upwards (FU/TnU) succession (typical of deepening or shallow to proximal offshore marine environments), dominating the northern and central part of the study area; and coarsening-upwards/thickening-upwards (CU/TkU) succession (typical of shoaling or proximal offshore to shallow marine environment), dominating the southern part of the study area. Overall, these lithofacies represents deposits within the littoral (marginal marine) and sub-littoral (shallow marine) environments.

Keywords Lithofacies · Facies association · Environments of deposition · Fining-upwards/thinning-upwards succession · Coarsening-upwards/thickening-upwards succession

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Introduction

Detailed geologic mapping and sedimentological logging have been carried out around Afikpo town and environs, which cover an area of approximately 574 km^2 (Fig. 1a). Outcrop data integrated with lithofacies and petrographic analyses have been used to improve the understanding of lithofacies, facies association and of environments of deposition across the Middle–Upper Cretaceous (Cenomanian–Campanian) successions in the southern Benue Trough. Studies have shown that distinctive sets of characteristics from rock units such as grain size and primary sedimentary structures are needed to delineate a lithofacies and understand the processes that were operational during sediment deposition in various environments (Miall 2000; Kendall 2005). The Cretaceous stratigraphic successions of the southern Benue Trough are characterized by a series of structurally deformed sediments that gave rise to a number of rapidly alternating parallel to sub-parallel sandstone ridges and shale lowlands outcropping in Afikpo and Ugep areas in Southeastern

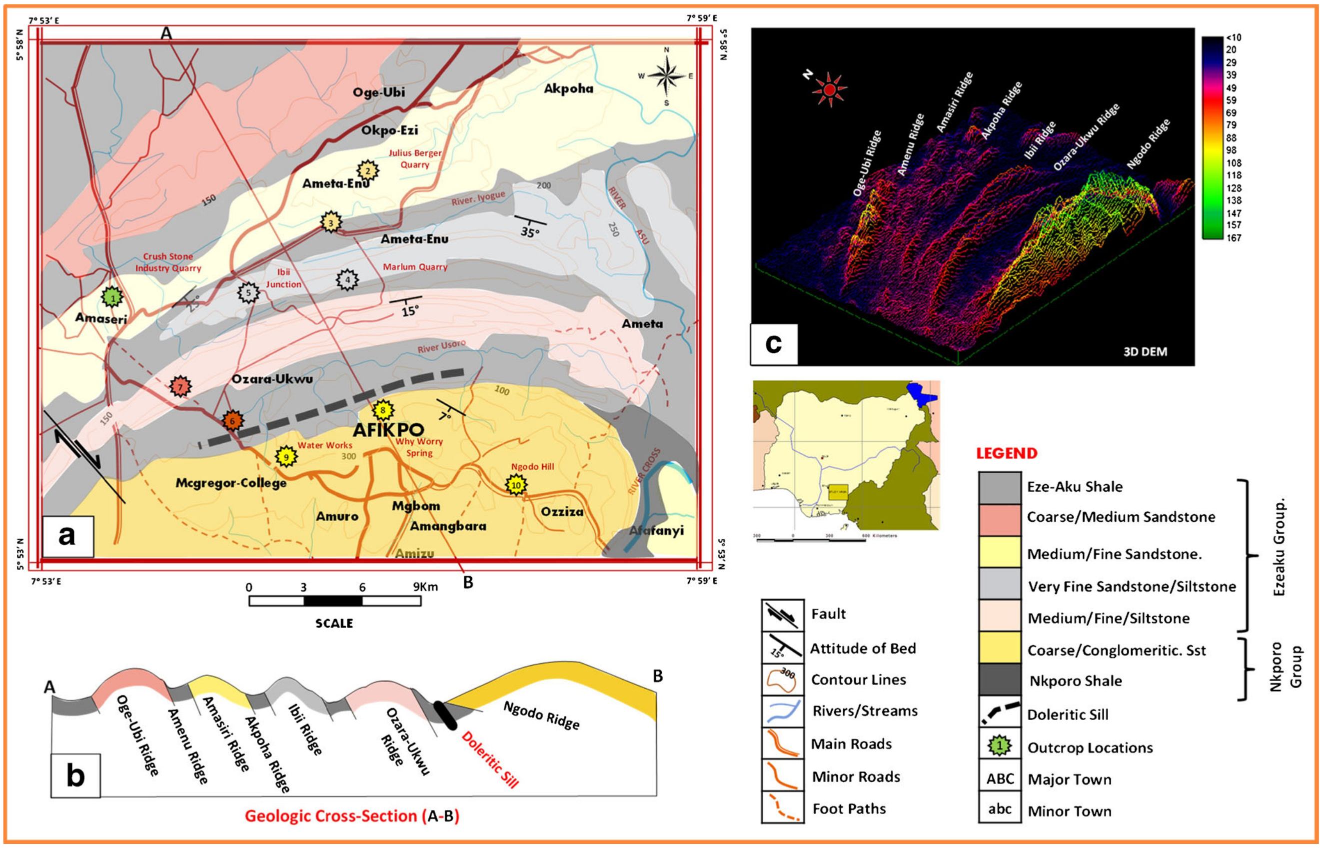

Fig. 1 **a** Geographic (accessibility, relief and drainage) and geologic map (outcropping lithogies and litostratigraphic units) of the Afikpo area and environs, Southeastern Nigeria, showing; **b** Geologic cross-section (*A*–*B*), across the study area; **c** 3D digital elevation map (DEM) of the study area showing the sandstone ridges (note: contours in feet; DEM in meters)

Nigeria. Associated with this sediment deformation are igneous intrusions. These are evident in the geologic features such as anticlines, fold limbs, deformational bands, faults, joints and igneous intrusives encountered in the across the study area. Benkhelil (1989) noted that these features were as a result of compressional folding, faulting and magmatism during the mid-Santonian tectonic episode that affected the southern Benue Trough. The Afikpo area and its environs are underlain by lithofacies belonging to three lithostratigraphic units namely; the Eze-Aku Shale and Amaseri Sandstone (Eze-Aku Group) and the Afikpo Formation (Nkporo Group). The Eze-Aku Group is made up of gray and dark calcareous shale, limestone, siltstone and sandstone whereas the Nkporo Group comprises of medium to coarse-grained sandstone, pebbly/conglomeritic sandstone and dark shales (Murat 1972 and Nwajide 2013).

Over the years, efforts at carrying out detailed outcrop studies across these areas have been limited due to the lack of good exposures. Attempts have been made to group the sandstone and shale units of the Eze-Aku Formation into several members (Ukaegbu and Akpabio 2009) and classify them into several lithofacies and depositional environments (Okoro and Igwe 2014). These have been done using information from a few exposed sections. Although sedimentological studies have been carried out (Simpsons 1954) and depositional models developed (Banerjee 1980; Amajor 1980, 1987) for the Middle–Upper Cretaceous units of the southern Benue Trough, these have generally been on a regional scale. Recently, quarrying has exposed some good sections of the ridges, prompting a renewed interest in the area (Fig. 2). The present study is aimed at carrying out a detailed outcrop mapping and integrating the data obtained from lithofacies analyses to better delineate lithofacies and understand the distribution of lithofacies successions, facies association and their environments of deposition.

Geologic setting

The Benue Trough is a NE–SW trending sedimentary complex of sub-basins of about 1000 km long and 50–100 km wide and contains up to 6000 m thick of Cretaceous sediments of which those predating the mid-Santonian have been folded, faulted and uplifted in several places (Whiteman 1982; Wright et al. 1985). Benkhelil (1989) observed that the compressional folding during the mid-Santonian tectonic episode affected the whole of the southern Benue Trough and was quite intense, producing many anticlinal and synclinal structures. Major

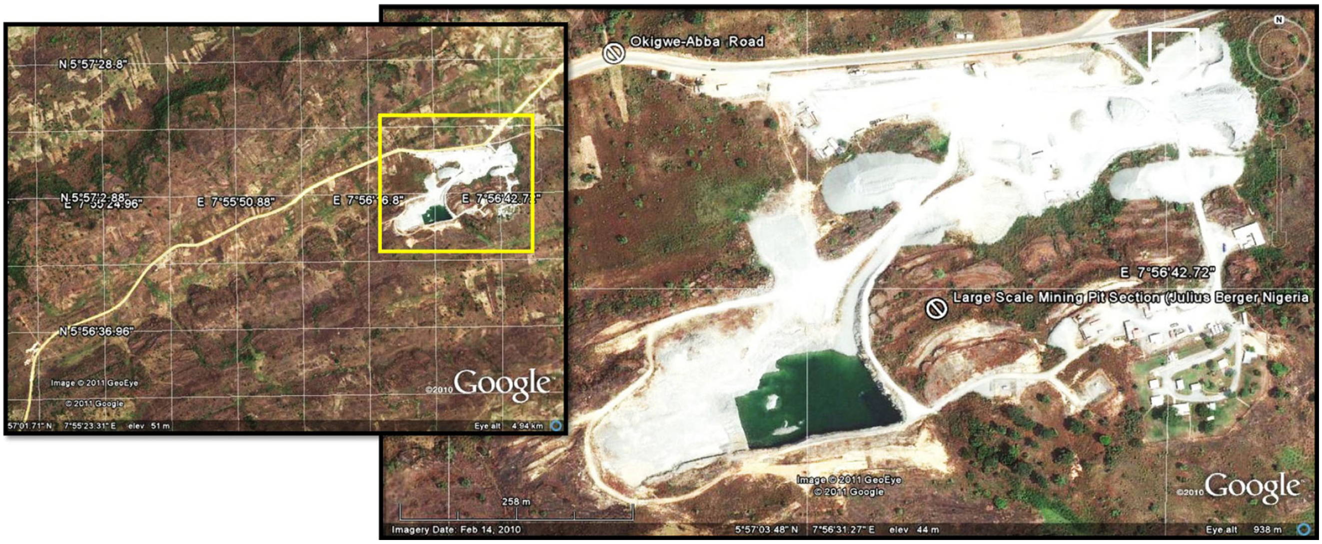

Fig. 2 Satellite imagery map showing exposed sections through large-scale quarry activities (Julius Berger, mining pit section) in some part of Akpoha area of Afikpo, along Abakaliki-Afikpo road, Southeastern Nigeria (source: Google Earth™)

deformational structures include the Abakaliki Anticlinorium and the Afikpo Syncline that are evident in the southern Benue Trough, which forms the focus of the present study (Fig. 3). Closely associated with the Santonian deformation was also the emplacement of numerous mafic intrusives and alkaline/calc–alkaline lavas and tuffs (Wright 1968). The sequence of events—rifting stage, the trough stage, the deformation stage with magmatism and the platform stage leading to the formation of the Trough—has been recorded by Burke et al. (1971); Grant (1971); Nwachukwu (1972); Olade (1975); Offodile (1976); Benkhelil (1982); Hoque and Nwajide (1985) and Ofoegbu (1985). The stratigraphic successions and sedimentologic history of the southern Benue Trough is well documented in Petters (1978); Hoque (1976) and Ojoh (1992). Although much work has been done with reference to stratigraphy of the southern Nigeria sedimentary basins, there still exist contrary views from the generally accepted thought that the Afikpo Basin and Anambra Basin are separate entities. Nwajide (2013) has opined that since both resulted from the same Santonian thermotectonic event in the southern Benue

