FACIES ARCHITECTURE, SEDIMENTARY ENVIRONMENT AND PALEOGEOGRAPHIC EVOLUTION OF THE PALEOGENE STRATIGRAPHY, SOUTH-EASTERN NIGERIA

EKWENYE, OGECHI CLEMENTINA

ROYAL HOLLOWAY, UNIVERSITY OF LONDON

A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

2014

Declaration of Authorship

I, Ekwenye Ogechi Clementina hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others, this is always clearly stated.

Signed:

Date: 15th November, 2014

ABSTRACT

The Paleogene strata of south-eastern Nigeria include the Imo Formation, Ameki Group and the Ogwashi Formation, which are collectively referred to as the outcropping Niger Delta succession and their ages range from Paleocene to Oligocene. This research involves the study of outcrops and borehole data for facies analysis, ichnology, palynology, clay mineralogy, petrology and heavy mineral analysis in order to reconstruct the paleogeography of the Paleogene period, develop new depositional models and re-interpret the depositional environments of the Paleogene strata. The results provide a new depositional environment for the lower Sandstone Member of the Imo Formation - tidal sandwave deposit and a new paleogeographic model for the Imo Formation. Improved facies and sequence stratigraphic models are developed for the deposits of the Ameki Group and these sedimentary deposits are re-interpreted as tide-dominated estuarine system. Novel depositional facies are produced for the Ogwashi Formation and the strata are also re-interpreted as tidally-influenced coastal plain deposit. Furthermore, the sand body geometries, their spatial distribution and continuity as well as the sandstone heterogeneities of representative outcrops of these formations are well documented in this research. Results from heavy mineral analysis suggest mixed provenance for the Paleogene sediments; the primary sources are polycyclic pre-existing sedimentary rocks, magmatic-gneiss complex and granitic rock of the Oban Massif and the magmatic-gneiss complex and the schist belt of the Western Nigerian Massif. This study proposed possible factors controlling the distribution of the heavy mineral suites in the Paleogene sediments to include river influx, tide and wave actions and hydraulic sorting. Four type-1 stratigraphic sequences, consisting of lowstand systems tracts and/or transgressive systems tracts and highstand systems tracts have been established for the depositional succession of the Paleogene strata. This detailed sedimentological research on the Niger Delta provides a new insight into the study of shallow marine environments.

TABLE OF CONTENTS

LIST OF FIGURES

List of Figures

List of Figures

LIST OF TABLES

ACKNOWLEDGEMENT

The success of this doctoral thesis would not have been achieved without the efforts and contributions of individuals and corporate bodies some of whom I wish to mention. I thank my sponsors Petroleum Technology Development Fund (PTDF) Nigeria for offering me full sponsorship for three academic years. I am thankful to the staff of PTDF who attended promptly to various issues on the sponsorship and logistics; some of whom are Mr Galadima, Hajiah Rabi, Mrs Bolanle, Mr Bako and Ms Rowena. I also wish to acknowledge the Central Research Fund (University of London Scholarship Fund) and the International Association of Sedimentologists (IAS) for awarding me grants for my laboratory analyses.

My profound gratitude goes to my supervisor, Dr Gary Nichols for his insightful discussions, corrections and suggestions during the course of this research. He steered this research to a successful end with his astute ideas and contributions. I wish to also acknowledge the immense assistance of my advisor and supervisor, Professor Margaret Collinson for her scientific advice and support. She was enthusiastic, always ready to help and assisted me immensely with my palynology analysis.

I remain grateful to Professor Nwajide, Professor Obi, Professor (Mrs) Umeji, Prof Ibe, as well as my field assistants, Mr Ugochukwu Nwachukwu, Mr Nwakwonta, and Mrs Ogechukwu (a doctoral student), who assisted me with my field work in Nigeria and willingly offered me their wealth of knowledge about the geology of south-eastern Nigeria. I thank Alozie and Happiness for accommodating me in Umuahia during one of my field works, and Chisom for providing vehicle for the field work. I am thankful to staff of Department of Geology, University of Nigeria, Nsukka and members of the university community who assisted me with necessary administrative matters during the course of my studies. Many thanks to Professor (Mrs) Umeji (the head of department), Professor Okogbue, Professor Onuoha, Dr Mamah and Dr Mode for their advice, support and for handling various academic issues while I was away on study leave. I am also thankful to Mr Oha, Mr Onwuka, Dr Anyiam, Dr Ogechukwu Illoanusi and Ms Amara Chukwuneke for their selfless support during this period. I thank Allen Archer for having time to proofread the ichnology aspect of my thesis.

I wish to acknowledge the staff of Global Energy, Lagos, Nigeria especially Mr Ayo, Mr Collins and Mr Kufre, who assisted me with my biostratigraphic analyses. Most of my rock samples were stored and analyzed in the department of Earth Sciences, Royal Holloway, University of London (RHUL). I am thankful to Kevin (for assisting me in storing my rock samples in the rock store and other issues such as using the optical laboratory for my thin sections), Dr Inga (for assisting me with my heavy mineral analysis), Dr Dave Alderton (for handling my clay mineralogy analysis), Neil (for preparing thin sections for petrology studies), Sharon (for assisting me in processing my rock samples for palynological analysis), Sue and Dr Duncan for general assistance in the laboratory.

I would like to acknowledge the academic and technical support of the Royal Holloway, University of London, particularly the library facilities, the research skills programmes and the computer facilities. I wish to thank the staff of the International Student Office, RHUL for organizing social events and for handling my visa issues. I also thank the department of Earth Sciences, Royal Holloway, University of London for their support and the grant offered to me during the course of my studies. I acknowledge the unsolicited assistance of Professor Pete Burgess, Professor Robert Hall, Dr Ian, Frank, Diane, Julie, Kathryn and Dave during my study period. I wish to commend the efforts and encouragement of my colleagues at the department of Earth Sciences, Royal Holloway, University of London, some of whom are Aji, Amanda, Alja, Anna, Claire, Emeliano, Hannah, Sylvester, Napan, Maria, Vicky, Holly, Naomi, Martin, Oo, Indra, Lydia, Rob and Juliana.

I will forever be thankful to our family friends, Angela and Alaistair Dijksman (Angela is so angelic, she is everything to me- a friend, a sister and a mother; she introduced me to the beautiful British lifestyle. Thank you Angela for the support and care you lavished on me and my family), Mandy Shirnia, Meg and Paul Griffith, Sally Thompson, Francis and Richard Stubbs, Elaine and Michael Cox, Sam and Daal, Anna Ngugi and members of Besom and St John's, Egham. Thank you all for your immeasurable support to me and my family during our stay in the United Kingdom. My thanks goes to Father Vilad, Father John, Alphra and members of the Catholic Students Association, RHUL/Church of Assumption for their support, encouragement and for all the social and religious gatherings.

I acknowledge the generous contributions and advice of my siblings, in-laws, nephews, cousins and relations whose names are too numerous to mention.

My heartfelt gratitude goes to my best friend, soul-mate and husband, Okezie Vincent (Esq.) for his patience and sacrifices. Okezie actively supported me through the intensive research years in the UK, especially with the birth our lovely sons Chinonso Corliss and Chinweotito Justice. I truly thank Okezie for his words of encouragement and for believing in me. He stood by my side and showered unconditional care and love to me and our little boys. I would like to thank Chinaemenma for caring for my sons while I proofread this thesis.

Acknowledgement

Above all, I thank God Almighty for making everything work for good and for making the PhD programme a success.

DEDICATION

I dedicate my doctoral thesis to my family: my dearest dad- Nze Paul Egbu; my mum, of blessed memory- Late Lolo Theresa Egbu; my wonderful siblings and most especially to my darling husband- Okezie Ekwenye (Esq.) and my lovely sons- Chinonso and Chinweotito.

CHAPTER ONE

INTRODUCTION TO THESIS

1.1 BACKGROUND INFORMATION

The surface Paleogene strata in south-eastern Nigeria extend from the upper Nsukka Formation to the Ogwashi Formation and outcrop in the Anambra Basin, the Niger Delta, Afikpo Syncline, and the Calabar Flank (Figure 1.1). The strata of the Imo Formation, Ameki Group and Ogwashi Formation are referred to as the outcropping equivalents of the subsurface Cenozoic Niger Delta (Reyment, 1965; Frankl and Cordy, 1967; Short and Stäuble, 1967; Petters, 1991; Nwajide, 2005). Previous studies have shown that the sandstone bodies of the Paleogene strata are embedded in mudrocks, leading to stratigraphic traps. These could be a major hydrocarbon traps in the subsurface packages. There is therefore a need for a detailed geologic evaluation of the reservoir potential of the Paleogene strata. Detailed sedimentological studies of the Paleogene outcropping units can provide analogs that would enhance reservoir characterization of the subsurface.

Previous work has included studies on the lithofacies, depositional environments, micropalaeontology, petrography and stratigraphy of some aspects of the Paleogene strata, without much emphasis on the reservoir heterogeneity, depositional or reservoir architecture. The research work presented here employs integrated tools and concepts such as detailed sedimentology (facies analysis and reservoir architecture), palynology, petrology, mineralogy (heavy mineral analysis), clay mineralogy, and sequence stratigraphic concepts to reduce the geological uncertainties of the Paleogene stratigraphy of south-eastern Nigeria.

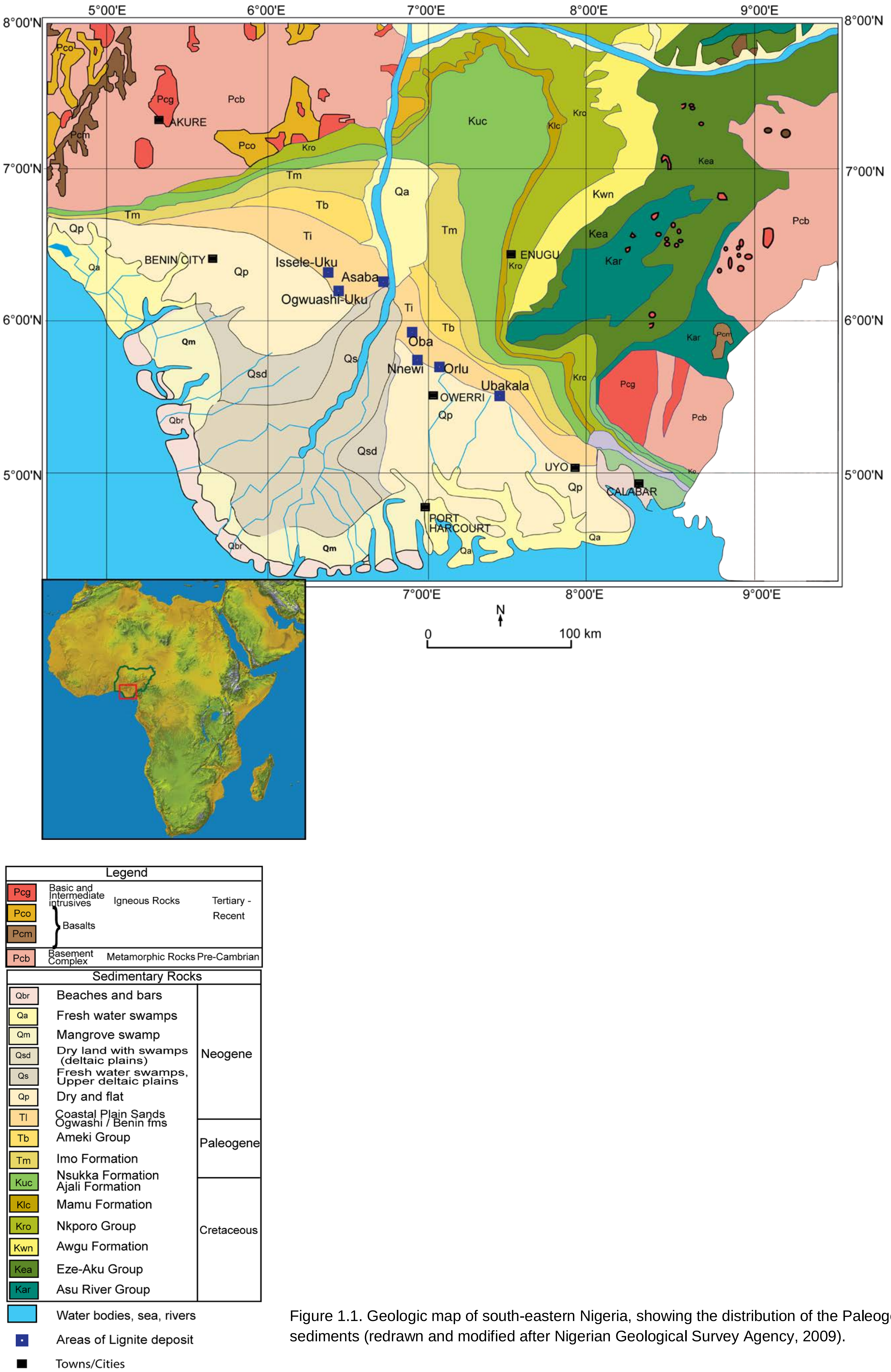


Figure 1.1. Geologic map of south-eastern Nigeria, showing the distribution of the Paleogene sediments (redrawn and modified after Nigerian Geological Survey Agency, 2009).

1.2 OBJECTIVES AND SCOPE

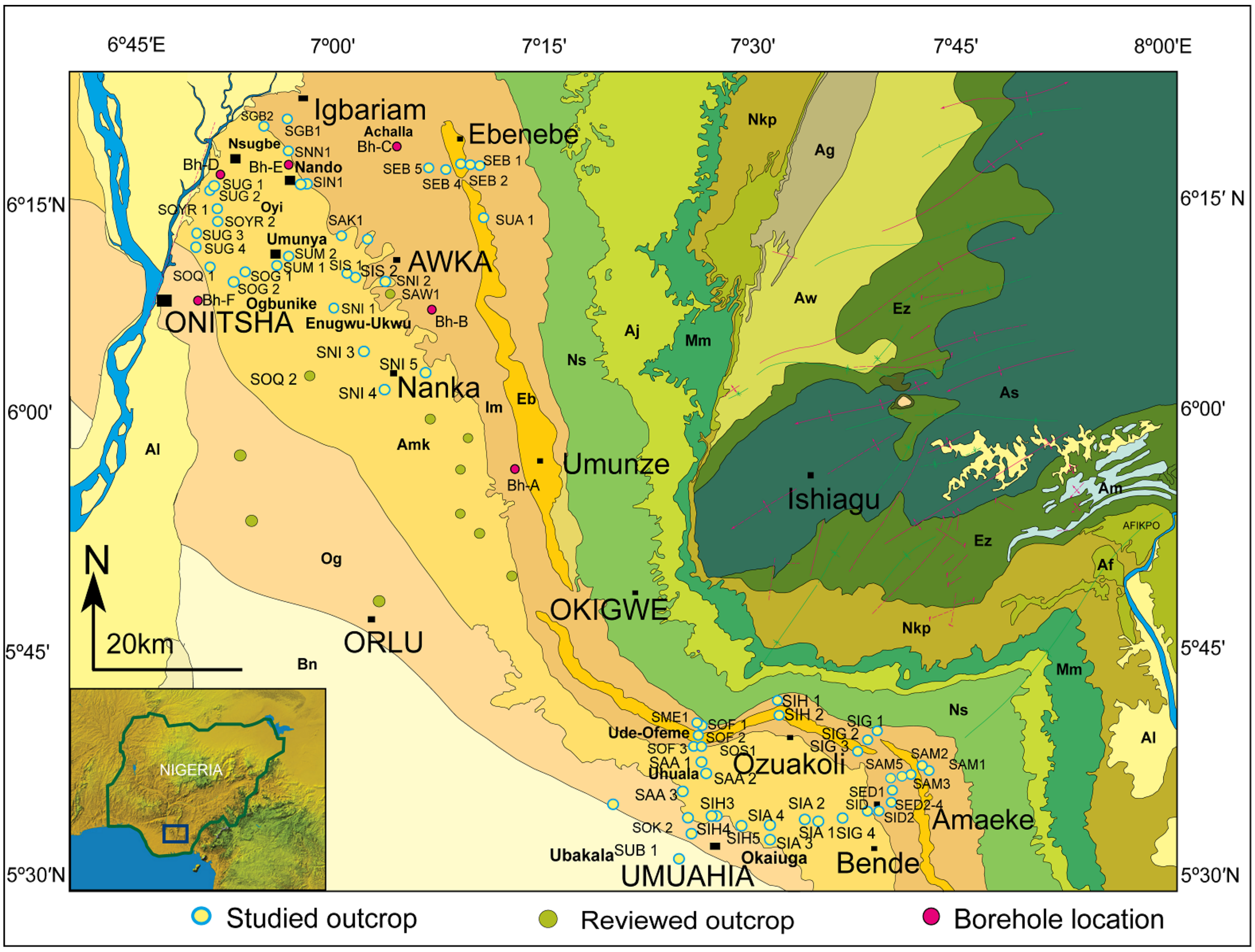
The objective of the research is to re-interpret the stratigraphic evolution of the Paleogene strata in south-eastern Nigeria by integrating sedimentology, ichnology, petrology, palynology and mineralogy. The research aims to:

- establish the depositional facies for the Paleogene strata (Imo Formation, Ameki Group and Ogwashi Formation) in south-eastern Nigeria using systematic and detailed sedimentological logging and facies analysis;
- re-interpret the depositional environments of the Paleogene sedimentary rocks, by integrating other approaches such as clay mineralogy, palynology and ichnology with sedimentology;
- reconstruct the paleogeography of the Paleogene strata through time and ascertain the possible controlling factors affecting sedimentation patterns;
- unravel the architecture of the clastic reservoir systems of the depositional environments and understand the reservoir heterogeneity at a macroscopic, mesoscopic and microscopic scales;
    - the macroscopic heterogeneity is based on the lateral and vertical variations in depositional or sedimentary facies that would affect the sandstone (reservoir) and non-reservoir geometry, as well as the reservoir compartmentalization;
    - the mesoscopic scale includes the vertical and lateral arrangement of lithofacies units, the distribution and type of architectural elements which would affect the distribution, continuity and connectivity of sand/shale bodies;
    - the microscopic heterogeneity is expressed at the scale of individual grains and pores of sediments, and

- establish the sequence stratigraphic framework of the Paleogene succession.

1.3 STUDY LOCATION

The study area has an areal coverage of about 5,050 square km and covers outcrops of the Paleogene age commonly referred to as the outcropping Niger Delta (Short and Stäuble, 1967). The study area includes the Imo Formation, the Ameki Group (which includes the Nsugbe Formation, the Nanka Formation and the Ibeku Formation (formerly known as the Ameki Formation) and the Ogwashi Formation. These formations are bounded by the Cretaceous sequence of the Anambra Basin to the north and they grade into the subsurface succession of the Niger Delta Basin to the south, where they are assigned the Akata, Agbada and Benin formations (Figure 1.1). The study area is divided into 2 regions, namely the Ebenebe-Onitsha axis and Umuahia axis (Figure 1.2). The Ebenebe-Onitsha region covers Igbariam, Awka and Nanka areas, while the Umuahia region includes Amaeke and Bende areas. 70 outcrop locations were encountered and their coordinates were recorded (Appendix A1.1); most of the outcrops were exposed as road cuts, quarries, river/stream cuts, gullies and excavation sites. The thickness of the studied outcrops varies between -3 m to 30 m thick. Poorly exposed strata such as the mudrocks are estimated using mathematical theory (Pythagoras theory) to deduce their true thickness from regional dip and lateral extents (see chapter 4). The overall thickness of the studied outcrops represent more than 40% of the actual thickness of the Paleogene strata. Available borehole data are used to provide additional information on the thickness of penetrated formations. Outcrops already studied and described by certain authors are considered in this study as reviewed outcrops.



Stratigraphic units	Age
Alluvium	Recent
Benin Fm	Oligocene - recent
Ogwashi Fm	Oligocene
Ameki Grp	Eocene
Imo Formation	Paleocene - Eocene
Nsukka Fm	Maastrichtian -Paleocene
Ajali Fm	Maastrichtian
Mamu Fm	Maastrichtian
Nkporo Grp (incl.Afikpo Sst)	Campanian-Maastrichtian
Awgu Fm	Coniacian
EzeAku Grp	Turonian
Asu River Grp	Albian

Legend

Figure 1.2. Geologic map of the study area, showing the outcrop locations and borehole locations in the study area (redrawn and modified after Nigerian Geological Survey Agency, 2009).

1.4 METHODOLOGY

The research method was implemented in four phases: a) desk study, b) field mapping, c) laboratory studies and d) data interpretation and integration.

1.4.1 Desk Study

This involved an intensive five month review of previous studies which had been done in order to evaluate the work, discussion and interpretation of other authors pertaining to the study area. During this phase, the research focus was established to address the limitations of previous works. The desk study also involves the study of (1: 100,000 scale) geologic and topographic maps which cover the study area. The area of interest was mapped out with its coordinates to produce a base map for the field work.

1.4.2 Field Mapping/ Investigation

The field area includes the Onitsha, Awka, Ebenebe, Bende, Amaeke, Umuahia regions. A GPS receiver was used to get accurate coordinates of the exposures (Appendix A1.1). Reconnaissance study was initially carried out in these areas to locate outcrops and detailed field work was carried for fourteen weeks from April to May, 2010 and December to January, 2011. This involved detailed sedimentological study which included:

- sedimentological logging (to unravel the rock types, textural features, sedimentary structures, nature of bedding and structural features) and mapping of bedding contacts;
- measurement of bed thickness, dips and strikes, lateral extent of outcrops. For heterolithic deposits, thickness variation of sand, silt or clay couplets were recorded. The Munsell colour chart was used to accurately describe the rock colours;

- systematic collection of mudrock samples at 20-50 cm intervals for micropaleontological analysis. Sandstone samples were collected at 1-4 m intervals and were used for petrographic studies and heavy mineral analysis;
- photopanorama mapping was carried for laterally extensive outcrops.

The field observations/investigations were used to:

- interpret the lithofacies units and facies assemblages;
- interpret the depositional environments;
- further reconstruct the paleogeography of the study area;
- interpret the architectural elements and heterogeneity of reservoirs, which includes:
  - geometries of sandstone bodies as well as mudrocks,
  - connectivity and spatial distribution of the sandstone bodies, and
  - internal heterogeneity of the reservoirs which acts as permeability baffles and barriers, such as mud drapes, large mud clast horizons, discontinuous finer-grained beds, accretion sets, amalgamation surfaces;
- predict the reservoir quality of the rocks.

1.4.3 Laboratory studies

Rock samples comprising sandstone, limestone, mudstone and shale samples were systematically obtained from the field at interval of 20-40 cm for the mudstones/shales and at intervals of 2-4 m for the sandstones. The sandstones were sampled for petrographic and heavy mineral analyses. The limestones were sampled for petrographic study, whereas mudstone and shale samples were collected for clay mineralogy and palynological analysis. Some methods used for this analytical work are discussed below:

Clay mineralogy

Clay mineralogy analysis was carried out at the Department of Earth Sciences, Royal Holloway, University of London. The X-Ray diffraction analysis was carried out on mudstone samples from the study area. The samples were oven-dried at 40^0C and disaggregated by using a jaw crusher or a mortar and pestle and completely crushed and ground using Tema vibratory disc mill. The crushed sample was then immersed in distilled water, and subjected to ultrasonic agitation to separate all the constituent grains (Humphreys et. al., 1991). Clay particles in suspension were decanted through a 32 micron sieve and centrifuged to obtain the 2 micron fraction. The clays were prepared as smear slides; run in air-dried, glycolated and heated first at 400^0C and then at 550^0C using Philips PW 1730 X-ray diffractometer (Jeans, 1978). Scans were performed from 3° to 35°, with a speed of 1°/minute and the radiation used was CuK (alpha) radiation which has a wavelength of 1.5418Å. The relative percentage of each clay mineral was determined using an empirically estimated weighting factor (Brindley and Brown, 1980).

Palynological methodology

Forty-five sedimentary samples of about 10 grams from both outcrops and borehole from south-eastern Paleogene sediments were processed for palynological analysis using the standard methods (HCl-HF-Acetolysis and flotation with Zinc chloride) in Global Energy Ltd, Lagos State, Nigeria and Department of Earth Sciences, Royal Holloway, University of London. Thirty-five samples yielded poorly to moderately preserved palynomorphs. The palynomorphs present in the thirty-five slides were identified and counted under a Zeiss microscope. A minimum of 150 palynomorphs were counted in each sample. The palynomorphs were grouped into different broad categories of taxa such as fresh water algal cysts, dinoflagellates, acritarchs, flowering plant pollen, spores, fungal remains and organic foraminifera linings. In addition unidentifiable palynomorphs, fragmentary palynomorphs, structured or unstructured phytoclasts, pyrite, amorphous organic matters (AOM) and resins were recorded. The presence of debris and cuticles were noted where relevant but not counted.

The samples were taken from distinct sedimentological facies or facies associations. These interpretations were verified or revised based on the key taxonomic grouping of palynomorphs (category, abundance, diversity) and other components of the palynological assemblage.

1.4.4 Data interpretation and integration.

Borehole ditch cuttings (Bh-A to Bh-F) were obtained from Imo-Anambra River Basin Authority, Imo State, Nigeria. The samples were taken at intervals varying between 0-3 m and arranged in core boxes. They were logged, described and were further calibrated to outcrops of analogous lithofacies. Results from the field and laboratory studies were integrated to address in detail the objective of the research. The interpretation of results is addressed systematically in the subsequent chapters.

CHAPTER TWO

REGIONAL GEOLOGY

2.1 REGIONAL TECTONIC SETTING

The geology of the southern Nigeria sedimentary basins has received considerable attention since the discovery of oil in Nigeria. The origin of these southern sedimentary basins is traced to the evolution of the Benue Trough (Figure 2.1A, B). The separation of the Afro-Brazilian plate during the Early Cretaceous led to the evolution of the Benue Trough (Reyment, 1965; Murat, 1972; Nwachukwu, 1972; Olade, 1975; Kogbe, 1976; Petters, 1978; Wright, 1981; Benkhelil, 1982, 1989; Hoque and Nwajide, 1984). The separation of the Afro-Brazilian plate initiated the opening of the South Atlantic during the Late Jurassic to Early Cretaceous times and reached Nigeria by Mid-Cretaceous (Fitton, 1980). The geodynamics of the Benue Trough is controlled by transcurrent faulting (sinistral wrenching) through an axial fault system, developing tensional and compressional regimes and resulting in basins and basement horsts (Benkhelil, 1989).

Nevertheless, various theories have been postulated about the evolution. Previous authors such as King (1950); Cratchley and Jones (1965), Stoneley (1966) and Wright (1968) proposed a rift structure due to tensional movements. An unstable RRF (Ridge-Ridge-Fault) triple junction model leading to plate dilation and the opening of the Gulf of Guinea was proposed by Grant (1971). Burke et al., (1971) and Olade (1975) proposed a failed arm of a Cretaceous RRR (Ridge-Ridge-Ridge) triple junction and an aulocogen resulting from the rise and cessation of a deep mantle upwelling beneath the Cretaceous hot spot. Fitton (1980) suggested a migrating rifting system over a “Y”-shaped hot zone for the Benue Trough and the volcanic Cameroon Line due to their similarity in shape and size. Adighije (1981) and Fairhead and Okereke (1987) suggested a failed rift of the triple junction which resulted in extensional and shear tectonics. However, a sinistral (strike-slip) wrenching system is proposed for the Benue

Trough (Benkheil, 1982, 1989; Binks and Fairhead, 1992) from geophysical studies and computer dynamics analysis (Maurin et al., 1986). Maurin et al., (1986) argued that rift models assume that normal faults bounded structure; Benkheil (1986) suggested that transcurrent faulting resulted in local compression and tensional regimes, which is responsible for the structural arrangement and geometry of the sub-basins.

Whiteman (1982) suggested that the Abakiliki-Benue trough first evolved as a tensional basin, then compressional and Genik (1993) suggested that the Benue Trough is part of the West and Central African Rift System that opened as a sinistral wrench complex. The Benue Trough is a NE-SW trending linear depression with about 4500 m Cretaceous sediments; it is about 1000 km long and 50-100 km wide. Olade (1975), Hoque (1984) and Benkhelil (1989) suggested magmatic activity during the opening and filling of the Benue Trough which led to the deposition of the Abakaliki pyroclastics. These volcanic rocks have alkaline affinities (syenite, monzonite, diorite, gabbro and their hypabyssal equivalent) and tholeiitic trend (dolerite and micro-gabbro). The intrusive rocks, dykes and lava flows mixed with breccias and tuffs are restricted to the Albian sediments. Contact metamorphism occurs around the intrusive bodies while low-grade metamorphism affected most deformed areas in the Abakaliki (Benkhelil, 1989; Obiora and Umeji, 2005).

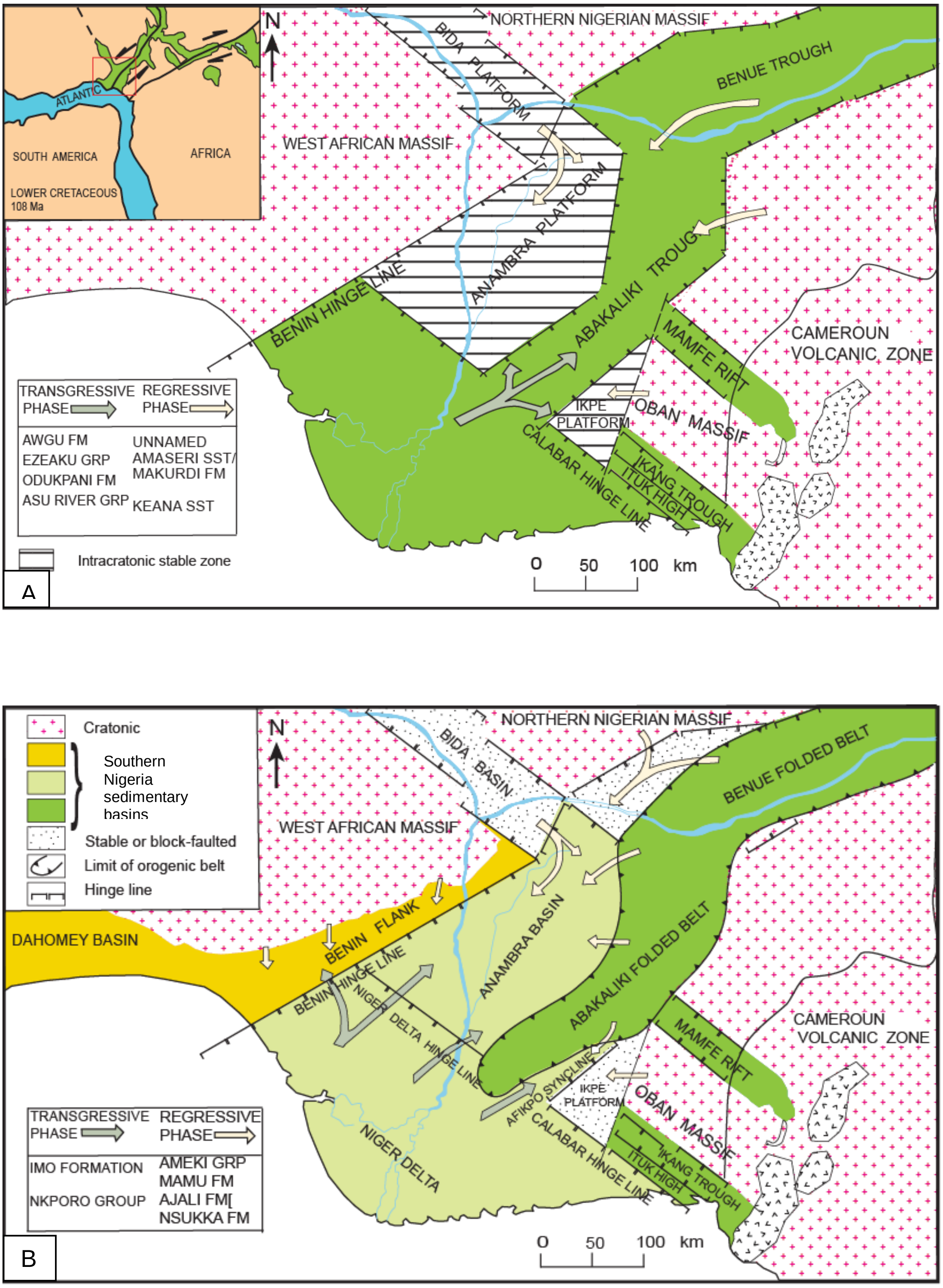


Figure 2.1. (A). Tectonic map of south-east Nigeria, from the Albian to Santonian ages. (B). Tectonic map of south-east Nigeria during the Campanian to Eocene (redrawn and modified after Murat, 1972).

