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Physical and Textural Characteristics of Eze–Aku Sandstone at Akpoha and Environs, Afikpo Basin, Nigeria

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ABSTRACT

Lithofacies defined by physical and textural characteristics, lithological contacts and diagenetic features in outcrops were studied to determine the paleo–depositional processes and environments of deposition, and petrographic classification of Eze–Aku sandstone at Akpoha and Evirons. Sedimentary structures identified include hummocky and swaley cross stratifications, decalcification holes, concretions, planar cross beds, inclined parallel bedding in aggradation-progradational sandstone units, parallel laminations to wave ripple laminations and some weathering features. Six lithofacies were identified and they include laminated silty shales/shales, hummocky and swaley cross stratified fine-grained sandstones, inclined parallel bedded medium- to coarse-grained sandstones, calcareous sandstones, cross bedded medium grained sandstone and horizontal to wave-ripple laminated very fine–to fine–grained sandstone. The characteristics and associations of lithofacies show that the sandstones of Eze–Aku Formation in the study area were deposited in storm dominated shallow marine environment. The sandstones are variably indurated and thin sections analysis shows cementation and intense compaction; angular to subrounded, poor to moderately sorted and fine to coarse grains, as well as minerology of grains consisting of monocystalline quartz, feldspar, rock fragments and cement with average percentage compositions of 55-60.5, 23-26.5, 1-5, and 5-8, respectively. The sandstones were therefore classified as immature arkosic sandstones formed from sediments transported by low density fluid and sourced from plutonic rocks. The variable degrees of induration of samples from different outcrops can be attributed to variable level of compaction by overburden load or tectonic compression and possibly mild metamorphism caused by Santonian thermotectonic event.

1. Introduction

Eze–Aku sandstone at Akpoha and environs is part of Eze–Aku Formation of Afikpo Basin- a sub-basin of Benue Trough of Nigeria. Eze–Aku Formation has been studied by several authors. According to Reyment (1965), it was deposited during the Turonian transgression, and has lithologies that include shale, sandstones and calcareous sandstones. Murat (1972) identified sandstones and shales of Eze–Aku Formation to represent marine regression and transgression respectively. Amajor (1987) adduced that the Formation was deposited in storm dominated depositional environment. Akpofure and Dedei (2018) were also of the view that it was deposited in shallow marine shelf environment. Ukaegbu and Akpabio (2009) identified an unconformity boundary separating the Turonian Eze–Aku Formation from the older Albian–Cenomanian Formation. They divided the sandstone of Eze–Aku Formation into five sandstone members, viz, Ibii, Akpo–Ezi, Akpoha, Amaseri and Amate–Elu sandstones. This paper is mainly on the Akpoha and environs sandstones.

The studied Eze–Aku sandstone outcrops are located partly at Amasiri and mainly at Akpoha and environs in Afikpo North Local Government Area (LGA) of Ebonyi State of Nigeria. The location is within the Afikpo Basin, south eastern part of Benue Trough in West Africa (Fig. 1). The study area lies between latitude 5^o54^I to 5^o58^I N and 7^o51^I to 7^o59^I E, and about 43 km from Abakaliki, the capital city of Ebonyi state. The area has an undulating topography with sandstone ridges and valley/plains of shales. The mean elevations above sea level ranged from 21 in lowland to about 52 m in highland areas and about 73 m on top of sandstone ridges. A study of outcrops at Akpoha and environs and the excellent works of most of the mentioned authors revealed few sedimentary structural and textural features that deserve further interpretations and documentation especially in the context of sedimentology. Their partial omissions in few past studies could be attributed to the numerousness of outcrops and restricted accessibility by civilization and vegetation. Therefore, the aim of this paper is to document: 1. The physical sedimentary structural and the textural features identified in the field and thin sections, and 2. The paleo-depositional processes and environments of deposition from the study of physical sedimentary structures and textural characteristics.

1.1. Geological Setting

The geology of the study area is that of Afikpo Basin of southern Benue Trough, Nigeria, well documented by Ukaegbu and Akpabio (2009) and others. Benue Trough is a Northeast-Southwest folded rift basin that runs diagonally across Nigeria (Reijers et al., 1997). It is divided geographically from northeast to south west into northern, central and southern Benue Trough. Its tectonic history dates to the Mid-Cretaceous (Aptian–Albian) times when the South American plate separated from African plate in a junction of triple rift directions (Brice et al., 1982). Two out of the three rifting directions successfully separated to form the divergent Atlantic Oceanic basin that today separates the African and south American continental plates. But the separation in the third rifting direction failed and has been described as an aulacogen (Burke 1970). However, taphrogenic subsidence along the transform faults of the failed rift resulted in the formation of an intracratonic basin or mobile zone called the Benue trough (Reijers et al, 1997). The southernmost section of the intracratonic mobile zone or the southern Benue Trough was the Abakaliki trough with western boundary separated from the stable craton by an extended platform called Anambra platform, while the eastern boundary was separated by the Ikpe platform from the stable craton of Ituk high and Oban massif (Murat, 1972). Between Santonian and Early Campanian, there was collisional tectonism associated with regional folding and traces of magmatism. Consequently, the Abakaliki trough in the southern Benue Trough was uplifted to form the Abakaliki anticline while the adjacent Anambra and Ikpe Platforms were down warped to form the Anambra basin in the west and the Afikpo basin in the east respectively. The axis of sediment deposition was displaced to that of Anambra and Afikpo basin. The folding associated with the Santonian folding also resulted in the formation of the Keana anticline and Awe syncline in the central Benue Trough (Akande et al., 2011).