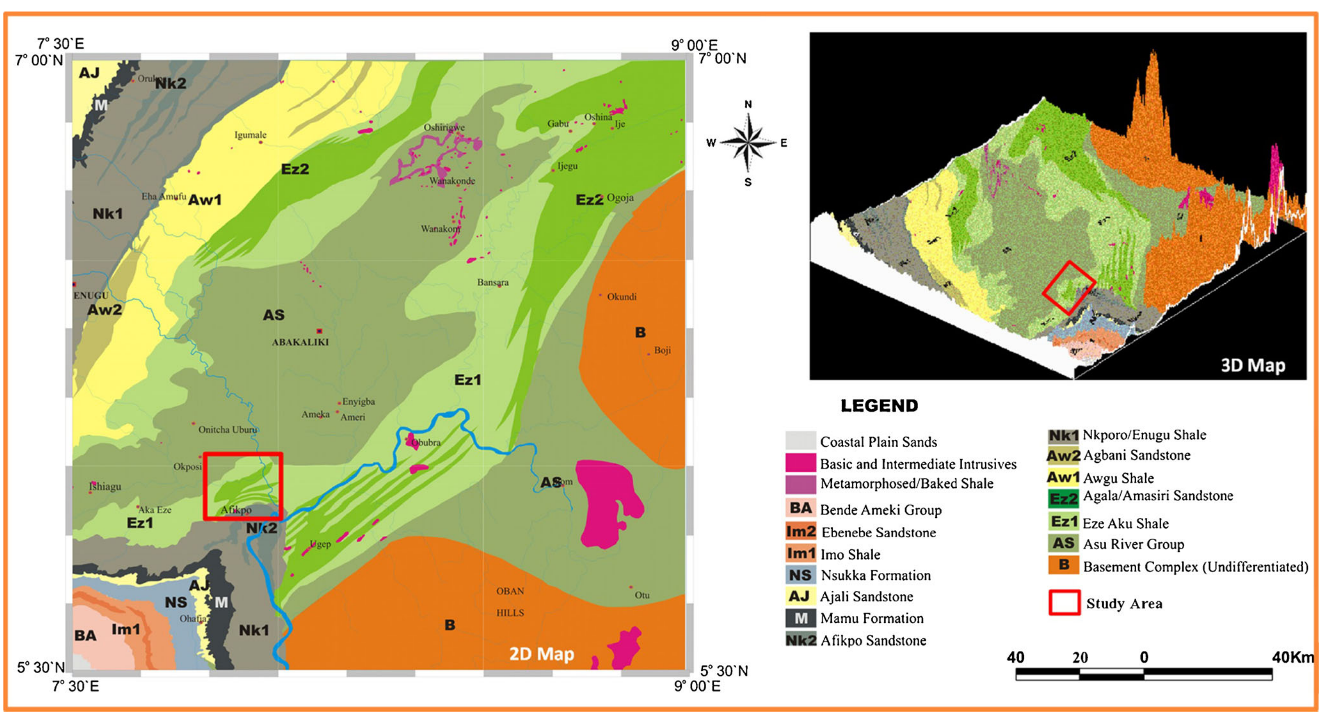

Fig. 3 2D and 3D geologic maps of the southern Benue Trough showing the lithostratigraphic units in the study area (adapted from Dim et al. 2014 and Oha 2014)

Trough with no physical separation or barrier between the two areas, therefore, there should be no justification for according the Afikpo area the status of a basin distinct from the Anambra Basin. The stratigraphic succession of the study area lies within the Middle–Upper Cretaceous sequence (Cenomanian to Campanian), spanning through southern Benue Trough (Abakaliki) and Anambra basins in the Southeastern (Fig. 4).

Method of investigation

Newly and previously exposed outcrop sections, specifically quarries and road cuts, were mapped, logged and sampled. The outcrop sections were assigned numbers ranging from 1 to 10 (Fig. 1a). Selected rock samples were subjected to petrographic analysis through megascopic (handheld specimen) and microscopic (thin section) studies, to provide data for interpretation of the textural and mineralogical characteristics of lithofacies. Lithofacies delineation was based on attributes of lithology/rock-type structural and textural features (bedding type, texture, grain size and shape, fossils, primary sedimentary and syn-depositional structures). Primary sedimentary structures were also studied and used in determining the hydrodynamic processes that were prevalent during sediment deposition and also infer possible depositional environment. Sandstones and carbonates were classified using the Folk (1959, 1974) and Dunham (1962) systems. Vertical log profile and sediment stacking patterns also gave insight on facies succession observed in this study. Delineated lithofacies were further group into various facies associations, which aided in the recognition of environments of deposition. Depositional and lithofacies models were also integrated to better interpret the delineated lithofacies and their corresponding environments of deposition. Sedimentologic logs (that were generated using data obtained from outcrop sections) were built using modified SedLog 2.1.4™ (Fig. 9).

Results and interpretation

Outcrop description

Outcrop sections logged across the northern through central part of the area are as follows: (i) Amaseri section—outcrop 1 (66.5 m thick of sediment), which lies on the Amaseri ridge along Amaseri–Okposi road is well exposed at the Crush

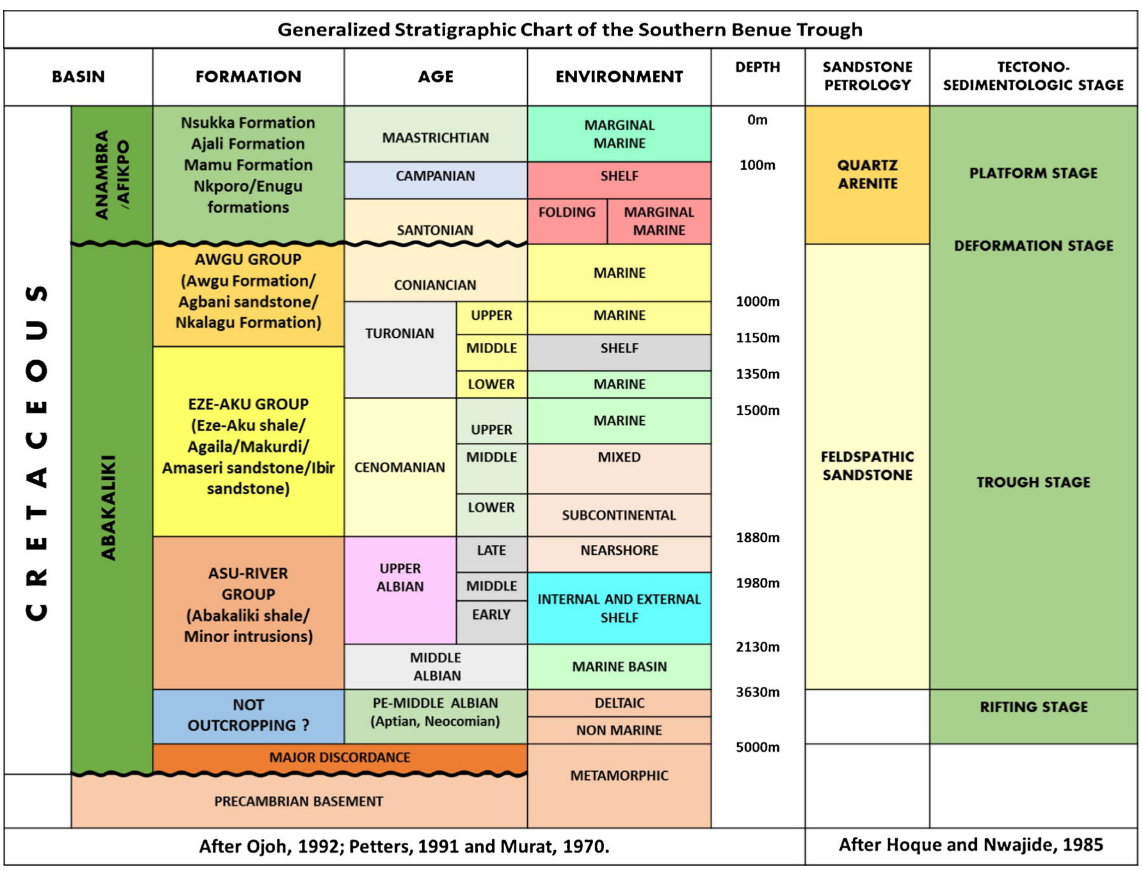

Fig. 4 Generalized stratigraphic chart of the southern Benue Trough (after Hoque and Nwajide 1985; Murat 1972; Ojoh 1992; Petters 1991)