The first marine transgression from the Gulf of Guinea occurred in the south and reached the Middle Benue Trough, depositing the Asu-River Group (Figure 2.2) in the trough during the Albian. Nwachukwu (1972) earlier suggested a tectonic event during the Cenomanian in the Abakaliki Basin that resulted to the restriction of the Cenomanian Odukpani Formation (now known as Mfamosing Formation) to the Calabar Flank and the occurrence of lead-zinc mineralization in the Albian strata. Notably, a post-mineralization deformation occurred in which the coarsely crystalline sphalerite and galena were extensively sheared, striated and grooved and an undeformed mineralization is associated with the Santonian thermo-tectonism. He also noted the greater intensity of folding in Albian sediments (40° to 55° dip of strata) than in the overlying Turonian Eze-Aku Group (30° to 40°). Other workers such as Benkhelil, 1986; Ojoh, 1992; Umeji, 2007 documented the presence of Cenomanian sediments in the Eze-Aku River section at Aka-Eze; Amaseri Sandstone, Umukwueke; Ibir and Ekukunella; Ezillo and Agala Formations and other areas in the Central and Northern Benue Trough. During the Turonian transgression, the Eze-Aku Group and part of Awgu Formation were deposited. The Conanian regression culminated with the deposition of the Agbani Sandstone Member in the Abakaliki Basin. Sedimentation in the Abakaliki Basin was halted due to the Santonian thermo-tectonism (Figure 2.2).

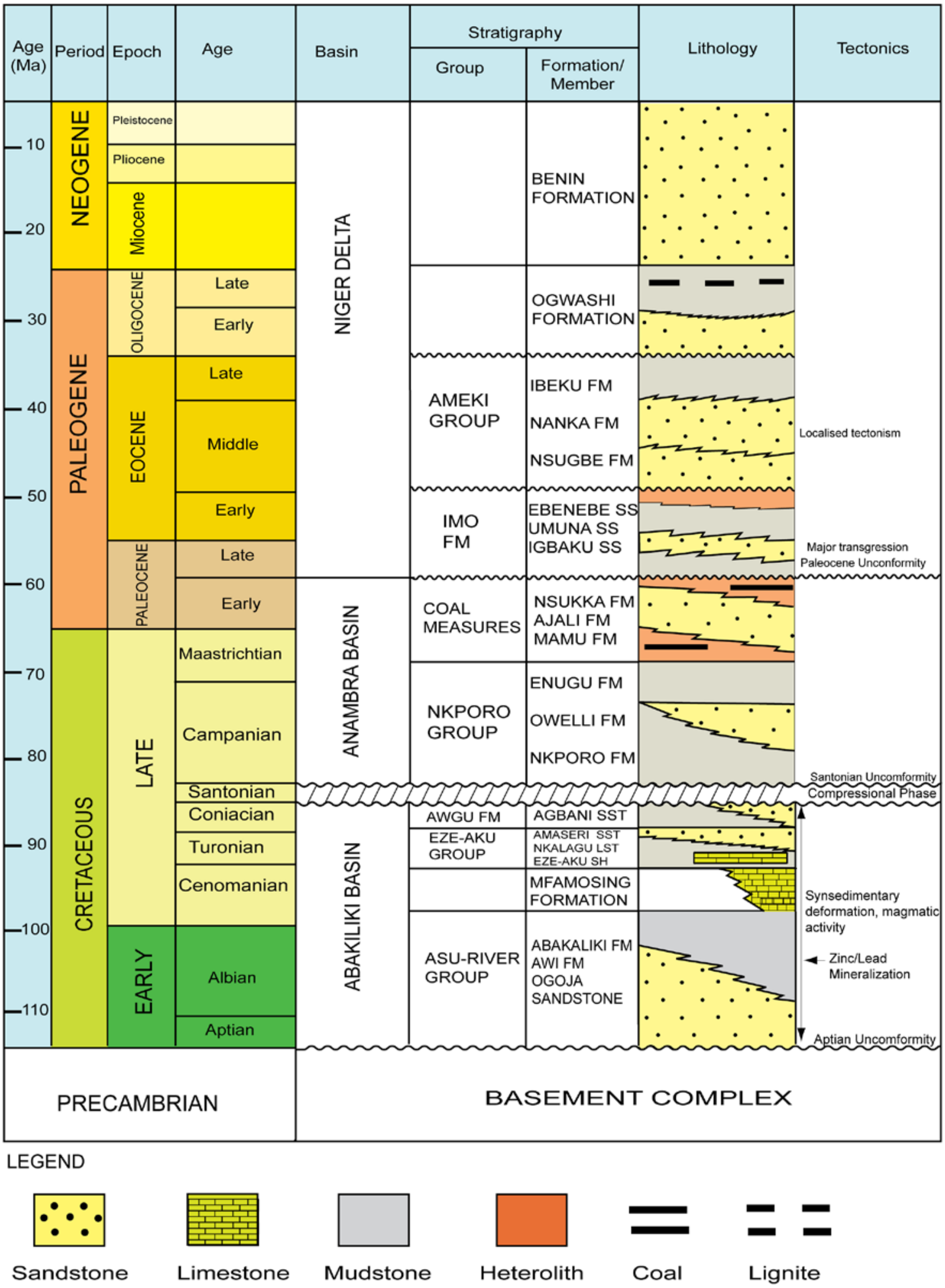


Figure 2.2. Stratigraphic succession in the Anambra Basin and outcropping Niger Delta (redrawn and modified after Short and Stäuble, 1967; Nwajide, 2013).

The Santonian compressional phase resulted in the folding, faulting and uplifting the Abakaliki Basin to form an anticlinorium; displacing depocentres westward and eastward to form the Anambra and Afikpo Basins. The folds trend N060°E with local defections due to the influence of the transcurrent faulting (Benkhelil, 1989). Sedimentary units of the Anambra Basin form a regressive offlap sequence, located on the continental crust and consist of the Nkporo Group and the Coal Measures, with the Nsukka Formation terminating sedimentation in the Anambra Basin (Nwajide, 2005). The Anambra Delta Complex was terminated by an extensive Paleocene transgression (Whiteman, 1982) and a Niger Delta sedimentation began in the late Paleocene (Short and Stäuble, 1967; Evamy et al., 1978; Nwajide, 2005). However, Whiteman (1982) suggested that the continental margin continued to subside during the early Paleocene, initiating the deposition of Paleocene and Eocene sediments in the Anambra Basin, Afikpo Syncline, Ikang Trough on the Calabar Flank and Dahomey Basin (Figure 2.1).

2.2 REGIONAL STRATIGRAPHIC SETTING

The stratigraphy, tectonics and depositional sequences of the Anambra Basin and the Afikpo Syncline are documented in several works (White, 1926; Reyment, 1965; Murat, 1972; Kogbe, 1976; Hoque, 1977; Nwajide, 1980; Arua, 1980, 1986; Agagu et al., 1985; Amajor, 1987; Ladipo, 1986; Mode, 1993; Nwajide and Reijers, 1996; Obi, 2000; Obi et al., 2001; Umeji, 2003, 2005; Obi and Okogbue, 2004; Oboh-Ikuenobe et al., 2005). Nwajide and Reijers (1996) briefly discussed the deltaic sedimentation and sequence stratigraphy of the Anambra Basin.

The stratigraphic framework of the southern sedimentary basins is represented in three depositional phases which are the Aptian-Santonian, the Campanian-Early Eocene and the Late Eocene-Pliocene depositional phases (Short and Stäuble, 1967; Nwachukwu, 1972, Murat, 1972; Oboh-Ikuenobe et al., 2005). The Aptian-Santonian phase began with scarcely outcropping Aptian sediments which are probably continental deposits (Benkhelil, 1989), characterised by non-fossiliferous, arkosic, cross-bedded quartzite sandstone (Short and Stäuble, 1967). Freeth (1990) referred the un-named Group as Late Jurassic to Neocomian deltaic to non-marine sediments. These strata rest unconformably on the crystalline and metamorphic basement complex and are overlain by the deformed Albian to Coniacian succession (Obi et al., 2001). The oldest sediments recognised in the Abakaliki Basin are the Asu River Group, which consist of dark micaceous sandy shale and micaceous sandstone. The maximum thickness of the formation is about 1,500 m (Benkhelil, 1989). The Cenomanian Odukpani Formation (now known as Mfamosing Formation) is restricted to the Calabar Flank (Nwachukwu, 1972; Benkhelil, 1989). It consists of alternating heterogeneous sandstone with sandy shale, shale, and fossiliferous limestone, deposited in a very shallow marine environment close to a shoreline along the bordering Oban Massif (Short and Stäuble, 1967).

The overlying Turonian Eze-Aku Group comprises calcareous shales with intercalated limestone lenses (Short and Stäuble, 1967); this grades laterally into sandy shale and calcareous sandstone of Amaseri Sandstone Member (Figure 2.2). The Eze-Aku Group varies in thickness to 1200 m. It is overlain by the late Turonian to Early Coniacian Awgu Formation, which comprises about 900 m bluish-grey, bedded shale with fine-grained carbonaceous limestone. Regression during the Coniacian resulted in the deposition of the Agbani Sandstone. Hoque (1977) generalised the lithic fill of the first depositional cycle as feldspathic sandstone based on petrographic studies. The Aptian-

Santonian sedimentary cycle ended with the Santonian thermotectonic event (Nwachukwu, 1972; Whiteman, 1982) that led to the uplift, faulting and folding of the sediments (Figure 2.1). Subsequent to the Santonian folding, the Abakaliki Basin became flexurally inverted forming anticlinorium and displacing the depocentre to the west forming Anambra Basin and to the south-east forming Afikpo Syncline (Nwachukwu, 1972; Whiteman, 1982; Nwajide, 2005).

The Campanian–Eocene sedimentary phase was initiated by a major marine transgression which led to the deposition of the Nkporo Group. The Campanian-Maastrichtian Nkporo Group is the oldest stratigraphic unit in the Anambra Basin while the Nkporo Formation occurs as the oldest sedimentary unit in the Afikpo Syncline (Arua, 1988). In the Anambra Basin, it consists of Nkporo Shale and its lateral equivalents, the Owelli Sandstone and Enugu Formation (Short and Stäuble, 1967). The Nkporo Shale is characterised by marine black shale with thin beds of oolitic ironstones and limestones (Arua, 1988). The Owelli Sandstone is composed of cross-stratified fluvio-deltaic sandstone (Obi and Okogbue, 2004), and the Enugu Formation consist of marginal to shallow marine carbonaceous mudstone and fine grained sandstone with thin coal seams at certain horizons (Reyment, 1965).

The succeeding Maastrichtian Mamu Formation consists of marginal marine mudstone and sandstones. Sediments of the Mamu Formation show lateral variation, in the north of Awgu, and consist of five coal-bearing tidal-intertidal cycles that reflect the infilling of an estuary bay-head (Nwajide and Reijers, 1996; Obi and Okogbue, 2004). In the distal basinal area south of Awgu, the Mamu Formation occur as metre-scale cycles of carbonaceous fissile shale-oncolitic mudstones-oolitic sandstone deposited in a shallow shelf-shoreface environment (Obi, 2000; Obi and Okogbue, 2004). Succeeding the Mamu Formation is the cross-stratified tidal channel/fluvial channel deposits of the Ajali Sandstone of Maastrichtian age (Ladipo, 1986; Obi, 2000). The Nsukka Formation which is Later Maastrichtian to Early Paleogene in age, consists of carbonaceous mudstone and sandstone lithologies, similar to those of the Mamu Formation (Reyment, 1965; Obi and Okogbue, 2004). Nwajide (2005) suggests that the Anambra Basin fill terminated with the Nsukka Formation. Nwajide (2005) further summarized the stratigraphic packaging in the Anambra Basin into two, namely the Nkporo Group and the Coal Measures. Clastic sediments of the second sedimentary phase are referred to as arenitic sandstones based on their composition (Hoque, 1977).

During the Paleocene, a major transgression extends across the entire area of southern Nigeria, terminating the advance of the Upper Cretaceous Delta and separating it stratigraphically from the modern Niger Delta which began to form in the Thanetian (Nwajide, 2005). Paleogene strata within southern Nigeria consist of a sedimentary succession that is thicker than 3500 m. These include the Upper Nsukka Formation (~350 m), Imo Formation (~480 m – 1000 m), Ameki Group (~1400 m), and Ogwashi Formation (~250 m) (Simpson, 1955; Reyment, 1965; Dessauvagie, 1975; Jan du Chêne et al., 1978; Nwajide, 1980; Arua, 1986; Anyanwu and Arua, 1990; Oboh-Ikuenobe et al., 2005). Obi et al., (2001) suggested a fluvio-deltaic sedimentation for the Nsukka Formation using sedimentological evidence. The Imo Formation is dated as Paleocene to Eocene based on based on macro and microfossils (Reyment, 1965; Adegoke et al., 1980; Arua, 1980) and it is composed of blue-grey clays, black shales with bands of calcareous sandstone, marl, and limestone (Reyment, 1965). The Imo Formation is referred as the oldest formation in the Niger

Delta (Petters, 1991). The Imo Formation shows lateral variation into sandstone in certain places in the south-eastern Nigeria, and is characterised by sandstones units that are laterally equivalent - the Ebenebe, Igbaku and Umuna Sandstone. A foreshore-shoreface environment was suggested for the sandstone member of the Imo Formation (Reijers et al., 1997), while Anyanwu and Arua (1990) suggested a delta front environment. The formation is assigned a Paleocene to Early Eocene age based on dinoflagellate cysts, miospore assemblages (Short and Stäuble, 1967; Oloto, 1992).

The Ameki Group consists of the Nsugbe Formation, Nanka Formation, and Ameki Formation (Nwajide, 1980), which are laterally equivalent. This formation consists of alternating sandy shale, clayey sandstone, fossiliferous shale (consisting of molluscs, foraminifera and corals) and fine-grained argillaceous sandstone with thin limestone bands (Reyment, 1965; Arua, 1986). The age of the formation is Middle Eocene (Lutetian) (Berggren, 1960; Reyment, 1965; Adegoke, 1969), but Oloto (1984) assigned Middle Eocene to Oligocene age to the formation based on dinoflagellate cysts and miospore assemblages. Kogbe (1976) considered the Ameki Group to be of Lutetian to Lower Bartonian age. The depositional environment has been interpreted as estuarine, barrier ridge-lagoon complex, and open marine, based on lithofacies interpretation and faunal content (Adegoke, 1969; Arua, 1986; Mode, 2002). Reyment (1965) suggested a partly non-marine to estuarine and a partly marine environment for the Ameki Group. Nwajide (1980) interpreted the Nanka Formation of the Ameki Group as the deposits of a tidally influenced marine shoreline environment. The Ameki Group is unconformably overlain by the Ogwashi Formation (commonly referred to as Ogwashi-Asaba Formation). The Ogwashi Formation consists of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Kogbe, 1976). Reyment (1965) indicated an Oligocene(?) to Miocene age for the Ogwashi Formation, while Jan du Chêne et al., (1978) suggested a Middle Eocene age for the basal part of the formation using palynological data.

The Paleogene formations are referred to as the lateral equivalents of the subsurface Niger Delta (Figure 2.3). The Paleogene strata are diachronous and extend into the subsurface where they are assigned different formation names (Petters, 1991). Short and Stäuble (1967) described the subsurface Akata Formation as a downdip continuation of the outcropping Imo Formation. The Akata Formation is characterised by monotonous dark-grey shale with local concentrations of sand, silt, plant materials and mica, it is assigned an Eocene to Holocene age (Kogbe, 1976; Short and Stäuble, 1967). The Agbada Formation is also referred to as the down-dip continuation of the outcropping Ameki Group and Ogwashi Formation. Details of the stratigraphy, depositional sequences, hydrocarbon potential, and structural framework of the Cenozoic sediments in southern Nigeria is limited to the subsurface Niger Delta because of its petrolific nature (Frankl and Cordy, 1967; Short and Stäuble, 1967; Weber, 1971; Oomkens, 1974; Weber and Daukoru, 1975; Evamy et al., 1978; Knox and Omatsola, 1989; Doust and Omatsola, 1990; Oboh, 1992; Allen, 1965; Oomkens, 1974; Doust and Omatsola, 1990; Reijers et al., 1997).

Figure 2.3. Correlation of subsurface and outcrop formations of the Niger Delta (redrawn and modified after Short and Stäuble, 1967, Avbovbo, 1978)

Subsurface			Outcrop		
Youngest known age	Formation	Oldest known age	Youngest known age	Formation	Oldest known age
Recent	Benin	Oligocene	Recent	Benin	Miocene
Recent	Agbada	Eocene	Miocene Eocene	Ogwashi Formation Ameki Group	Eocene Eocene
Recent	Akata	Paleocene	Lower Eocene	Imo Formation	Paleocene

2.3 GEOMORPHOLOGY

2.3.1 Topography

The topography of the study area is dominated by plains and lowlands of under 200 m above sea level and high areas of the Awka-Orlu Cuesta and Nsukka-Okigwe or Enugu Cuesta. The cuesta reaches over 520 m in the Nsukka region (Ofomata, 2002). Ofomata (1975) noted that the formation of plains and lowlands may have resulted from alternate denudational and aggradational activities. The denudation was concentrated on the highlands and provided materials for the aggradational materials that formed the plains. But Obi et al., (2001) suggested that the formation of the highlands may have resulted mainly from the tectonic and geomorphic evolution of the Abakaliki Basin. Two, out of the three types of plains and lowlands found in the south-eastern Nigeria occur in low proportions in the study area (Figure 2.4; 2.5). The three landform regions are:

- the Niger-Omambala lowlands which occur at the Onitsha-Aguleri region,
- the undulating lowlands and coastal plains are observed in the eastern Umuahia region of the study area
- the Cross River plains do not occur in the study area.

The Niger-Omambala lowlands are covered with recent alluvium from the Niger and Omambala rivers (Ofomata, 2002). The Niger lowland has an extensive flood plain that is usually engulfed with floodwaters when the river overflows its banks. The undulating lowlands and coastal plains are found at the sides of the Niger-Omambala lowlands. They are uniformly undulating except for the northern parts where the outcrops of Ameki Group abut with a minor scarp against the Awka-Orlu Cuesta in a rolling topography (Ofomata, 2002). In the low-lying area, east of Umuahia, the undulating lowlands and coastal plains show a complex topography of narrow ridges and valleys, formed by the interplay of resistant and non-resistant rocks.

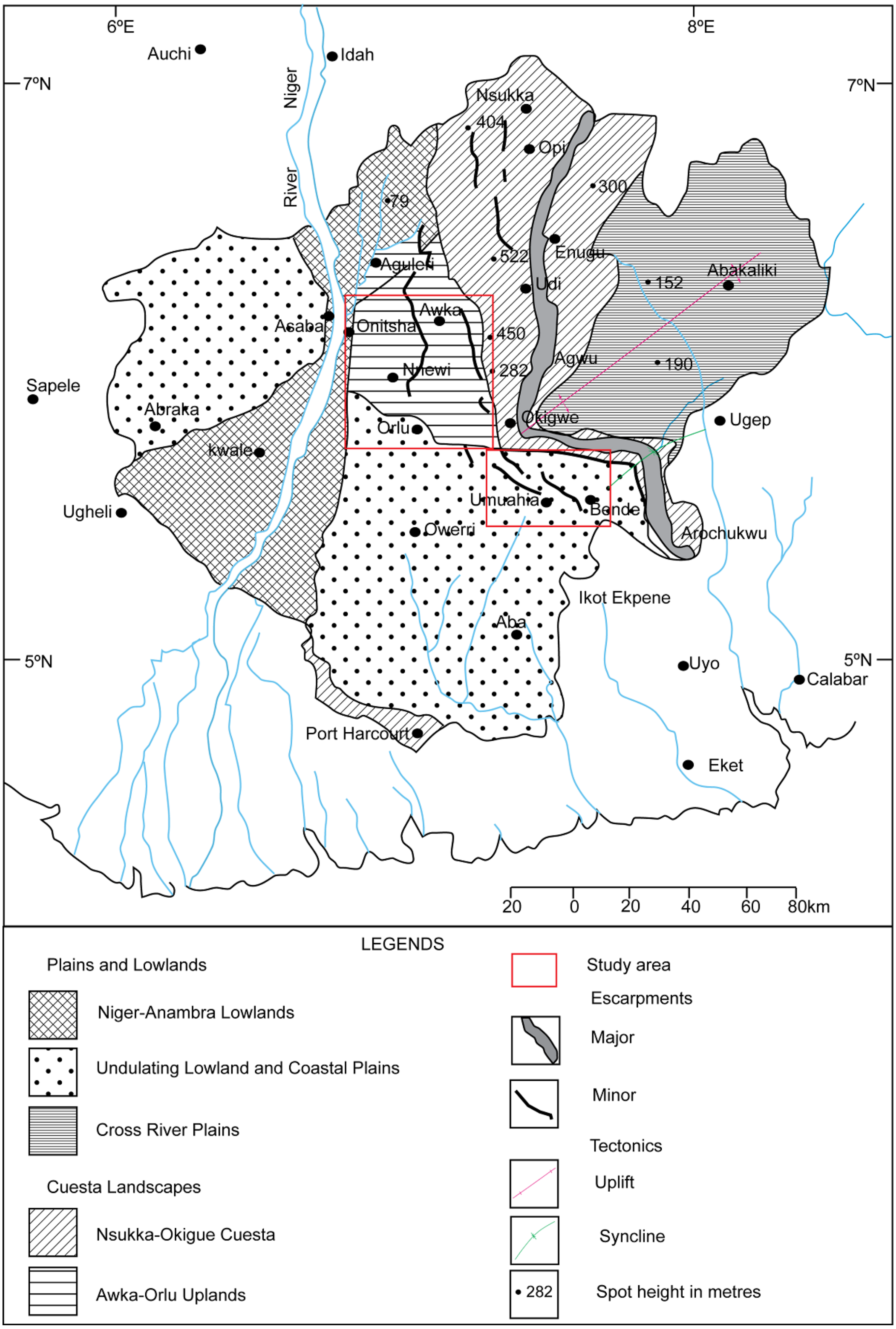


Figure 2.4. Landform regions of the south-eastern Nigeria (redrawn and modified after Ofomata, 2002).

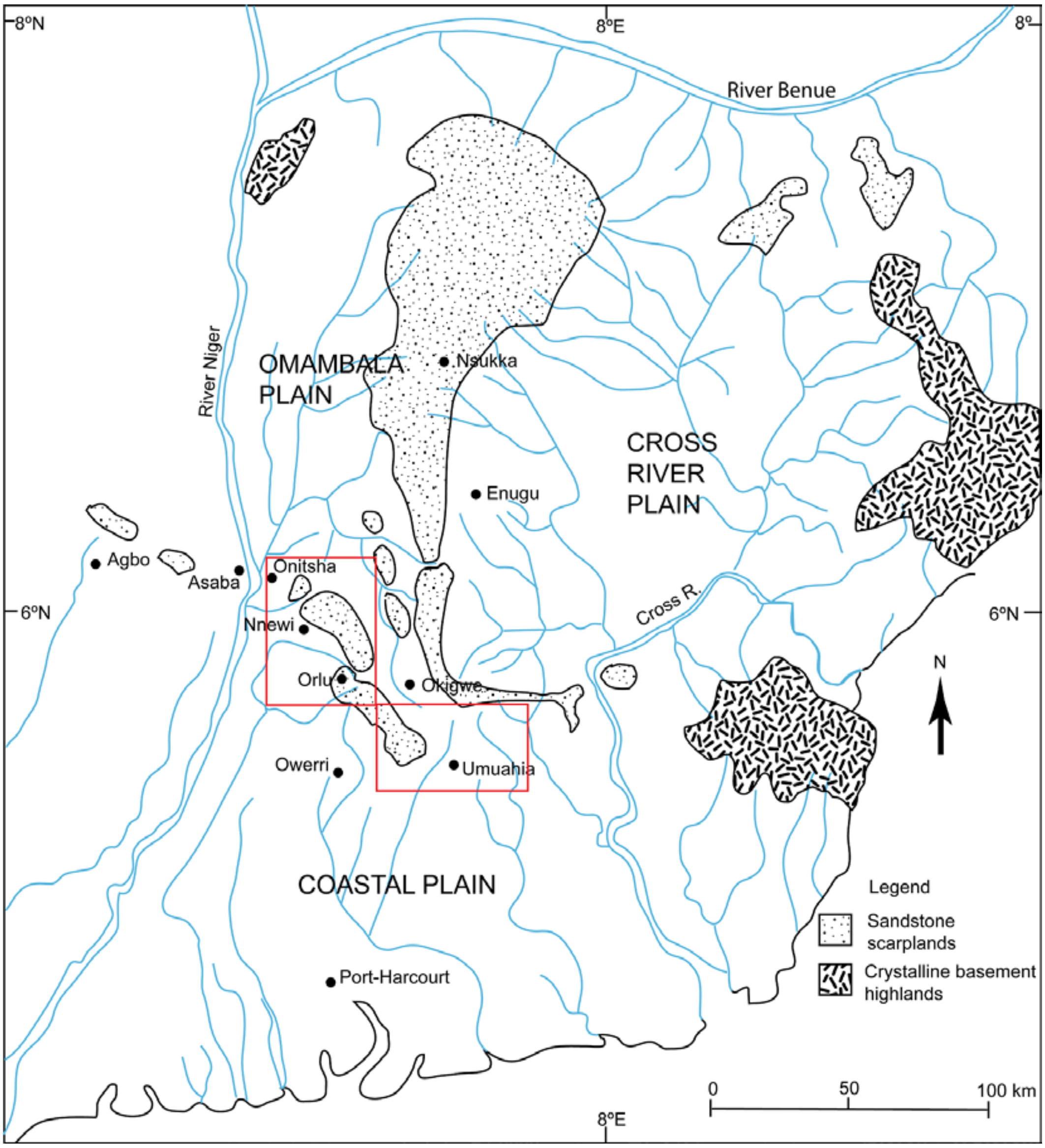


Figure 2.5. The scarplands of south-eastern Nigeria (redrawn and modified after Ofomata, 2002).

The Awka-Orlu Upland or Cuesta is predominant in the study area, while the Nsukka-Okigwe Cuesta (Ofomata, 1975, 2002), also called the Enugu Cuesta (Obi et al., 2001) is observed only in the Okigwe region. The Ameki Group is exposed by erosion in the uppermost part of the Awka-Orlu upland. In the central part of the upland, the Awka-Umuduru ridge includes the Nanka Formation reaching over 333.5 m above the sea level close to Agulu, Nanka and Ekwulobia regions; these are areas of intense gully erosion.

The Enugu Cuesta rises north-eastwards from Idah to Okaba and turns southwards, passing through Enugu and Okigwe. At Okigwe, it turns southwest to Arochukwu and flattens towards Cross-River (Obi et al., 2001). Ofomata (1975) subdivided the Enugu cuesta into three landform units - the Cross-River plain, the Enugu and Awgu Escarpment and the Udi-Nsukka Plateau. In the study area, at Okigwe, the escarpment is formed by the resistant sandstone of the Ajali Sandstone and the Nsukka Formation. The Udi-Nsukka plateau has been narrowed by headward erosion of the Imo River tributaries in the Okigwe region. But towards the eastern part of Okigwe, the plateau forms a hogback ridge approximately 244 m high and 1.6 to 4.8 km wide, which forms the watershed between the Cross River and Imo River systems (Ofomata, 1975).

2.3.2 Drainage

The drainage systems in study area are Anambra River, Mamu River and Imo River systems (Figure 2.6). They are observed at the gentle dip-slope of the Cuesta, and occur dominantly as pinnate and trellis patterns. The Anambra River has its headwaters from the Ajali Formation in Ankpa region. Its main tributaries which are the Okulu and Ofu rivers do not occur in the study area. Other minor tributaries such as the Oyi River, occurs as a trellis pattern.

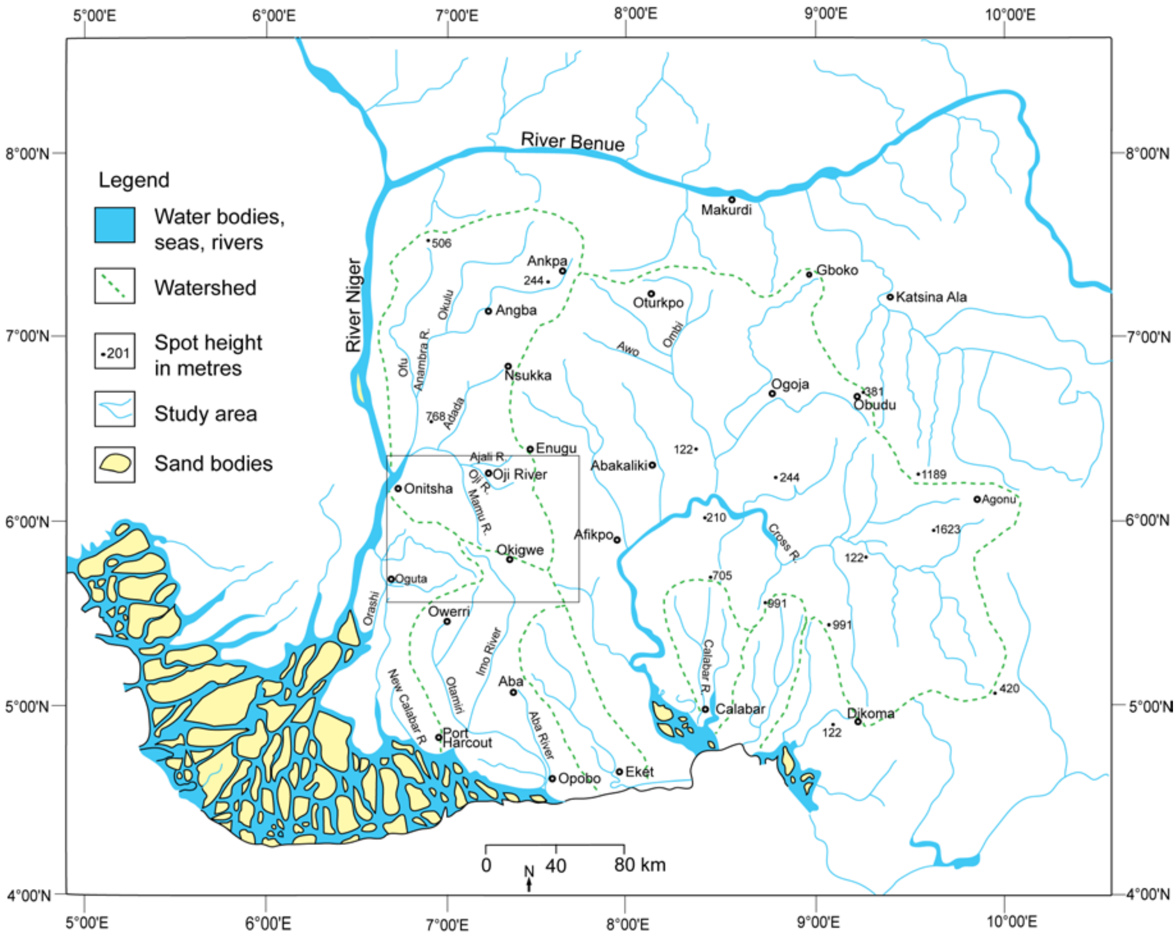


Figure 2.6. Drainage systems of the southern Nigeria, showing the study area (redrawn and modified after Inyang, 1975).