From Albian to Maastrichtian, the Benue trough was subjected to episodes of marine transgression and regression resulting in the formation of sedimentary cycles. But the extent of marine transgression decreased over time resulting in the decrease of marine sedimentary rock units' thickness from south to north of the trough. Therefore, the stratigraphy of southern Benue Trough, where the study area is located consists of three unconformity bounded sediment deposited in three sedimentary depositional cycles of transgression and regression: Albian - Cenomanian, Turonian–Coniacian and Campanian–Maastrichtian sedimentary cycles (Akande et al., 2011). The oldest Aptian–Cenomanian successions called the Asu River Group was deposited in the first depositional (Albian–Cenomanian) cycle (Fig. 1A). It consists of volcaniclastics, arkosic sandstones, siltstones, marine shales and limestone which overly the Pre–Cambrian to Lower Paleozoic crystalline basement rocks (Akande et al. 2011; Whiteman, 1982). Asu River Group being the deposit of the first marine transgression is widespread across the trough. The Asu River Group is overlain by the second sedimentary (Turonian–Coniacian) cycle successions called Eze–Aku and Awgu Formations consisting predominantly of marine shales, siltstones calcareous sandstones and sandstones (Ukaegbu and Akpabio, 2009). The Eze–Aku Formation is overlain by the third sedimentary (Campanian–Maastrichtian) cycle, the post Santonian tectonic sediments called the Proto–Niger delta successions consisting of Nkporo/Enugu shale, the coal measures-Mamu, Ajali and Nsukka Formations (Fig. 1A). Due to the limited landward extent of Campanian marine transgression, the post-Santonian sediments were not deposited in the study area. The only outcropped Pre-Santonian sediments of the first and second depositional cycle in the study area have been folded, faulted and uplifted and are clearly marked by major anticlinal and synclinal structures consequent to the Santonian tectonism (Akande et al., 2011; Ukaegbu and Akpabio, 2009).

2. Method of Study

Method of study includes identification of outcrops in the area of study. Lithofacies, lithological contacts and structural characteristics of each outcrop were studied by using: 1. hand lens to identify inorganic and organic sedimentary structures as well as grain sizes and vertical changes in grain sizes, 2. compass clinometer to determine the attitude of geological structures, 3. Global Positioning System (GPS) to determine outcrops' coordinates and elevations (Table 1), 4. 10% diluted hydrochloric acids to test for carbonates, and 5. hammer to collect samples for laboratory studies. Associations of lithofacies were used to determine paleo-depositional processes and environments of deposition. The coordinates acquired with GPS were used to draw the location map of the studied outcrops (Fig. 1B). Thin sections were made from samples at Akpoha and environs to determine detrital constituents and diagenetic features. Thin section samples were impregnated with blue resin to highlight petrographic porosity. Photomicrographs of the thins section as viewed under the microscope were taken with a digital camera. Sandstone types, provenance and maturity were classified using the scheme of Pettijohn (1975).

3. Results and Discussion

3.1. Physical sedimentary structures

Physical sedimentary structures are used to deduce the processes and conditions of deposition, and the directions of the currents which deposited the sediments (Tucker, 2003).

They are the most important sedimentary features for the interpretation of depositional environment, because unlike others, they cannot be recycled (Selly, 2000). Therefore, the following structures were identified at different locations were Eze–Aku Sandstone are visibly outcropped in the study area.

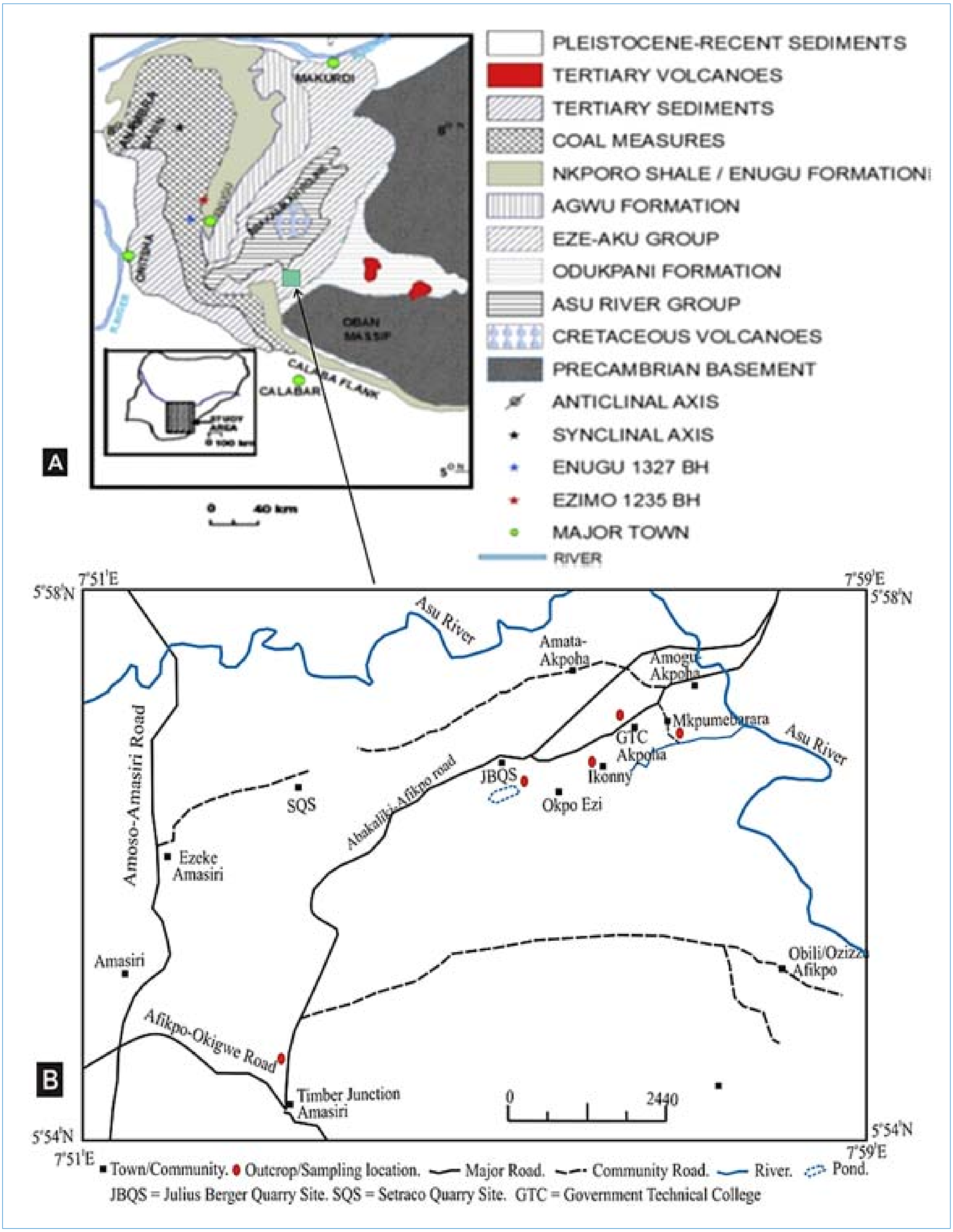

Fig. 1. A: Geological map of Southern Benue Trough showing the stratigraphy (modified from Ojo et al., 2009) and B: The map of the study area, showing locations of the studied outcrops and their accessibility