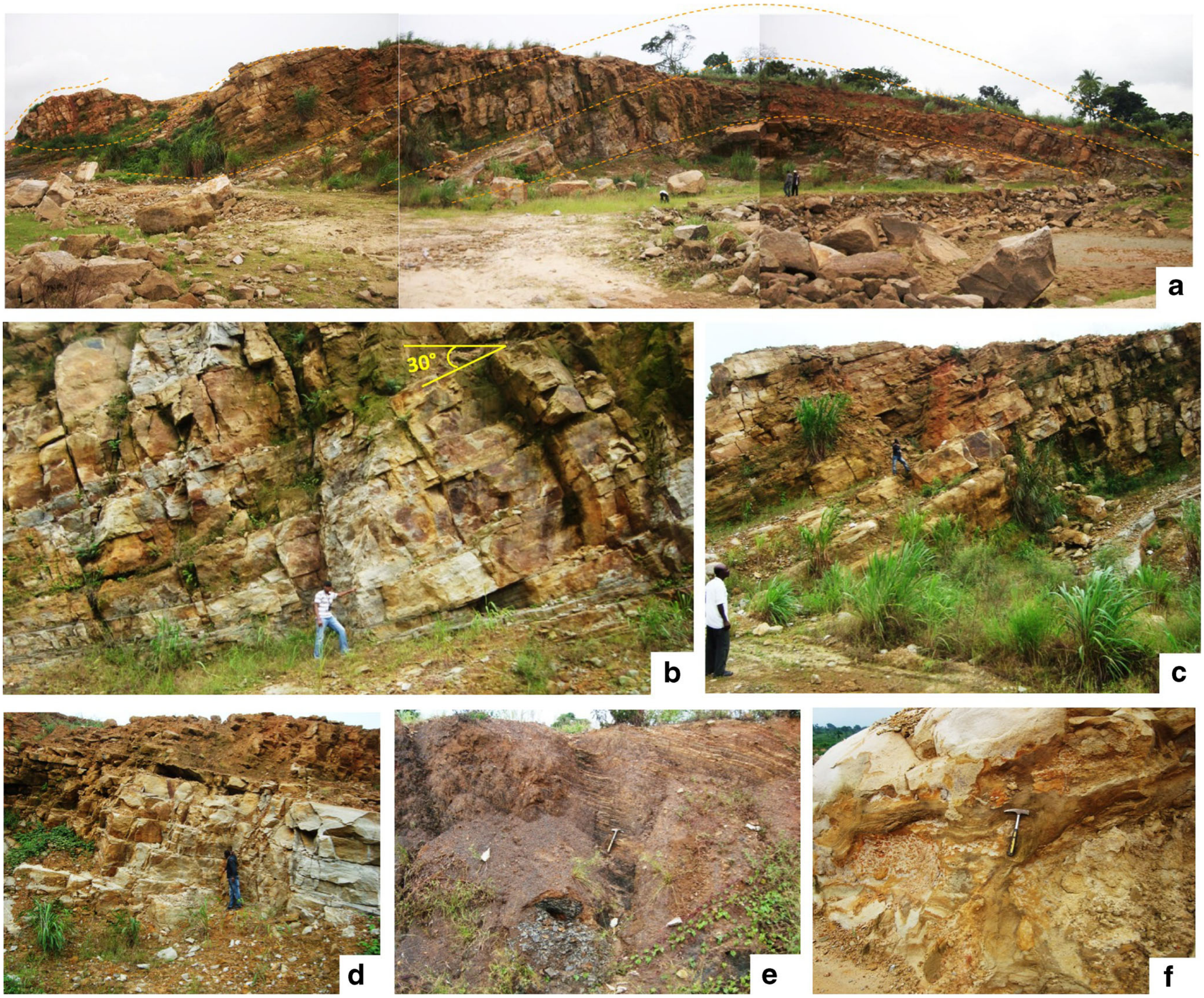

Fig. 5 **a** A photomosaic showing high-angled tilted sediments (anticlinal fold structure) in a NE–SW trending quarry section; **b** A close-up on the middle section showing the fold axis, with thick sediment package of well-stratified fine to coarse-grained sandstone unit (MCS–facies); **c** A close-up on RHS section, showing the limb of the fold (MCS–facies); **d** A close-up on the lower section showing sandstone package overlain by shale that is partly eroded; **e** Tilted, laminated dark gray-brown silty-shale unit (MS–facies); **f** Convolute structure—soft sediment deformation on fine-grained sandstone unit (MCS–facies). (NB: Fig. 5a–f: outcrop exposure on the Amaseri Sandstone ridge (Crush Stone Industry quarry site) in the western side of the studied area, Northwest of Afikpo town off Amoso-Amaseri Rd. Person for scale approximately 1.8 m [5.9 ft] tall)

Stone quarry site (Fig. 5a–f); (ii) Akpoha section—outcrop 2 (70.3 m thick of sediment) is well exposed on the Akpoha ridges along Okigwe–Abba Omega road and stretches from an artisan local quarry through the Julius Berger quarry site in Akpoha (Fig. 6a–g); (iii) Ibii section—outcrop 4 and 5 (about 180.5 m thick of sediment) conformably overlies the shale units of Akpoha–Ibii section (Fig. 7a–i); (iv) Ozara-Ukwu sections—outcrop 6, 7 and 8 (three sub-section of about 221 m thick of sediment (Fig. 8a–e); (v) Ozara–Ukwu/ Afikpo section—outcrop 8 (37 m thick of sediment (Fig. 8f–h); (vi) "Why Worry Spring"–Afikpo section—outcrop 9 (40 m thick of sediment) is exposed around Mcgregor College–Afikpo Junction (Fig. 8i); (vii) Ngodo Hill section—outcrop 10 (53 m thick of sediment) is exposed at Ngodo town, few kilometers from Mcgregor College–Afikpo Junction (Fig. 8j–m). Outcrop 1–5 are exposed at the northern and the central part and Outcrop 6–7 at the southern part within the sandstone ridges and shale lowlands of the area. The prominent sandstone ridges include those of Amaseri, Akpoha, Ibii, Ozara–Ukwu and Ngodo ridges (Fig. 1b, c). On the basis of orientation, the ridge belts have been subdivided into two, namely the NE–SW trending ridges paralleling the axis of the Benue Trough and the E–W ridges. Sand bodies occurring within the area are discontinuous (less than 1 km to few kilometers in length) and trend in E–W and ENE–WSW directions.

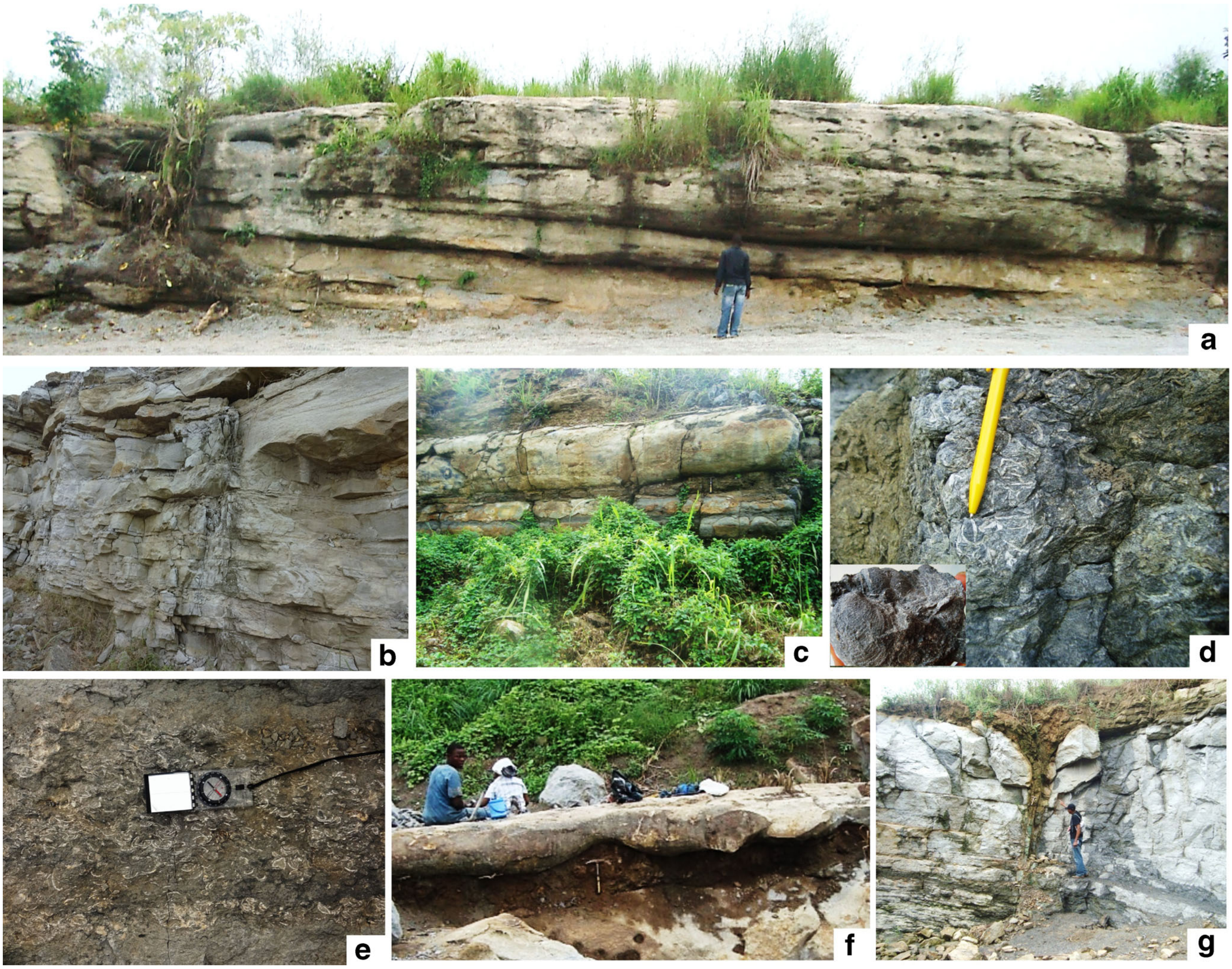

Fig. 6 **a** Thick tilted section of highly fossilferous, calcareous silt to very fine-grained sandstone characterized by parallel laminated medium to coarse-grained sandstone (MCS facies); **b** Well stratified tilted sitty to fine-grained sandstone unit partly fractured (joints); **c** Sand and shale interstratification (BSt and MS facies); **d** Bioclastic limestone unit (with shells of bivalves—BsL facies (observe an *inset* of a handheld of a bivalve (**e**) limestone bed characterized by substantial amount of calcareous shells fragment of the bivalves and brachiopods; **f** Load structure (soft sediment deformation) at basal part of Akpoha outcrop section; **g** Joint structure with infilling of indurates rock on a dipping silty-sandstone unit at Akpoha outcrop section (NB: Fig. 6**a**–**e**: outcrop exposure on in Akpoha sandstone ridge (Julius Berger quarry site). Figure 6**f**–**g** are quarry section about 100 m to Julius Berger Quarry along Abba Omega road, Afikpo North, southeastern, Nigeria. Person and geologic hammer for scale are approximately 1.8. m [5.9 ft] tall and 1 ft, respectively)

Structural influences are seen on stratigraphy as sediment packages are highly tilted, with each succeeding logged outcrop section overlying the preceding outcrop section across the area (Fig. 9). The attitude of beds is such that they strike 54° ENE–234° WSW and dip in a direction 144° SSE, with high angles of dip (25°–40°) in the northern through central part and relatively low angle of dip (9°–7°) in the southern part, which dip mostly southerly. A prominent feature of an anticlinal plunge fold is well exposed in the Amaseri section (Fig. 5a–e). Bed thicknesses range from 0.25 to 2.5 m. Lithologies include fine, medium and coarse-grained calcareous sandstone, pebbly to cobbly conglomeritic sandstone, siltstone, shale, silty-shale and limestone units. The area is characterized by series of shale and sandstone interstratification. Soft-sediment deformational features such as convolute laminated and load cast structure are seen on the fine-grained sandstone units (Figs. 5f and 6f). Some of the sandstone units show rip-out and intact boulders/rock clast and occassional near oval to oval vugs/clast aligned along bedding planes (Fig. 7a, f). Primary sedimentary structures such as laminations (parallel and wave-ripple) and cross-beddings (tabular, trough, herringbone and hummocky), also characterize some of the sandstone units (Fig. 8a, b, c, f). Visible on the lithologic units are also joint structures and deformational bands, which are evidence of sediment deformation (Figs. 6g and 8h, 8j). Evidence of bioturbation and burrowing are present as complex network of horizontal burrows (*Planolites and Thallassinoides*), and vertical burrows (*Ophiomorpha*) are