2.3.3 Climate and Vegetation

The climatic condition in the south-eastern Nigeria is categorized based on the amount of rainfall, duration of dry season, temperature and other environmental parameters (Inyang, 1975). The Umuahia and Bende regions have three dry months with a total rainfall of less than 60 mm (Figure 2.7) while the annual total rainfall ranges between 1,875 mm and over 2,500 mm. August-break or the ‘little dry season’ occurs with the rainy seasons. The regions provide ideal conditions for economic plants such as oil palm, cocoa, citrus, sugar cane, yam, plantain, banana, cassava, coconut, cocoyam, pineapple, rice and maize. Raffia palm and rubber are also grown in the regions. The Onitsha and Okigwe axes fall into the climatic region with four months in which precipitation is less than 60 mm with the driest month having less than 28.75 mm. The total annual rainfall ranges from 1,600 mm to more than 2,000 mm (Inyang, 1975). The dominant crops are yam, cassava, banana, plantain, citrus, maize, sugarcane, pineapple and rice been the dominant cereal. Beans and cowpeas are grown in the southerly regions.

Though the south-eastern Nigeria is predominantly a tropical rainforest zone, Igbozurike (1975) was able to categorise the region into four major vegetation types. Lowland rain forest and Rain forest-Savannah ecotone dominate the study area. Swamp and coastal forest is restricted to the part of Onitsha where recent alluvium deposit predominates (Figure 2.8). The Umuahia region is covered by lowland rain forest, though human activities have restricted the lush vegetation cover to protected reserves areas and some uncultivated farm lands. The primary tree type observed everywhere is the oil palm ‘*Elaeis guineensis*’. The forest is characterised by abundant plant species of over 150 different species per hectare (Igbozurike, 1975).

The vertical arrangement of plant structure shows a sequence of canopies which is obvious in the reserve areas where deforestation is lowest. Herbaceous plants such as *Geophila* and *Costus* occur on the forest floor. Plants of intermediate level (10-25 m high) are represented by trees such as *Musanga Smithii* and *Albizza Zygia*, whereas plants of the highest level (50-65 m high) include *Khaya ivorensis*, *Chlorophora excelsa* and *Ceiba pentandra*. Viniferous climbers such as *Ficus* spp., and epiphytic accretion like *Platycerium* and *Nephrolepis* spp. occur in abundant. Plants species found in the lowland rain forest also occur in the Rain Forest-Savanah Ecotone, though more grassed occur in the latter. In areas like Okigwe and Onitsha, closed or semi-closed forest occur due to the high rainfall and humidity. Hydrophytic plants like elephant grass *Pennisetum purpureum*, *Hyparrhenium* spp. and *Andropogon* spp. are common.

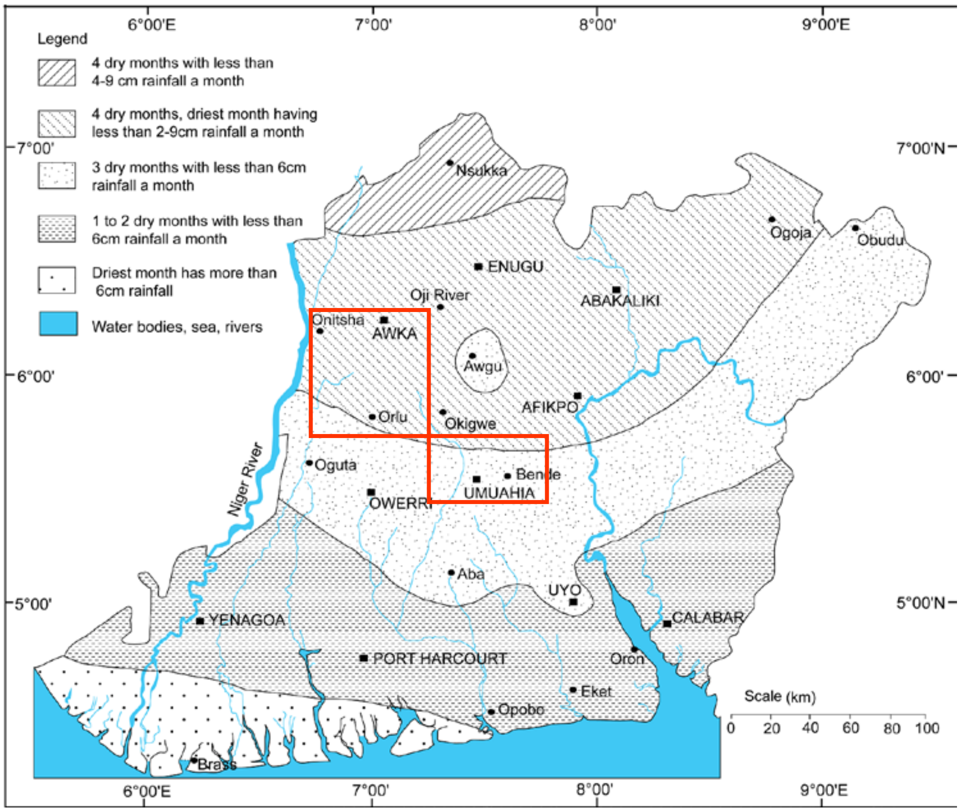


Figure 2.7. Climatic conditions of the south-eastern Nigeria (redrawn and modified after Inyang, 1975).

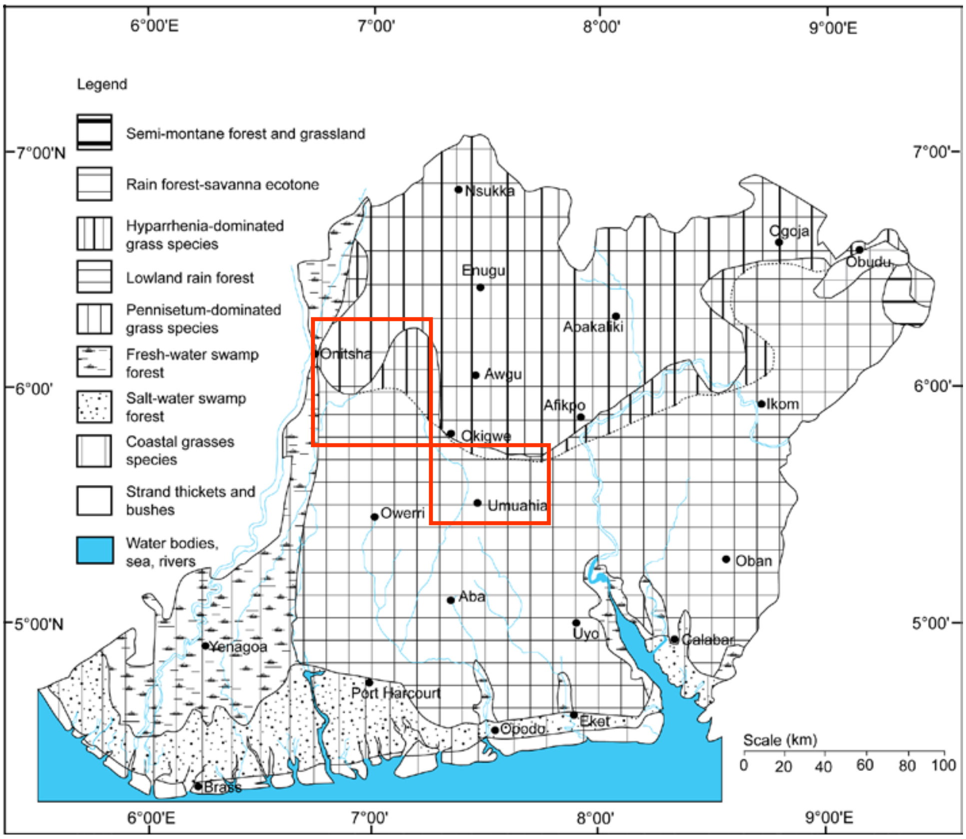


Figure 2.8. Vegetation types in the south-eastern Nigeria (redrawn and modified after Inyang, 1975).

CHAPTER THREE

FACIES ANALYSIS

3.1 INTRODUCTION

Field data obtained by sedimentological logging of about 69 outcrops in the study area is classified into lithofacies. Bed units are assigned facies based on their lithology, grain size, texture, the presence and absence of sedimentary structures, trace fossils, bed contacts, unit geometry and depositional processes. A total of nineteen facies and twenty three subfacies are identified from the studied outcrop sections.

Facies codes are designated to bed(s) based on their internal sedimentological features. Sub-facies are extracted from facies with variation in a particular sedimentary feature, which may infer slight variation in depositional processes. Facies code Gc is used for conglomerate facies, S is for sandstone, while F is for finer grains such as siltstone and mudrocks. Ls is designated to the limestone facies. The sedimentary facies scheme used in the study area is modified after Miall, 1996 and is summarized in table 3.1.

3.2 LITHOFACIES DESCRIPTION

3.2.1 Conglomerate facies (Gc)

Description

The Conglomerate facies (Gc) is subdivided into sub-facies Gc1, Gc2, Gc3 and Gc4. The Conglomerate facies are observed at the basal units of Ugwu-Akpi section, Okaiuga section and Umuezeoma-Uhuala section (Ogwuashi-Asaba Formation); and also at the basal units of Amumu Nsugbe, Ugwu-Nnadi quarry section and Ugwu-Nnadi Heterolithic section (Nsugbe Formation of Ameki Group). Sub-facies Gc1 is made up of matrix to clast supported, poorly sorted, monomictic conglomerate. The clasts are subrounded to well rounded with clayey to coarse sandy matrix. The conglomerate is creamy white to light brown in colour. Bed thickness is about 1 m to 3 m, and has erosional base and planar top. The beds are structureless and show no clasts imbrication, but it grades gradually into very coarse grain sandstone (Figure 3.1) at Ugwu-Akpi, Enugwu-Ukwu. This facies may contains burrows and exhibits low to intense bioturbation. Intense bioturbation observed in the matrix to clast supported conglomerate, with dominant *Skolithos* ichnofacies such as *Ophiomorpha nodosa, Paleophycus heberti, Diplocraterion* and *Planolites* at Ugwu Akpi sandstone quarry in Enugwu-Ukwu. No burrows or bioturbated occur at the facies at Amumu Nsugbe. This facies occurs in the basal Eocene Ameki Group and the Oligocene Ogwashi Formation. This facies forms a channel-like to tabular-shaped geometry.

Gc2 is a clast supported, poorly sorted orthoconglomerate. The clasts are subangular to well rounded and have low sphericity. The matrix is made up of clayey sands to granules and form about 15% of the sediment volume. Mud chips, mud pebbles probably altered feldspar grains and mud drapes were also observed. Bed thickness is from 60 cm to 2 m and the beds have erosional bases and planar tops. This sub-facies is characterised by crudely stratified trough and planar cross beds. Foresets of planar cross beds trend in a northeast direction of 300° to 312° at angles of 10° to 15°. But the trough cross beds, however trend in northwest direction of 212°. Clasts show a preferred orientation ranging from 072° to 094° (Figure 3.2). It is associated with medium to coarse grained, horizontally bedded sandstone (Sh) and planar cross-stratified sandstone (Sp).

At Umuezeoma-Uhuala, the erosive base of a conglomeratic bed is strongly burrowed by Glossifungites ichnofacies such as *Thalassinoides, Ophiomorpha nodosa, Arenicolites* isp.*, Planolites* and *Paleophycus heberti.* The subfacies extend laterally to about 30 m to 50 m. It also observed at a quarry site in Okaiuga-Umuahia, along the

Umuahia- Okigwe Expressway and occurs in the Oligocene Ogwuashi-Asaba Formation.

Gc3 consists of clast supported, poorly sorted orthoconglomerates, horizontally bedded with pebbles to cobbles range in clast sizes. The clasts are subrounded to rounded and have low sphericity. The matrix consists of poorly sorted coarse to granules, which represent less than 15% of the rock volume. Bed thickness is about 30 to 40 cm and has an erosional base and planar top. The clasts show imbrication and are aligned to a south-west direction. They occur as channel lag in Nsugbe at Ugwu-Nnadi quarry and is associated with the Nsugbe Formation of the Ameki Group.

Gc4 facies comprises brecciated mudstone, which occurs in a low angle inclined sandy heterolithic units in Nsugbe and forms low angle cross-stratification. Beds are thinly bedded (<30 cm thick), and less than 3.5 m long, except for some rip-up clasts that occur in the toesets of foresets. The beds have scoured bases and sharp contacts. The monomictic brecciated mud clasts consists of mostly irregular shaped centimetre to millimetre scale clasts (Figure 3.3A). They occur in several centimetre-scale cycles and form lenticular geometry. A large scale (35/20 cm) mud clast occurs as an intraformational clast (Figure 3.3B). This interval is also burrowed with *Ophiomorpha, Arenicolites, Planolites* and *Laminites*.

Table 3.1. Summary of description and interpretation of lithofacies in the Paleogene strata, south-eastern Nigeria.

Facies Code	Lithofacies	Subfacies	Textures	Sedimentary sturctures	Ichnology	Depositional process
Gc	Conglomerate	Gc1: Massive conglomerate	Matrix to clast supported, poorly sorted, Clasts are subrounded to well rounded.	Bed is structureless, shows normal grading but no clasts imbrications.	Intense bioturbation, possibly *Skolithos* Ichnofacies	Cohesive debris flow in a sub-aqueous setting.
		Gc2: Cross stratified conglomerate	Clast supported, poorly sorted orthoconglomerates.	Crudely stratified trough and planar cross beds.	*Glossifungites* ichnofacies- *Thalassinoides, Ophiomorpha, Arenicolites, Planolites, Paleophycus.*	Surging debris flow in a sub-aerial setting. Stratifiaction occur as bedforms migrate in bedload traction.
		Gc3: Horizontally bedded conglomerate	Clast supported, poorly sorted orthoconglomerates, clasts are subrounded to rounded.	Horizontally bedded with pebbles to cobbles range in clast sizes, clasts show imbrications.	None	Longitudinal bedform, channel lag deposit, sieve deposit.
		Gc4: Brecciated mudstone	Monomictic brecciated mud clasts, mostly irregular shaped, isolated large intraformational clast.	Low angle cross-stratification, beds are thinly bedded (<30cm thick).	Associated with *Ophiomorpha, Arenicolites, Thalassinoides, Planolites* and *Laminites* burrows	Scour fills
Sp	Tabular cross-stratified sandstone	Sp1: Medium scale planar cross-stratified sandstone	Medium to very coarse grained, moderately to poorly sorted sandstone.	Normal grading of the foresets, foresets are planar (angular based). Mud clasts, extra-formational clast occur.	*Ophiomorpha, Skolithos, Arenicolites, Diplocraterion, Lockeia*	Migration of straight-crested bedform.
		Sp2: Mud draped tabular cross-stratified sandstone	Fine to coarse grained, moderately to poorly sorted.	Single to double mud drapes on foresets. Mud clasts and saucer-shaped mud lenses occur locally.	Sparely *Skolithos* Ichnofacies	Migration of straight-crested bedform. Mud drapes occur during slack water conditions.
		Sp3:Asymptotic cross-stratified sandstone	Coarse grained sandstone and poorly sorted.	Usually tabular cross-stratified sandstone with concave base.	None	Increasing velocity during the migration of straight-crested dunes.
		Sp4:Large scale planar cross-stratifed sandstone	Fine to very coarse grained and well to poorly sorted.	Foresets show normal grading and are up to 25 m long. Reactivation surfaces, pebble horizons, counter current ripple-laminations, and mud chips are common.	Poorly burrowed- *Ophiomorpha* , *Paleophycus* .	Avalanching of sediments along the slipface of dunes.
		Sp5: Low angle planar cross stratified sandstone	Coarse to very coarse grained sandstone, poorly sorted.	Mud drapes, mud chips and wavy bedding at certain horizon.	None	Low amplitude migrating megaripple. Mud drapes and wavy bedding reflect fluctuation of energy .
St	Trough cross-stratifed sandstone	St1: Trough cross-stratified sandstone	Medium to very coarse grained, moderately to very poorly sorted, ferruginised sandstone.	Large scale (>40cm thick) trough cross stratification.	None	Migration of lunate or sinuous-crested bedform.
		St2: Trough cross- stratified with mud drapes	Medium to coarse grained, moderately to poorly sorted, poorly consolidated sandstone.	Medium scale (20cm to 30cm thick) and large scale (>40cm thick) trough cross stratification, mud balls, mud drapes and thick mud plugs.	*Ophiomorpha nodosa, Thalassinoides* , *Planolites, Paleophycus*	Migration of lunate or sinuous-crested bedform. Fallout of suspended sediments at slack water periods.
Sx	Sigmoidal cross-stratified sandstone	Sx1: Sigmoidal cross-stratified sandstone	Medium to coarse grained, moderately to poorly sorted sandstone.	Sigmoidal shaped foresets graded into tabular cross beds with tangential and concave foresets.	None	Increase in flow velocity during migration of megaripples.
		Sx2: Sigmoidal cross-bedded sandstone with mud drapes	Fine to medium grained, well to moderately sorted sandstone.	Single to double mud draped foresets, with mud draped rippled toesets and mud draped reactivation surfaces	Low diversity and abaundance of ichnofossils- *Ophiomorpha* , *Paleophycus, Planolites* , *Beaconites, Cylindrichnus, Skolithos.*	Migration of megaripples as flow velocity decelerates. Mud drapes formed during slack water conditions.
Sxh	Herringbone cross stratified sandstone		Medium to coarse grained, moderately to poorly sorted sandstone.	Small and large scale bi-directional cross beds. Some foresets are wavy (rippled) and mud draped.	Rare	Periodic reversals in current direction as a result of tidal action.
Sh	Horizontally stratified sandstone	Sh1: Parallel laminated sandstone	Fine grained, well to moderately sorted sandstone.	Parting lineation	None	Upper flow-regime flat bed produced by high flow velocity.
		Sh2: Horizontal bedded sandstone	Medium to coarse grained, moderately to poorly sorted sandstone.	Parallel bedding	None	Lower flow-regime flat bed produced by decelerating current.
Sb	Bioturbated sandstone		Fine to coarse grained, well to poorly sorted sandstone	Relics of ripples, tabular cross beds and horizontal bedding; structureless beds.	Moderate to intensed bioturbation- *Skolithos* and *Cruziana* ichnofacies; rhizoliths.	Stress condition in a marginal-marine environment due to low and /or fluctuating salinity levels. Rhizolith indicates paleosol.
Sht	Sandy heterolithic facies	Sht1: Non-inclined heterolithic facies	Intercalation of well sorted, very fine to fine grained sandstone and mudstone.	Intercalation of mm-dm scale sandstone and mudstone.	Low diversity and moderate to high abandance of *Skolithos* and depauperate *Cruziana* ichnofacies	Tidal rhythmites
		Sht2: Inclined heterolithic facies	Well sorted, fine grained, mm-dm thick sand, silt and mud	High angle to low angle inclined amalgamated and non-amalgamated cyclic rhythmites of sand, silt and mud.	Low diversity and moderate to high abandance of *Skolithos* and depauperate *Cruziana* ichnofacies	Lateral accreting point bar
Mht	Muddy heterolithic		Grey mudstone, with very fine grained sands and silts	Cyclic rhythmic and non-cyclic rhythmic alternation of cm to m-scale mudstone and mm-scale sand and silt.	Low-diversity ichnofossils- *Teichichnus, Planolites* and *Thalassinoides* .	Low or wanning energy flow condition
Sr	Current ripple laminated sandstone		Fine to coarse grained, well to poorly sorted sandstone.	Climbing ripples, ripple laminations, counter current ripples, flaser bedding, and wavy bedding	*Ophiomorpha* , ?*Arenicolites* , escape burrows, *Conichnu* s	Migration of unidirectional current in water or during deceleration of high velocity current.
Sw	Wave ripple laminated sandstone		Very fine to fine grained, well sorted, micaceous sandstone.	Symmetrical and asymmetrical wave ripple laminations, convolute lamination, load casts, slumping.	Rare	Oscillatory waves or combination of oscillatory waves and unidirectional currents.
Fs	Siltstone		Well sorted micaceous siltstone with intercalation of finer silt and organic rich laminae.	Rhythmites-alternating parallel laminated greenish grey sitly layers and dark grey organic-rich layers	Rare	Combine seasonal and tidal actions. Also wave reworking.
Fm	Mudstone	Fm1: Carbonaceous mudstone	Mudstone characterised by carbonaceous and plant matters -lignites, petrified leaves and plant fragments	Thickly laminated to structureless dark grey mudstone. Locally contains streaks of siltstone	*Planolites* locally occur.	Supratidal condition or localised vegetated peat mires
		Fm2: Massive mudstone	Massive to laminated mudstone/ claystone occassionally with micaceous siltstone or gypsiferous layer.	Structureless to thinly laminated mudstone or claystone	Rare	Episodic settling of mud/silt from suspension (for laminated mudstone). Continuous and rapid deposition from suspension (for massive mudstone).
		Fm3: Laminated mudstone	Laminated mudstone,with fine streaks of siltstones and sandstone.	Parallel lamination and lenticular bedding	Rare	Episodic settling of mud/silt from suspension.
		Fm4: Fossiliferous mudstone	Fossiliferous, micaceous thinly laminated mudstone.	Sideritic concretions,shells of gastropods, corals, bivalves and shark teeth are common	Slight burrowing - *Planolites*	Low energy conditions
Fl	Shale	Fl1: Fossiliferous shale	Greenish-grey fossiliferous shale, with limestone nodules	Abundant fossils rays, sharks, ambers and coquina. Sideritic concretions are common	Rare	Limited oxygenated bottom water conditions.
		Fl2: Non-fossiliferous shale	Light bluish gray to dark gray shale	Sideritic concretions are common	Rare	Low energy and reducing conditions
Fg	Gypsiferous Shale		Greyish black to brownish black shale	Gypsum crystals, amber, carbon (lignite) material, large petrified logs and fossilised wood fragments.	*Teredolites longissimus*	Marginal-marine condition
Fc	Marl		Dark grey calcareous mudstone	Associated with thinly bedded fossiliferous limestone.	Rare	Low-energy condition with little terrigenous influx
Ls	Limestone		Bioclastic limestone layers interbedded with fine grained, fossiliferous sandstone.	Abundant whole and some fragments of bivalves, gastropods and molluscs.	Rare	Low-energy condition
Sm	Structureless sandstone	Sm1:Fossiliferous structureless sandstone	Fine grained, micaceous fossiliferous structureless sandstone	Associated with thin fossiliferous limestone beds	Rare	Gradual aggradation of sediments beneath steady flows; or rapid deposition.
		Sm2: Non-fossiliferous structureless	Medium grained, non-fossiliferous structureless or massive sandstone		Rare	
Fmc	Variegated facies		Variegated coloured and bioturbated fine to medium grained clayey sandstone and nodular mudstone	Carbonaceous materials, desiccation and shrinkage cracks are common	Rhizoliths	Poorly drained paleosol

Interpretation

Gc1 is indicative of cohesive debris-flows in a subaqueous setting. Lack of preferred clasts orientation is common in subaqueous debris-flow conglomerates (Boggs, 2009), this suggests a more viscous debris-flow deposit (Reineck and Singh, 1980). The presence of abundant trace fossils reflects activities of organisms after deposition. Gc1 occur as a channel fill of about 8-15 m wide, forming an isolated channel.

Gc2 consists of cross-stratified sandstone that may have resulted from either an upward decrease in matrix strength or an increase in water content (Backert et al., 2010). The planar and trough cross-bedded sandstone bodies represent deposits developed under the waning traction current of a stream flow. Foresets of clast dunes reflect bedform migration in bedload traction. Reineck and Singh (1980) referred this facies as stream channel deposit, where the conglomerates may show imbrications and the sandstones show cross-bedding. The deposit is typical of the upper part and midfan area of alluvial fan deposit. Stream-flow conglomerates exhibit abundant cross-stratification (Boggs, 2009)

Presence of mud drapes and trace fossils may represent periods of quieter current regimes. The occurrence of *Glossifungites* ichnofacies at the base of Gc2 facies suggests a firmground substrate (Pemberton et al., 1992). The burrows are mud and sand-fill suggesting burrowing into underlying mudstone.

Gc3 is deposited as lag during strong, erosive current winnowed gravelly sands, taking other sand grains into saltation or suspension (Collinson et al., 2006), representing a sieve deposit. The pebbles are then left behind and concentrated as a thin layer. The clasts may be transported via traction current under conditions of lower flow regime (Ghazi and Mountney, 2009). The rounded clasts was probably a result of abrasion during cyclic sediment transport and storage (Uba et al., 2005). Channel lag deposit occupy the lowest part of a channel or point bar sequence and indicates the base of a channel (Reineck and Singh, 1980). Horizontal stratification represents migration of longitudinal bedforms.

Gc4 occurs as scour fills and reflects re-deposition of probably dewatered, cohesive mud that has been reworked by periodically strong tidal currents (Rebata et al., 2006a). Some brecciated mud clasts occur in the sand matrix and others, such as the large scale intraformational mud clast, slid down inclined surfaces, occurring on the toesets of the inclined surfaces.

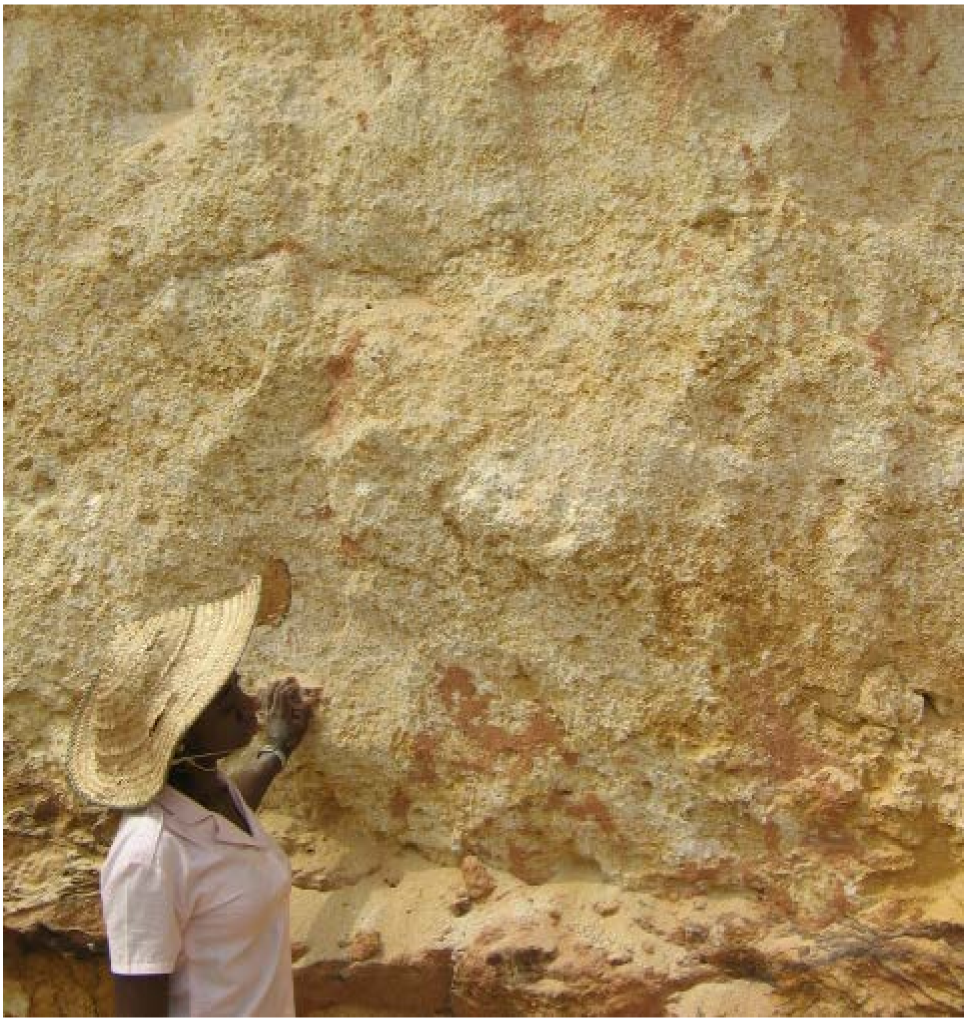


Figure 3.1. Matrix supported monomictic conglomerate (Gc1 facies) at Enugwu-Ukwu sandstone quarry, (Oligocene, Ogwashi Formation). The conglomerate shows no clast imbrications.

Figure 3.2. Larger clasts (light blue arrow) show preferred orientation in a north-east direction, observed at Okaiuga sandstone quarry (Gc2 facies), (Oligocene, Ogwashi Formation).

Figure 3.3 (A) Brecciated mudstone (Gc4 facies) in a low angle inclined sandy heteroliths in Nsugbe. (B) Well rounded intraformational clast rolled into the inclined sandy heteroliths (Eocene Ameki Group).

3.2.2 Tabular cross-bedded sandstone facies (Sp)

Description

The tabular cross-bedded sandstone facies (Sp) is characterised by planar foresets with angular bases and curved foresets with asymptotic (tangential) or concave toesets. This facies is composed of five sub-facies (Sp1-5) and it is common throughout the study area. The tabular cross-bedded sandstone facies are occur at the lower and middle parts of outcrop sections observed at Nsugbe, Ishiagu, Awka, Ifite-Awka, Oyi, Nibo, Ugwu-Akpi, Umunya, Ebenebe, Umuezeike, Abam, Okaiuga.

Sp1 is the planar cross bedded sandstone facies which comprises medium to very coarse grained, moderately to poorly sorted sandstone. The sands are mostly unconsolidated, creamy white to light brown colour except for the ferruginsed, reddish brown consolidated sandstone which outcrops at Nsugbe town about 2 km from Nwafor Orizu College of Education Junction. This sub-facies is characterised by normal grading of the foresets from pebbly or coarse grains to finer grains. The foresets are planar (angular based), and they are bounded at base and top by sharp contacts, at Awka some of the bounding surfaces are draped with mud. Bed thickness ranges from 20 cm to1 m. Individual foreset beds range from few millimetres to several centimetres thick. Reactivation surfaces are common as observed in Awka and Ishiagu sections. Mud clasts and extra-formational clast occur in the Awka and Ishiagu section (Figure 3.4). Sand-filled concretions are observed in Nsugbe area (Figure 3.5).

Sp1 is sparsely burrowed, with low diversity, opportunistic burrows belonging to *Skolithos* ichnofacies (*Skolithos, Arenicolites, Diplocraterion, Lockeia*) occurs in Ishiagu while a monospecfic *Ophiomorpha* burrow dominate the Nwafor Orizu College of Education Junction section at Nsugbe. The *Lockeia* isp. is associated with bivalve escape structures. This sub-facies Sp1 occurs as sheets covering about 20 to 50 m and as wedge-like shape, where it laterally changes to other facies.