Table1. Shows outcrop locations, coordinates and mean elevations above sea level

Outcrop location	Sample names	GPS coordinates	Elevation (m)
Julius Berger Quarry Site	JBQS	N05^0, 57.064^1, E007°56.546^1	42
Government Technical College, Akpoha	GTC	N05^0, 57.559^1, E007°57.731^1	50
Ikonny	Ikonny	N05^0, 57.156^1, E007°57.426^1	45
Mkpumebarara	Mkp	N05^0, 57.442^1, E007°58.236^1	23
Timber Junction, Amasiri	Amasiri	N05^0, 54.196^1, E007°54.483^1	40

3.1.1. Hummocky and Swaley Cross Stratifications

The identified hummocks in the area of study are characterized by convex-up beds and have thickness that ranged from 0.34 to 1.2 m (Fig. 2). The wavelength of the hummocky cross stratification ranged from 2.2 to 3.5 m (Fig. 2B). It has a planar erosive base and sharp contact with the underlying and overlying rock units respectively. A set of hummocks is separated by swaley stratifications which is convex downward.

Hummocky and Swaley Cross stratifications are products of wave generated oscillatory flow or combination of storm-generated and geostrophic currents (Swift et al., 1983). These structures are seen in offshore transition zones and not seen in shoreface deposits above fair-weather wave base due to reworking of the sediment by ordinary wave processes (Nichols, 2009). It was identified at Julius Berger quarry Site (JBQS), and opposite the Government Technical College (GTC) Akpoha where bidirectional dip angles that ranged from 13 to 16^0 were determined on a ridge that strike Northeast–Southwest direction (Fig. 2B). Akpofure and Didei (2018) also identified swaley cross stratifications behind GTC Akpoha. This can be attributed to differential energy distribution in which in some areas higher energy storm oscillatory flow erodes the hummocky parts resulting in the preservation of only swaley cross stratifications.

3.1.2. Decalcification Holes or Rain Spot Impressions

Decalcification holes formed by acidic raindrops reacting with carbonate bearing rock were identified at Ikonny or Ikoni (Fig. 3). Some authors described it as potholes, pits or caves. The holes have similar shallow depth and asymmetrical shape, indicating direction of water flow. Decalcification is a dissolution method of chemical weathering in which calcite bearing rock reacts with the carbonic acid component of rainwater resulting in the breaking down of the rock into calcium and bicarbonate ions. Holes or mould (cast of concretions) can also be formed by the removal of aragonitic component of calcitic sandstone as aragonite mineral is rarely preserved (Tucker, 2003).

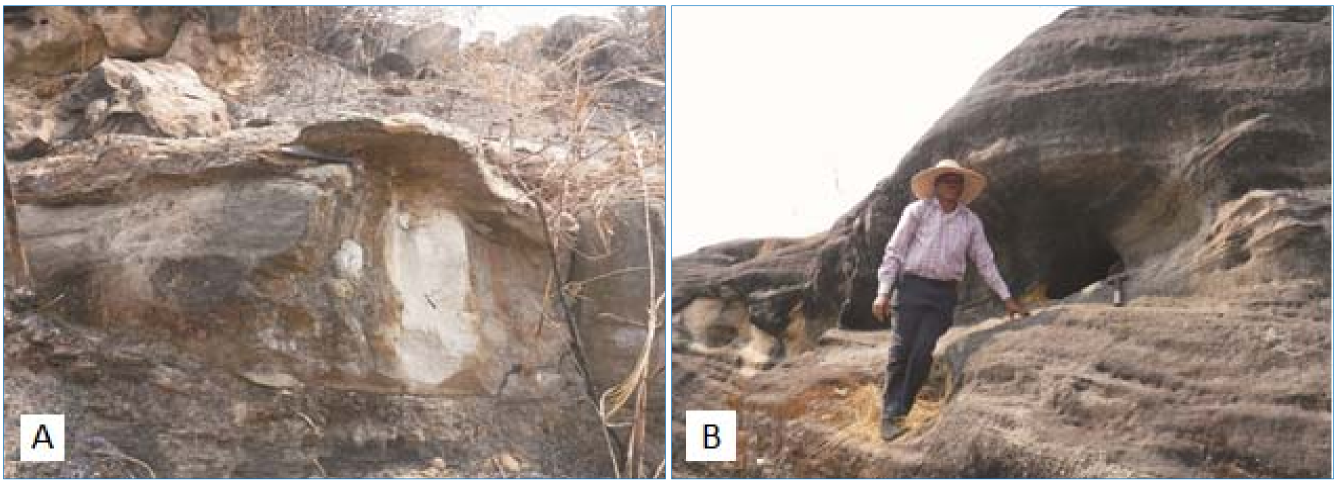

Fig. 2. A: Shows a 1.2 m thick hummock overlain Eze-Aku shale at Julius Berger Quarry Site (JBQS). The length of hammer is 37 cm. B: Shows hummocky and swaley cross stratifications opposite Government Technical College (GTC). The height of the man in the picture used as scale is 1.73 m

3.1.3. Concretions

Concretion is a hard, compact mass of mineral in sedimentary rock, that is commonly ovoid or spherical in shape and formed by mineral cement precipitation within the spaces between particles (Glossary of Terms in Soil Sciences,1976; Marshal and Pirrie, 2013). These structures were identified at JBQS (Fig. 4). The concretions are dark brown in colour and occur distinctly within fine-grained sandstone. They have diameters that ranged from 2.5 to 38.8 cm. Holes or cast of concretions, where the concretions have been weathered away are also common. The concretions gave fizzing or effervescence reaction when tested with hydrochloric acid, indicating calcium carbonate composition. Akpofure and Didei (2018) also identified similar concretions in Amasiri sandstone ridge at Ibii of Afikpo basin. It shows that concretions and cast of concretions are not an uncommon feature in Eze-Aku Formation.