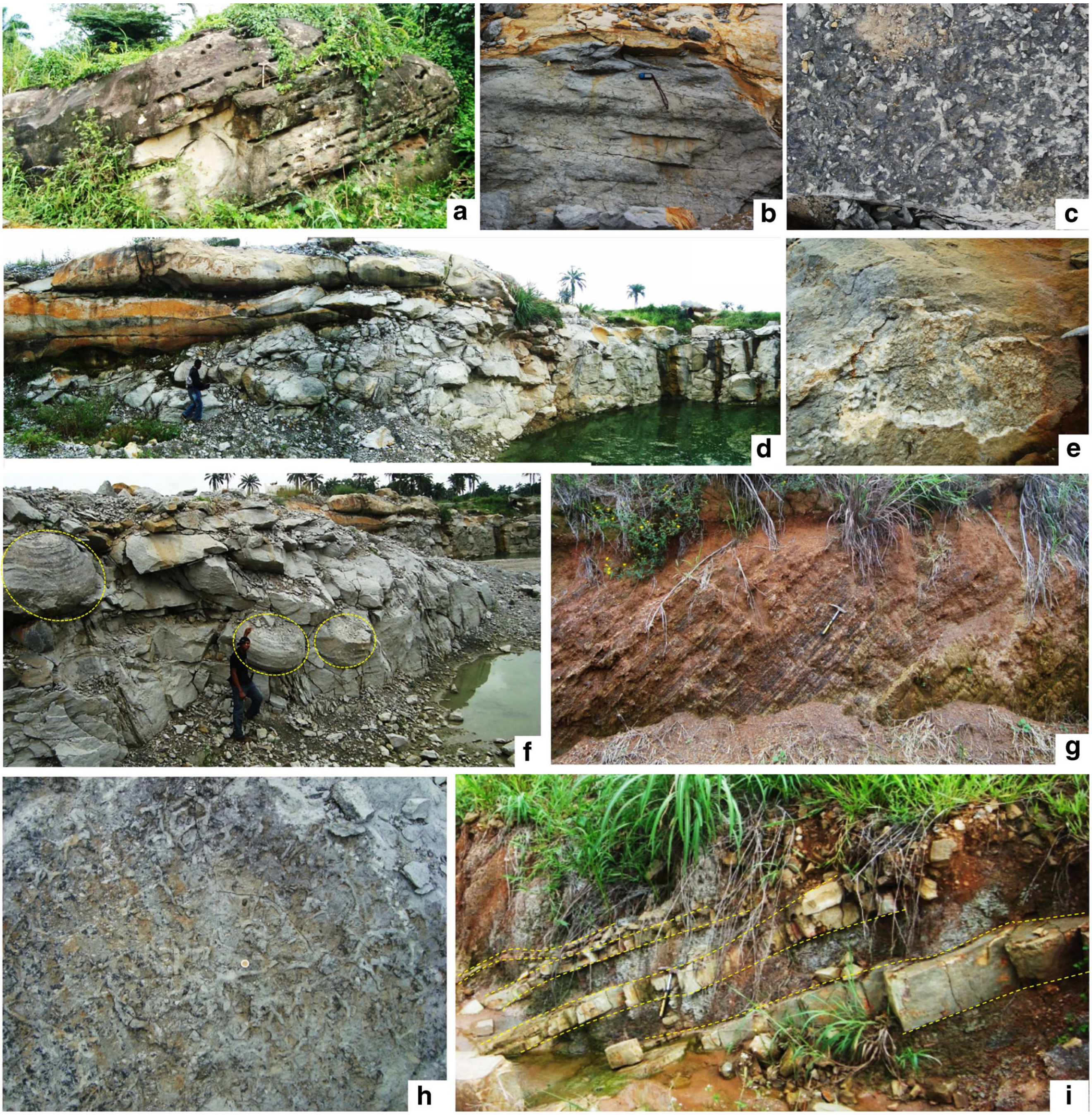

Fig. 7 **a** Sandstone unit characterized by vugs (created by silt/mud clast) parallel to bedding plane; **b** Siltstone with highly bioturbated section (BSt facies); **c** *Thallassinoides* burrows (*Glossifungites* ichnofacies) (BSS facies); **d** Photomosaic of a tilted of a thick fine-grained sandstone to siltstone sediment in Ibii outcrop section (sandstone ridge) exposed at the eastern side of the study area (looking N–NE of quarry section); **e** Calcite mineralized fracture/zones on calcareous siltstone unit (BsL facies); **f** Large ball clast/boulder occurring as concretion on very thick fine-grained sandstone/siltstone units at Ibii outcrop section of Afikpo area, southeastern, Nigeria (FS facies); **g** A highly dipping, laminated and fissile shale unit exposed at lower section of Ibii area; **h** Complex network of horizontal burrows—*Planolites* (*Cruziana* ichnofacies), (BSt facies); **i** Interstratification of sandstone and shale unit showing a thinning-upward sand and thickening-upward shale package. (NB: Fig. 7**a**–**c**: outcrops on road cuts and abandoned quarry along Akpoha-Ibii road through Ibii Junction; Fig. 7**d**–**i**: outcrop exposed on Ibii sandston ridge (Marlum Civil Engineering quarry site) of Akpoha-Afikpo road, Afikpo, southeastern, Nigeria. Persons and geologic hammer for scale are approximately 1.8 m [5.9 ft] tall and 1 ft respectively),

observed in the siltstone and sandstone units (Figs. 7b, c, h and 8l, m). Outcrop mapping in the area also reveals the occurrence of a basal doleritic intrusion, which has the same angle of dip with the overlying shale unit (Fig. 8g). This intrusive body has been classified as a sill, because it is conformable with the local stratigraphic package in the area.

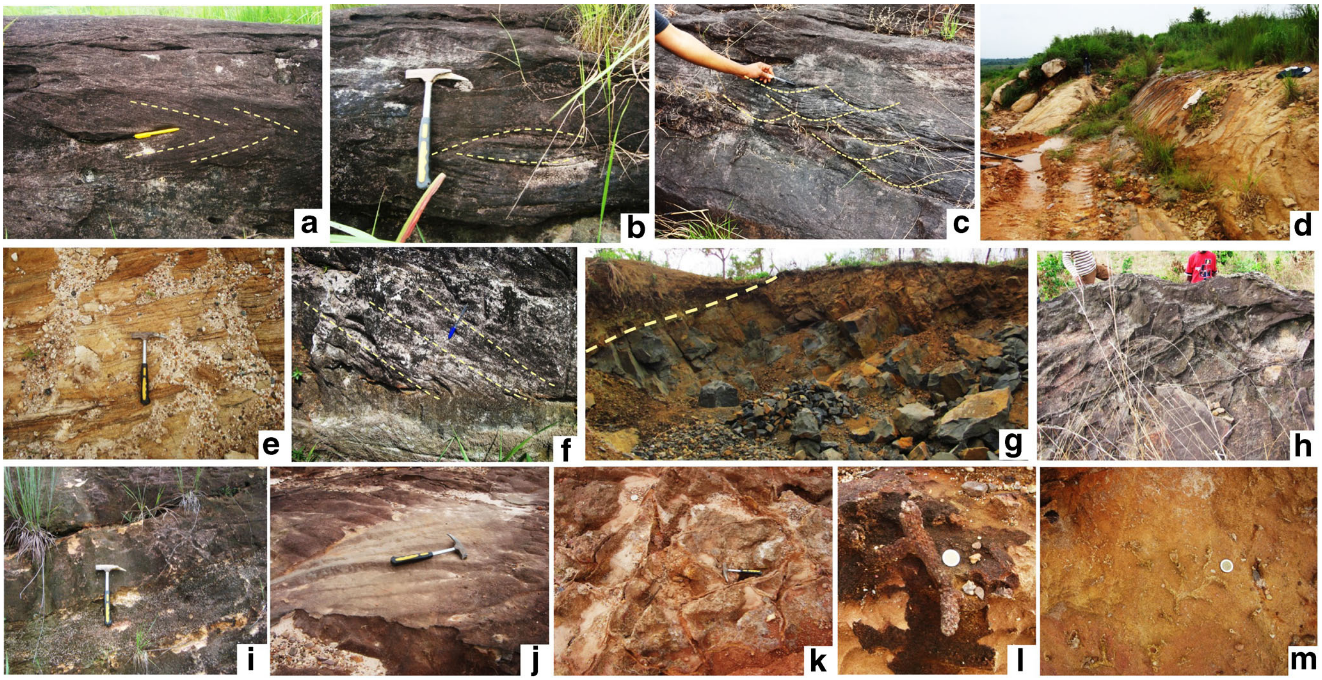

Fig. 8 **a** Herringbone cross-bedding structure on sandstone unit (CBS sub-facies); **b** Hummocky cross-bedding structure on sandstone unit (CBS sub-facies); **c** Trough cross-bedding structure on sandstone unit (CBS sub-facies); **d** Highly tilted sandstone and shale unit interstratifications; **e** Planar/parallel laminated sandstone unit (PPLS facies); **f** Tabular/planar cross-bed at a road-cut exposure along Afikpo road, about 300 m from Amaseri Junction (CBS facies); **g** Dolerite sill at Afikpo/water-works outcrop section (*yellow stripe* shows contact between the igneous body and conformable overlying shale unit; **h** Deformational bands on pebbly/conglomeritic sandstone unit exposed at Afikpo outcrop section (CS facies); **i** A road-cut exposure of Afikpo outcrop section showing probably a channel-fill sediment package with a basal conglomeritic unit; **j** Wave rippled structure on sandstone unit (RLS facies); **k** Conglomeritic clayey sandstone unit characterized by anastomosing joint structure; **l** Vertical burrows *Ophiomorpha* on pebbly medium-grained sandstone unit (CS facies); **m** Horizontal burrows of *Thallassinoides* on conglomeritic sandstone (CS facies). (NB: (Fig. 8**a**–**e**: outcrops of Ozara-Ukwu sections exposed on the sandstone ridges Ozara-Ukwu, Afikpo Area, SE Nigeria; Figs. 8**f**–**i**: Outcrops of Afikpo, water works and "Why worry spring" sections exposed on road-cuts and mining pits exposed along Afikpo road, SE Nigeria; Fig. 8**j**–**m**: Outcrops of Ngodo Hill section exposed at Ngodo area along Afikpo College road, Afikpo, SE, Nigeria; Person and geologic hammer for scale approximately 1.8 m [5.9 ft] tall and 1 ft, respectively)

Lithofacies and facies succession

Ten (10) lithofacies were identified across the Amaseri, Akpoha, Ibii, Ozara-Ukwu, Afikpo and Ngodo stratigraphic successions, and include the following: (i) medium–coarse sandstone (MCS) facies; (ii) fine sandstone (FS) facies; (iii) bioclastic limestone (BcL) facies; (iv) mudstone (MS) facies; (v) bioturbated siltstone (BSt) facies; (vi) bioturbated sandstone (BSs) facies; (vii) planer-parallel-laminated sandstone (PPLS) facies; (viii) ripple-laminated sandstone (RLS) facies; (ix) cross-bedded sandstone (CBS) facies; and (x) conglomeritic sandstone (CS) facies. Vertical log section at the various outcrop indicates the occurrence of two (2) stratigraphic/facies successions. These include the following: (i) fining-upwards/thinning-upwards (FU/TnU) succession that contains coarser grained facies near the base and progressively becomes finer upwards; and (ii) coarsening-upwards/thickening-upwards (CU/TkU) stratigraphic/facies successions that show overall finer grained facies near the base, which progressively becomes coarser grained (overall) towards the top with variable thickness of sediment package from few centimeters to meters. The northern through the central parts of study area shows a dominance of FU/TnU facies successions. This is contrary to the stratigraphic successions of outcrop sections in the northern part, which shows a predominance of CU/TkU facies succession (Fig. 9). These successions are made up of sediment packages that belong to various lithofacies. Detailed interpretation on these lithofacies is given below (Table. 1).