Sp2 is a mud draped tabular cross-stratified sandstone with single to double mud drapes on some foresets. The toesets would be asymptotic or planar (Figure 3.6A-C). The sands are fine to coarse grained, moderately to poorly sorted and creamy to light brown colour. The bed thickness ranges from 40 cm to 1 m and the bed contacts are sharp to gradational bases and tops. This sub-facies consist of mud clasts and saucer-shaped mud lenses as observed in Ugwu-Akpi at Enugwu-Ukwu. The Sp2 occur as sheets covering about 20 to 50 m or as channel fills in Oyi, Nibo, Ugwu-Akpi, Umunya and Ishiagu sections.

Sp3 represents tabular cross-stratified sandstone with asymptotic (tangential) or concave base. This sub-facies consists of coarse grained, poorly sorted, creamy to light brown coloured sands. The bed thickness range between 20 cm to 1.5 m and has a tangential or curved basal contact and a sharp to gradational top contact. It is uncommon and occurs at Ishiagu, Awka and Ifite-Awka.

Sp4 is represented by large scale planar cross-stratified sandstone. The sands are fine to very coarse grained and well to poorly sorted, they are friable and have a white to creamy colour with some iron stains due to oxidation. Bed thickness varies from 2 m to about 10 m. Beds have erosional or non erosional bases and tops. Avalanche foresets show normal grading and are up to 15 m or 25 m long at Ebenebe and Umuezike, Mkpa Junction sections, with high dip angle of 15° to 35° (see Chapter 4: Figure 4.6). While at Abam, Nando, Ifite-Awka and Ishiagu, the foresets are about 4 to 8 cm and have high dip angles of about 10° to 25°. In the Ebenebe, Umuezeike and Ameke Abam sections (Figure 4.8), the cross beds are associated with reactivation surfaces, conspicuous horizons of pebbles, counter current ripple-laminations, and consist of mud chips. The sub-facies at Ebenebe, Umuezeike and Ameke Abam occur as a lens-shape, extending throughout the study area, it strikes in a general northwest-southeast direction. The Sp4 in other outcrops are sheet or wedge-like in shape. This facies is tens of meters thick and aerially extensive, covering more than 100 km^2.

Sp5 consist of coarse to very coarse grained, poorly sorted, low angle cross–bedded sandstone. The sands are light brown in colour and poorly consolidated. Bed thickness is between 60 cm to 3 m, with sharp bases and planar tops. The sub-facies is draped with mud, contains mud chips and also wavy at certain horizon as observed in Okauiga section. It forms a tabular geometry.

Interpretation

Sp suggests the migration of straight-crested bedforms, in the middle part of the lower-flow regime. Flow strength over the crest can strongly influences the shape of the foreset, weak flow creates angular foresets as observed in Sp1 facies whereas, stronger flow leads to tangential foresets typical of Sp3 facies (Collinson et al., 2006). Kohsiek and Terwindt (1981) noted that during the full vortex stage of dune migration, increasing velocities results in the formation of angular, tangential and concave cross-bedding. The impoverished *Skolithos* ichnofacies in Sp1 are dwelling structure of suspension feeders which indicates high energy condition in a stress brackish-water condition (Buatois et al., 2002).

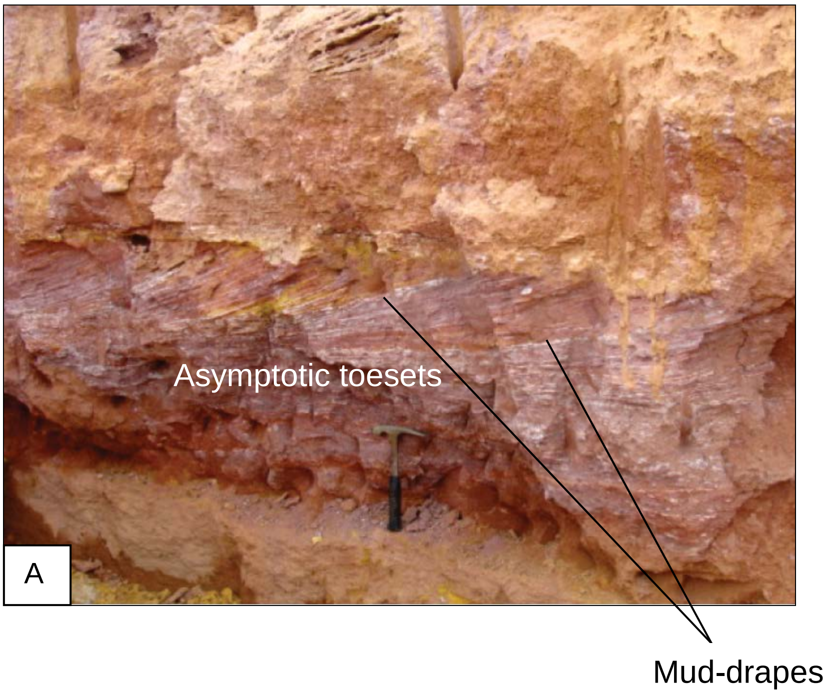
Small-scale cross-bedding (10 to 30cm) reflects migration of small-sale bedforms with low relief. The presence of reactivation surfaces in Sp1 may result from reworking by waves during emergence of a bedform between successive flood events that commences bedform migration (Collinson et al., 2006). It may also result from subordinate tidal flow due to reversals in flow direction such that a bedform’s leeside is changed into the stoss side resulting in substantial bedform modification (Allen and Homewood, 1984). Mud drapes on cross beds foresets in Sp2 are deposited during slack water conditions in response to semi-diurnal tidal fluctuation (Shanley et al., 1992). The high occurrence of iron mineral as observed in the ferruginised sandstone of Sp1 facies and iron-rich (haematite) concretions suggest post-depositional effect due to sub-aerial exposure and an oxidizing condition.

Large-scale cross-beds (Sp4 facies) are formed by avalanching of sediments along the slipface of dunes (Nio and Yang, 1991). The occurrence of this large scale planar cross beds can reflect advance of a delta with steep slopes, for instance the Gilbert-type delta (Oti and Postma, 1995; Collinson et al., 2006; Zaghloul et al., 2010) or advance of large bars of a channel or offshore tidal sandwaves (Stride, 1982). Large sandwaves formed by unidirectional current may generate sharp-crested high angle (30° or more) forms, with a lee slope steep enough for avalanching (Flemming, 1980). The large scale planar cross bed show development of regressive small ripples, moving upward along foreset laminae (backflow) as counter-current ripples or the small ripples are developed in form of climbing ripples (Reineck and Singh, 1975). Counter-current ripples are formed at high flow velocities, when the roller vortex is strong to create a counter current at the base of the dune slip face which generates ripples (Nichols, 1999; 2009).

Low angle cross-beds (Sp5) reflect migration of megaripples with low amplitude (Leithold and Bourgeois, 1984).

Figure 3.4. Ferruginised rim of extraformational clasts- xylic substrate in a cross-stratified sandstone (Sp1 facies) Eocene Ameki Group.

Figure 3.5. Iron-rich sand fill concretions observed in the ferruginised sandstone at Nsugbe (Sp1 facies). (Eocene Ameki Group). Scale: 15 cm.


Asymptotic toesets
A
Mud-drapes

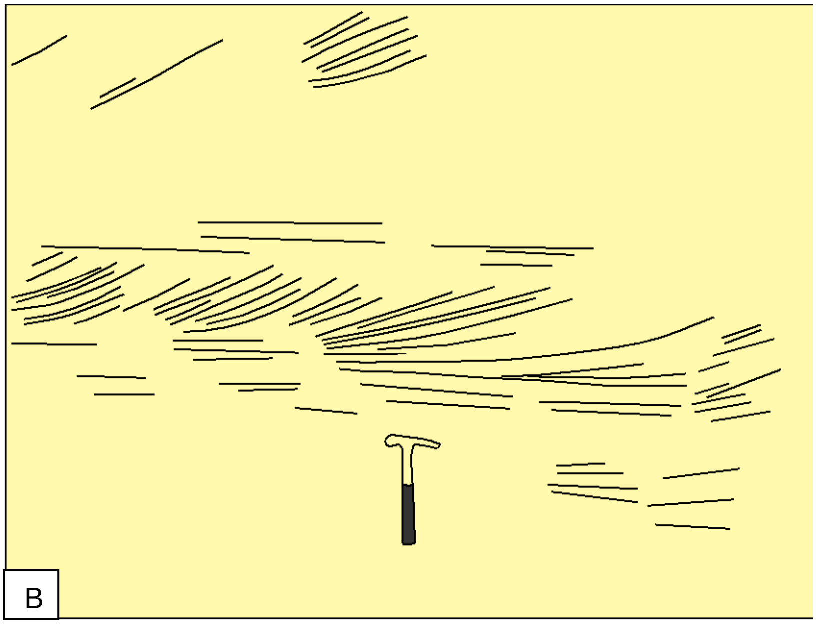

B

Figure 3.6. Tabular cross-bedded sandstone facies (Sp) (A) Outcrop photo and (B) schematic diagram showing mud draped tabular cross-beds (Sp2 facies) with asymptotic toesets (tangentially based) as observed at Ugwu-Akpi quarry, Enugwu-Ukwu (Eocene Ameki Group). (C). Mud draped foresets of tabular cross-beds with planar toesets (angular based) as observed at Nibo Section (Eocene Ameki Group).

3.2.3 Trough cross-bedded sandstone facies (St)

Description

The trough cross-bedded sandstone facies (St) is characterised by three-dimensional dunes with spoon-shaped or scallop-shaped scours. This cross-stratification has also been referred to as festoon bedding (Boggs, 2009). It is subdivided into two subfacies, St1, trough cross-bedded sandstone, and St2, trough cross-bedded sandstone with mud drapes. This facies is occurs dominantly at the lower part of the outcrop sections observed at Ugwu-Nnadi sandstone quarry in Nsugbe, Nando, Nibo and Ogbunike quarry.

St1 is characterised by medium to very coarse grained and moderately to very poorly sorted sandstone. The sands are creamy to dark reddish brown coloured, poorly to well consolidated and ferruginised. Large-scale (>40 cm thick) trough sets occur and the individual foresets are centimetre thick and grade from pebbly to very coarser to finer grains (Figure 3.7). Trough sets have sharp tangential basal contacts and sharp concave top. Bed thickness varies from 80 cm to 4 m. The sands obviously void of burrows. The subfacies forms amalgamated channels, covering an aerial extent of more than 100 m. It is observed at Ugwu-Nnadi sandstone quarry in Nsugbe.

St2 consists of medium to coarse grained, moderately to poorly sorted sandstone. The sands are light brown in colour, and poorly consolidated. Trough sets occur as medium scale (20 to 30 cm thick) and large scale (>40 cm thick) troughs. This subfacies is characterised by mud balls, mud drapes on foresets (Figure 3.8) and thick mud plugs at the troughs. It is poorly to strongly burrowed with *Skolithos* ichnofacies (robust *Ophiomorpha nodosa, Thalassinoides paradoxicus*, *Planolites montanus, Paleophycus tubularis)* as observed at Nibo and Ogbunike quarry. At Nando, the subfacies is associated with facies current ripple cross lamination (SxR), as it changes laterally, pinching out in both directions to form a lens. At Ogbunike, the trough cross-bed is partially mud draped, burrowed and associated with herringbone cross-stratification. It grades laterally into planar cross-beds in a north-west direction, forming a wedge-like shape.

Interpretation

Formation of trough cross-stratification suggests migration of lunate or sinuous-crested bedform, at a deeper and higher velocity flow than straight–crested dunes (Collinson et al., 2006). It occurs at the upper part of the lower-flow regime. Erosional surfaces may be induced by fluctuation of flow velocity or depth during bedform migration (Zaghloul et al., 2010). Variable grain texture is controlled by variation in sorting due to fluctuating hydraulic conditions. The presence of mud drapes on foresets of St2 facies reflects fallout of suspended sediments at slack water periods. The accumulation of thick mud plugs/balls on foresets/troughs are accelerated by rapid flocculation, with decreasing current velocity, they often known as fluid (or water–rich) mud and are common in tidally influenced setting (McIlroy, 2004). The low diversity *Skolithos* and *Cruziana* ichnofacies suggest stressful conditions due to low and/or fluctuating salinity levels, common in marginal marine realm (Taylor and Gawthorpe, 1993).

Figure 3.7. Large-scale trough cross-stratification (St1) in ferruginised sandstone at Ugwu-Nnadi sandstone quarry in Nsugbe (Eocene Ameki Group).

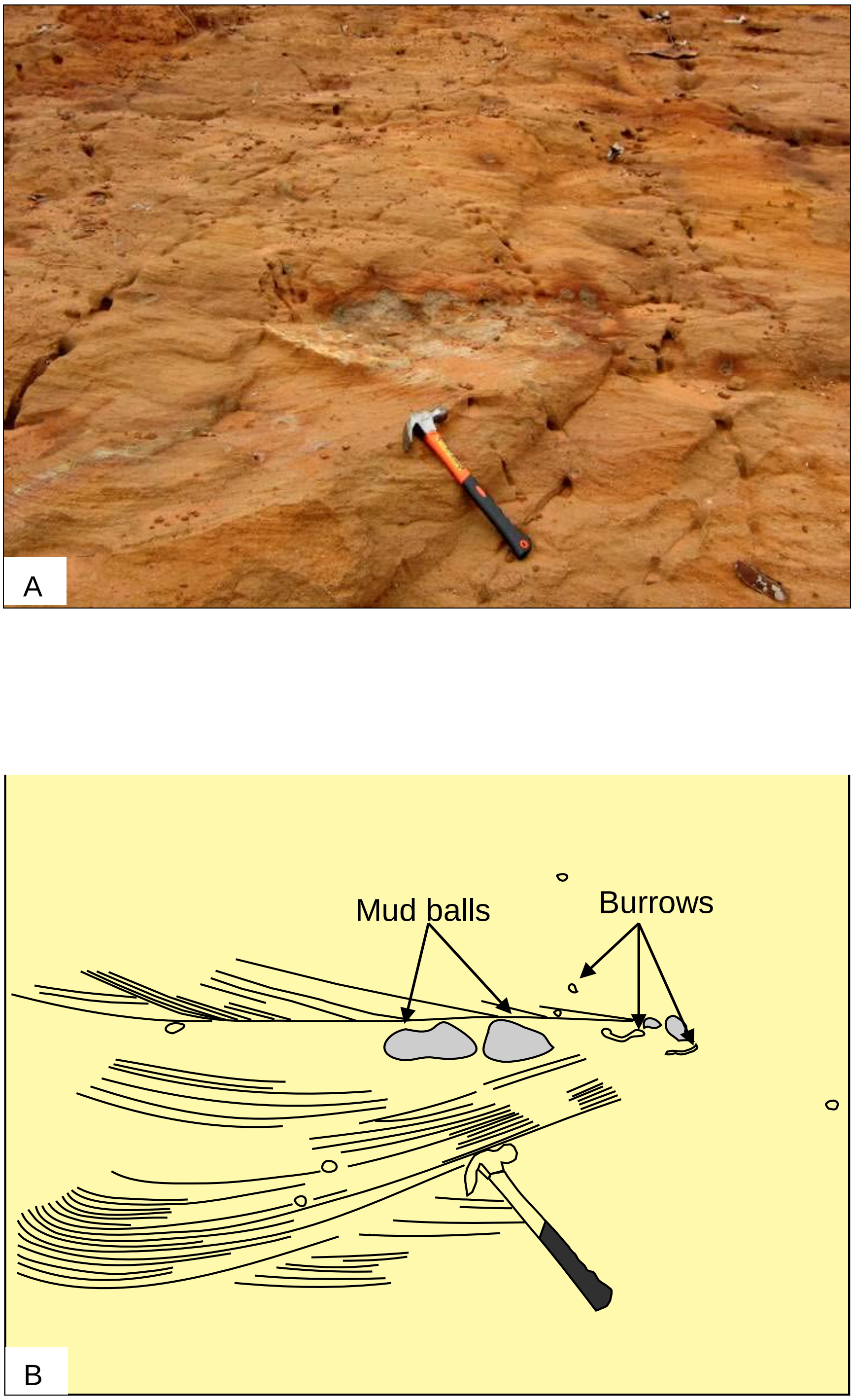


Figure 3.8. (A) Large-scale trough cross-bed (St2) with mud drapes and mud balls, moderately burrowed. Basal unit of the Nibo Section (Eocene Ameki Group). (B) Schematic diagram shows the scallop-shaped scour with well curved forests.

3.2.4 Sigmoidal cross-stratified sandstone facies (Sx)

Description

Sigmoidal cross-stratified sandstone facies (Sx) exhibits a gentle, sigmoid to avalanche-type cross-bed foreset back to sigmoidal shape (Kreisa and Moiola, 1986). The foresets have convex-up topset and tangential toeset laminae.

The Sx facies is composed of two sub-facies. Sub-facies 1 comprises medium to coarse grained, moderately to poorly sorted sandstone with yellowish brown to light brown colour. Bed thickness is about 2m, with sharp base and top contacts. A set of sigmoidal shaped foresets developed into tabular cross beds with tangential and concave foresets as the dune migrate downstream in a south-western direction, resulting to a lens or wedge-like shape sand body. This is observed at Ishiagu and Awka sandstone quarries.

Sub-facies 2 is a fine to medium grained, well to moderately sorted sandstone. It is creamy white to light brown on fresh surface, but dark grey on weathered surface. Bed thickness is between 10cm to 80cm, with rippled or planar sharp bases and tops. This sub-facies is characterised by single to double mud draped foresets, with extensive mud draped rippled toesets that form asymptotic bottomsets. The internal structure of the asymptotic bottomsets is characterised by wavy bedding and bifurcated wavy flaser bedding as observed at Umunya. Mud draped reactivation surfaces are very common (Figure 3.9), and the sandstone is moderately burrowed with *Skolithos* ichnofacies, consisting of *Ophiomorpha nodosa, Paleophycus heberti, Planolites montanus*, *Beaconites, Cylindrichnus concentricus* and *Skolithos*. Sub-facies 2 forms a tabular or sheet-like geometry.

Interpretation

Sigmoidal cross-stratified sandstone facies is produced during migration of megaripples as flow velocity decelerates (Kohsiek and Terwindt, 1981). The topset is generated during deceleration, and the full vortex action (tangential toeset) is formed during maximum high flow velocities (Kohsiek and Terwindt, 1981). Sx1 records a shift from sigmoidal to tangential and concave-shaped tabular cross-beds with suggest increase in flow velocity. The formation of Sx facies records a transition between dune and upper flow regime (Collinson et al., 2006).

Sx2 are interpreted as tidal bundles, generated and modified in response to spring/neap tidal cycles during the migration of tidal current (Kreisa and Moiola, 1986; Shanley et al., 1992). The tidal bundles at Umunya display cyclic thickening and thinning of foresets that corresponds to the neap/spring tidal fluctuations. The tidal bundle sequence is characterised by thick and thin mud draped foresets, bounded by mud drapes and/or reactivation surfaces (Yang and Nio, 1985). The sandy thick foresets and bottomset lamina which were deposited by dominant tidal current; followed by mud drapes on foresets deposited during relatively slack water periods. Whereas, the thin sandy layers were deposited during subordinate current flow, while subsequent mud drapes were deposited during slack water periods following the subordinate current stage (Visser, 1980; Yang and Nio, 1985). A mud draped reactivation surface reflects a strong subordinate current. The gently dipping to more steep dipping and back to gentle dipping of the sigmoidal foreset represents acceleration changing to full vortex flow conditions, followed by deceleration with a single tide (Kreisa and Moiola, 1986). Asymptotic bottomsets reflects continuous deposition of thin rippled sands and muds in the downdip direction of the toesets of the tidal bundles, during deceleration phase (Figure 3.10). The thick asymptotic bottomsets and the ripple cross-bedding reflect decelerating flow conditions during neap-spring tidal cycles (Martinius and Van den Berg, 2011). Kreisa and Moiola (1986) referred it as pause plane and interpreted the mud drape as fallout from suspension during the slackening phase of tidal flow.

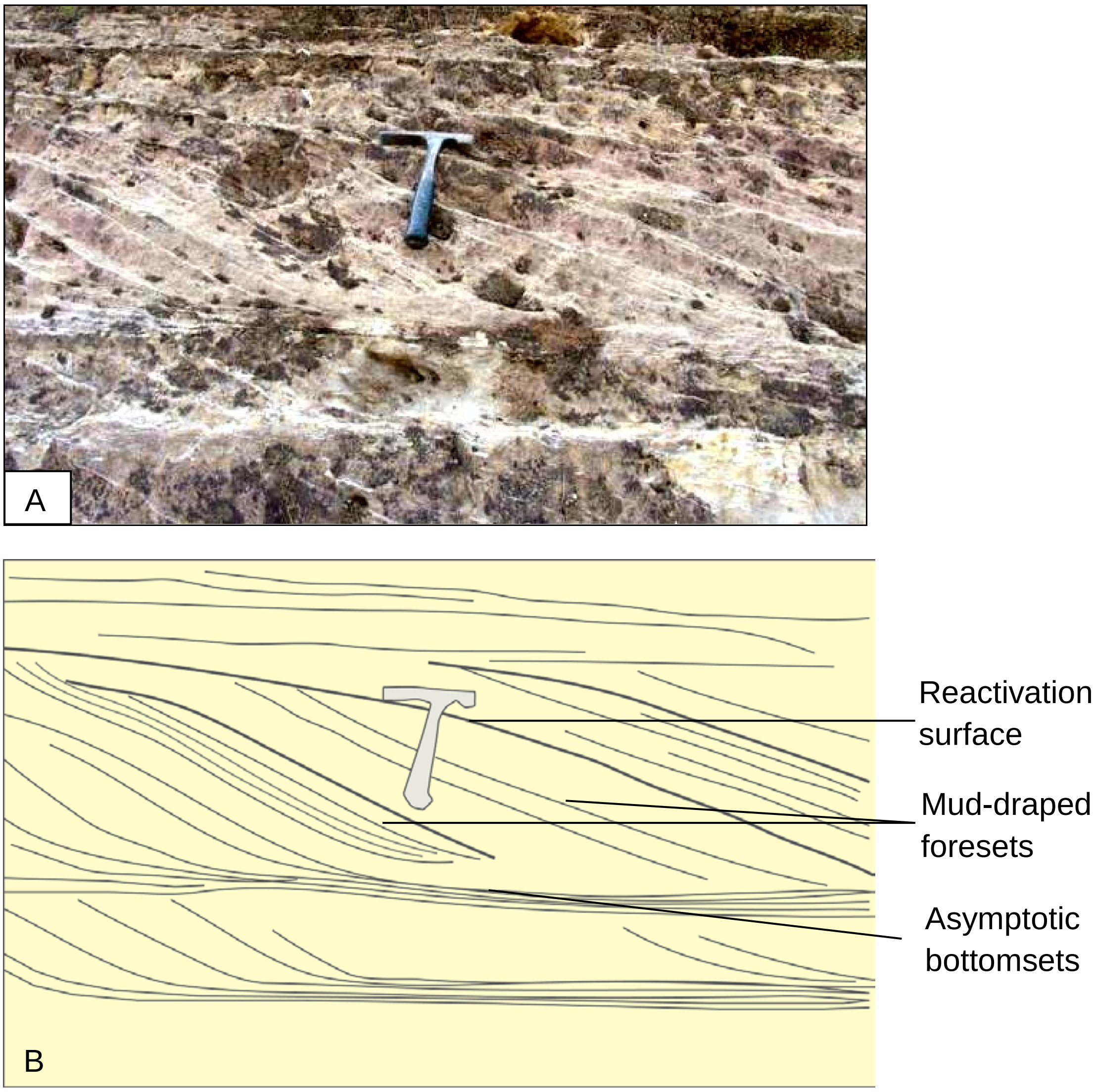
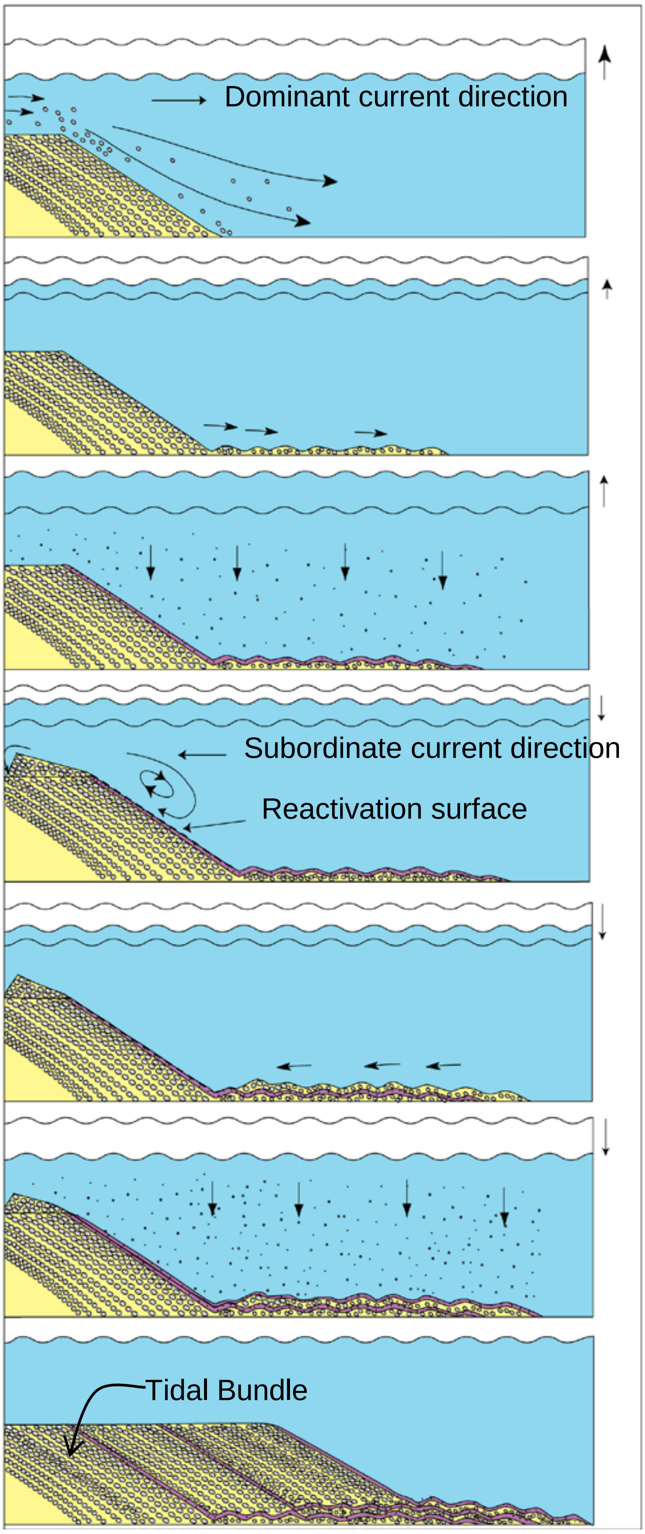


Figure 3.9. (A) Mud draped sigmoidal cross-beds (SxS) with mud draped reactivation surfaces (hammer head is on the reactivation surface), Umunya section (Eocene Ameki Group). (B). Schematic diagram showing the mud draped sigmoidal cross-beds.



Flood tide current: Onshore flow as tide rises. Traction development of foresets due to maximum flow velocity.

Increasing (accelerating) tide: As flow velocity reduces (decelerating flow), fine sand-size clastics move along the toeset by rolling.

High tide (slack water): Suspension fallout of mud drapes due to low flow velocity.

Ebb tide current: Subordinate current flowing the offshore direction.

Decreasing (decelerating) tide: Decelerating flow resulting to fine sand-size clastics move along the toeset.

Low tide (slack water): Suspension fallout of mud drapes due to low flow velocity.

Deposits of subordinate flows are easily eroded by dominant flows. Tidal bundles are formed from repeated cycles of low and high tide (neap-spring tidal cycles).

Figure 3.10. Formation of tidal bundles and rippled asymptotic bottomsets during semi-diurnal tidal cycle (redrawn and modified after Visser, 1980; Dalrymple, 1992).

3.2.5 Herringbone cross-stratified sandstone facies (Sxh)

Description

Herringbone cross-stratification occurs at the lower interval of outcrops observed at Ebenebe, Nando and Igbariam.

Sxh facies consists of medium to coarse grained, moderately to poorly sorted, creamy to brown colour sandstone. Bed thickness varies from 15 to 80 cm, with erosional or non-erosional bases and planar tops. Sxh is characterised by small scale bi-directional cross-beds as observed at Ebenebe section and large scale bi-directional cross-beds. At Nando, the foresets of the herringbone structure are wavy (rippled), with some, mud draped. Herringbone structure also occurs at toesets and topsets of planar cross-beds (Figure 3.11) and associates with cross ripple laminations as observed at sandstone quarries in Igbariam. It is poorly or moderately burrowed. Sxh facies is associated with cross-ripple laminated sandstone facies (Sr). The sandstone bodies occur in lensiodal-shape (<2 m in length) and sheet-like shape covering a 100 m^2 dip extent.

Interpretation

Sxh signifies periodic reversals in current direction as a result of tidal deposition. The occurrence of herringbone requires floods and ebb currents to occur at difference times where the rate of sedimentation is enough to preserve them (Nichols, 1999). The presence of bimodal rippled foresets with mud drapes implies migration of ripples formed by maximum tidal currents, followed by deposition of mud layer due to sediments fallout from suspension during slack water period (Dalrymple, 1992). The herringbone cross-stratification records bi-directional flows of N298.5W and the opposing S128E, their dip angles vary from 12° to 24°. Bimodal pattern (two main directions of flow) is observed at Nando; whereas the bipolar (two opposite directions of flow) (Nichols, 2009) are common at Nibo (320^0 /150^0) and Ebenebe (350^0 /170^0) sections. This bipolar cross-stratification is commonly known as herringbone cross-stratification (Nichols, 2009). This bedform is associated with variation in flow velocity and direction. It is typical of tidal currents (Carmona et al., 2009, Nichols, 2009).

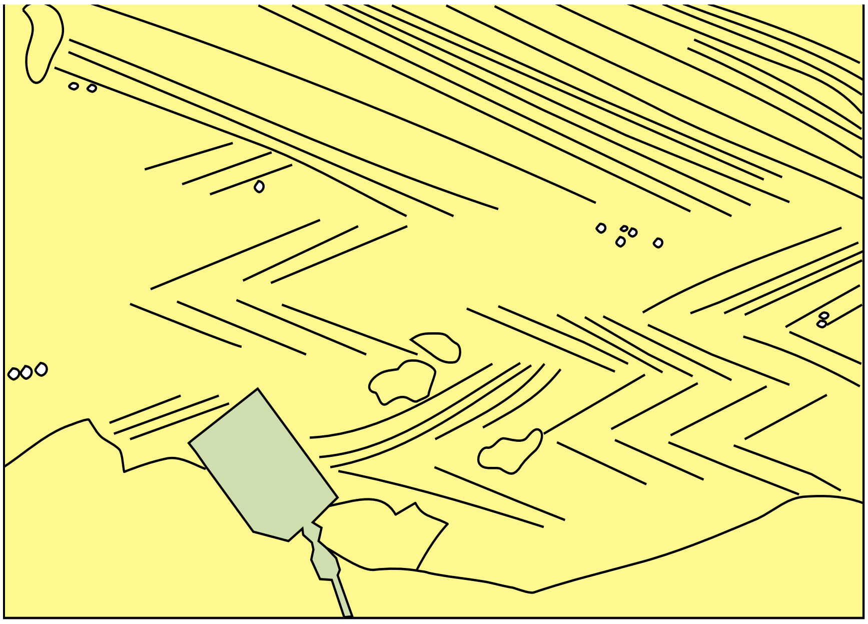


Figure 3.11 (A). Herringbone cross-stratification facies (Sxh) at the toesets of planar cross bed, which occurs at the basal unit of Nando Section (Eocene Ameki Group). (B). Schematic diagram showing the herringbone cross-stratification observed in Nando Section.