3.1.4. Inclined parallel beddings

Inclination of beds can be attributed to either tectonic deformational tilting or deposition parallel to depositional slope such as continental shelf and delta slopes. Inclined parallel beddings were identified at JBQS (Fig. 5). The beds are characterized by sharp boundaries with an average apparent dip of about 18^0. The height of the ridge is about 6.96 m from ground level. From the ground level to about 2.18 m, it has an average bed thickness of 12.26 cm (0.12 m), with no obvious trend in thickness, suggesting an aggradational bed units. But from 2.18 m above the ground level to the top of the ridge, bed thickness increased upward from 0.5 to about 1.12 m, which indicates progradational depositional trend in shallow marine shelf regression setting (Catuneanu, 2006). The progradational unit of the ridge is overlain by concretions bearing sandstone bed unit of about 1.3 m thickness.

Fig. 3. Decalcification holes or rain spot impressions identified on an indurated rock at Ikonny. Length of compass clinometer used as scale is 10 cm

Fig. 4. Shows calcareous concretions and cast of concretions at JBQS

3.1.5. Tabular Planar Cross-Beds

Tabular planar cross-beds have planar foresets bounded on top and below by parallel/sub-parallel set boundaries (Selly, 2000). They represent products from migration of straight crested (2D) dune under unidirectional traction current (Nichols, 2009). They are suggestive depositional imprints in sedimentary rocks formed in lower flow regime in either marine (deltaic) or terrestrial (fluvial) environment. These bedding structures were identified at Ikonny, and Amasiri with foreset bed thickness that ranged from 6.5 to15 cm and an average dip angle of about 23° dip and occur in sandstone ridges that strike generally in Northeast - Southwest direction (Fig. 6).

3.1.6. Parallel Laminations to Wave Ripple Laminations

Parallel lamination is planar or horizontal rock layering with vertical thickness less than 1 cm. It is produced from planar bed form or migration of straight crested ripple. In fluvial deposition, it represents upper and lower plane-bed phase deposition in upper flow regime for fine-grained sandstone and lower flow regime for coarse grained sandstone respectively (Tucker, 2003). While parallel lamination in shale or silty- to very fine-grained sandstone is attributed to deposition of suspend load by settling in quiet or slack water. Parallel laminations were identified in highly indurated fine-grained sandstone behind GTC Akpoha (Fig. 7). The parallel laminations were found to grade vertically upward to wave-ripple laminations which is produced from wave ripple migration (Fig. 7B). The asymmetry of the wave ripples suggests shoaling wave action (Catuneanu, 2006). In another outcrop at Akpoha, parallel lamination was identified to overlain planar cross bedding, indicating decreasing energy flow condition (Fig. 6A).

3.1.7. Exfoliation Joints and Root Wedge Fractures

Exfoliation joints and root wedge fractures in a rock are evidences of physical and biological processes of rock weathering respectively. Exfoliation joints which is like onion peeling result from expansion and relaxation of rock surface in response to hotness and cooling of the ambient temperature, while root wedge fracture result from cracks in rock pry-opened by plant root. Though these features cannot be used for paleo-environment of deposition interpretation, they however indicate that the rock is indurated and not friable. These two rock features were identified on a ridge at Ikonny and MkpumeBarara (Fig. 8).

3.2. Lithofacies and Depositional Environment Interpretations

Lithofacies is a term used for the description of a rock unit based on the physical and chemical properties (Nichols, 2009). Physical properties include structural and textural properties, while chemical properties include reaction with hydrochloric acid. Based on these properties, the following six lithofacies were established in the study area.

3.2.1. Laminated Shale/Silty Shales

The lithofacies named laminated shale/silty shales rock is dark grey in colour, parallel laminated (< 1cm thickness), fissile (tendency to break in one direction, parallel to bedding plane) and outcropped in low elevation areas, especially at GTC and JBQS. It is overlain by sandstone with a sharp boundary that suggest storm current erosion surface or unconformity (sequence boundary) (Fig. 9). It lacks obvious bioturbation structures. It reacts effervescently with hydrochloric acid suggesting marine clay deposition. The parallel lamination is attributed to formation from gradual suspended load settling in quiet water such as in offshore environment. The lack of bioturbation structures suggest deposition in low oxygen environment (Gingras et al.,2007;

Oyanyan and Oti, 2015). The dark grey colour can be attributed to the presence of organic matter and because of finely disseminated pyrite, which also forms under reducing conditions (Nichols, 2009). The shale is believed to be part of the Eze-Aku shale which Murrat (1972) believed was deposited under marine condition and represents period of transgression. It was called Amaseri shale by Ukaegbu and Akpabio (2009).

Fig. 5. Low angle inclined beddings at JBQS. The ridge consists of basal aggradational and middle progradational rock units, and top bed unit characterized by concretions indicated with pink coloured rings. The height of the man in picture used as scale is 1.77 m

3.2.2. Hummocky and Swaley Cross Stratified Fine-Grained Sandstones

A light-grey to white fine-grained sandstone, characterized by hummocky and swaley cross stratification. It occurs as sandstone ridge at GTC environs and at JBQS where it unconformably (with a sharp boundary) overlain laminated shale rock unit (Fig. 9). The sharp boundary indicates erosive surface by storm generated current. Hummocky and swaley cross stratified fine-grained sandstone are products of storm waves and deposition in the outer shoreface and transition zone between fair-weather wave-base and storm wave-base (Tucker, 2003).