The medium–coarse sandstone (MCS) facies consists of basically horizontal bedded sandstone units. This facies outcrops at the basal part of Amaseri and upper part of Akpoha and Ibii sections (Figs. 5a, b, c and 11). They are grayish brown, highly consolidated fine, medium and coarse-grained sandstone units with moderately to poorly sorted sediment particles. They are devoid of internal sedimentary structures. MCS facies are found within a FU/TnU facies succession and litthofacies thickness varies from 0.1 to 0.5 m. Hand specimen of the MCS facies show sub-rounded mineral grains (Figs. 10a–e). In thin section, the facies consists of quartz

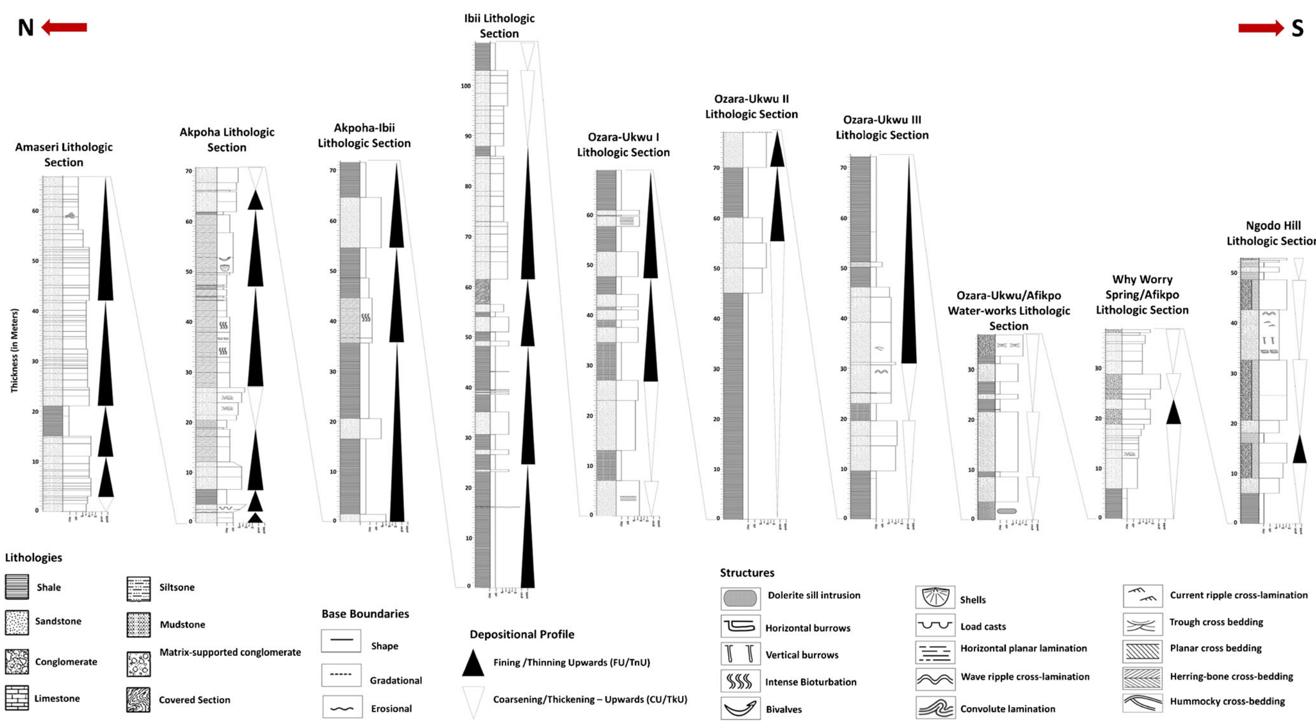

Fig. 9 Detailed measured sedimentological logs and stacking pattern/stratigraphic succession across Amaseri–Akpoha–Ibii–Ozara-Ukwu–Afikpo–Ngodo Hill outcrop sections (*N–S*), in Afikpo area and environs, southeastern Nigeria. (Note: thickness is in meters)

(about 60–70 %), feldspars (10 %), mica (2 %) and rock matrix (of about 20 %, mainly clay and silt-sized quartz, mica, feldspar and heavy minerals). The fine-grained units associated with this facies show a convolute laminated structure (a soft-sediment folding), which is the characteristic of beds of fine sand deposited rapidly by events such as turbidity currents or storms (Fig. 5f).

The fine sandstone (FS) facies is composed of well-sorted fine-grained sandstone with siltstone and shale units (Fig. 10g). This lithofacies outcrops mainly at the middle and upper parts of Ibii section (Fig. 11). The lithologic units of the FS facies are calcareous and the sandstone units exhibit concentric marks on the surface of large boulders (Fig. 7f). The sandstone units also show parallel lamination which suggests a rapid deposition from sediment laden flow (Nichols 2009). The FS facies is associated with interstratified sandstone and shale unit. The shale units of this facies are highly fissile, and the sections are dark gray to bluish gray but tends to be yellowish-reddish brown when weathered. MCS facies and FS facies, which comprise of fine, medium and coarse-grained sandstone, make up the bulk percentage of lithofacies occurring in the southern part of the study area (Table 1).

Bioclastic limestone (BcL) facies consists of gray colored, highly fossilferous lime-mud bed. They are exposed partly at the upper parts of Akpoha and Ibii outcrop sections (Figs. 6d, e and 11). The BcL facies were found occurring within silty-sandstone units. Hand specimen shows molds and calcite-mineralized shells of bivalves and brachiopods are present in the limestone units (Fig. 10h, i). BcL facies are characterized by the occurrence of grain-supported (sandy skeletal grain-rich packstone) allochems with sub-equal spar and micrite content. Lithofacies thickness ranges from 0.1 to 1 m. BcL facies are characterized by rock units that are typical of poorly washed bioclastic limestone as classified by Dunham (1962) and are attributed to the processes close to shallow marine shelf setting (Boggs 2001).

Mudstone (MS) facies comprises of two subordinate litofacies. These are the silty-shale and shale sub-lithofacies. Silty-shale sub-lithofacies is made up of dark gray colored, highly fissile shales with siltstone interlamination (lamina is about 2.0 mm). This sub-lithofacies appears to be heterolithic in nature, quite extensive in occurrence and are well exposed in the basal parts of Amaseri, Akpoha, Ibii and Ozara–Ukwu outcrop sections (Figs. 5e and 7g, i). Shale sub-lithofacies varied from slightly silty, laminated, brown shales to highly calcareous, fossiliferous, marine, gray shales. Another group of shales observed in outcrop were red, green, and purple mottled, calcareous shales. Lithofacies thickness varies from 0.5 to about 4 m. These outcrop at the basal and upper parts of Ozara–Ukwu, Afikpo and Ngodo Hill sections. The mudstone (MS) facies (silty-shale and shale sub-lithofacies) indicates deposits that may have formed as a result of tidal differences (Reyment 1965). This also reflects suspension deposit in low-energy settings below storm wave base (Banerjee 1980 and Boggs 2001).

Table 1 Lithofacies occurrence and characteristics, facies association and depositional process interpretation in the Afikpo area and environs, southeastern, Nigeria

	Lithofacies and subordinate lithofacies	Facies association	Characteristics	Occurrence	Depositional processes and interpretation
1	Medium–coarse sandstone (MCS)	FA 2	Medium to coarse-grained sandstone, well stratified and partly massive. These are associated with sandstone units and shows convolute laminated structure which is an evidence of soft-sediment deformation	Abundant	Deposited rapidly by such events as grain flow and turbidity currents and storms events (Miall 2000, Nichols 2009)
2	Fine sandstone (FS)	FA 3	Well-sorted very fine to fine-grained calcareous sandstone units. These are associated with siltstone and shale units	Common	Rapid deposition from sediment-laden flows (Nichols 2009)
3	Bioclastic limestone (BcL)	FA 4	Gray to dark gray fossiliferous limestones with substantial amount of calcareous shell fragment. BcL comprises of sandy skeletal grain-rich packstone with subequal spar and micrite content	Probably minor	Patch reef deposits washed by wave and tide action. Lagoonal to near shallow (Proximal) marine shelf settings (Spring and Hansen 1998; Boggs 2001)
4	Mudstone (MS)—(silty-shale and shale sub-lithofacies)	FA 1	Dark-gray silty-shale with thin siltstone to very fine-grained sandstone interlamination; laminated clay shale with millimeter-scale laminae	Abundant	Deposits mostly within oxygenated, low-energy setting, probably below fair-weather and storm wave base (Boggs 2001), in marine setting (Reyment 1965; Banerjee 1980; Pemberton et al. 1992)
5	Bioturbated siltstone and sandstone (BSt)	FA 2	Bioturbated silty shale, siltstone, and very fine to fine-grained sandstone. Intensity of bioturbation increases near bed tops; beds are completely burrowed by *Planolites* ichnofossils (*Cruziana* Ichnofacies)	Common	Deposits below fair weather wave base in marine setting. *Cruziana* ichnofacies, reflecting the work of an equilibrium community developed under fully marine conditions (Frey et al. 1990, Pemberton et al. 1992, MacEachern and Pemberton 1994)
6	Bioturbated sandstone and sandstone (BSs)	FA 2	Bioturbated fine to coarse-grained sandstone, characterized by the presence of *Thallassinoides* and *Ophiomorpha* burrows that belongs to the *Glossifungites and Skolithos* ichnofacies respectively	Minor	Sediments deposited below fair weather wave base (Frey et al. 1990; Pemberton et al. 1992)
7	Planer-parallel laminated sandstone (PPLS)	FA3	Light gray to brownish very fine to coarse-grained sandstone, with thin bedded planer/parallel laminated sandstones	Common	Planer bed flow, deposition under upper flow-regime, plane-bed conditions in marine setting (Miall 1978)
8	Cross-bedded sandstone (CBS)—(tabular/planar; trough; Herringbone and Hummocky cross-bedded sandstone sub-lithofacies)	FA 4	Medium to very coarse-grained sandstone and partly pebbly. CBS lithofacies are characterized by solitary to grouped planar, trough, herringbone and hummock cross-beds in sets a few decimeters to 1 m thick	Minor	Dunes (lower flow regime), (Miall 1978, 1996). Bars deposits within tidal inlets
9	Ripple laminated sandstone (RLS)	FA 5	Very fine to very coarse and partly pebbly. These are characterized by ripple cross laminated structures	Minor	Lower flow regime (Miall 1978). Oscillatory wave processes that dominate in the upper shoreface environment, above fair-weather wave base (Gowland 1996)
10	Conglomeritic sandstone (CS)	FA 5	Muddy conglomeritic sandstone associated with coarse-grained sandstone containing dispersed pebbles. Characterized by abundant *Thalassinoides* (*Glossifungites* ichnofacies)—bearing muddy sandstone and *Ophiomorpha* (*Skolithos* ichnofacies)—bearing sandstone	Minor	Transgressive lag deposits above firm ground in a shallow sandy shoreline (Pemberton et al. 1992; MacEachern and Pemberton 1994)