3.2.6 Horizontally stratified sandstone facies (Sh)

Description

Sh facies is subdivided into two sub-facies Sh1 and Sh2. This facies is dominantly observed at Nsugbe (Sh1) and at Idoyi-Abam, where it occurs at the uppermost part of the outcrop sections.

Sh1 is a parallel laminated sandstone facies, characterised by fine grained, well to moderately sorted sandstone that is completely ferruginised, consolidated and dark brown in colour in Nsugbe. It is about 1.5 m thick and has gradational basal and top contacts. Parting lineation was observed on the bedding surface at Ugwu-Nnadi at Nsugbe.

Sh2 is a parallel or horizontal bedded sandstone facies. It comprises medium to coarse grained, moderately to poorly sorted sandstone. The sands are creamy white to brown in colour, with patches of dark grey on weathered surfaces and bed thickness varies from 40 cm to 15 m. Beds have erosional or non-erosional basal and top contacts. Sh facies form a sheet-like geometry of about to 10 m thick more than 3 km^2 lateral extent.

Interpretation

The fine grained horizontally laminated sandstone facies denotes upper flow-regime flat bed produced by high flow velocity as flow accelerates, but at shallow depth (Collinson et al., 2006; Nichols, 2009). The presence of parting lineation on the horizontally laminated sandstone also indicates high current velocities and suggests deposition during upper plane bed conditions (Allen, 1982). Whereas the coarse grained horizontally bedded sandstone may suggest a lower flow-regime flat bed produced by decelerating current; it also occurs at high flow velocity in the upper flow regime (Nichols, 2009).

3.2.7 Bioturbated sandstone facies (Sb)

Description

Sb facies comprises fine to coarse grained, well to poorly sorted, brown to reddish and yellowish brown coloured sandstone. Some weathered surfaces are dark grey coloured. Bed thickness ranges from 20 cm to more than 2 m and has erosive or gradational basal and planar top contacts.

The fine grained bioturbated sandstone (Sbf) is micaceous; most of the internal structure is obliterated, but contains relics of ripple lamination. At Umunya and Nsugbe, a moderately to strongly bioturbated fine to medium grained sandstone exhibits trace fossil suites of *Skolithos-Cruziana* ichnofacies. Burrows such as *Ophiomorpha nodosa, Cylindrichnus*, *Teichichnus*,*? Asterosoma, Beaconites, Paleophycus* and *Planolites* are observed in Umunya (Figure 3.12; see Chapter 5, figure 5.18). *Rhizocorallium*, *Taenidium satanassi, Paleophycus, Teichichnus, Arenicolites, Planolites, Skolithos* burrows and body fossils (articulated bivalves) occur in Nsugbe heterolithic units (see Chapter 5, figure 5.10).

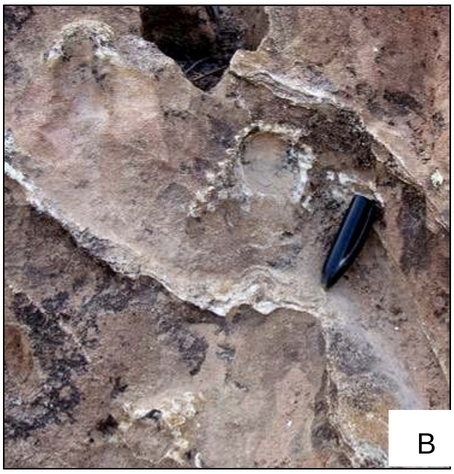
The medium to coarse grained bioturbated sandstone (Sbc) may be structureless, or contain relics of planar cross beds, ripple cross lamination and horizontal bedding. Sbc facies is dominantly *Skolithos* ichnofacies, with depauperate *Cruziana* ichnofacies that is characterised by low diversity, but high abundance suites trace fossils, dominant burrows are *Ophiomorpha nodosa* boxwork, *Skolithos*, *Lingulichnus*, *Paleophycus, ?Rosselia and Cylindrichnus*; others are *Arenicolites, Planolites*, *Conichnus* and equilibrium/escape burrows at Ogbunike (Figure 3.13A; see Chapter 6, figure 6.17). The coarse to very coarse sandstone at Okaiuga exhibits dominantly vertical shafts and some horizontal tunnels of *Ophiomorpha nodosa;* other burrows are *Skolithos, Planolites* and escape/equilibrium burrows. While monospecific *Ophiomorpha nodosa* is observed at 33 Junction, Nsube with relics of climbing ripples (Figure 3.13B). At Abagana (close to Enugwu-Ukwu) and Ezi-umunya, the medium grained bioturbated sandstone is characterised by mud-filled burrows with shrinkage cracks with streaks of carbonaceous material, probably rhizoliths. Sb facies occurs as sheet-like geometry, channels and covers areal extent of about 50-500 m^2.

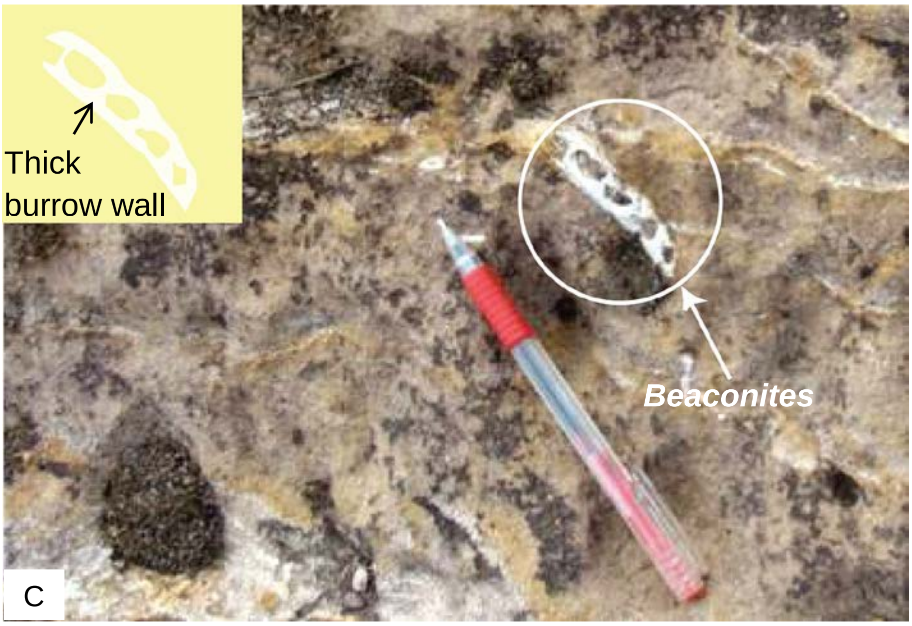
Interpretation

Ichnology is an important tool in sedimentology as it provides an *in situ* record of the environment and environmental change in rock succession. They are used to identify depositional facies and facies changes, changes in hydrodynamic energy and salinity.

The occurrence of both *Skolithos* and *Cruziana* ichnofacies is typical of marginal marine environment (Taylor and Gawthorpe, 1993) and can be indicative of shallow, subtidal conditions (Ekdale et al., 1984; Pemberton and Wightman, 1992). The occurrence of monospecific and high faunal density suggest high environmental stress in a marginal-marine environment due to low and /or fluctuating salinity levels (Taylor and Gawthorpe, 1993). *Ophiomorpha, Arenicolites, Diplocraterion* and *Skolithos* are formed by formed by suspension-feeder dwelling burrows that reflect high-energy environments typical of shallow subtidal to intertidal deposits (Howard and Frey, 1984; Dam, 1990). The dominance of *Ophiomorpha* burrows suggest condition of moderate to high energy sediment influx and predominance of the vertical shafts suggest that sedimentation was periodic causing a successive upward extension of shafts (Dam, 1990). *Lingulichnus* are languid dwelling traces typical of brackish and estuarine setting (Buatois et al., 2005). Escape structures and spatial adjustment traces are indicative of rapid sedimentation. The presence of deposit-feeders such as *Teichichnus, Rhizocorallium, Taenidium* and *Asterosoma* indicate a quiet and stable condition. Details on the trace fossils are discussed in chapter seven.


A


B


Thick
burrow wall
Beaconites
C

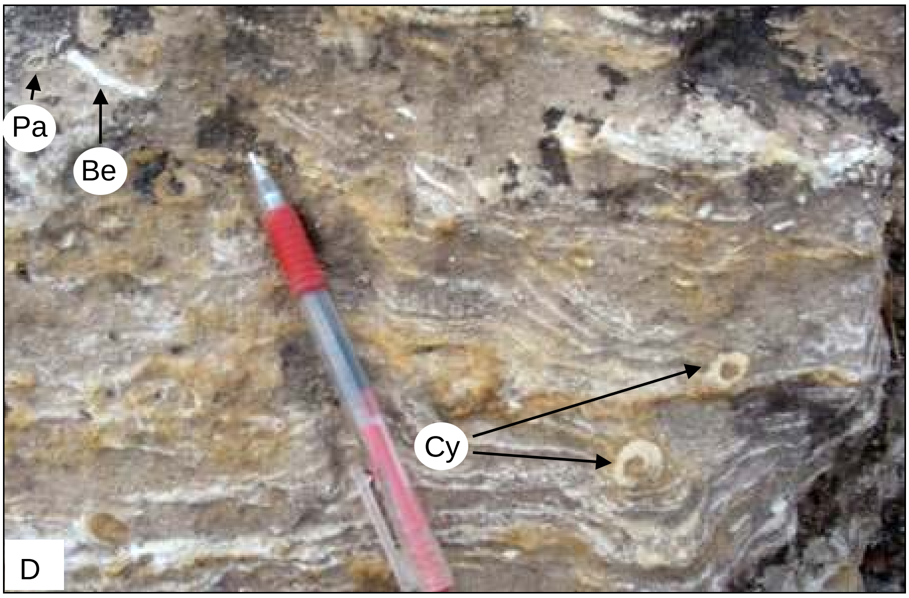


Figure 3.12. Bioturbated sandstone facies (Sb) at Umunya section (Eocene Ameki Group) shows low diversity *Skolithos-Cruziana* ichnofacies. (A) *Planolites* (B) *Ophiomorpha nodosa* (C) *Beaconites* (D) *Cylindrichnus* (Cy), *Beaconites (B*e), *Paleophycus* (Pa).

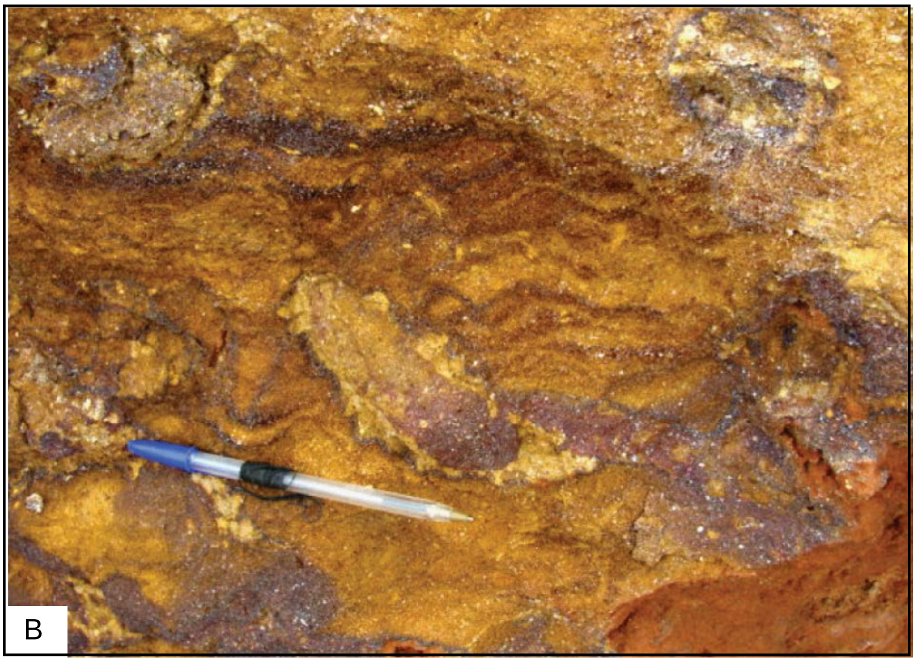


Figure 3.13 Bioturbated sandstone facies (Sb). (A). Low diversity, but high abundance of *Skolithos* ichnofacies in Okaigua section (Oligocene Ogwashi Formation). Abundant: *Ophiomorpha nodosa, Skolithos, Planolites.* Others are *Arenicolites,* escape burrows. (B) Monospecific *Ophiomorpha nodosa* burrow in tidally-influenced fluvial channel (rippled sandstone) at Nsugbe (Eocene Ameki Group).

3.2.8 Sandy Heterolithic facies (Sht)

Description

Sandy heterolithic facies occurs in the lower and middle units of the Ugwu-Nnadi heterolithic section, and throughout the exposed units at 33 Junction, Nsugbe and at Paully petrol station at Ogbunike.

Heterolithic facies consists of two sub-facies 1, and 2. Sub-facies 1 is represented by non-inclined heterolithic facies, it is further sub-divided into 1a and 1b. Sub-facies 1a comprises well sorted, fine grained sandstone of centimetre scale and mud of millimetre scale. The sand colour is reddish brown while the mud is light grey in colour.

Bed thickness is about 1.2 m and has sharp to gradational basal and planar top contact. It is characterised by parallel laminated sand with mud intercalation. Sub-facies 1b is represented by well sorted, very fine grained sandstone of millimetre-decimetre scale and mud of millimetre-decimetre scale. Sand colour varies from yellowish brown to reddish brown, while the mud is light grey in colour. The laminae thickness varies between 5 mm to 30 cm and has sharp (not erosional) contacts within the sand and mud laminae.

Other sedimentary structures associated with the sub-facies 1 include continuous and discontinuous wavy lamination, flaser bedding, and small scale trough and planar cross laminations, with synaeresis cracks (Figure 3.14). The heterolithic unit is moderately to strongly burrowed with suites of *Skolithos* ichnofacies that include *Paleophycus, Planolites, Cylindrichnus, Ophiomorpha nodosa*, *Conichnus,* and *Skolithos* are observed at 33 Junction, Nsugbe. At Ugwu-Nnadi, Nsugbe, a mixed *Skolithos* and *Cruziana* ichnofacies such as *Rhizocorallium, Skolithos, Arenicolites, Planolites, Thalassinoides, Paleophycus, Teichichnus, Taenidium satanassi, Ophiomorpha sp.* with articulated bivalves is noted. It occurs as a tabular or sheet geometry and covers areal extent of about 30 km^2.

Sub-facies 2 is inclined heterolithic facies that denotes a well sorted, fine grained, millimetre to decimetre thick sand, silt and mud. It is brownish to white coloured and characterised by low angle (9 -11°) inclined amalgamated and non-amalgamated cyclic rhythmites of sand, silt and mud. The inclined heterolithic have rippled tangential toesets, but angular based toesets are more common. The amalgamated cyclic rhythmites exhibit millimetre thick interlamination of sands, silts and muds couplets/triplets with sharp contacts, mud flasers, wavy lamination and sand-filled shrinkage cracks (Figure 3.15). It is moderately to strongly burrowed with *Planolites, Rhizocorallium, Paleophycus, Skolithos, Arenicolites, Thalassinoides, Taenidium, Ophiomorpha sp.* with articulated robust bivalves and unidentified networks of burrows. It is then followed by non-amalgamated rhythmites of centimetres to decimetres thick sand, silt and mud heteroliths, with increase in mud.

Interpretation

Intercalation of (non-inclined and inclined) millimetre-centimetre scale sands, silt and mud denote cyclic accumulation of vertically and laterally accreted sediment, referred to as tidal rhythmites (Kvale, 2006). Sand laminae are deposited by asymmetrical tidal currents during the period of falling tide and the rising limb of the following high tide whereas the silt/mud lamina represents deposition from suspension during slack water at high tide (Gibson and Hickin, 1997). Thicker sand layer represent flood or ebb tides during spring period, also thicker mud layer represent slack-water period during spring. Similarly, thinner sand lamina represent flood or ebb tides during neap period while thinner mud lamina suggest slack water periods during neap period. Lack of erosional contacts between layers and the presence of rippled and cross laminated heterolithics, flaser bedding, and wavy bedding within the sandy intervals suggest that the sediments are formed under a relatively weak energy condition. Lack of well developed sand-fill polygonal cracks pattern on bedding plane and lack of other subaerial exposure such as roots and paleosol suggest that the cracks are subaqueous shrinkage cracks or synaeresis cracks within muddy sediments under different salinity (Shanley et al., 1992). The presence of Skolithos and Cruziana ichnofacies suggests a brackish condition.

The presence of inclined heterolithics represent lateral accreting bar of a (channel) point bar (Rebata et al., 2006; Hovikoski et al., 2008; Nichols, 2009). Lateral accreted bars are also characteristics of meandering point bar deposits of a fluvial system (Nichols, 2009). The inclined surfaces of the heterolithics are considered as lateral accretion surfaces because they are of low angle (9 - 11^0) and perpendicular (126^0) to the flow direction of the adjacent trough and planar cross-beds (219^0). Such large scale inclined surfaces are also common in the foresets of the Gilbert-type deltas, though Gilbert-type deltas is characterised by toeset, foreset and bottomset arrangement of beds and the grain sizes are conglomerate to sandstone (Oti and Postma, 1995; Boggs, 2006, Nichols, 2009).

The centimetre-decimetre scale sand and mud layers could result from repetitive autocyclic changes which involves changes in current velocities, changes in sedimentary inputs and the shifting of channels and shoals (Rebata et al., 2006). These sand-mud couplets could also result from annual changes in precipitation, temperature or wind direction (Dalrymple et al., 1990). The centimetre-decimetre scale sand-mud couplets in Ogbunike and Nsugbe are similar to the decimetre scale (10-80 cm thick) sand-mud couplets described in Rebata et al., (2006) in the Nauta channel complex of Marañón Foreland sub-basin, Peru. The couplets were interpreted as annual (seasonal) cycles which represent deposition during rainy and dry seasons.

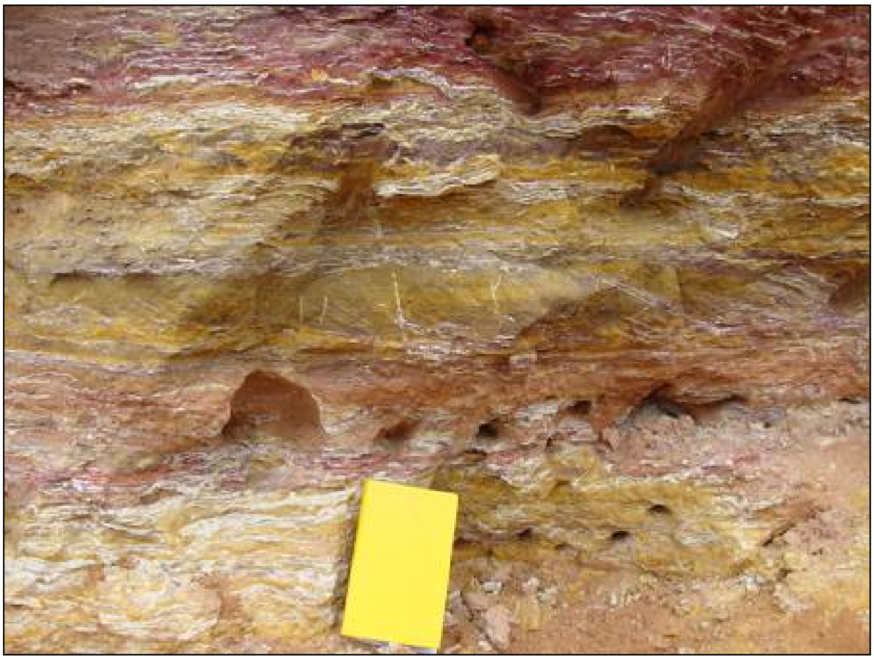


Figure 3.14. Sandy heterolithic facies (Sht). (A) Displays continuous and discontinuous wavy lamination, flaser bedding, and small scale planar cross laminations (33-Junction, Nsugbe). (B) Centimetre-decimetre scale heterolithic, the sandy intervals show wavy and flaser bedding (Eocene Ameki Group).

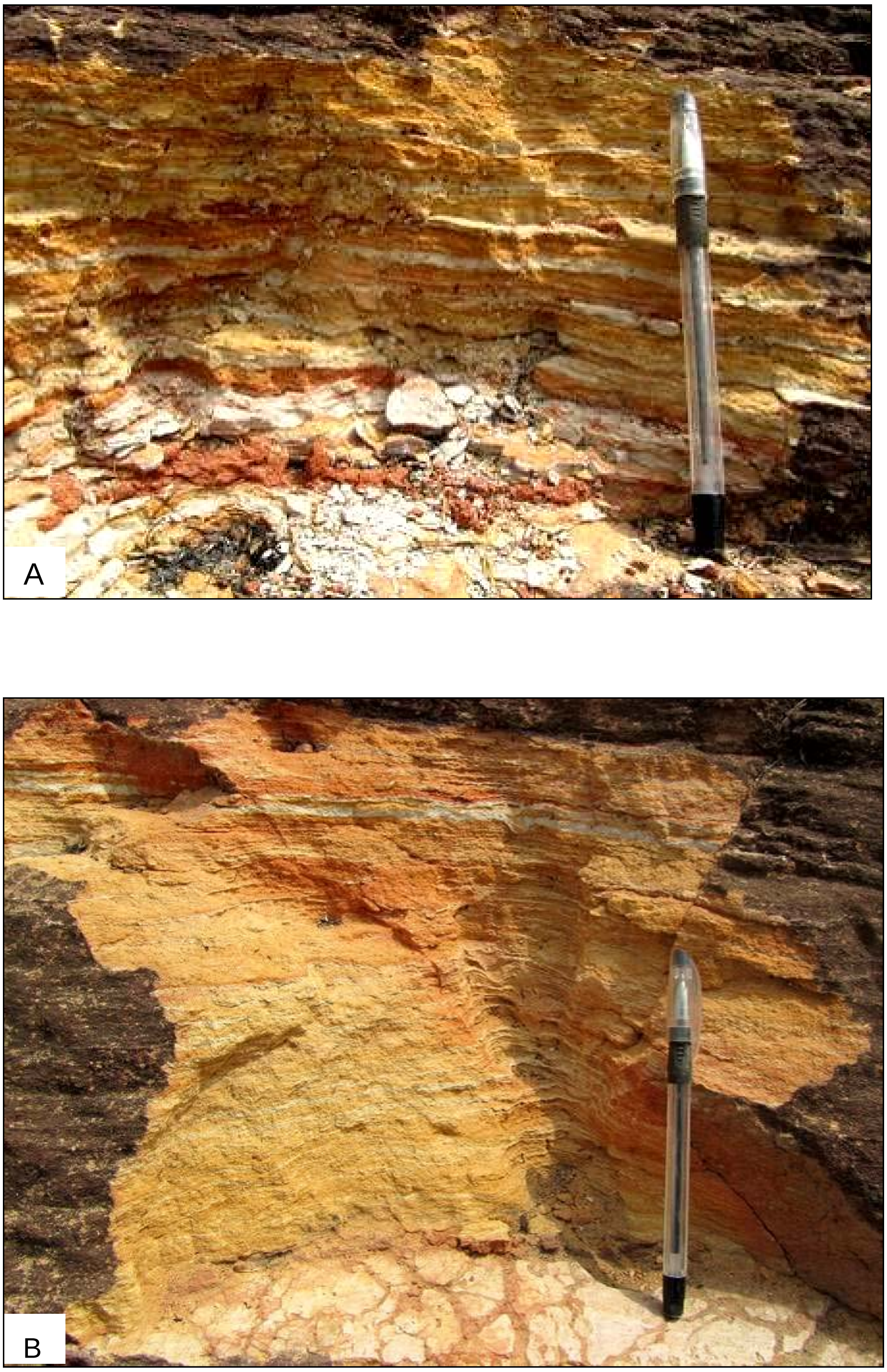


Figure 3.15 Sandy heterolithic facies (Sht). (A). Millimetre-scale sand and silt /clay couplets showing cyclic rhythmites. (B). Sand-fill shrinkage cracks on a bedding surface of the inclined heterolithic stratification (IHS).

3.2.9 Muddy heterolithic facies (Fmt)

Description

The muddy heterolithic facies is observed at the upper part of the Ugwu-Nnadi heterolithic section. The Fmt is characterised by inclined stratified mudstone, with IHS sand/silt laminae and lenticular bedding. Sand stringers also occur in the mudstone. The muddy heterolithic units vary between 1 to 6 m thick and consist of dominantly light grey mudstone, with light brown to white coloured very fine grained sands and silts. This facies exhibits an initial cyclic rhythmic alternation of centimetre-scale mudstone and millimetre-scale sand and silt of about 50 cm to 2 m thick and graded into a non-cyclic rhythmites with alternation of metre-scale mudstone and millimetre-scale sands/silts (Figure 3.16). The metre-scale mudstone consists of 50 cm to 4 m thick massive to laminated mudstone and about 5 to 20 cm thick irregular occurring sand laminae and sand stringers. The heterolithic facies has a low depositional dip of about 10^0. This unit has very low-diversity ichnofossil assemblages consisting dominantly of monospecific *Teichichnus*. Uncommon burrows are *Planolites* and tiny *Thalassinoides*. This facies directly overlies the sandy heterolithic facies at Nsugbe, and it re-occurs in cycles.

Interpretation

The inclined stratified mudstone generally indicates a low energy flow, with the presence of silt and sand laminae reflecting a combination of traction flow, suspension and deposition (Zonneveld et al., 2001). The occurrence of low-diversity trace fossils suggest stressed brackish-water conditions generated by fluctuations in salinity, oxygenation levels and sediment supply (Rebata et al., 2006b).

Figure 3.16. Cyclic rhythmic alternation of centimetre-scale mudstone and millimetre-scale sand and silt which graded laterally into a non-cyclic rhythmites with alternation of metre-scale mudstone and millimetre-scale sands/silts.

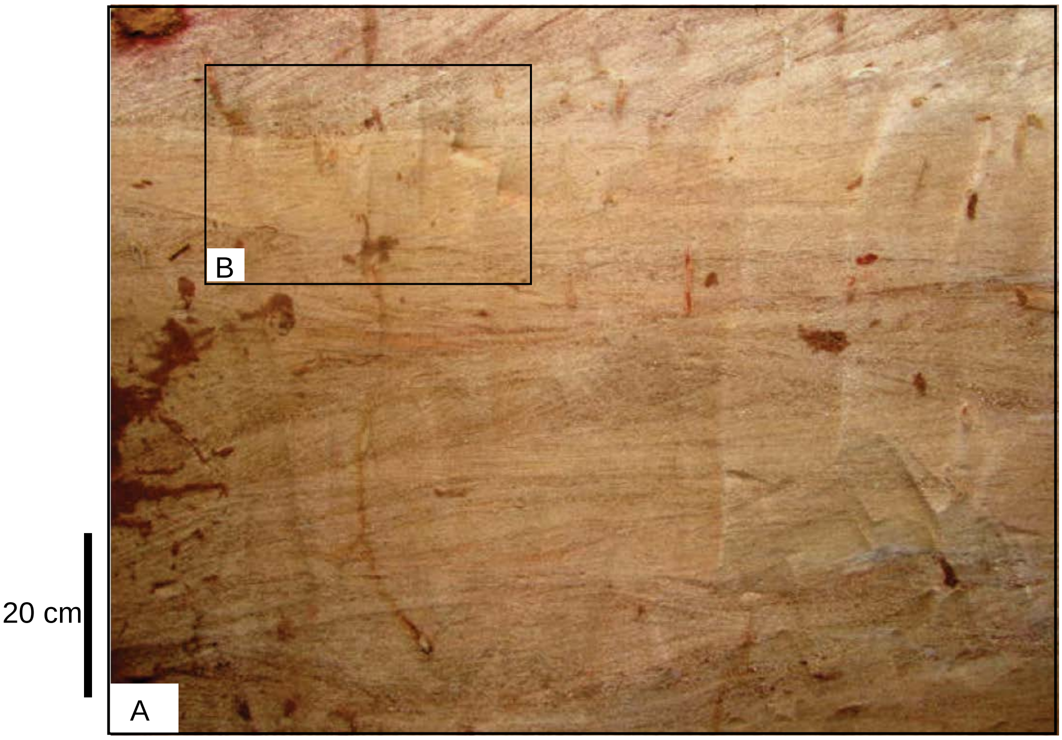
3.2.10 Current rippled laminated sandstone facies (Sr)

Description

This facies occurs at the lower part of the outcrop exposure at Ameke-Abam sandstone quarry and at the middle part of outcrop observed at Okaiuga sandstone quarry. Current rippled laminated sandstone facies is fine to coarse grained, well to poorly sorted sandstone. Sands are brown to white coloured, with subordinate mud that is light to dark grey. Bed sets vary from about 5 to 25 cm thick and cosets is about 1 m thick. Beds have sharp or gradational base and wavy top contacts. Observed sedimentary structures include climbing ripples, ripple lamination, counter current ripples, flaser bedding, and wavy bedding. Sr may occur in association with heterolithic facies, trough cross-bedded sandstone facies and herringbone cross-stratified sandstone facies. The countercurrent ripples occur in association with large scale planar cross beds as observed in Ameke-Abam sandstone quarry. This facies is poorly to moderately burrowed as observed at Okaiuga sandstone quarry, with few *Ophiomorpha nodosa* shafts, ?*Arenicolites*, escape burrows and *Conichnu*s (Figure 3.17). Most outcrops in the study area partly or wholly exhibit the current rippled laminated sandstone facies. It occurs laterally and changes to other structures, forming sheet or tabular geometry.

Interpretation

Current rippled laminated sandstone occurs as a result of migration of unidirectional current in water or during deceleration of high velocity current. Current ripples are small bedforms formed by the effects of boundary layer separation on a bed of sand (Baas, 1999). Cosets of ripple cross lamination result from the migration of ripples combined with a net accumulation of sediment on the bed (Collinson et al., 2006). Climbing ripples (ripple drift) indicate high sedimentation rate as ripples migrate resulting to bed aggradation (Reineck and Singh, 1975; Collinson et al., 2006). The presence of escape burrows, *Conichnus* and vertical *Ophiomorpha nodosa* burrows further suggest high sediment influx in a relatively high energy environment. Countercurrent ripples occur at the toesets of cross beds at high flow velocities when roller vortex is strong to generate ripples which migrate a short distance up the toe of foreset (Nichols, 1999; 2009). The wavy and flaser bedding reflects fluctuations in flow velocity during deposition or occurs as a result of sediment supply due to fluctuation in current. During periods of current activity, the sand is deposited as ripples while mud is entrained in suspension. When the current wanes, the mud floccules are deposited in troughs or completely cover the ripples (Reineck and Singh, 1980). The sand ripple is can also be formed by the maximum current of the dominant tide, followed by deposition of mud layer during the slack–water period of the subsequent weaker tide (Finzel et al., 2009).