3.2.3. Inclined Parallel Bedded Medium to Coarse-Grained Sandstones

Light grey coloured medium- to coarse-grained sandstone, in low angle inclined bedding with sharp contacts, characterized by moderately bioturbated mud layer at inter-bed boundaries (Fig. 10). It consists of aggradational-progradational bed units, overlain by calcareous sandstone in a ridge. It occurs at JBQS and about 800 m from a coarsening upward sandstone deposit at Okpo-Ezi described by Ukaegbu and Akpabio (2009). The light grey colour suggests lack of preserved organic matter. Medium to coarse grains suggest a depositional area not quite distant from sediment source and the presence of drainage pattern delivering detritus (Nichols, 2009). Bed boundaries are dark brown in colour suggesting eo-genetic iron (Fe) cement at sediment/water interface preserved as drab-coloured ferrous oxide or pyrite and indicating post-depositional preservation in phreatic zone (Selly, 1985).

The bioturbated boundaries suggest periods of reduced current and sub-emergent condition. The sharp bed boundaries, coarse detritus and bioturbated mud layer at inter-bed boundaries suggest proximal amalgamated beds of sand deposited by strong storm current during continuous supply of sand, by high river flood or convergent of sediment flux, to marine environment (Nichols, 2009). The gradation from thin aggradational units to thick progradational bed units suggest change from amalgamated proximal tempestite deposition by strong storm current between storm and fair-weather wave base at offshore-shoreface transition zone to shoreface deposition above fair-weather wave base.

This lithofacies was identified at JBQS, few meters down-dip from the locations of hummocky cross-stratified sandstone, suggesting storm-wave deposition giving way to strong current deposition in an environment with huge detritus supply. The occurrence in a ridge suggest deposition from flows generated by eddy current related to storm in shoreface zone (Stubblefield et al. 1984).

3.2.4. Calcareous Sandstones

The calcareous sandstone occurs either as massive or sheet sand units characterized by carbonate concretions or sub-aerially characterized by decalcification holes (Figs. 3-4, 6). Calcite precipitates in alkaline marine environment and dissolves in acidic terrestrial environment. Therefore, the carbonate concretions are interpreted as shallow-marine eo-genetic product. It suggests depositional environment distance from terrestrial environment characterized by decaying organic matter, and period of reduced rainfall resulting in the concentration of calcium and bicarbonate ions in the sediments' interstitial alkaline fluid, prerequisite for the precipitation of carbonate concretions (Worden and Burley, 2003). The calcareous sediment indicates that the sediment was source from and transported through subaerial, humid and warm environment where there was intense chemical weathering that release calcium and bicarbonate ions into the pore fluid. Also, colonization of shallow-marine sandstones by shelly invertebrates during reduced fluvial sediment influx can lead to an abundant supply of the components needed for carbonate authigenesis (Worden and Burley, 2003).

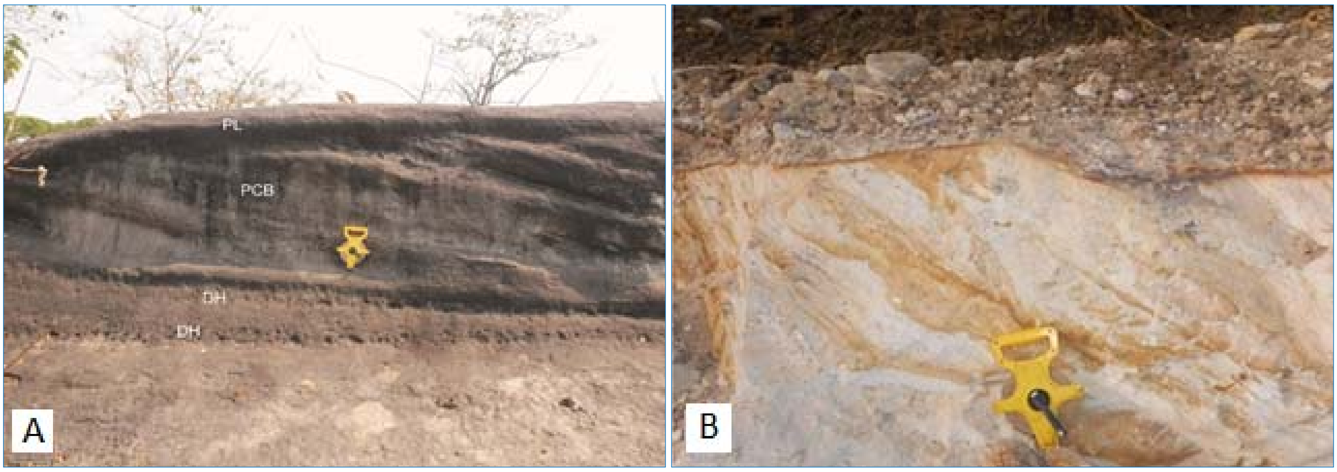

Fig. 6. A: Shows planar cross beddings (PCB) in a rock overlying a rock unit characterized by decalcification holes (DH) and overlain by a rock unit with parallel laminations (PL) at Ikonny. B: Planar cross stratification on a fresh surface of a sandstone ridge at Amasiri. Length of measuring tape used as scale is 24 cm