BSt facies are made of light gray to brown calcareous siltstone unit associated with very fine-grained sandstone units and calcite mineralized veins/veinlets and surfaces (Fig. 7e). They are intensely bioturbated and burrowed by *Skolithos* ichnofossils and *Planolites* ichnofossils (Fig. 7c, h). These ichofossils belong to the *Skolithos* ichnofacies and *Cruziana*

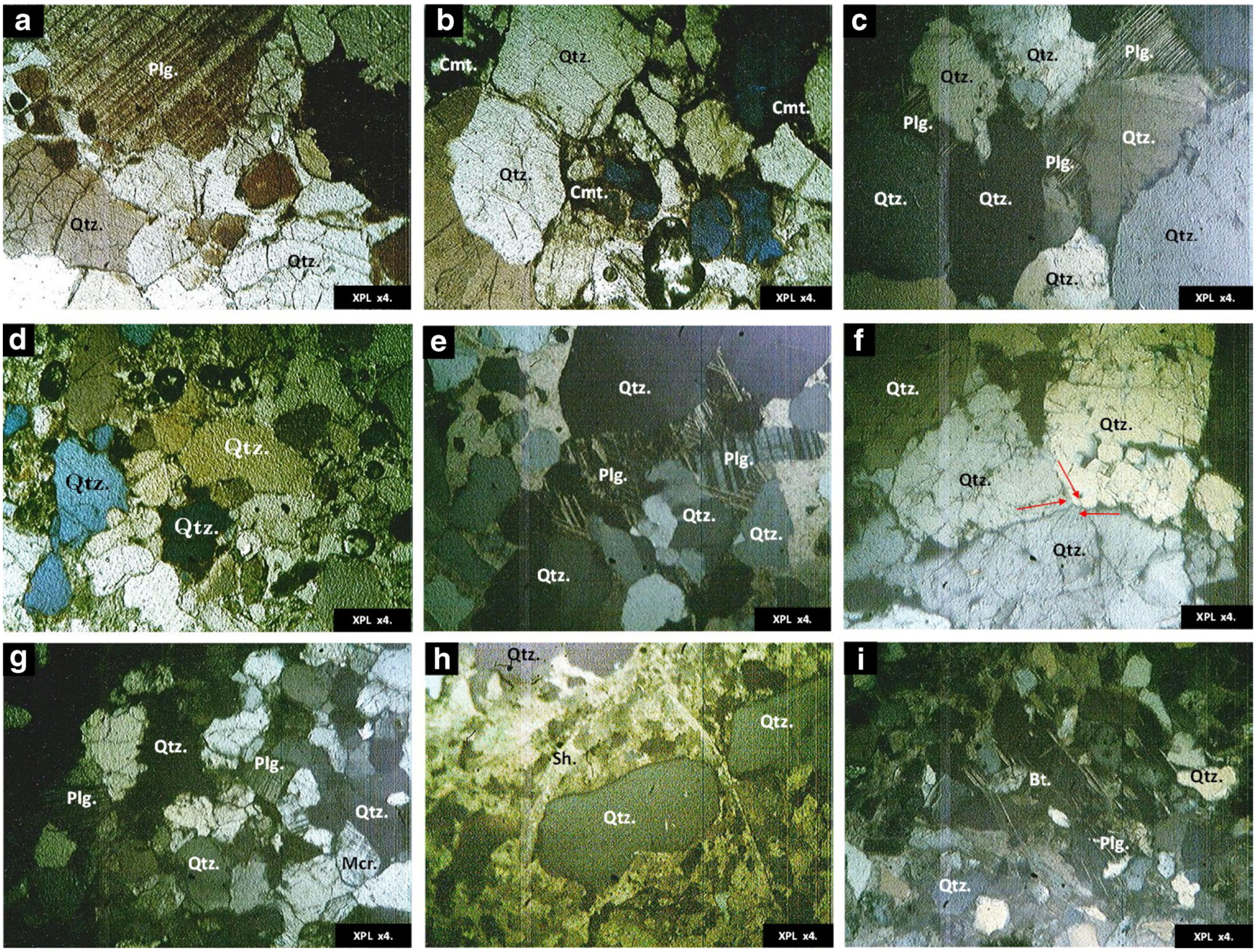

Fig. 10 **a** Photomicrograph of a pebbly poorly sorted, medium to coarse-grained sandstone, plagioclase (well-developed polysynthetic twinning) and quartz grain show fractures due to deformation; **b** Photomicrograph of a moderately sorted, medium to coarse-grained sandstone with quartz grain and accessory mineral forming cements; **c** Photomicrograph of a moderately sorted, coarse-grained sandstone with angular to sub-angular minerals; **d** Photomicrograph of a sub-round, moderately sorted, medium-grained sandstone; **e** Photomicrograph of a moderately sorted, fine to medium-grained sandstone; **f** Photomicrograph of a well-sorted, quartz-rich, coarse-grained, sandstone showing the presence of sutured grain contact and quartz grain, which displays dark streaks and healed fractures due to deformation; **g** Photomicrograph of a poorly rounded, well-sorted, fine-grained sandstone with feldspars minerals; **h** Photomicrograph of a bioclastic limestone with calcite-filled bivalve shell that shows floating grain contact; **i** Photomicrograph of moderately sorted, fine-grained siltstone showing some partial crystal alignment; (NB: Fig. 10**a**–**d** photomicrograph = thin section of rock samples Amaseri outcrop section; Fig. 10**e**–**g** photomicrograph = thin section of rock samples from Akpoha outcrop section; Fig. 10**h**–**i** photomicrograph = thin section of rock samples from Ibii outcrop section. *Abbreviations*: *Qtz.* quartz, *Plg.* plagioclase, *Mrc* microcline, *Bt.* biotite, *Cmt.* cements, *Sh.* shell. Thin sections are displayed in XPL = cross-polarized light)

ichnofacies respectively, which are softground substrate-controlled, found in high and medium energy marine environments (Pemberton et al. 1992). Their thicknesses are in the range of 0.1 to 0.5 m. In thin section, the facies shows the presence of quartz (45 %), feldspar (25 %), calcite (27 %), rock fragment (1 %) and accessory minerals (2 %), such as biotite (Fig. 10i). This outcrops at the basal and upper parts of Akpoha and Ibii section (Fig. 7b, c, d, h).

BSs facies consists of yellowish to reddish brown, bioturbated, pebbly medium to coarse-grained sandstone units. They are characterized by the presence of *Thallassinoides* and *Ophiomorpha* burrows that belong to the *Glossifungites* and *Skolithos* ichnofacies, respectively. These ichnofacies are dwelling burrows of deposit and suspension feeder found within the shoreface to offshore marine environments (Frey et al. 1990). These burrows and bioturbation disturbed original sedimentation features and somewhat homogenized the sediment, giving it a massive appearance. This facies suggests deposits of fully marine condition with sediments deposited below fair weather wave base (Pemberton et al. 1992). They outcrop at the Afikpo and Ngodo Hill sections (Fig. 8l, m).

PPLS facies consists of mainly gray to brown colored fine and medium-grained sandstone units with thin-bedded laminations of 0.01 to 0.20 m thick. The sandstone units of this

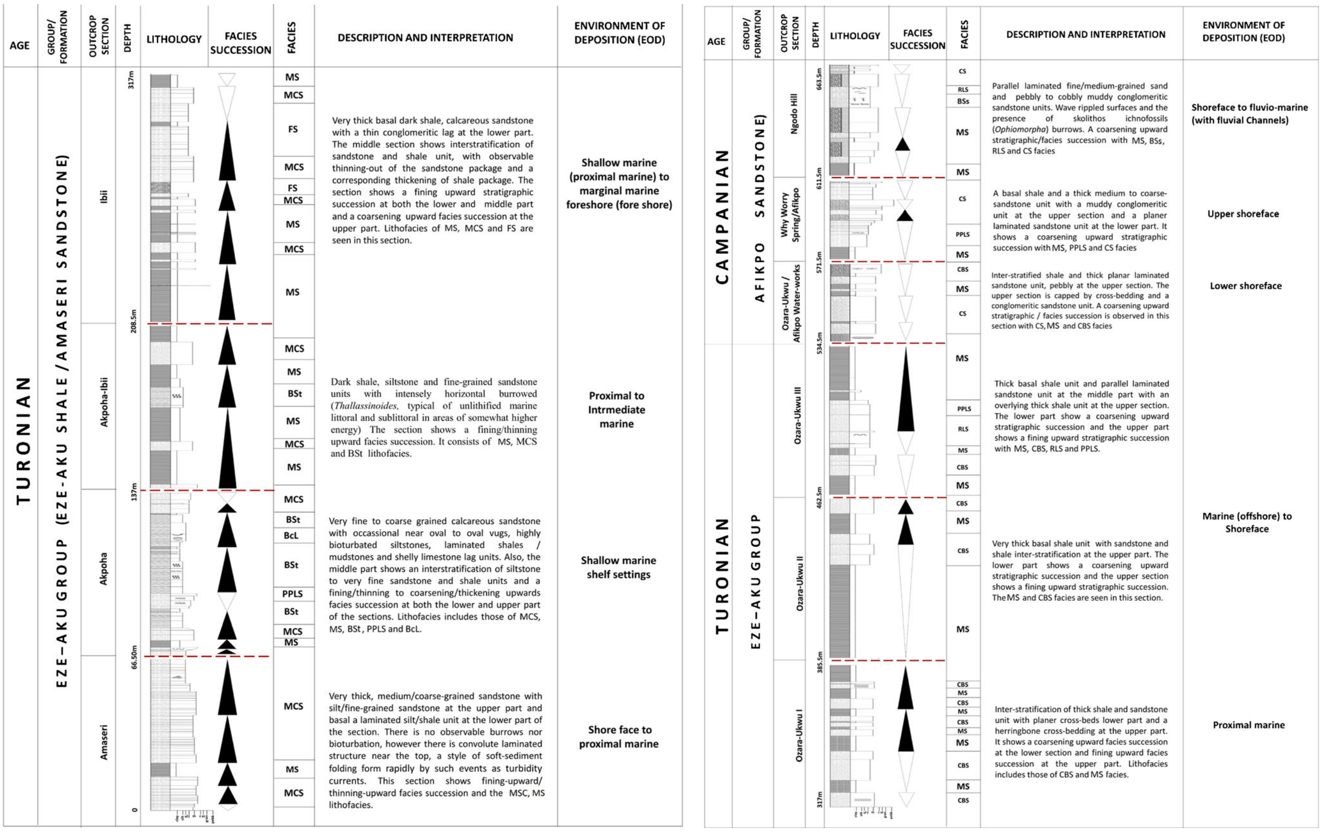

Fig. 11 Stacked sedimentologic log of the outcrop sections showing lithofacies, facies succession and their environments of deposition implication