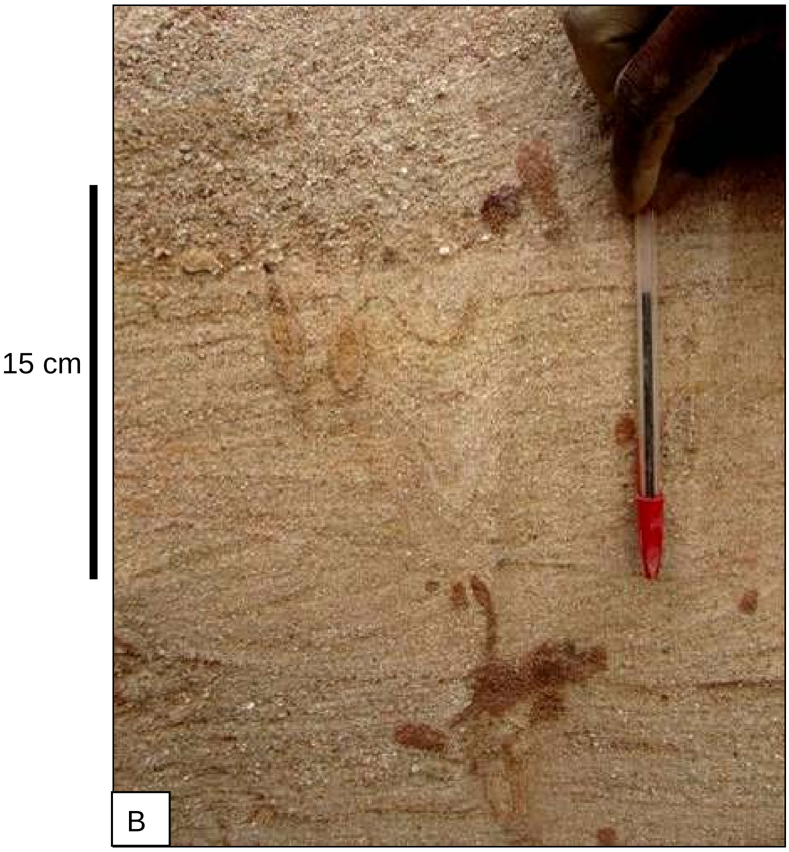


Figure 3.17. Current rippled laminated sandstone facies (Sr) (A) Slightly burrowed with escape burrow, trough-cross bed (lower interval) and climbing ripples (Sr) (mid and upper intervals). (B) Low diversity burrows of *Conichnus*, *Ophiomorpha nodosa* and ?*Arenicolites* are common.

3.2.11 Wave rippled laminated sandstone facies (Sw)

Description

The wave rippled laminated sandstone facies is observed at the lower part of outcrop exposure at Idoyi-Abam. Wave ripple heterolithic facies is observed at the middle and uppermost part of Umunya section and Oyi River section (only middle interval). The Sw facies includes well sorted, very fine to fine grained, micaceous sandstone. Sands are light brown to yellowish brown in colour. Bed thickness is millimetre to centimetre thick with sharp wavy base and top contacts. Sedimentary structures are symmetrical (modified by interference ripple pattern) and asymmetrical (heterolithic) wave ripple laminations (Figure 3.18), convolute lamination, load casts, slumping, this is observed at the upper part of the Umunya section. Other structures are wavy, flaser and lenticular bedding. Sw facies occurs as an upward-thickening profile of wedge-shaped sandstone body in Idoyi-Abam whereas the heterolithic wave ripple lamination forms a sheet-like geometry of about 1 km as in Umunya and Oyi River.

Interpretation

Wave action in the study area is indicated by the presence of symmetrical and asymmetrical ripples with rounded crest. The former is as a result of oscillatory waves while the latter is produced as a combination of oscillatory waves and unidirectional currents. Collinson et al., (2006) demonstrated that ripples are symmetrical when wave orbital velocities are similar and become asymmetrical when there is an asymmetry in the orbital current due to the combination with unidirectional current. Structures such as convolute lamination, load casts and slumping structures occur within the wave ripples facies in Umunya. These are syndepositional soft sedimentary structures and their occurrence within the heterolithic wave rippled sandstone suggests liquefaction and fluidization of unconsolidated sediments in a discrete zone. They were more obvious at the lower part of the sections. Their occurrence may be aided by breaking waves during emergence of the bed or by the rise and fall of the water table through the sediment (Collinson et al., 2006). The flaser/wavy and lenticular bedding associated with the wave rippled sandstone may have resulted from variations in wave activity or sediment supply due to changing wave action.

Figure 3.18. Wave rippled laminated sandstone facies (Sw) showing (A) intercalation of wave rippled sandstone and mudstone (uppermost interval of Umunya section) and (B) symmetrical wave ripple characterised by interference ripple pattern (Umunya section).

3.2.12 Siltstone facies (Fs)

Description

This facies occurs at the uppermost interval in Ajata-Ibeku and Uhuala-umuezeoma sections and throughout the exposed outcrop at Ohuhu Umuahia section. The siltstone facies is composed of well sorted micaceous siltstone with intercalations of finer silt and organic rich laminae. The siltstone is greenish grey with light coloured finer silt and dark grey organic laminae. Bed thickness varies from 2 to 40 cm, with sharp and gradational basal and top contacts. The organic-rich laminae are of constant thickness of about 2 to 5 cm thick whereas the silty layers vary from 4 to 40 cm thick. Sedimentary structures observed are alternating parallel laminated greenish grey sitly layers and dark grey organic-rich layers which form rhythmites (Figure 3.19A). The parallel rhythmite layers increase or decrease in thickness throughout the section. An initial increase in thickness is observed followed by decrease in thickness and a subsequent increase in rhythmites thickness. Reworked undulating lamination with wave length less than 1m (Figure 3.19B) is observed in some silty intervals at Ohuhu Umuahia section along Umuahia-Okigwe expressway. It is characterised by convex-up and concave-up laminae. The height of undulations is within 12 to 18 cm, and the wavelengths are between 50 and 70 cm long. The siltstone facies also occur at the uppermost horizon in Ajata-Ibeku and Uhuala-umuezeoma.

Interpretation

The intercalation of silty layers and organic–rich laminae in the study area is compared with that of the Squamish delta (Gibson and Hickin, 1997) where the silty layer is suggested to be deposited during combined flood and high-tide periods during summer when suspended-sediments is high, whereas the organic laminae represent the collapse marsh vegetation which occurred during the autumn and gradually covered as sedimentation from suspension continued. The decrease in bed thickness with increasing elevation is associated with an up-section increase in organics and decrease in clastic input to the marsh environment (Yeo and Risk, 1981; Gibson and Hickin, 1997). Subsequently, increasing bed thickness suggests increase clastic input during high-tide. The undulating lamination indicates reworking by strong wave action in shallow water.

Figure 3.19. Siltstone facies (Fs). (A). Siltstone layers alternating with organic-rich laminae as observed in Ajata-Ibeku (Eocene Ameki Group). (B). Wave reworked lamination in the siltstone intervals of the Siltstone facies (Ohuhu Umuahia section).

3.2.13 Mudstone facies (Fm)

Description

The mudstone facies is further sub-divided into four (Fm1-4) based on their internal structures and characteristics. Fm1 facies are exposed at the middle and upper units of the outcrop sections at Oyi and Ogbunike. The facies is a carbonaceous mudstone that is characterised by abundant carbonaceous and plant matters. It is thickly laminated, dark yellowish brown, and medium to dark grey in colour. It contains streaks of siltstone; the colour changes laterally and vertically. The medium dark grey mudstone is strongly bioturbated at certain intervals. Bed thickness is millimetre to centimetre and has a sharp to gradational basal and top contacts with underlying and overlying beds as observed at Oyi and Ogbunike. At Ubakala, the dark grey mudstone is structureless, but contains copious amount of lignite, petrified leaves and plant fragments (Figure 3.20A-C).

Fm2 facies occurs at the lower to middle units of the gully section at Akwuzu (Figure 3.21) and the quarry site at Ubakala (Figure 3.20). The Fm2 facies characterises a massive to laminated mudstone that consist structureless to finely laminated mudstone. The mud/claystone varies from dark grey to light grey in colour (fresh surface) and greyish yellow on weathered surface. The mudstone shows conchoidal to thick and crudely laminated fracturing. At Akwuzu, a very thin (4 cm) gypsiferous layer occurs with the structureless to thinly laminated mudstone. The mudstone is about 3 meters thick, unfossiliferous, and contains rootlets at the topmost part of the mudstone (Figure 3.21). At Ubakala, the 8m thick structureless claystone contains thin (20 cm) micaceous lensoidal layer of siltstone.

Fm3 facies are observed within the middle and upper intervals of outcrops at Umunya, 33 and Ogbunike sections. This facies is characterised by laminated mudstone that exhibits finely, parallel laminated mudstone sometimes with fine streaks of siltstones and sandstone forming lenticular bedding. The mudstones are white to very light grey coloured and are observed at Umunya, 33 and Ogbunike sections.

Fm4 facies are observed at the lower to middle units of the outcrop exposures at Ajata-Ibeku and Umuezeoma-Uhuala. The facies consists of medium dark to dark grey fossiliferous, micaceous thinly laminated mudstone with streaks of clayey siltstone lamina and scanty carbonaceous matters at Ajata-Ibeku. Tiny shells of gastropods, corals, bivalves and shark teeth are common. Similar outcrop with sideritic concretions is also observed at Umuezeoma-Uhuala. The mudstone is also slightly burrowed at certain intervals, with *Planolites montanus* observed. On the weathered surface, the dark grey mudstone appears brownish grey with white colour streaks of clayey siltstone. Micritic limestone of about 15 cm thick occurs as boulders in the unit. The mudstone unit is highly jointed and fractured.


A

Figure 3.20. Fossilized wood stems (A) and leaves (B) from the massive mudstone deposit (C) as observed at Ubakala, Oligocene Ogwashi Formation.

Figure 3.21. Paper laminated mudstone with very thin gypsiferous layer, exposed as a gully at Akwuzu (Eocene Ameki Group).

Thin gypsiferous (anhydrite) layer

Interpretation

The mudstone facies suggests dominance of low energy conditions where the muds are deposited by suspension settling, episodic sedimentation and /or fallout during one or several slack-water periods. The presence of brownish black with plant matters suggest subaerial or supratidal conditions. The lack of internal structure in Md2 (massive or structureless mudstone) may be due to very homogeneous, continuous and possibly rapid deposition from suspension (Backert et al., 2010; Collinson et al., 2006), the presence of fossilized wood steam and leaves support rapid deposition and burial of vegetation. Laminated mudstone reflects episodic settling of mud/silt from suspension in quiet water. The dark grey to black colour of the shale is caused by high organic content of the shales.

3.2.14 Shale facies (Fl)

Description

Shale facies (Fl) are mostly exposed as low-land exposure (at Okputong-Bende, Idima Abam), gully erosion site (Ameke-Abam section) and excavation site (Ebenebe section). Fl1 facies is characterised by greenish-grey fossiliferous shale that consist of whole and fragments of ornamented bivalves and gastropods. The shale unit has gradational basal and top contacts with underlying and overlying beds. At Okputong-Bende, the fossiliferous shale contains limestone nodules. The limestone nodules occur in particular horizon. At Idima Abam, abundant fossils of rays, sharks, amber and coquina were observed in the fossiliferous shale.

Fl2 is a light bluish gray to dark gray shale that becomes clayey upwards. It may be non-fossiliferous or may contain minute (insignificant) fossils. This is typical of Imo Shale observed at Ebenebe and Ameke Abam sections.

Interpretation

The presence of body fossils such as bivalves, gastropods, shark teeth, coquina and the lower abundance of trace fossils are indicative of limited oxygenated bottom water conditions. Arua (1986) characterised the dominant fauna-gastropod *Turritella* and bivalve *Glans* as typical of shallow marine condition. The fish fauna is also dominated by *Odontaspis* which indicates tropical shallow water (Arua, 1991). The occurrence of sideritic concretions indicates a reducing condition for the deposition of dark shales whereas the presence of limestone nodules suggests early diagenesis induced from alkaline pore waters.

3.2.15 Gypsiferous Shale facies (Fg)

Description

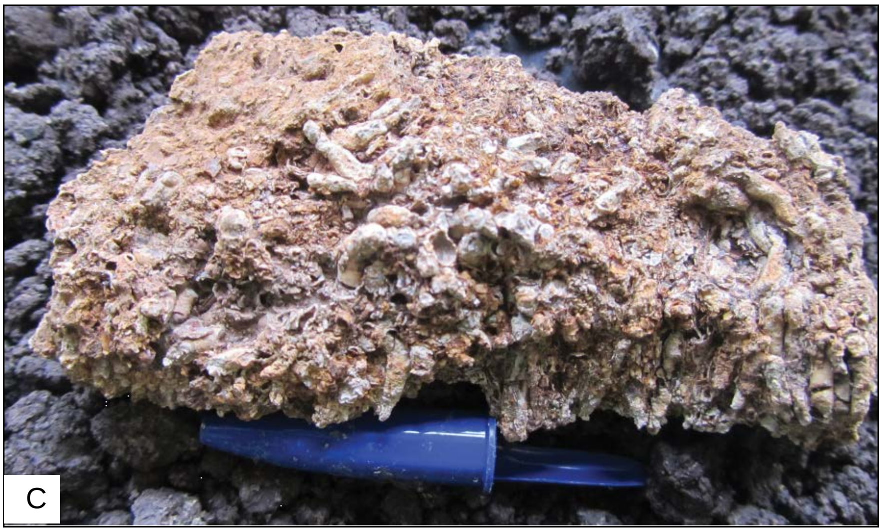
Gypsiferous shale facies is observed as low-land exposure at Ude-Ofeme. Fg facies includes greyish black to brownish black shale characterised by abundant gypsum crystals, amber, carbon (lignite) material and large petrified logs and fossilised wood fragments (60 cm long) bored by *Teredolites longissimus* (Fig. 3.22). The gypsum crystals occur mostly in single and in masses along the some fracture and joint planes in Ude-Ofeme.

Interpretation

The abundance of fossilized wood (including *Teredolites longissimus)*, petrified logs, amber, carbon materials and the occurrence of *Teredolites longissimus* in calcareous concretions as observed by Arua (1991) suggested a drift of estuarine/mangrove elements into intertidal-lagoonal environment (Arua, 1991). Savrda (1991) linked the presence of abundance fossilized wood and/or *Teredolites* in marginal-marine to marine mudstone to sea-level rise. The occurrence of gypsum crystals in the shale possibly suggests oxidation of sulphide from the shales.


A


c
B



C

D

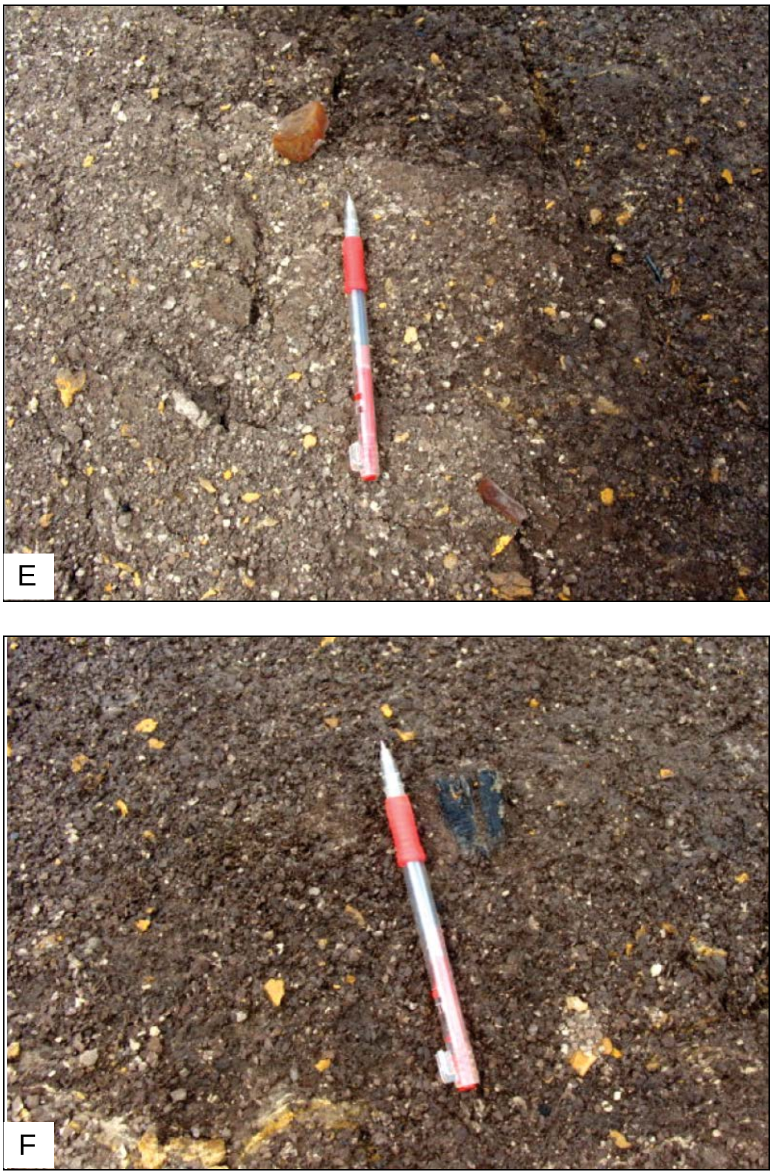


Figure 3.22. Gypsiferous shale facies (Fg) of Ameki Group characterised by (A) Gypsum crystals (B) fossilized logs with (C)*Teredolites longissimus* (D) petrified woods (E) ambers (F) and piece of carbonaceous material, observed at Ude-Ofeme.

3.2.16 Marl facies (Fc)

Description

Marl facies occurs as dark grey calcareous mudstone Fc1 and was observed in a road cut at Dam, along Bende-Ozum Abam road. The marl facies is associated with thinly bedded (22 cm thick) fossiliferous limestone (Figure 3.23).

Interpretation

The limestone thin bed may suggest a condensed section, where there was maximum starvation of siliciclastics sediments resulting to precipitation and accumulation of calcium carbonate forming thin limestone bed (Taylor and Gawthorpe, 1993).

Figure 3.23. Calcareous mudstone (marl) with thinly bedded limestone observed along Bende-Ozu Abam road.

3.2.17 Limestone facies (Ls)

Description

Ls facies occur as bioclastic limestone layers within fossiliferous sandstone at Bende. Ls is characterised by abundant whole and some fragments of bivalves, gastropods and molluscs with calcareous matrix. The bed unit varies from 30 to 50 cm thick and has gradational basal and top contacts with surrounding sandstone units. The limestone layers are interbedded with fine grained, well sorted fossiliferous micaceous sandstone. This lithologic sequence also occurs in Ozitem.

Interpretation

The dominance of articulated fauna confirms a low-energy environment where there is good preservation and low reworking of fauna. The limestone facies is associated with fine-grained fossiliferous sandstone which reflects fluctuation in depositional processes.

3.2.18 Structureless (massive) sandstone facies (Sm)

Description

The structureless sandstone facies are observed as road cuts and they occur throughout the outcrop section. The facies is subdivided into sub-facies Sm1 and Sm2. The Sm1 is a fine grained, micaceous fossiliferous (calcareous) structureless sandstone of about 4 m thick. It is observed at Bende and associated with thin fossiliferous limestone beds. Sm2 are non-fossiliferous (calcareous) structureless or massive sandstone. This sub-facies rarely occurs in the study area. The sandstone is medium grained and moderately sorted.

Interpretation

Structureless sandstone is suggested to originate from gradual aggradation of sediments beneath steady or near-steady flows (Johansson et al., 1998). Massive sandstone can also occur as a result of intense bioturbation or rapid deposition, through deceleration of a heavily sediment-laden current (Collinson et al., 2006).

3.2.19 Variegated facies (Fms)

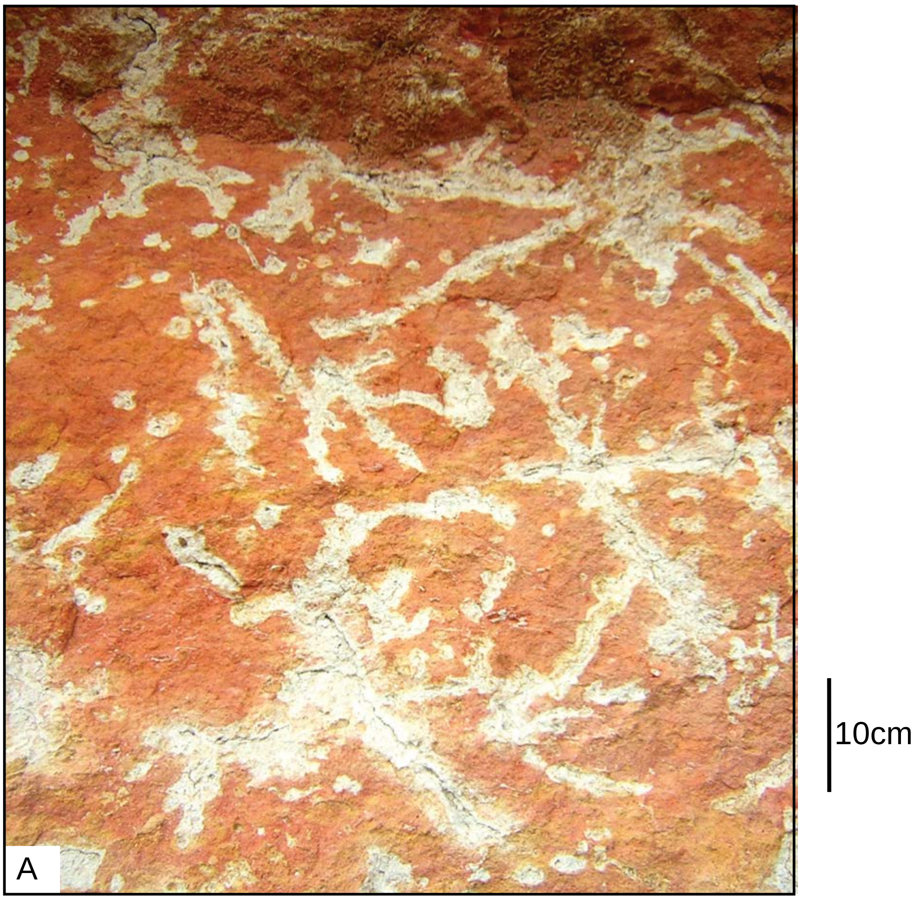
Description

Variegated facies is commonly observed at the uppermost units of outcrop sections exposed at Ezi-Umunya, Uhuala, Ifite-Awka and Nando. The Fms facies is characterised by variegated coloured (grey, yellow-brown, and reddish brown), and bioturbated fine to medium grained clayey sandstone and nodular mudstone (Figure 3.24A-C). The clayey sandstones (observed at Ezi-Umunya) are reddish-brown in colour, non-calcareous and characterised by thin carbonaceous matters, and branching tubes (rhizoliths) filled with clay. The mud-filled tubes are elongate, branch downward and laterally, and they exhibit yellowish-brown rims. They are further characterised by strands of carbonaceous materials and shrinkage cracks. The vertical dimension of the tubes varies from 3 to 90 cm while the horizontal thickness is within 1 to 50 cm. The mudstone is characterised by grey coloured rhizolith with yellowish-brown rim. The nodular mudstone (observed at Uhuala) is variegated with light gray, reddish brown to purplish colour, with desiccation cracks. Its contact with the overlying bed is burrowed with suites of *Glossifungites* ichnofacies.

Interpretation

Most rhizoliths have both vertical and horizontal orientation indicating that they are formed *in situ* (Owen et al., 2008). The observed fossil root system is grouped into three (3) based on Klappa's (1980) rhizolith classification: (i) root cast: this is the infilling of root mould by sediment or cement; (ii) root mould: this is a tabular void left after roots have decayed in partly or wholly lithified sediment; (iii) root petrification: this is the replacement and impregnation of organic matter by mineral matter without total loss of root features. Most of the roots networks are root cast- fill with clay and silty clay. Rhizoliths are indicators of paleosols and subaerial vadose environment. Kraus and Hasiotis (2006) suggested that the elongate grey mottles (rhizohaloes) with yellow-brown (goethite) rims and the presence of carbonaceous root fossils with rhizoliths reflect poorly drained paleosols. The presence of Fe concentration in the matrix around rhizohaloes indicates surface-water gleying caused by perched water table (Kraus and Hasiotis, 2006).

The paleosols are classified using methods employed by Retallack (2001) for interpreting ancient environment of soil formation. The dominant occurring paleosol is Gleska pedotype (red clayey soil) with minor occurrence of connate pedotype (brown clayey soil). The soil type is characterised as ultisol based on the US soil taxonomy (Soil Survey Staff, 1999). The variegated colour of the nodular mudstone (light grey, reddish brown to purplish) and the presence of desiccation cracks also indicate periods of subaerial exposure suggesting paleosol. The red, ochre, and purple pigments indicate variable content of goethite and hematite (Tardy and Roquin, 1992), which are characteristics of paleosols.


A
10cm


B

Figure 3.24. Variegated facies (Fms). (A,B) Clay and Silty clay-filled rhizoliths in Abagana and Ezi-Umunya respectively (C) Grey mottles (rhizohaloes) with yellow-brown (goethite) rims observed at Ezi-Umunya.

3.3 DISCUSSION AND CONCLUSIONS

In this chapter, 19 lithofacies and 23 subfacies have been recognised in the Paleogene strata of the south-eastern Nigeria and they are dominated by siliciclastics with less commonly occurring limestone and marl facies. The siliciclastics include conglomerates, very coarse to fine sandstone, siltstone, mudstone and shale. The lithofacies are key sedimentary units that represent specific style and process of sediment transport and deposition. The high occurrence of subfacies within the lithofacies suggests variation in sedimentary processes. Changes in flow regime are common in shallow marine environments were flow velocities fluctuate, and different processes such tidal, current and wave processes occur and interact within one another. The tidal and current processes are more dominant in the study area, whereas waves, storm and seasonal processes are less dominant. Lithofacies formed as a result of and/or in association with tidal processes include mud-draped tabular and planar cross-stratified sandstone, sigmoidal cross-stratified sandstone, herringbone cross-stratified sandstone, bioturbated sandstone, sandy heterolithic, and muddy heterolithic facies. Planar and trough cross-stratified sandstone, horizontally stratified sandstone and current ripple laminated sandstone facies are typical of current processes whereas wave ripple laminated sandstone is associated with wave processes in the study area. Other lithofacies such as conglomerate, siltstone, mudstone, shale, marl, limestone and variegated facies may occur across the depositional processes (Table 3.1).

These facies are further grouped to form facies associations; this is discussed in subsequent chapters of this work. The internal characterises geometry and stacking pattern of the facies associations are utilised to determine depositional environments;

while the sequential variation and changes in depositional environments are employed to establish sequence stratigraphic framework and reconstruct the paleogeographic evolution.

CHAPTER FOUR

DEPOSITIONAL EVOLUTION OF THE PALEOCENE-EOCENE IMO FORMATION

SUMMARY

A new interpretation of the Palaeocene to Eocene strata of south-east Nigeria has been developed based on field facies analysis and borehole data from the area. The area is considered to have been a tidally-dominated shelf setting which underwent a series of changes in sea level during the deposition of the Imo Formation. An initial transgression led to the deposition of a widespread marine shale unit that is interpreted as an offshore succession. This was followed by an influx of sands that are texturally mature, coarse to fine-grained that show large-scale cross-stratification with dip angles of between 15° and 25°. These are interpreted as the deposits of large sandwaves on a tidally-dominated shelf. Transport direction determined by the dominant large scale cross beds indicate a north-westerly transport direction. The presence of illite and nontronite clay mineral types in the offshore shales typically suggest a marine environment whereas the occurrence of kaolinite indicates terrestrial influence. A shale bed above the sand wave unit is overlain by wave-ripple cross laminated sandstone is considered to have formed in an upper shoreface setting. An overlying fossiliferous shale with a restricted fauna and shell lag is interpreted as having been formed in a lagoon with restricted circulation. The progradational succession is capped by a return to deeper water facies comprising a mixed carbonate-siliciclastic succession. This includes mudstone with limestone layers, calcareous sandstone with fossiliferous marl beds, fossiliferous and bioturbated sandstone. These beds represent a relative sea level rise on the shelf, accompanied by a decrease in siliciclastic input.

4.1 INTRODUCTION

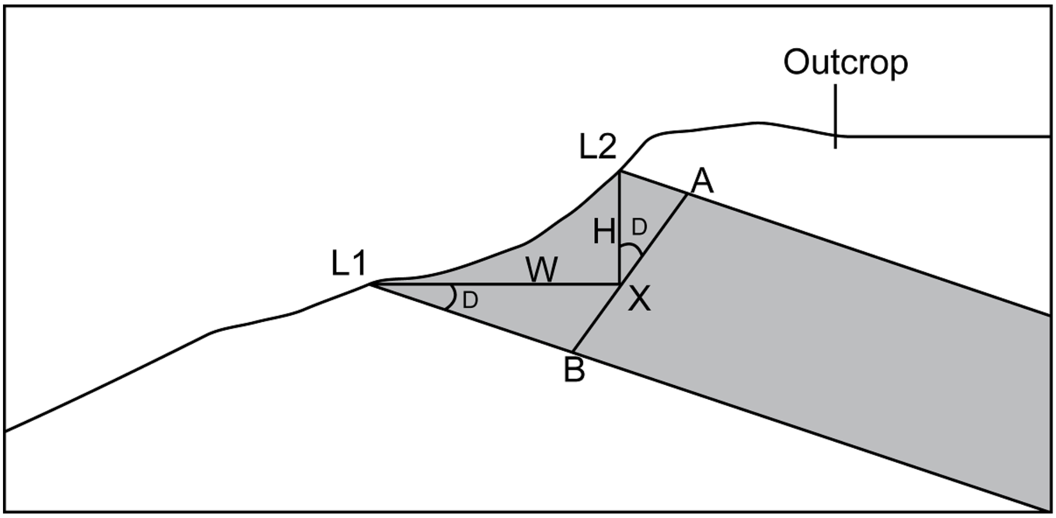
A discussion of the Imo Formation formerly referred to as Imo Shale was first published under the title ''Imo River Shales'' by Tattam (1944). The unit is widely distributed across south-eastern Nigeria, and dated Paleocene to Lower Eocene (Short and Stäuble, 1967). Its outcrop area extends from the Calabar Flank, through the Afikpo area, across the River Niger and westwards to the Okitipupa ridge (Figure 2.1). It is referred to as the proto-Niger Delta and known to be the lateral equivalent and an updip continuation of the subsurface Akata Formation of the Niger Delta Basin (Frankl and Cordry, 1967; Short and Stäuble, 1967; Kogbe, 1976; Petters, 1991). The unit is estimated to be *ca.* 1000 metres thick (Reyment, 1965, p. 90), but Dessauvagie (1975) estimated a thickness of 490 m for the type area at Okigwe-Umuahia road. The Imo Formation contains three sand bodies – Ebenebe Sandstone, Umuna Sandstone and Igbaku Sandstone. Various palynological, sedimentological and stratigraphic studies have depicted the lower sandstone member as a foreshore-shoreface deposit (Reijers et al., 1997), delta front facies (Anyanwu and Arua, 1990), and an estuarine lithic fill (Oboh-Ikuenobe et al., 2005). A sequence stratigraphic framework has been formulated for the unit (Odunze and Obi, 2011). Most palynological studies are limited to the Umuahia axis (Oboh-Ikuenobe et al., 2005), not much study has been carried out in the Ebenebe-Awka axis.

This study uses facies associations and results of clay mineral studies to propose a new paleogeographic model for the Imo Formation and its sandstone members. Palynology is also integrated to provide additional information on the depositional environment of the Imo Formation, particularly the Ebenebe-Awka axis and to test the interpreted paleoenvironment of deposition based on sedimentological facies analysis.

4.2 METHODOLOGY

The field investigation and laboratory methods used are as discussed in chapter one. Sedimentological logging and rock sampling were carried out in several localities – Oji River, Awka, Ebenebe, Amaeke, Umuahia and Abam. Most exposures were in quarries, gullies, river banks, and road cuts. Lateral extent of the exposures ranges from 10 m to 2 km and the thickness was up to about 30 meters thick. Poorly exposed strata such as the mudrocks are estimated using Pythagoras theory to deduce their true thickness from regional dip and lateral extents as observed in the field and/or geologic map.