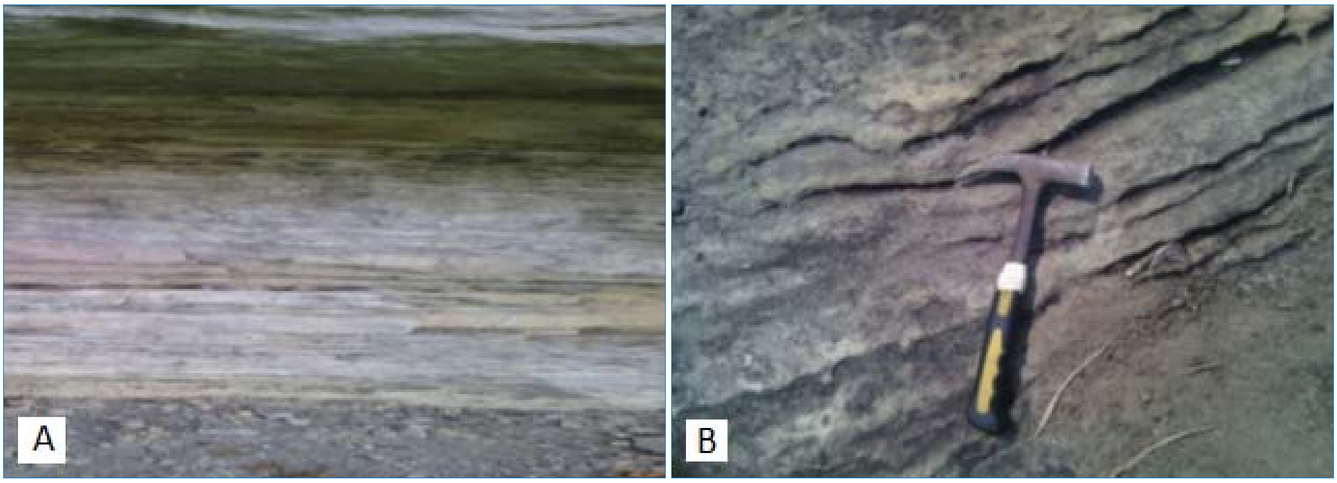

Fig. 7. Laminations in an outcrop behind GTC, Akpoha. A: Shows parallel lamination. B: Show parallel laminations grading to wave-ripple laminations. Length of hammer used as scale is 35 cm

3.2.5. Cross Bedded Medium-Grained Sandstone

Cross bedded medium-grained sandstone was identified in a ridge top at Ikonny and Amasiri. Fresh surface of the lithofacies is light grey to light brown suggesting deposition in an aerobic environment. It lacks visible evidence of bioturbation suggesting high rate of sediment supply which gives no room for sediment colonization by macro-organisms. It is variably indurated, with higher induration at Ikonny. The variability in induration can be attributed to differential tectonic compaction or cementation. The exposed base of the lithofacies at Ikonny shows that it overlain calcareous sandstone which indicates shallow marine deposition. It therefore suggests that the lithofacies as a subaqueous sand dune in shallow marine shelf.

3.2.6. Horizontal to Wave-Ripple Laminated Very Fine to Fine-Grained Sandstones

Indurated (very hard), grey coloured and parallel to wave-ripple laminated very fine- to fine-grained sandstones identified at Mkpumebarara and behind GTC Akpoha (Figs. 7-8). Flat and parallel bedding/laminations occurs in diverse depositional environments, including fluvial, delta front and beach (Selly, 2000). But fine grains and parallel or planar laminations grading to wave-ripple cross laminations suggest shallow marine of quiet or slack water characterized by suspension settling gradually grading to zones characterized by wave action. At a location, horizontal/parallel laminated sandstone overlain planar cross bedded sandstone which suggest deposit of a decreasing current energy, possibly of terminal distributary channel supplying detritus to shallow marine environment (Fig. 7). Induration can be attributed to cementation or effect of extensive compaction under overburden load.

Fig. 8. Evidence of physical weathering of rock. (A) Exfoliation or onion peeling joints in an indurated rock at Ikonny. (B) Root wedge fracture on an indurated rock at Mkpumebarara

Fig. 9. Shows closed-up view of sharp boundary between hummocky cross stratified sandstone and the underlying Eze-Aku shale. The length of hammer is 34 cm

3.3. Petrographic Textural Characteristics of Indurated Sandstone Lithofacies

Textural characteristics include size, shape and arrangement (packing and fabric) of component elements of the sedimentary rock (Pettijohn, 1975). They can be used to determine the energy and chemistry of paleo-depositional environments as well as provenance and distance of travels of the sediment grains that were lithified to form the sedimentary rock.

3.3.1. Detrital Mineral Grains

GTC, Ikonny and JBQS thin section samples show angular to subangular and moderately sorted coarse grains while MKP sample shows sub-angular to subrounded and well sorted fine grains (Fig. 11). The coarse-grained and fine-grained samples were sourced from outcrops with mean elevation of 45.6 and 23m above sea level respectively. The minerology of grains consist of monocystalline quartz, feldspar, rock fragments and cement with average percentage compositions of 55-60.5, 23-26.5, 1-5, and 5-8, respectively.

Fig. 10. Close-up view of aggradational unit of inclined medium- to coarse-grained sandstone. Green coloured arrows show eo-genetic iron (Fe) cement and bioturbated mud layer at inter-bed boundaries

With quartz less than 75%, feldspar more than rock fragments and matrix absent or less than 15%, the sandstone is classified as arkosic sandstone formed from sediments transported by low density fluid and sourced from plutonic rocks such as granite (Pettijohn, 19975). In line with the findings of Amajor (1978), the studied Eze-Aku sandstone is texturally and compositionally immature. Also, being sourced from plutonic rocks suggest provenance from nearby granitic complex of Oban Massif in conformity with the views of Odigi and Amajor (2008) and Ukaegbu and Akpabio (2009).

3.3.2. Diagenetic Features

Sandstones samples from various outcrops shows varied degree of induration and rare to lack of petrographical porosity as a result of varied level of mechanical compaction and cementation. Evidences of intense compaction include broken grain and grains' contact that ranged from line to Concavo-Convex contact, which is the first stage of pressure solution (Adams et al., 1988). The evidences of compaction indicate that the sandstones were not cemented early in diagenesis (Adams et al., 1988). Among all the samples, only GTC and JBQS samples which are coarsed-grained showed some petrographical porosity due to less compaction and cementation.