facies show planar or parallel laminated primary sedimentary structures with no observable burrows nor bioturbation (Fig. 8e). They occur within the coarsening and thickening-upward facies succession. PPLS facies are well exposed at Akpoha, Ibii and Ozara–Ukwu sections. The PPLS facies suggest deposition under upper flow-regime, typical of plane-bed conditions in marine setting (Miall 1978, 1996; Blatt et al. 1980).

Cross-bedded sandstone (CBS) facies comprises of four (4) sub-facies. These include the following: (i) tabular cross-bedded or planar-bedded sandstone; (ii) trough cross-bedded sandstone; (iii) herringbone cross-bedded sandstone; and (iv) hummocky cross-bedded sandstone (Fig. 8a, b, c, f). The CBS facies consist of a grayish brown, fine, medium and coarse-grained sandstone. They are moderately well to poorly sorted, with pebbly and conglomeritic beds at some sections. The thickness is in the range of 1.0 to 6.0 m. They are characterized by planer cross-beds with tangential contacts, trough cross-beds, herringbone cross-beds and hummocky cross-bed structures. The CBS facies outcrops at the basal, middle and upper parts of the Ozara-Ukwu and Afikpo sections. The CBS facies are formed by the migration of straight to sinuous crested dunes or bars (Miall 1978, 1996; Kendall 2005 and Nichols 2009). Tabular cross-bedding is formed mainly by migration of large-scale, straight-crested ripples and dunes. The foreset laminae of tabular cross-beds are curved so as to become tangential to the basal surface. It forms during lower flow regimes (Boggs 2006). Trough cross-bedded sandstone are associated with sand dune migration, with foreset beds that are curved and merge tangentially with the lower surface. The herringbone cross-bedded sandstones are formed in tidal areas, which have bidirectional flow, and structures are formed with alternating layers of cross-beds dipping in opposite directions that reflect the alternating paleocurrent (Nichols 2009). Hummocky stratification apparently is formed most commonly by re-deposition below normal fair-weather wave base of fine sand delivered offshore by flooding rivers and scour of the shoreface or shoals by large waves (Dott and Bourgeois 1982). Deposition involves both fallout from suspension and lateral tractive flow due to wave oscillation.

RLS facies consists of mainly grayish-brown pebbly and conglomeritic clayey sandstone and fine-grained sandstone units. The thickness of RLS facies ranges from 0.1 to 3.5 m. They are characterized by wave ripple laminated structures (Fig. 8i). They outcrop at Ozara–Ukwu and Ngodo Hill sections. The RLS represents sediment deposits formed at lower flow regime condition in marine setting (Miall 1978, 1996; Blatt et al. 1980).

Conglomeritic sandstone (CS) facies is made up of brown to reddish-brown muddy conglomeritic sandstone. The lithofacies thickness varies from 0.5 to 4 m. The sandstone units are pebbly to cobbly and are characterized by vertical

Ophiomorpha (*Skolithos* Ichnofossil) and horizontal *Thalassinoides* burrows (*Glossifungites* ichnofossil) (Fig. 8h, j). This CS facies is seen at the Ozara–Ukwu, Afikpo and Ngodo Hill section with a coarsening/thickening facies succession. Conglomeritic sandstone facies (CS) consists of *Thalassinoides*-bearing muddy sandstone that belongs to *Glossifungites* ichnofacies and *Ophiomorpha*-bearing sandstone which belongs to *Skolithos* ichnofacies. This lithofacies suggests sediment deposited as transgressive lag above firm ground in a shallow sandy shoreline (Pemberton et al. 1992; MacEachern and Pemberton 1994).

Facies associations

Identified lithofacies were grouped into five (5) genetically related facies associations (comprising dominant and subordinate lithofacies) to aid paleo-depositional environment interpretation. This grouping was based on observed vertical facies succession, lateral facies transition, nature and geometry of bedding contacts, sedimentary structures and gross mineralogical composition. Overall, interpreted facies associations broadly reflect deposition in a tide-influenced, storm wave-dominated shelf setting. Figure 12 shows the spatial distribution of these facies associations and their environments of deposition.

Facies association (FA) 1—oxygenated offshore/open shelf deposits This facies association is dominated by the mottled, gray, laminated shale sub-facies, and dark-gray, fissile interlaminated silty-shale sub-lithofacies of MS facies. This association typically marks the base of the studied sections, extending laterally across the study area. The observed mottled appearance is the result of intense biogenic activity and points to deposition within oxygenated, low-energy environmental conditions, which allowed marine organisms to thrive (Pemberton et al. 1992). Also, the laminated nature of the shale further suggests deposition within a mostly low-energy setting, probably below fair-weather and storm wave base (Boggs 2001).

Facies association (FA) 2—storm wave-dominated shelf deposits This facies association is dominated by moderately to poorly sorted, high consolidated medium–coarse-grained sandstone of MCS facies; hummocky cross-bedded sandstone sub-lithofacies-4 (CBS), BSs facies, BSt facies and PPLS facies. The association of FA 2 with FA 1 suggests deposition in an adjacent environment, inferred to be a storm wave-dominated shelf. Sand input was probably initiated during periodic storm events, which generated shallow water turbidity currents on the shelf (c.f. Walker 1985, Pattison et al. 2007). The reduced feldspar content of MCS facies and

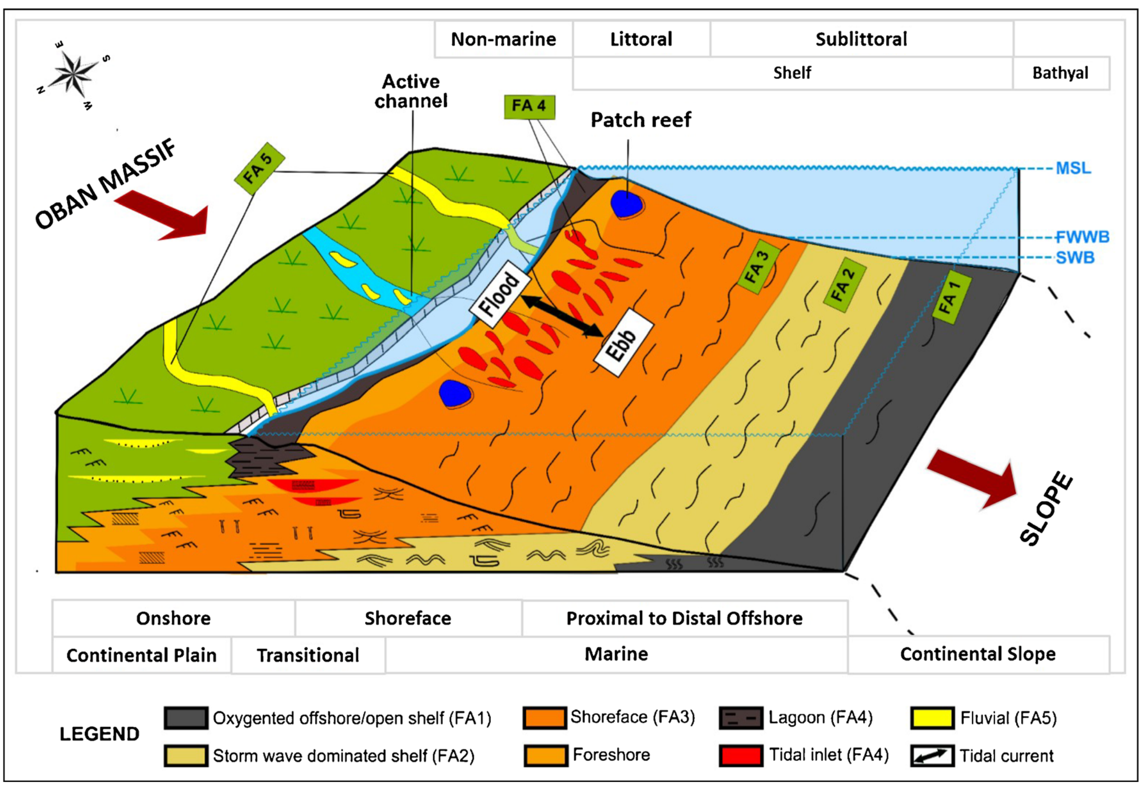

Fig. 12 Block diagram of environments of deposition model showing the distribution of facies association of various lithofacies delineated in the Afikpo area and environs

dominance of quartz may indicate storm wave reworking of adjacent shoreface deposits and redeposition as shelfal "turbidites" or tempestites, mainly during relative sea level fall (c.f. Wonham et al. 2014). Indeed, storm deposits are similar in character to turbidity current deposits, only differentiated by the preservation of hummocks and/or swales in the rock record (Einsele 2000; Karim 2007). BSt and BSs facies developed below fair-weather wave base and above storm wave base, during quieter periods following storm events. The zone described herein has also been referred to as the "lower shoreface" zone (Weise 1980) and the "offshore transition" zone (Walker and Plint 1992).