The method used is shown below (Figure 4.1):



Where D is the dip of the outcrop section

W is the width of the outcrop section

H is the elevation difference between the contacts (L1 and L2)

AX = H cos D

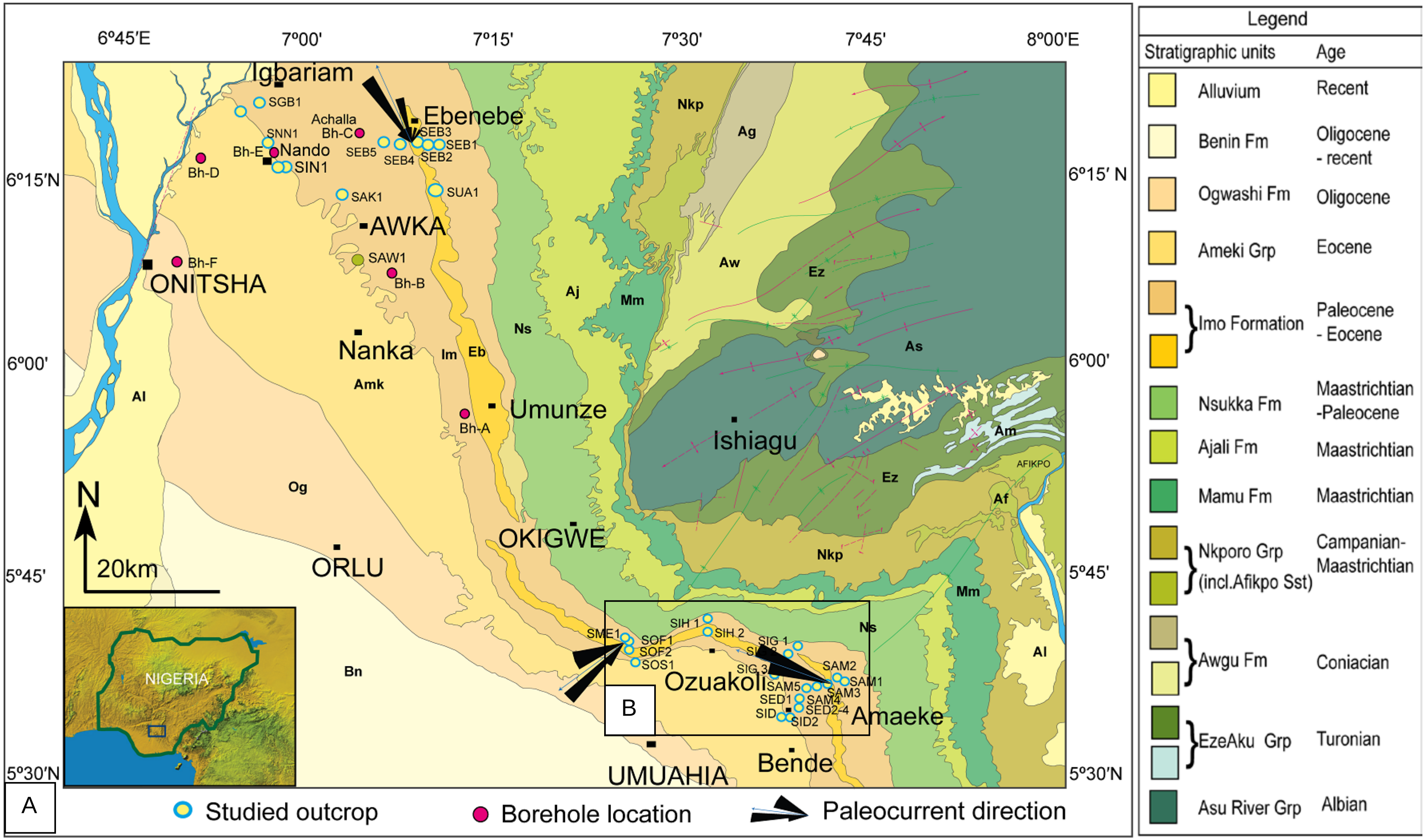
BX = W sin D

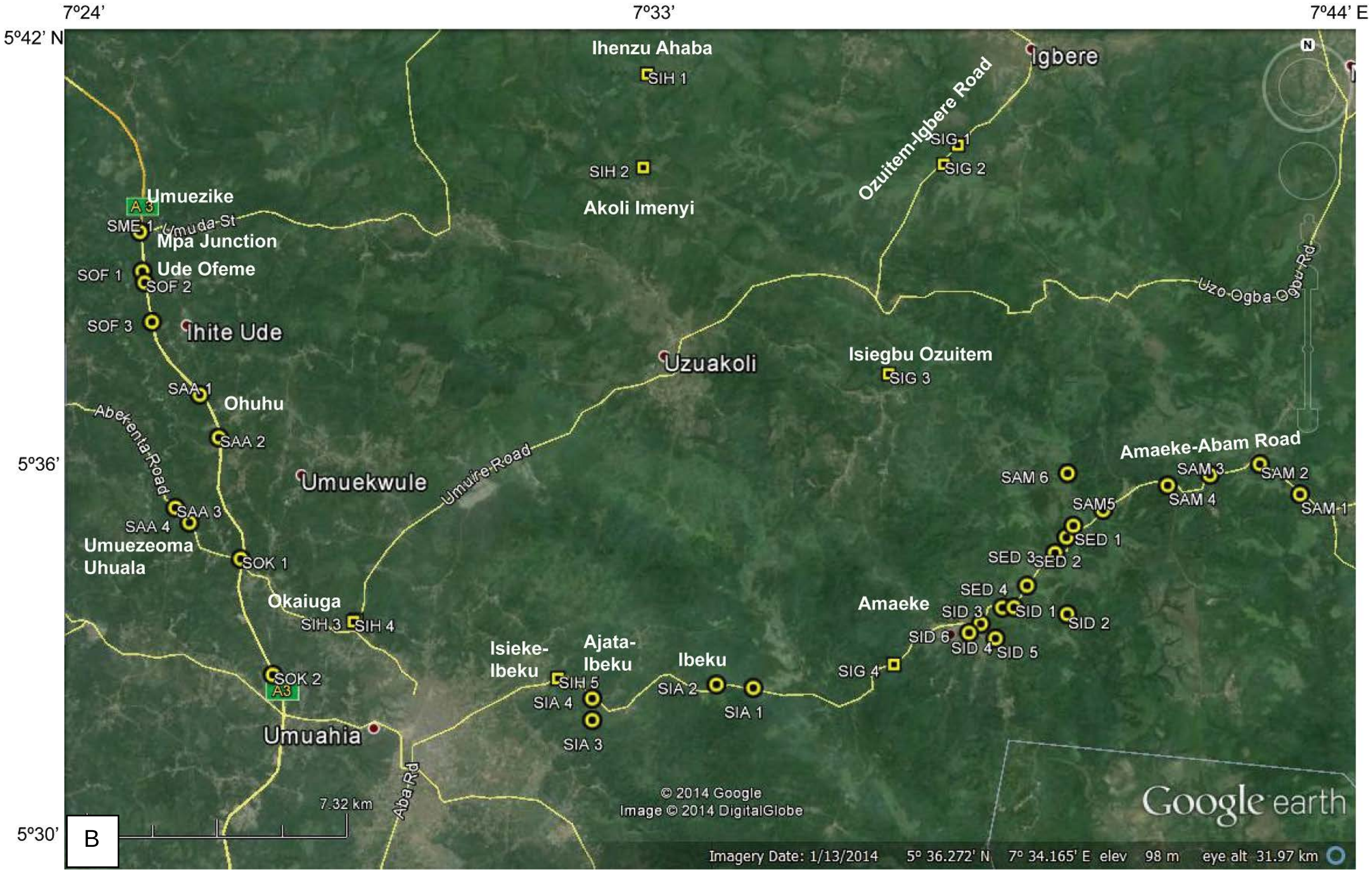
AB = W sin D + H cos D

AB = True Thickness

True thickness is W sin D + H cos

Figure 4.1. Schematic diagram illustrating field measurement of poorly exposed outcrops.


6°45'E
7°00'
7°15'
7°30'
7°45'
8°00'E
6°15'N
6°00'
5°45'
5°30'N
6°15' N
6°00'
5°45'
5°30'N
Igbariam
Ebenebe
Achalla
SGB1
SNN1
Bh-C
SEB3
SEB1
SEB2
SEB4
SEB5
Bh-E
Nando
SIN1
Bh-D
SAK1
SUA1
AWKA
SAW1
Bh-F
ONITSHA
Bh-B
Nanka
Amk
Im
Eb
Umunze
Bh-A
Al
Og
ORLU
OKIGWE
Bn
N
20km
NIGERIA
Nkp
Ag
Aw
Ez
Aj
Mm
Ns
As
Ishiagu
Am
AFIKPO
Af
SME1
SOF1
SOF2
SOS1
SIH 1
SIH 2
SIG 1
SIG 3
SAM2
SAM1
SAM3
SAM4
SAM5
SED1
SED2-4
SID
SID2
Ozuakoli
Amaeke
B
UMUAHIA
Bende
A
Studied outcrop
Borehole location
Paleocurrent direction
Legend
Stratigraphic units
Age
Alluvium
Recent
Benin Fm
Oligocene - recent
Ogwashi Fm
Oligocene
Ameki Grp
Eocene
Imo Formation
Paleocene - Eocene
Nsukka Fm
Maastrichtian -Paleocene
Ajali Fm
Maastrichtian
Mamu Fm
Maastrichtian
Nkporo Grp (incl.Afikpo Sst)
Campanian- Maastrichtian
Awgu Fm
Coniacian
EzeAku Grp
Turonian
Asu River Grp
Albian


7º24'
7º33'
7º44' E
5º42' N
5º36'
5º30'
B
Ihenzu Ahaba
SIH 1
SIH 2
Akoli Imenyi
Igbere
Ozuitem-Igbere Road
SIG 1
SIG 2
Umuezike
A 3
SME 1
Umuda St
Mpa Junction
Ude Ofeme
SOF 1
SOF 2
SOF 3
Ihite Ude
Uzuakoli
Isiegbu Ozuitem
SIG 3
Uzo-Ogba-Ogbu Rd
SAA 1
Ohuhu
Abekenta Road
SAA 2
SAA 3
SAA 4
Umuekwule
Umuire Road
Amaeke-Abam Road
SAM 6
SAM 3
SAM 2
SAM 4
SAM 1
SAM5
SED 1
SED 3
SED 2
SED 4
Umuezeoma Uhuala
SOK 1
Okaiuga
SIH 3
SIH 4
Amaeke
SID 3
SID 1
SID 2
SID 6
SID 4
SID 5
Isieke-Ibeku
Ajata-Ibeku
Ibeku
SIH 5
SIA 4
SIA 2
SIA 1
SIA 3
SIG 4
SOK 2
A3
Umuahia
Aba Rd
7.32 km
© 2014 Google
Image © 2014 DigitalGlobe
Google earth
Imagery Date: 1/13/2014 5º 36.272' N 7º 34.165' E elev 98 m eye alt 31.97 km

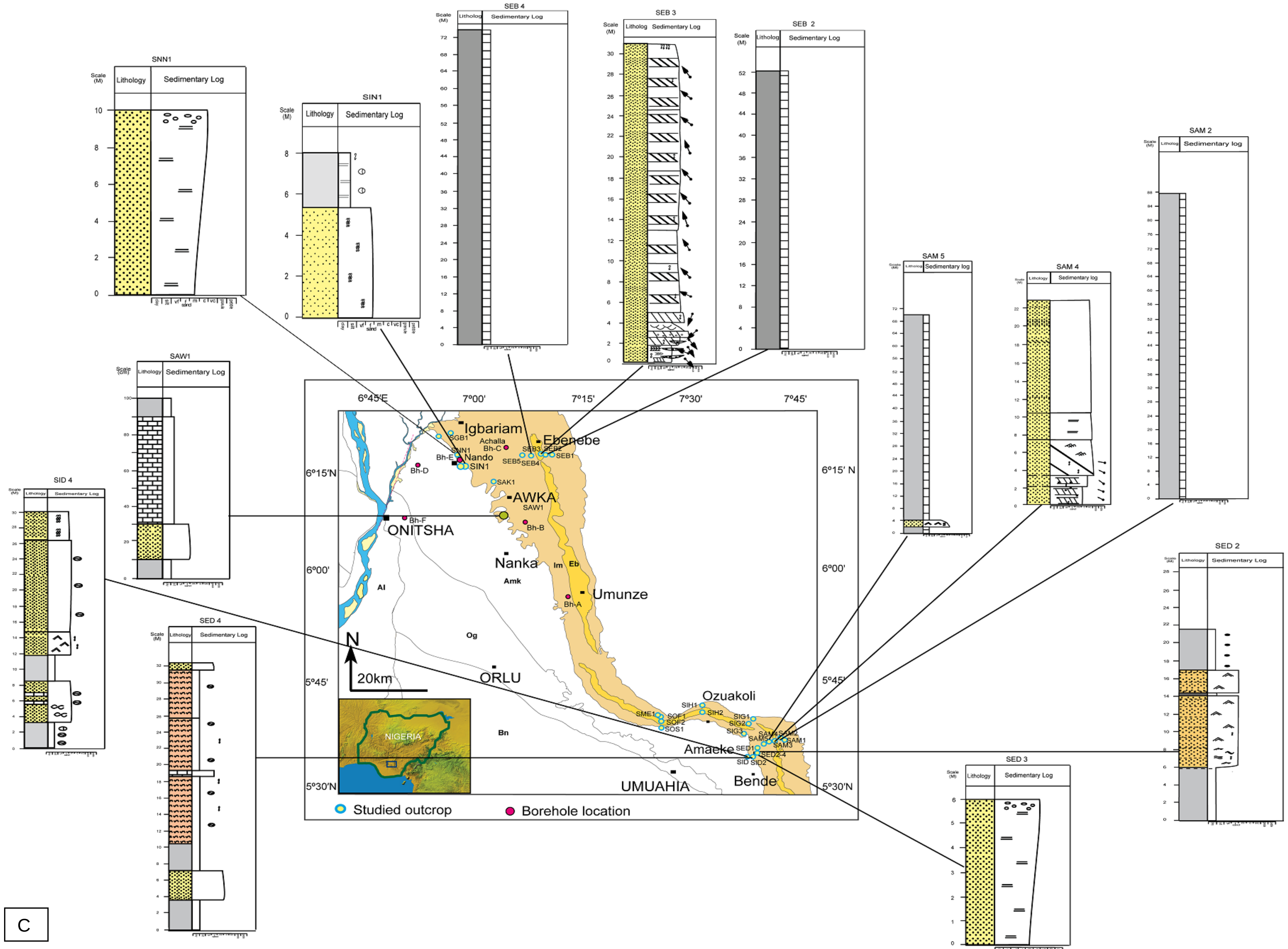


Figure 4.2. A. Geologic map of the study area, showing the outcrop locations of the Paleocene -Eocene Imo Formation (redrawn and modified after Nigerian Geological Survey Agency, 2009). B. Accessibility map of the study area (Umuahia axis) extracted from Google earth. C. Geologic map of Imo Formation showing distribution of outcrops

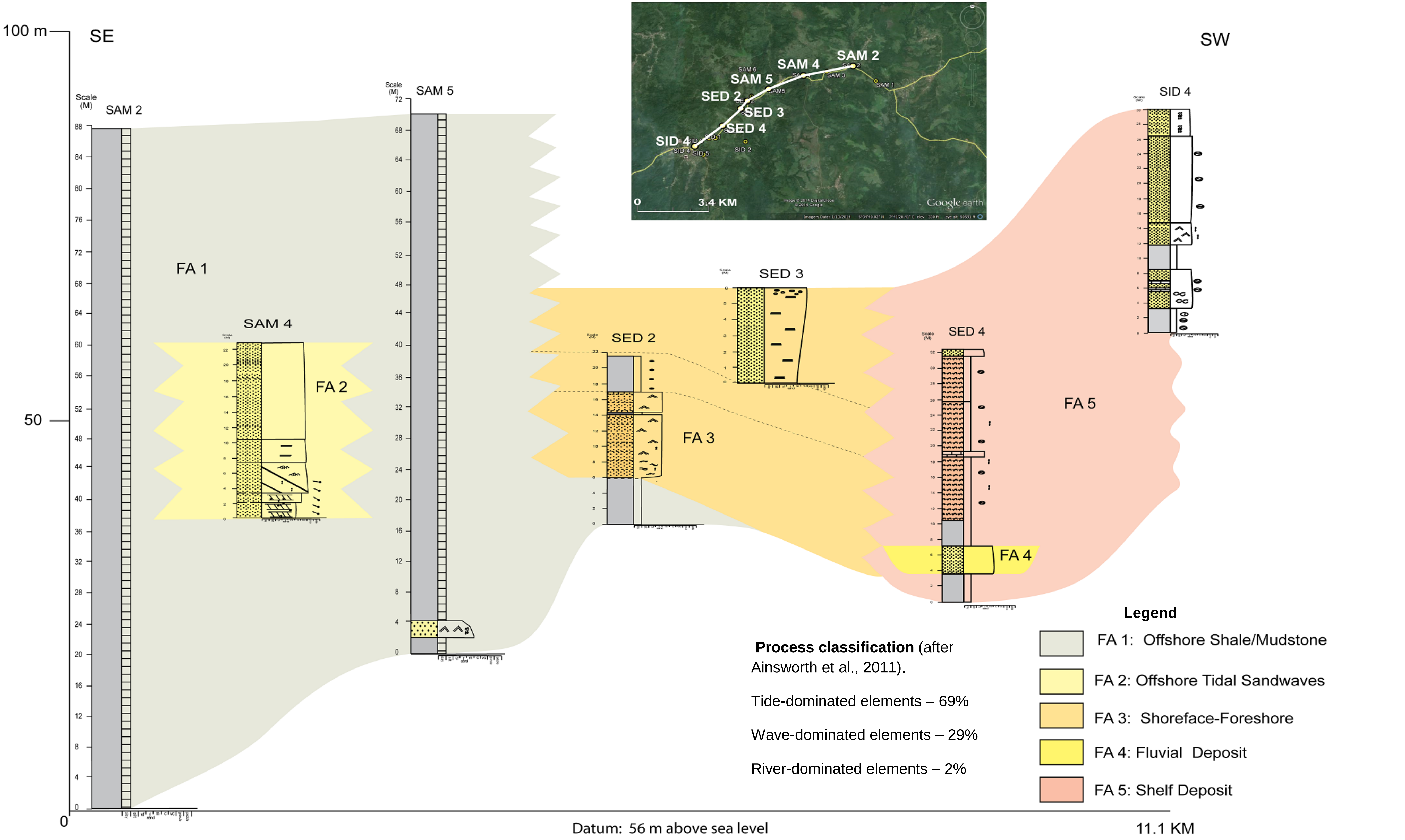


Figure 4.3 Correlation panel of some outcrops from the Umuahia axis (Imo Formation) showing distribution of depositional facies.

4.3 RESULTS

4.3.1 Facies Association (FA)

The characteristics of the Imo Formation were observed and recorded from two different regions: the Umuahia axis and the Ebenebe-Awka axis (Figure 4.2). Ten facies and three subfacies from the study area were grouped into five depositional facies associations based on their vertical and lateral facies assemblages, nature of bedding contacts with adjacent units, overall geometry of bounding and erosion surfaces and stacking patterns of lithofacies. The facies associations are described in ascending stratigraphic order, with each facies association representing changes in the environment of deposition. These changes record a series of sea-level fluctuations in a pattern of transgression-regression-transgression.

Pattern of depositional facies distribution in the Imo Formation is observed from the correlation panel from the Umuahia axis (Figure 4.3).

FA 1 (Offshore Shale/Mudstone)

Facies Association 1 dominates the lower part of the formation and is characterised by grey shale to clayey shale facies (Fl). This shale facies is poorly exposed; it comprises the basal shale facies which occurs before the sandstone bodies (FA 2) and the upper shale facies which occurs after the sandstone bodies (FA 2). The exposed basal shale facies (Fl), observed in an excavation pit at Ebenebe is about 3 m thick (Figure 4.4). It can be traced for over 100 m to 2 km in the study area and has a low dip of about 4^0. The FA 1 comprises highly fissile, light bluish to dark grey shale which becomes more clayey upwards, with rare body fossils (e.g. bivalves). The shale has a sharp basal contact with the underlying sandstone member of Nsukka Formation. Rocks of the shale facies are laterally extensive and encase the thick sandstone-rich deposits of the tidal sandwaves (FA 3).

The basal shale facies observed at Ameke-Abam (in the Umuahia axis) is estimated to be 87 m thick (Figure 4.1C), whereas at Ebenebe is it calculated to be 52.8 m thick (Figure 4.1C). The upper shale facies encase the sandstone bodies and it is estimated 70 m thick in the Umuahia axis and 73.3 m in Ebenebe axis (Appendix B4.1). Borehole log (Bh-E) from Nando (ie Ebenebe axis) (Appendix B4.2) shows that the upper shale facies is as thick as 64 m.

FA 2 (Offshore Tidal Sandwaves)

Facies Association 2 is dominated by large scale planar cross-bedded sandstone facies (Sp4), with subordinate planar cross-bedded sandstone facies (Sp1), herringbone cross-stratified sandstone (Sh) and trough cross-bedded sandstone facies (St1) (Figure 4.5).

The sandstone is tabular to lenticular and is completely encased in offshore shales of Facies Association 1. The sandstone outcrop is 20 to 30 m thick and consists of large-scale tabular cross-beds with avalanche foresets with dip angles of ranging from 15° to 40° (Figure 4.6), interpreted as unidirectional-flow sand waves or tidal-current sand waves (Allen, 1980). Sandwaves are subaqueous, lower flow regime transverse bedforms of sand that have larger wave-lengths than dunes (Stride, 1982). They are usually associated with spring peak tidal currents with speeds corresponding to about 50 cm/s at 3 m above the bed in 30 m water depth.

The paleocurrents are dominantly unimodal with a subordinate bimodal pattern, and suggest a regional net sand transport direction to the north-west based on the dominant paleoflow of the large scale cross-beds at Ebenebe (SEB 3). The medium and small scale cross-beds reflect a south-east direction suggesting the impact of a subordinate current system. Large scale planar cross-beds with high angles of 26° to 40° and azimuthal trend of south-west direction were observed at Umuezike (Mkpa) Junction (SME 1). At Ameke Abam (SAM 4) (Figure 4.7) sandstone quarry, the common sedimentary structures are climbing ripples, counter-current ripples, large and small scale planar cross-beds. The dominant cross-bedding trend is to the north-west.

Grain size diminishes downdip, while the foresets show normal grading with poorly to moderately sorted, pebbly to fine grained intervals. The toesets are commonly well sorted, and fine-grained. The decreasing grain size is associated with decreasing peak current strength (Stride, 1982). The pebbly to coarse foresets suggest deposition by avalanching grain flow on a subaqueous steep slope due to gravity (Longhitano, 2008; Rohais et al., 2008). Other internal structures (Figure 4.8A-C), such as cm-scale scours and fill structures with pebbly infills, small scale herringbone cross-beds, medium scale planar and trough cross-beds, mud clasts, counter-current ripples and climbing ripples, suggest fluctuation current velocity and are associated with ancient offshore tidal current activity (Stride, 1982). Scour and fill structures are products of strongly enhanced energy input or hydraulic jump in flow velocity (Sarkar et al., 1991; Longhitano, 2008; Nichols, 2009). Mud clasts occur due to partial break-up of mud layers. The entire sandstone is slightly burrowed with low diversity *Ophiomorpha nodosa, Paleophycus heberti.* Boxworks of *Thalassinoides horizontalis* with well preserved polygonal pattern occur at the topmost horizon of the lower sandstone member of Imo Formation observed at abandoned sandstone quarry at Ugwuoba (SUA 1) along the Awka-Enugu Express way (Figure 4.9). The burrows are assigned to a firmground *Glossifungites* ichnofacies developed at hiatal surfaces and marking erosional discontinuities in sedimentary successions (MacEachern et al., 1992; Pemberton et al., 1992; MacEachern and Burton, 2000). The intense burrowing reflects cessation of deposition and subsequent increase in accommodation that led to the deposition of shallow marine shales (Figure 4.10) that enclosed the lower sandstone bodies.

Earlier authors (Anyanwu and Arua, 1990; Oboh-Ikuenobe et al., 2005) interpreted the lower sandstone member of the Imo Formation as a delta front and a fluvial channel of an estuarine fill respectively, but the stratigraphic succession indicates that the sandstone body is enclosed in shallow marine shales and the sandstone clearly exhibits tidal signatures and shallow marine ichnofossils. These authors did not appreciate the entire stratigraphic succession, but rather based their conclusions on the characteristics of only the sandstone body. Thus, a new interpretation based on detailed field evidence, sedimentary structures and successions is that the lower Sandstone Member of the Imo Formation consists of offshore tidal sandwave deposits. This interpretation is similar to that for the sandwaves on the large sand-bar complex in Cobequid Bay (Darlymple, 1984) and other works such as by Allen (1980); Darlymple (1992) and Stride (1982).

Figure 4.4. Excavation pit at Ebenebe (SEB 1) were the dark bluish grey shale (Fl1 facies) of lower Sandstone Member of Imo Formation outcrop.

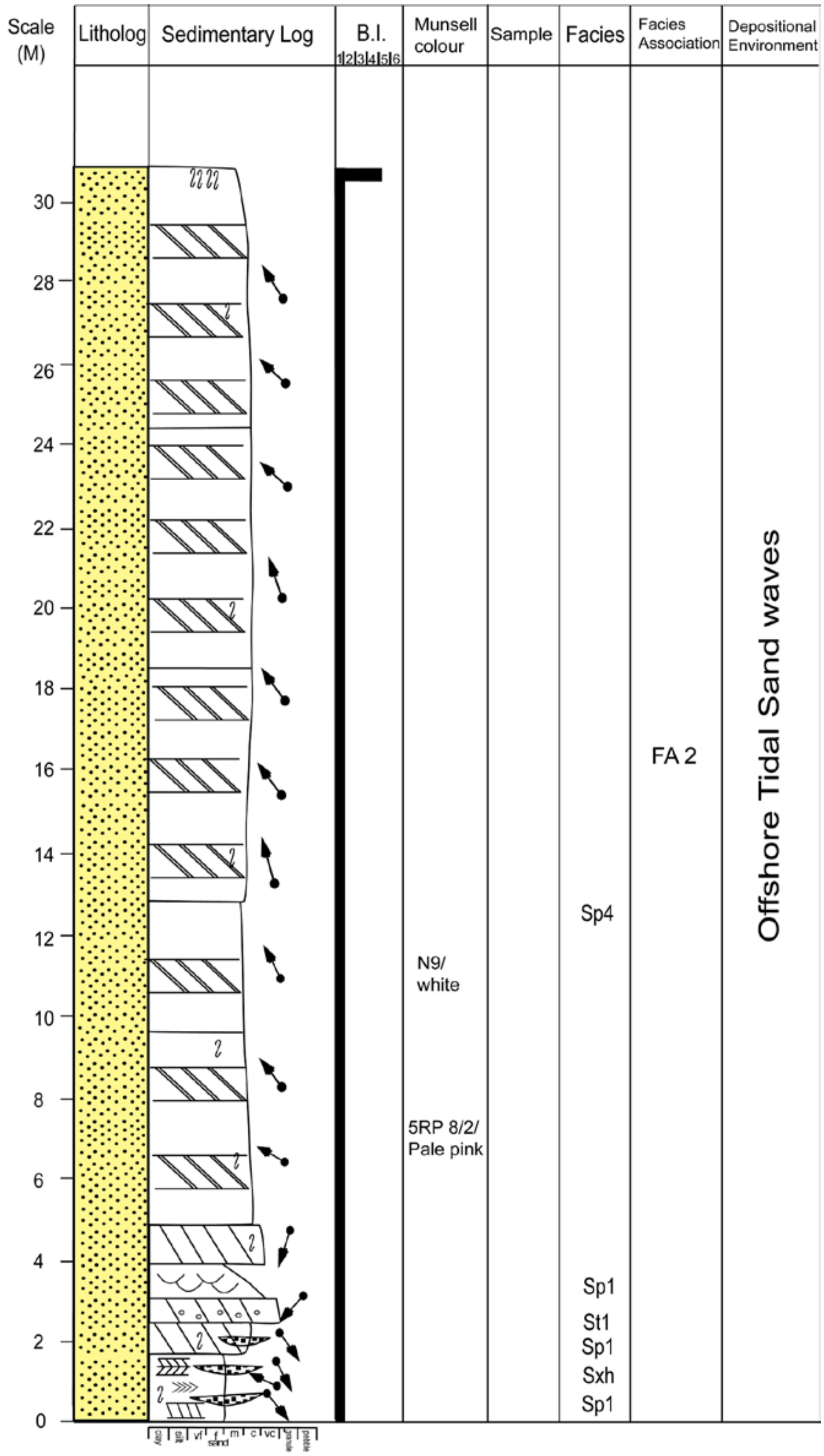


Figure 4.5a. Lithostratigraphic log profile of Ebenebe section showing the Ebenebe Sandstone Member of the Imo Formation.