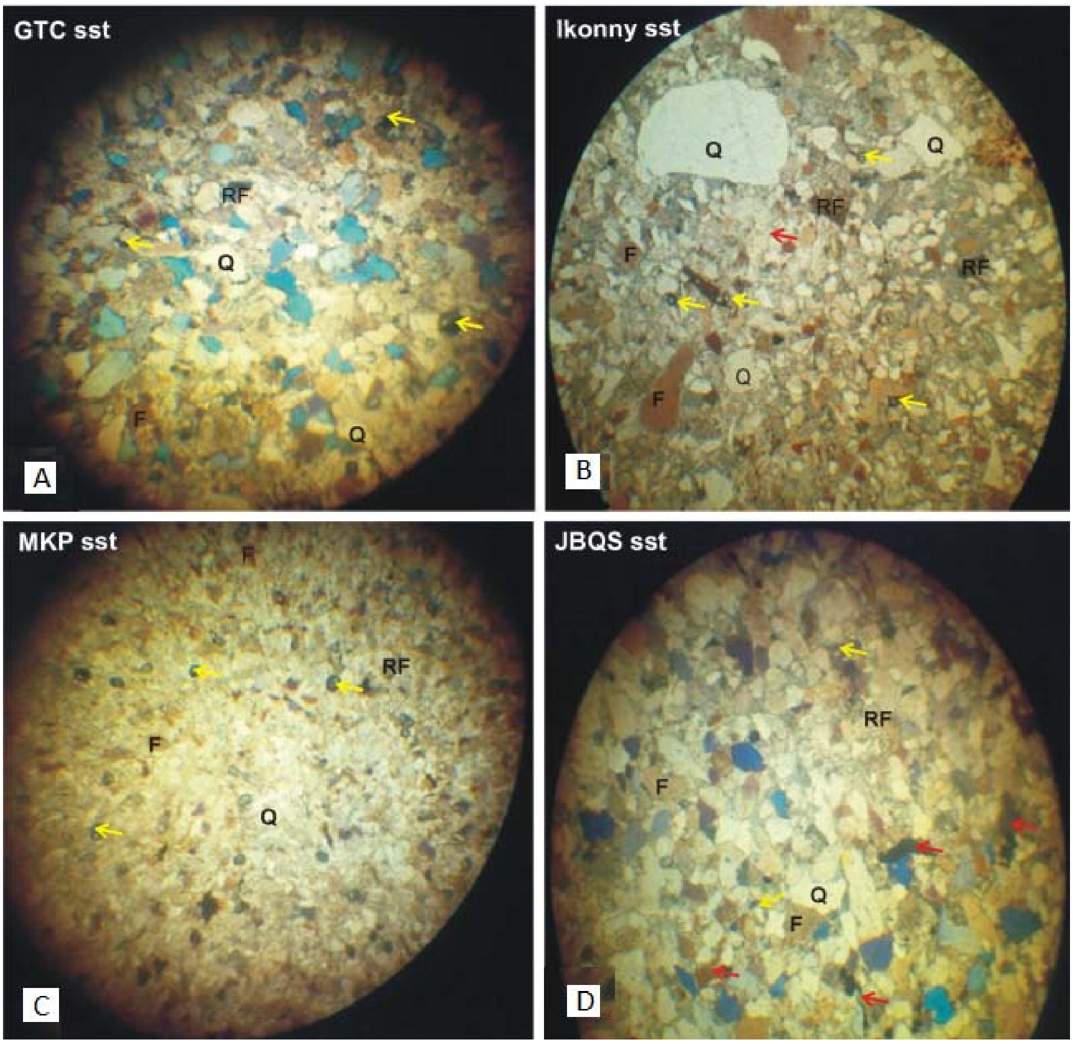

Fig. 11. Shows the detrital constituents and lithological characteristics of Eze-Aku sandstone in Akpoha and environs. All samples consist of monocrystalline quartz (Q), feldspar (F), rare rock fragments (RF) grains. A: GTC sample shows angular to subangular and moderately sorted coarse grains, petrographical porosity (bue colour), concavo-convex contact and hematite coated grains (yellow arrows), B:Ikonny sample shows angular to subangular and moderately sorted coarse grains, concavo-convex contact and hematite coated grains (yellow arrows) and rare suture contact (red arrow) C: MKP sample shows Line contact, rounded to subangular and well sorted fine grains, and hematite coated grains (yellow arrows), D: JBQS sample shows angular to subangular and moderately sorted coarse grains, petrographical porosity (bue colour), concavo-convex contact, hematite coated grains (yellow arrows), and some iron oxides or hematite filled pores (red arrows)

Planar or line to Concavo-convex contacts were identified in Ikonny, GTC and JBQS medium- to coarse-grained samples, while line contacts were more dominant in the MKP fine-grained sample. The variable degrees of induration of samples from different outcrops can be attributed to variable level of compaction by overburden load or tectonic compression and possibly mild metamorphism caused by Santonian thermotectonic event.

Each sample was however found to be characterized by uniform compaction fabric except Ikonny sample where you have zones with grains floating in calcite cement with no grains' contact to point contacts and zone with concavo-convex or long contact (Fig. 11B). Varied quantity of grains with iron oxides or hematite rim or coatings were identified in all the samples, while hematite filled pores were mostly identified in JBQS sample (Fig. 11D). Calcite cementation and iron oxides coating in early diagenesis could have inhibited silica cementation in form of quartz secondary overgrowth that was not identified in any of the thin sections.

3.4. Lithofacies Association and Depositional Processes

Differential weathering and erosion resulted in the outcropped of one or set of lithofacies at different locations in the study area. Indurated sandstone commonly found in ridges, while argillaceous rocks are found in low-elevation areas. The identification of boundaries between lithofacies in different ridges, which all have the same strike (NE - SW) direction, enabled inference of age differences between lithofacies based on the principle of superposition. The boundaries (gradational, sharp or erosive) indicate either change in depositional environment or processes/energy. The association and vertical succession of lithofacies based on depositional boundaries identified in one or more locations resulted in the understanding of depositional processes/environment and the determination of idealized vertical lithological sequence for Eze-Aku Formation respectively (Fig. 12).