Facies association (FA) 3—shoreface deposits This facies association is dominated by amalgamated, coarsening and thickening-upward, medium-grained planar and trough cross-bedded sandstone sub-lithofacies of CBS facies, wave-RLS facies, and fine to medium-grained PPLS facies, which in most parts directly overlie offshore mudstones (FA 1) and/or hummocky cross-stratified sandstones (FA 2). The occurrence of symmetrical wave, wave-ripple laminated sandstone suggests deposition/reworking by oscillatory wave processes or wave reworking of tractional current ripples that dominate in the upper shoreface environment, above fair-weather wave base (Gowland 1996), while observed coarsening and thickening-upward trend suggest increasing energy level during progradation/shoaling (c.f. Ekwenye et al. 2014). Planar and trough cross-beds, horizontal to low-angle planar parallel laminations, wave ripples and prominent *Ophiomorpha* burrows are interpreted to be the result of vigorous current and wave activity, which compares favorably with that found in the upper shoreface zone of intermediate to high-energy wave coasts of Howard and Reineck (1979, 1981). Non-amalgamated sandstone units that are occasionally moderately bioturbated and interbedded with siltstone units (BSt, BSs and FS facies) were probably deposited in the lower shoreface setting.

Facies association (FA) 4—tidal inlet/lagoonal deposits Observed herringbone cross-bedded units (CBS facies, Fig. 8a) and fine sandstone – siltstone/shale couplet described for FS facies are interpreted to have been deposited as bars within tidal inlets. Subordinate facies include planar cross-bedded sandstone sub-lithofacies (CBS) and trough cross-bedded sandstone sub-lithofacies (CBS). Bimodal current (herringbone) patterns are the result of opposing and alternating flood and ebb tidal currents, although these are of minor occurrence within the study area. More commonly preserved are unimodal current patterns that suggest a southwesterly dominant net sand transport direction and a weaker opposing direction. Abundant mud drapes, preserved at the foresets of cross-beds during low-tide periods and the occasional heterolithic bedding, are a common feature of tide-influenced depositional environments (c.f. Hassan et al. 2013). Associated with the tidal inlet deposits are gray colored, highly fossilferous lime-mud bed with broken-up bivalves and brachiopod shell fragments (facies BcL). Mineralogically, they are classified as packestones (Table 1) using the Dunham (1962) scheme. The limestone beds are thought to have accumulated in transgressive shallow waters (patch reef deposits), but were subsequently broken up and washed into adjacent lagoon by wave and tide action.

Facies association (FA) 5—fluvial channel deposits This facies association is dominated by reddish-brown muddy conglomeritic sandstone (facies CS), trough and planar cross-bedded sandstone sub-lithofacies (CBS). Subordinate lithofacies include planar parallel and ripple laminated sandstone facies (PPLS and RLS). On a finer scale, the muddy conglomeritic sandstone typically marks the base of erosive channel-like structures. However, overall, this facies association is stacked to form coarsening/thickening-upward successions that indicate waxing fluvial currents, typical of fluvial channels settings (Howard and Reineck 1979, 1981). This facies association dominates the Afikpo Sandstone unit.

Discussion

Stratigraphic evolution and provenance

Outcrop studies show that several factors affected sedimentation, thus controlling depositional environments during Cenomanian to Campanian time. The high frequency of sandstone and shale units interstratification across the study area, occurring during the Turonian to Coniancian age (Eze-Aku Group— comprising of Eze-Aku Formation and Amaseri Sandstone in Abakaliki Basin) is an indication of sediments deposited at various episodes of relative sea level changes (Simpsons 1954; Amajor, 1987). This suggests two depositional conditions, namely: (a) marine transgressive episodes, where sandstones/siltstones (typical of nearshore deposit) are being overlain by shale (typical of shallow marine deposit) and limestone (marine deposit) indicating sediment deposition during a time of sea level rise and (b) marine regressive episodes, where marine deposits are overlain by shallower marine and nearshore deposits, indicating sediment deposition during a time of falling sea level (Fig. 1). This conforms to the findings of Ukaegbu and Akpabio (2009). Evidence of tectonic activities (structural deformation which gave rise to folded, tilted and fractured rock units) and magmatism (igneous/intrusive emplacement) observed within the area are geologic features associated with the mid-Santonian tectonic episode that affected the southern Benue Trough (Benkhelil 1989). Major plate reorganization related to the Santonian compressional event (Olade 1975; Benkhelil 1989) led to a change in prevailing depositional environment and the establishment of a fluvial system that shed sediment from the uplifted units into the Campanian (Nkporo Group—Afikpo Formation) Anambra Basin. Relatively undisturbed sediment packages (Afikpo Formation) observed at the southern part of the study area with low stratigraphic dip shows that these sediments were deposited after the deformation stage (Hoque and Nwajide 1985; Murat 1972; Petters 1991; Ojoh 1992).

The study area consists of three (3) lithostratigraphic units deposited during the Turonian to Coniancian (Eze-Aku Group—comprising of Eze–Aku Formation and Amaseri Sandstone) and Campanian age (Nkporo Group—Afikpo Formation) of the Middle–Upper Cretaceous successions of Southeastern Nigeria (Fig. 1). Petrographic studies on some litofacies of Amaseri sandstone show texturally immature sandstones (poor to moderate sorting and angular to subangular nature of mineral grain) belonging to the arkosic or feldspathic mineral class on account of the high feldspar content up (to 25 %). The abundance of feldspars (which in many cases weather easily when compared to quartz) may be due to the high feldspar content from parent rock and relatively short distance transport or near-source provenance. These sedimentary materials were probably derived from proximal southeastern basement granites (Oban Massif). This agrees with Hoque and Nwajide (1985) classification, as feldspathic sandstones which were formed during the trough stage in the evolution of the Benue Trough.

Lithofacies and environments of deposition

Lithofacies analysis reveals that the distribution of the ten (10) lithofacies delineated in this study is such that the MS (silty-shale sub-lithofacies), MCS, FS and BcL, BSt lithofacies outcrops mainly in the northern and central parts whereas MS (shale sub-lithofacies), BSs, PPLS, CBS and CS facies outcrops mainly in the southern part. The occurrence of these lithofacies ranges from abundance to common and minor (Table 1). More also the distribution of lithofacies successions across the study area shows a predominance of the following: (i) fining-upwards/thinning-upwards (FU/TnU) succession in the northern and central part, an indication of a deepening or shallow to proximal offshore marine environments (transgressive environment—shoreline advancing landward with time), and (ii) coarsening-upwards/thickening-upwards (CU/TkU) succession towards the southern part, an indication of shoaling or proximal offshore to shallow marine environment (regressive shelf environment—shoreline advancing seaward with time). This does not all agree with the model developed by Banerjee (1980) which classified the facies succession as only a vertical growth in coarsening upward succession typical of sub-tidal sand bars.

In addition, the grouping of these lithofacies and subordinate lithofacies into five (5) facies association gave more insight to the understanding of the environments of deposition. The mudstone–MS lithofacies (silty-shale and shale sub-lithofacies) represents deposits within oxygenated offshore/open shelf (FA 1) in mostly low-energy setting, probably below fair-weather and storm wave base. The medium-coarse-grained sandstone—MCS lithofacies; cross-bedded sandstone—CBS lithofacies (hummocky cross-bedded sandstone sub-lihofacies 4), bioturbated siltstone—BSt lithofacies, bioturbated sandstone—BSs facies and planar-parallel-laminated sandstone—PPLS lithofacies are storm wave-dominated shelf deposits (FA 2). Okoro and Igwe (2014) argued for a deep water depositional environment for observed similar characteristics of this facies association, on the premise that there was a marked absence of sedimentary structures of storm origin. However, the present study shows the occurrence of hummocky cross-stratified sandstones (Fig. 8b), associated with MCS facies. The CBS lithofacies (tabular/planar, trough cross-bedded sandstone sub-lithofacies) and ripple laminated sandstone—lithofacies (wave ripple laminated sandstones) comprises of shorefaces deposits (FA 3) above fair-weather wave base. Subordinate lithofacies such as herringbone cross-bedded sandstones (CBS lithofacies) and bioclastic limestone—BcL lithofacies (transgressive shallow waters deposits, subsequently broken-up and washed into adjacent lagoon by wave and tide action) constitute parts of tidal inlet/lagoonal deposits (FA 4), respectively, in a shelf environment. The occurrence of BcL facies concurs with the work of Hoque (1976), which recorded that the siliciclastic Eze–Aku Formation contains scattered lenses and layers of bioclastic limestone within fine bioturbated silty-sandstone. The conglomeritic sandstone (CS) lithofacies with associated subordinate lithofacies such as CBS, PPLS and RSL indicates fluvial channel deposits (FA 5). Primary sedimentary structures associated with these lithofacies such as laminations and cross-beddings suggest deposition in a shelfal environment. The BSt and BSs lithofacies, characterized by the abundance of *Planolites* (*Cruziana* ichnofacies) and multidirectional burrows, suggest deposits of fully marine and that there was sufficient time between energy pulses for fossil fauna to thoroughly colonize the sediment-water interface. The CS lithofacies, which is characterized by the presence of *Ophiomorpha* burrows (*Skolithos* ichnofacies), also reflects deposits at the upper shoreface environment whereas the *Thallassinoides* (*Glossifungites* ichnofacies) found in unlithified marine littoral and sub-littoral surfaces suggests moderate-energy settings or in areas of somewhat higher energy where semi-consolidated micritic or siliciclastic substrates offer resistance to erosion (Pemberton et al. 1992). Overall, interpreted facies succession and lithofacies association are the result of multiple shoreline regression and transgression and deposition of progradational and retrogradational units, respectively, from the Turonian to end Coniacian. Detailed facies analysis suggests deposition in a mixed tide and storm wave-dominated, thus spanning from the littoral (marginal marine) to sub-littoral (shallow and partly deep marine) environment of depositions (Fig. 12).

Conclusion

Detailed geologic mapping of various outcrop sections (Amaseri, Akpoha, Ibii, Ozara-Ukwu, Afikpo and Ngodo sections) and generated sedimentologic logs integrated with lithofacies analysis have provided useful data for interpreting processes that were prevalent during sediment packages and lithofacies deposition and their environments of deposition (EOD) in southeastern part of the southern Benue Trough. Ten (10) lithofacies with their associated subordinate lithofacies and (5) lithofacies associations delineated across the Amaseri–Ngodo outcrop sections span various environments of deposition. These include sediment packages deposited in the following: (i) oxygenated offshore/open shelf (FA 1) in mostly low-energy setting, probably below fair-weather and storm wave base; (ii) storm wave-dominated shelf deposits (FA 2) in a shelfal environment; (iii) shorefaces deposits (FA 3) above fair-weather wave base; (iv) tidal inlet/lagoonal deposits (FA 4) in a shelf environment; and (v) fluvial channel deposits (FA 5). Furthermore, there is predominance of a fining-upwards/thinning-upwards (FU/TnU), typical of deepening or shallow to proximal offshore marine environments in the northern and central part, and dominance of coarsening-upwards/thickening-upwards (CU/TkU), typical of shoaling or proximal offshore to shallow marine environment in the southern part of the area. Generally, these lithofacies represent sediment package deposited in the littoral (marginal marine) through sub-littoral (shallow and partly deep marine) environment of depositions.

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