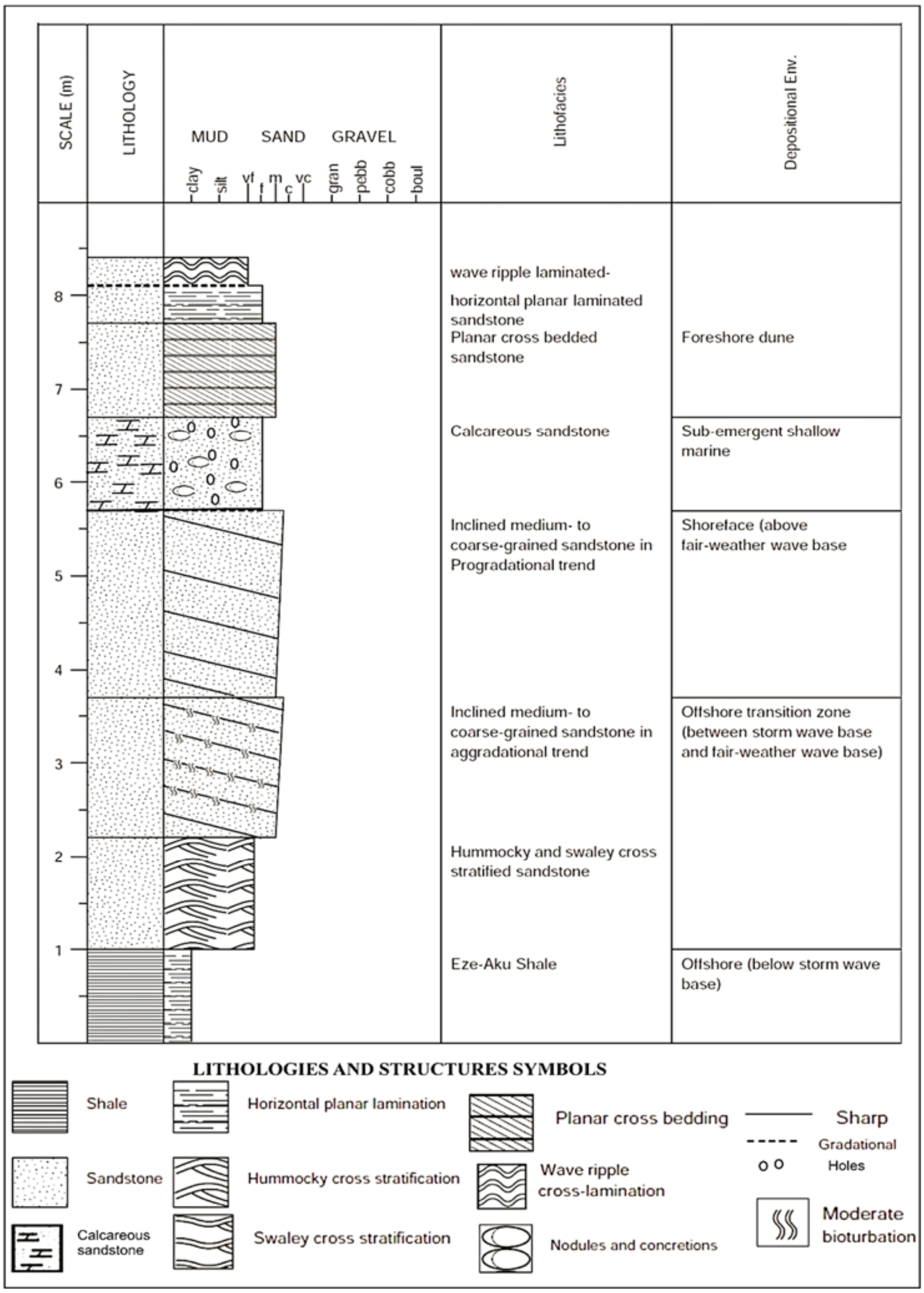

Fig. 12. Idealized schematic graphic log showing vertical successions of deposition processes of Eze-Aku Formation lithofacies in paleo-environments using JBQS, GTC and Ikonny outcrops (not drawn to scale)

The characteristics and associations of lithofacies show that the sandstone of Eze-Aku Formation was deposited in storm dominated shallow marine environment. This is in line with the views of Akpofure and Dedei (2018), Amajor (1978) and Reyment (1965). Sands depositions were controlled by storm, wave action and sediments' discharge rate which was a function of climate and tectonics. Vertical sequence of lithofacies shows that deposition was initiated by the deposition of Eze-Aku shale in offshore environment below storm-wave base (Fig. 12). Above the storm wave base is offshore transition zone where storm influenced wave current and hyperpycnal (gravity) flows can transport and deposit sediment (Reading and Collinson, 1996). High rate of sediment supply to the paleo-shelf resulted in the deposition of hummocky and swaley cross stratified sandstone in this water-depth zone. An increase in storm resulted in the conversion of storm influenced oscillatory flow to storm unidirectional current which transported and deposited the low angle inclined aggrading coarse-grained sandstone units described as proximal tempestite. Waning storm current and consistent high rate of sediment supply, due to either high river flood or convergent of sediment flux, shifted deposition surface to above fair-weather wave base.

At this water-depth zone, the prograding base in the inner-shelf was overlain by shoreface prograding units of the inclined medium- to coarse-grained sandstone units. Rate of decrease in accommodation creation over rate of sediment supply as a result of high rate of sea level fall resulted in sub-emergent of the shoreface environment. This was followed by decrease in sediment supply or temporal isolation of inner shelf from sediment supply due to climatic factors which resulted in the occurrence of conditions favourable for carbonate concentration and precipitation in shoreface sediment (Tucker and Wright 1990). Resumption of or increase in sediment supply due to change in climatic conditions resulted in the deposition of sand dunes in foreshore zone preserved as planar cross bedded and horizontal wave ripple laminated sandstone.

4. Conclusions

1. Lithofacies types and characteristics showed that Eze-Aku sandstones in Akpoha and environs are deposits of shallow sandy seas dominated by storm. Generally, Sands depositions were controlled by storm, wave action and climatic/tectonic controlled sediments' discharge rate.

2. Petrographic compositions shows that the sandstones are texturally and compositionally immature and it is classified as arkosic sandstones formed from sediments transported by low density fluid and sourced from plutonic rocks. In conformity with the view of former reserchers on Eze-Aku Formation, the plutonic rock should be the nearby granitic complex of Oban Massif.

3. Sandstones at Akpoha and environs are variably indurated. The induration of sandstone is attributed to cementation and intense compaction indicated by planar and concavo-convex grain contacts. The sandstone compaction was either by overburden load or tectonic compression. Cementation was the combination of hematite (eo-genetic iron oxides) and calcite cements. The variable degrees of induration of samples from different outcrops can be attributed to variability in level of cementation and compaction by overburden load or tectonic compression; and possibly mild metamorphism caused by Santonian thermotectonic event.

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