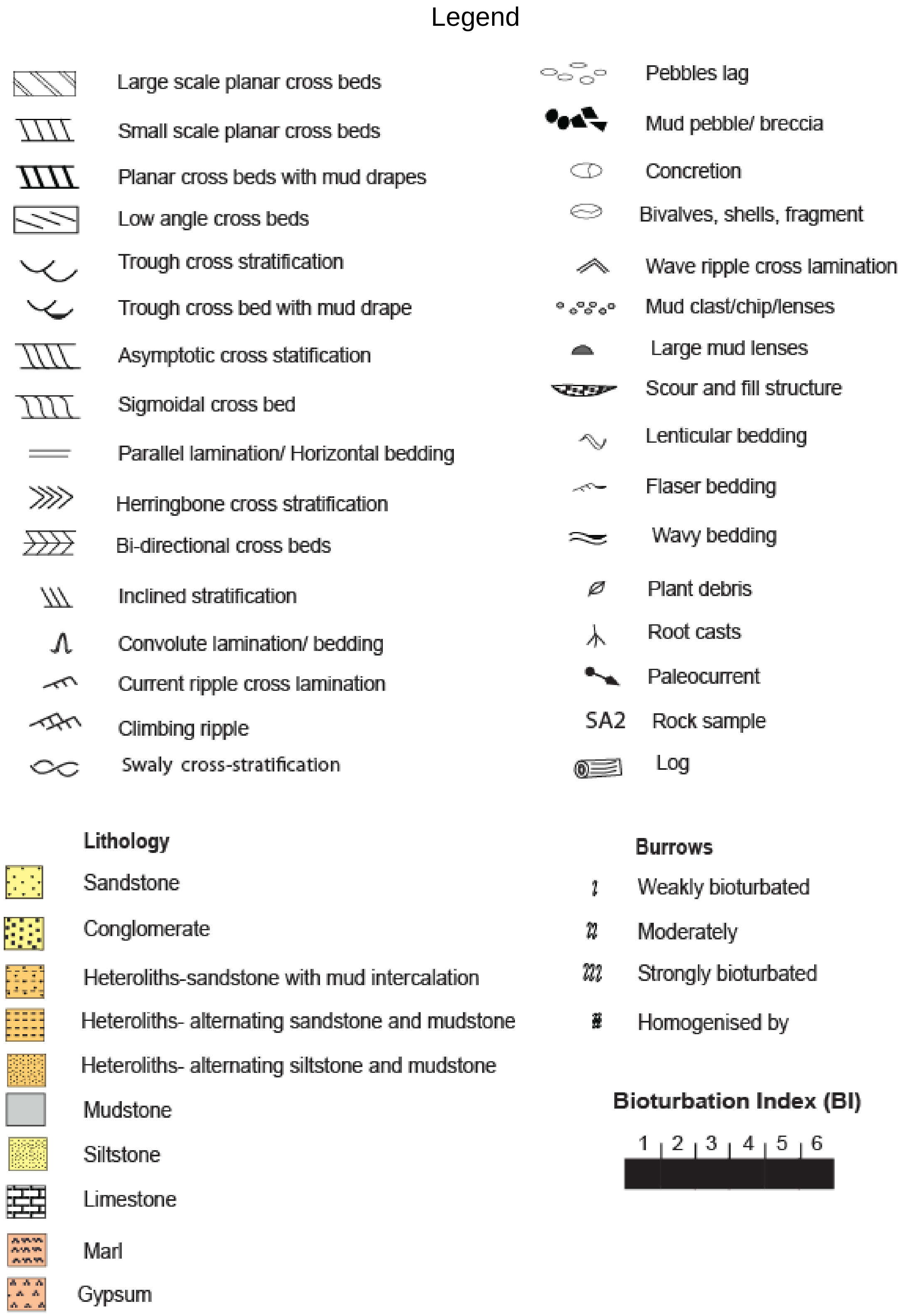
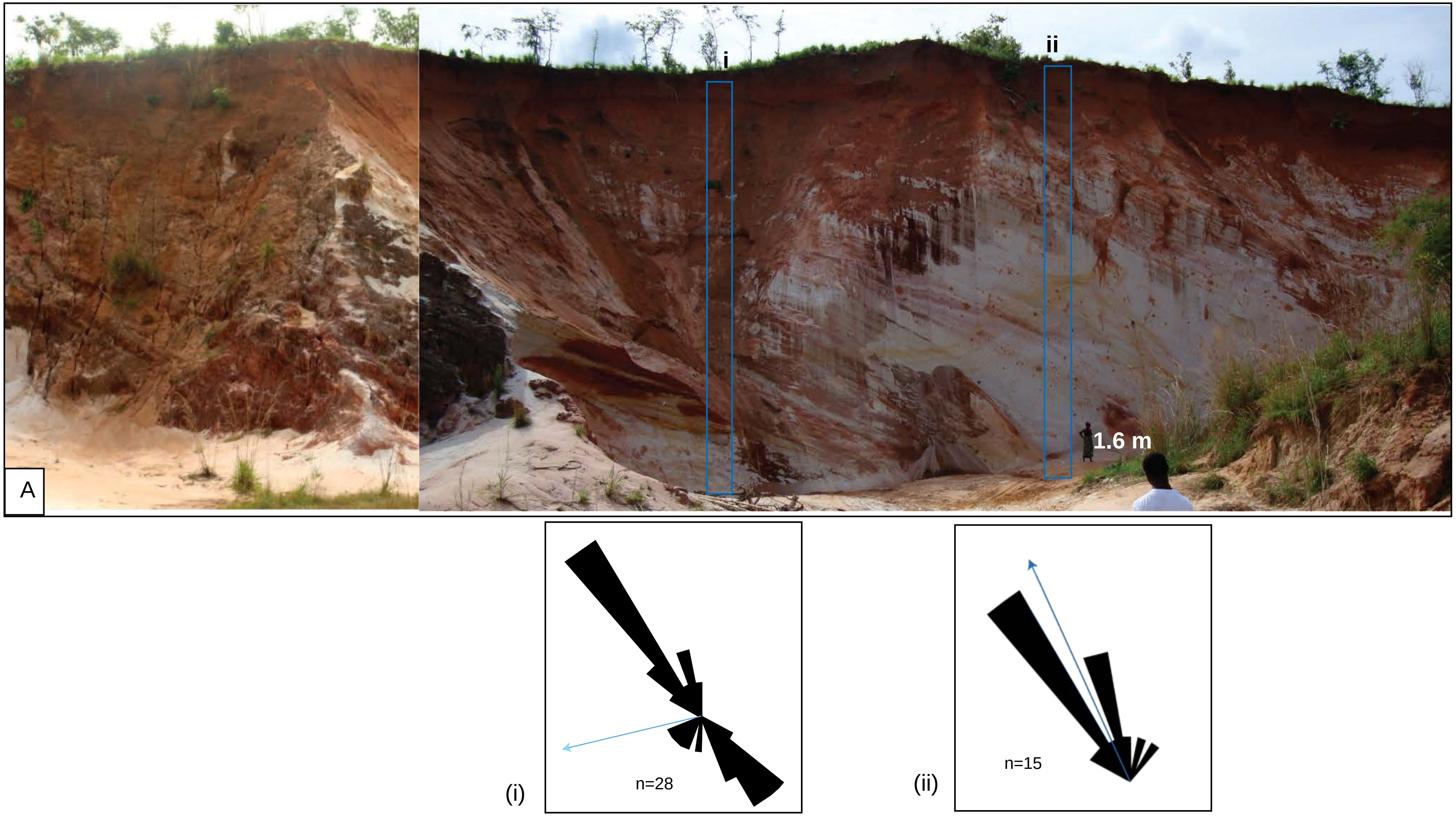


Figure 4.5b. Legend for lithologs.


A
i
ii
1.6 m
n=28
(i)
n=15
(ii)

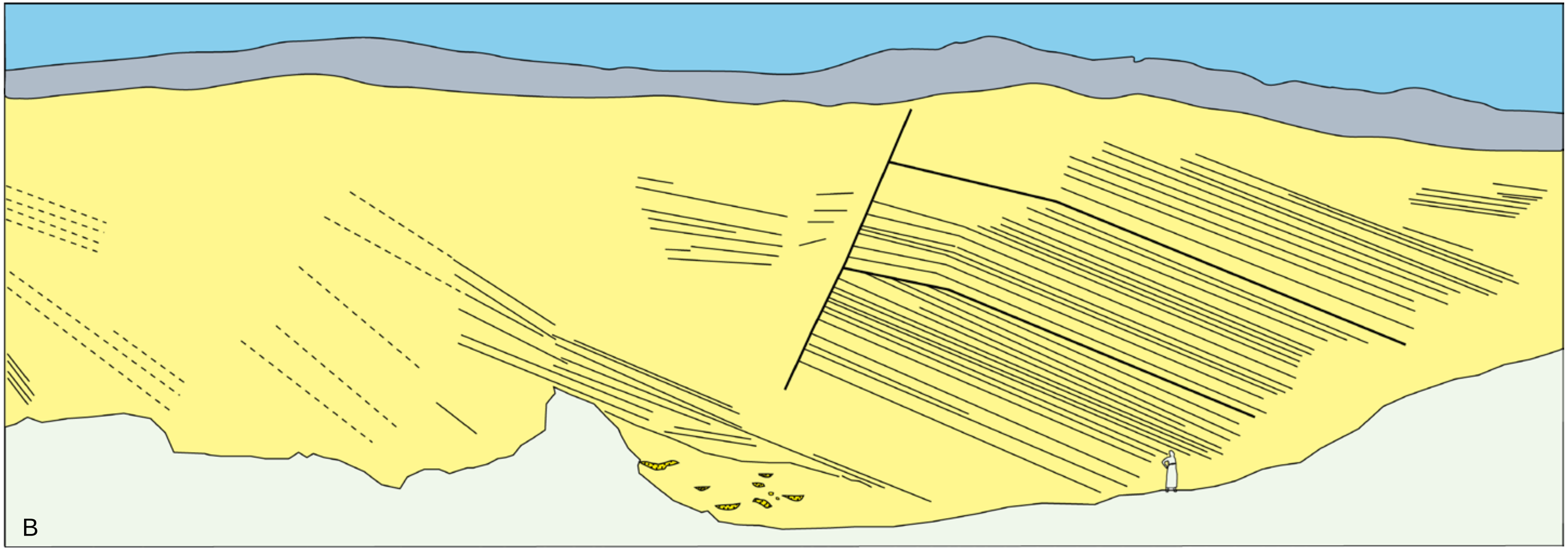


Figure 4.6 (A) Lower Sandstone Member of Imo Formation (Ebenebe Sandstone) observed at Ebenebe sandstone quarrying site. Dominant paleocurrent trends (i & ii) show north-western direction. (B) Schematic diagram shows large scale cross-beds with avalanching foresets.

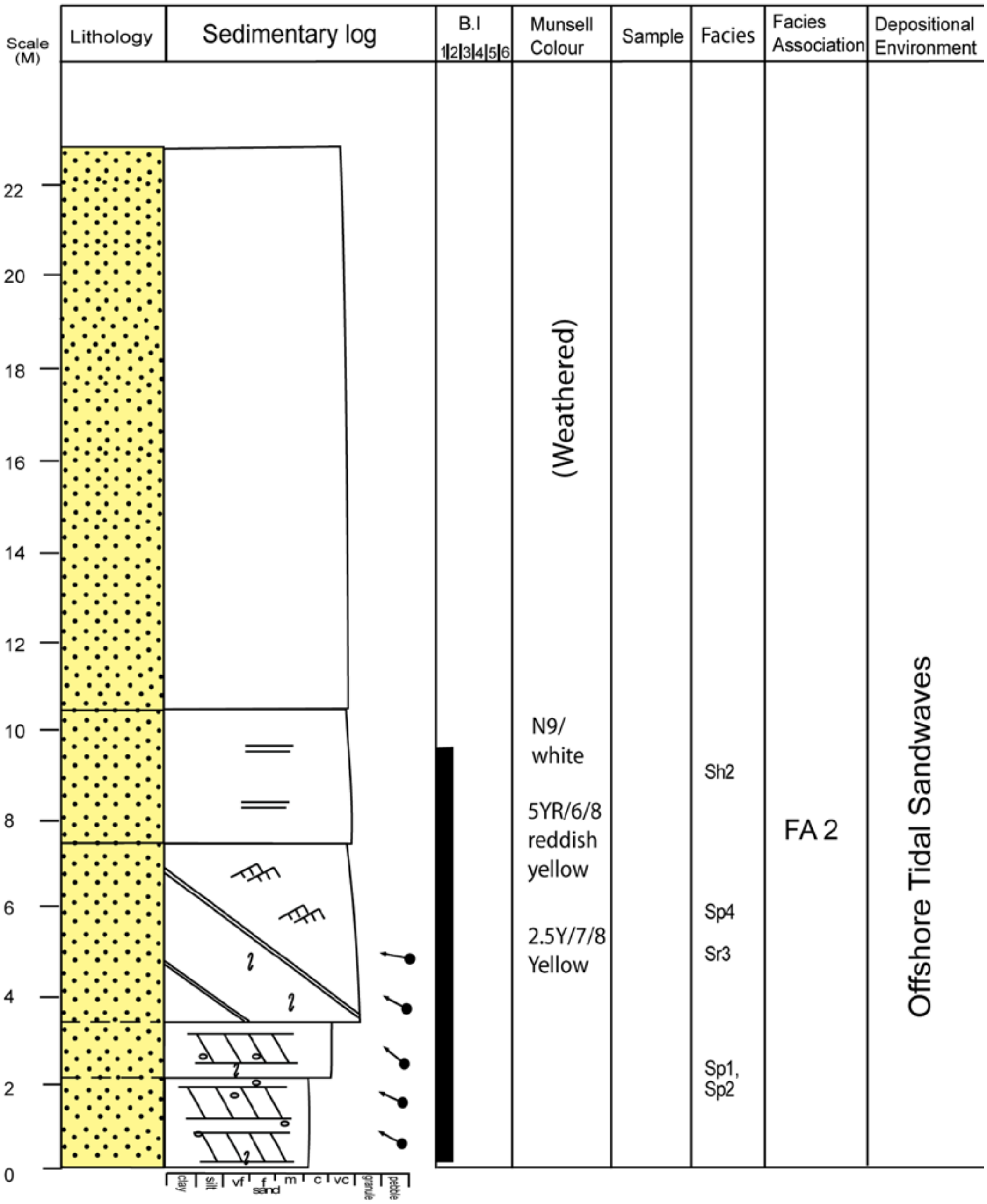
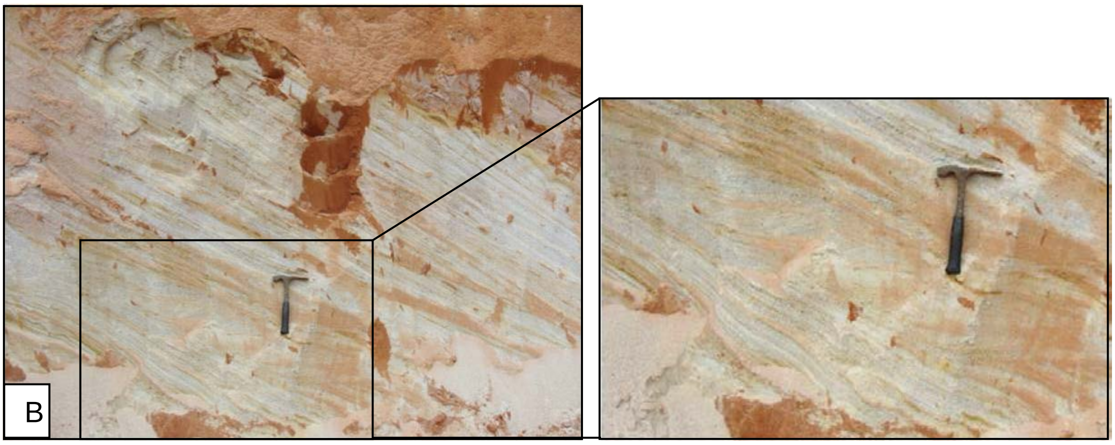


Figure 4.7. Lithostratigraphic log profile of Ameke Abam section showing the Igbaku Sandstone Member (Imo Formation).


A


B

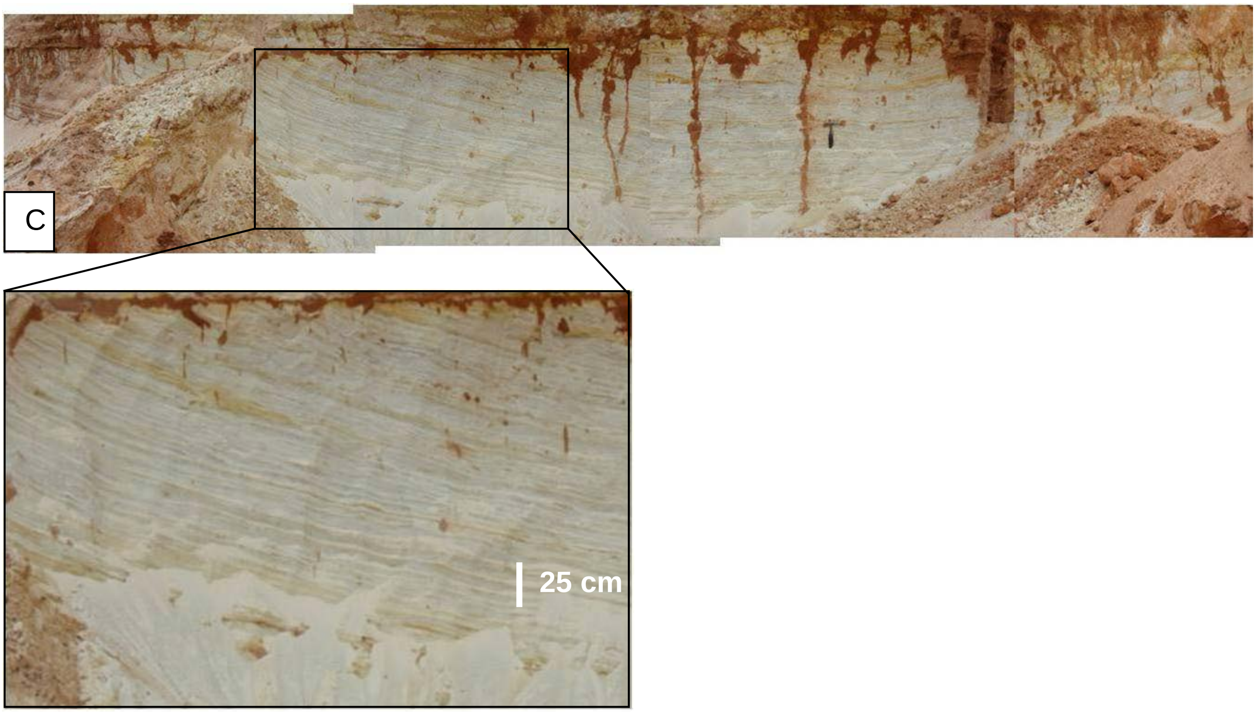


Figure 4.8 (A). Herringbone structure (Sxh facies) with *Ophiomorpha* burrows (in black arrows) and probably *Paleophycus* burrow (in red arrows) in the Igbaku Sandstone. (B). Countercurrent ripples (Sr facies), erosional surfaces and large scale planar cross-bedding (Sp4) at Ameke Abam. (C). The large scale planar cross-bedding migrates to climbing ripples in a northward direction.

Figure 4.9. Well preserved *Thalassinoides paradoxicus* boxwork (Sb facies) observed at abandoned sandstone quarry along Oji River-Awka Expressway.

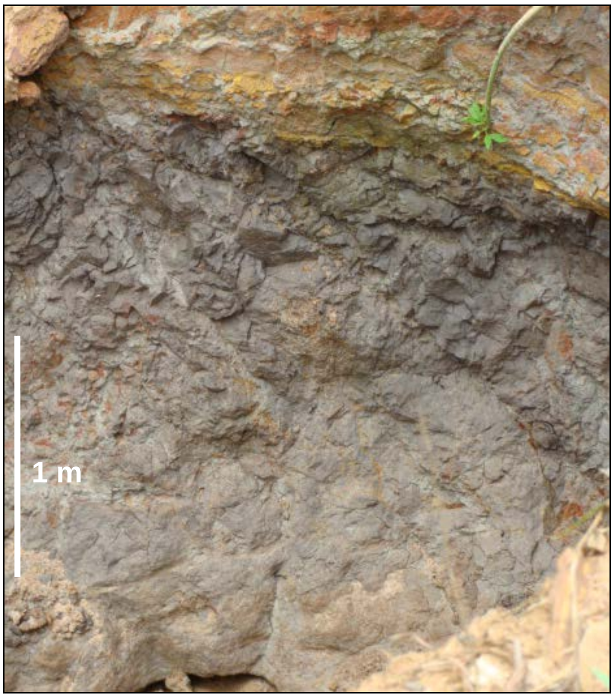


Figure 4.10. Gully exposure of medium bluish grey (5B 5/1) shales (Fl2 facies; SAM3) of the upper Sandstone Member of the Imo Formation, exposed at Ameke Abam (sample SAA).

FA 3 (Shoreface-Foreshore)

Facies association 3 is the middle part of the Imo Formation and it is composed of non-fossiliferous dark grey shale facies (Fl2), wave rippled laminated sandstone facies (Sw), current rippled laminated sandstone facies (Sr), fine grained bioturbated sandstone facies (Sbf), horizontal bedded sandstone facies (Sh2), and dark grey fossiliferous facies (Fl1). This facies association occurs in the Umuahia and Ebenebe-Awka axes.

Facies association 3 (FA3) directly overlies facies association 2 (FA2). The non-fossiliferous dark grey shale facies (Fl2) occurs at the top of FA 2 and continues to the base of FA3, where it encloses a lenticular shape, discontinuous bioturbated fine grained rippled sandstone. Trace fossils observed include small horizontal and inclined mud-lined burrows of *Ophiomorpha nodosa,* and *Paleophycus heberti*. Few physical structures are preserved. This sandy unit is interpreted as a result of episodic storm events and also reflects post-storm colonization of opportunistic burrowers (Vossler and Pemberton, 1989). The lack of obvious internal structure may be due to bioturbation during the post-storm event. Similar rippled-bedded sandstone with horizontal burrows observed in the Viking Formation, Alberta Basin have been described by Beaumont (1984) as an offshore facies. Allen (1982), also demonstration the formation of storm sand layer in shallow offshore waters; where sand beds, enclosed by shelf mud are characterised by ripples and/or planar lamination, mud clasts, shells and burrows.

The Fl2 facies is succeeded by wave rippled laminated sandstone facies as observed at Idoyi Abam (SED 2) in Umuhia axis (Figure 4.11). The wave rippled laminated sandstone facies (Sw) is represented by well sorted, fine grained, micaceous sandstone that exhibited wavy/flaser and lenticular bedding at the lower interval (Figure

4.12A,B) whereas the upper section is characterised by symmetrical wave rippled lamination, sharp based contact with continuous thin mud horizons and horizontal lamination. This unit is moderately burrowed, and the dominant burrows are *Ophiomorpha*, *Skolithos, Arenicolites* and *Planolites*. These structures are considered to have formed in middle to upper shoreface setting, where fair-weather oscillatory flows dominate. Continuous winnowing by wave surges resulted in well sorted sandstone, while the interbeds of thin mud horizons typify lower energy conditions as the wave energy wanes (Rice, 1984). Lack of a lower shoreface environment (usually characterised by hummocky cross-stratification or/and a high concentration of bioturbation, with remnants of ripple and parallel laminations) indicates a high wave and low storm impact on the shoreline at the time. This sedimentary facies is similar to those described by Howard and Reineck (1979) on the high-energy coast of Ventura-Oxnard area, where the upper shoreface is very thick and dominated by wave surge and wave-generated currents. Overlying the wave rippled sandstone is fossiliferous shale (Fl1) with a restricted articulated fauna and thick ornamented shells, which is interpreted as having been formed in a lagoon with restricted circulation. The lack of fragmentation of the shells suggests short transportation (Rice, 1984). At Okputong-Bende (SED 3), a 10 meter thick horizontally bedded, medium to pebbly sandstone (Sh2) shows a coarsening-upward succession that indicates increasing energy levels probably due to shoaling (Figure 4.13A). This horizontally bedded facies is interpreted as wave swash produced on the foreshore (Figure 4.13B). Lower shoreface deposits were observed in the Ebenebe-Awka axis, at Amawbia. They consist of a coarsening-upward succession characterised by very fine to fine grained, micaceous, well sorted, rippled sandstone in the lower unit. The lower interval is moderately to intensely burrowed with mainly vertical and inclined burrows of *Ophiomorpha, Skolithos,* *Planolites*, and *Arenicolites* (Figure 4.14). This unit grades into a coarse to pebbly, horizontally bedded sandstone.

At Isinyi Nando (SIN 1) in the Ebenebe-Awka axis, a bioturbated, fine grained, micaceous sandstone, is overlain by dark grey coloured mudstone with iron-rich concretions (Figure 4.15). About 100 m from Ikem Nando is a coarsening upward sandstone consisting of monotonous, medium to very coarse and pebbly sands exhibiting planar cross beds, wave-ripple lamination, herringbone cross stratification (bi-directional currents) and trough cross bedding which typify an upper shoreface deposit (Figure 4.16). Though a complete vertical facies succession was not observed, probably due to erosion, the observed sedimentary structures of facies association 3 are interpreted as progradational shoreface-foreshore environment based on similarity with those described by Howard and Reineck (1979) and McCubbin (1982), where deposits of beach-offshore environments were observed in the Ventura-Oxnard coast, California. Yoshida (2000) characterised 'sequence A' of the lower Castlegate Sandstone, Book Cliff, Utah as shoreface to foreshore facies based on the sedimentary facies (horizontal and wavy lamination, oscillation ripples and hummocky cross-stratification) observed and ichnology (*Skolithos* and proximal *Cruziana* ichnofacies). Oboh-Ikuenobe et al., (2005), also interpreted sediments of the middle Sandstone Member of the Imo Formation outcropping in Abam-Bende region of the Umuahia axis as shoreface-foreshore deposits based on the sedimentary facies, ichnology and palynological interpretation.

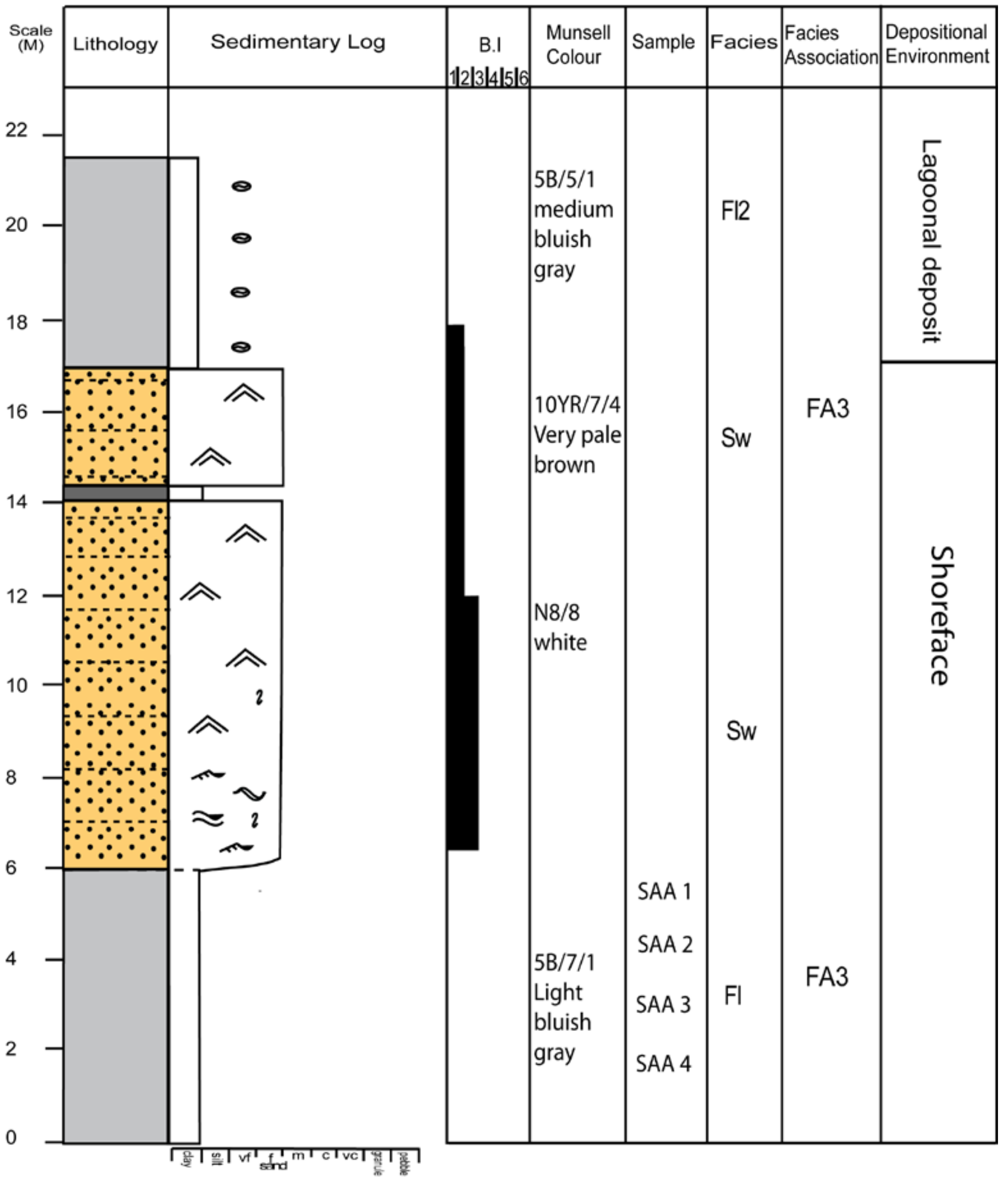


Figure 4.11. Lithostratigraphic log profile of Idoyi-Abam Section

Figure 4.12. (A). Road-cut exposure of the wave rippled laminated sandstone facies (Sw) in Idoyi-Abam (Facies Association 3). (B). Wavy and lenticular bedding occurring at the basal interval of the wave-rippled laminated sandstone facies (Sw) in Idoyi-Abam (Facies Association 3).

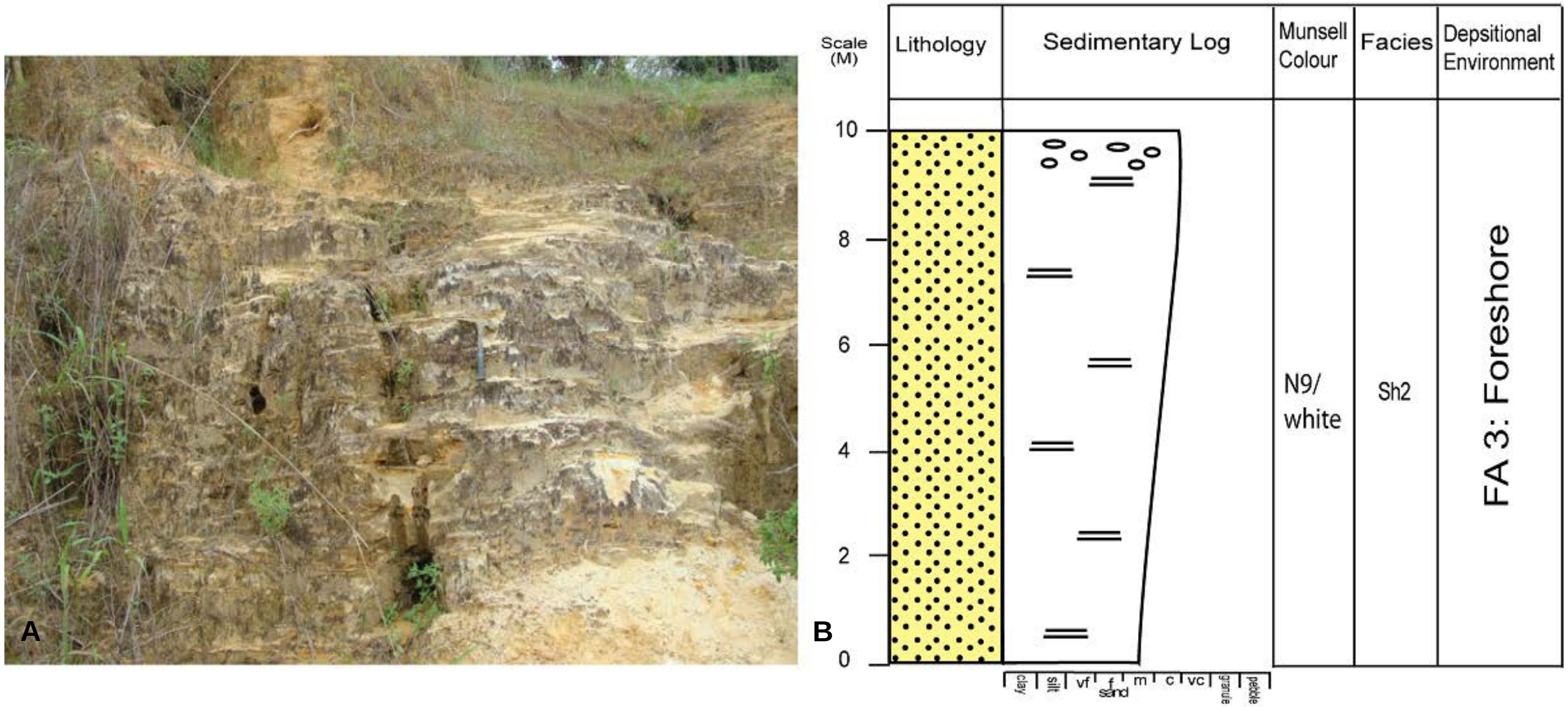


Figure 4.13. (A) Outcrop section of the coarsening upward (medium grained to pebbly) horizontal bedded sandstone facies (Sh1) in Okpotong-Bende (Facies Association 3). (B) Lithostratigraphic log profile of Okputong-Bende Section

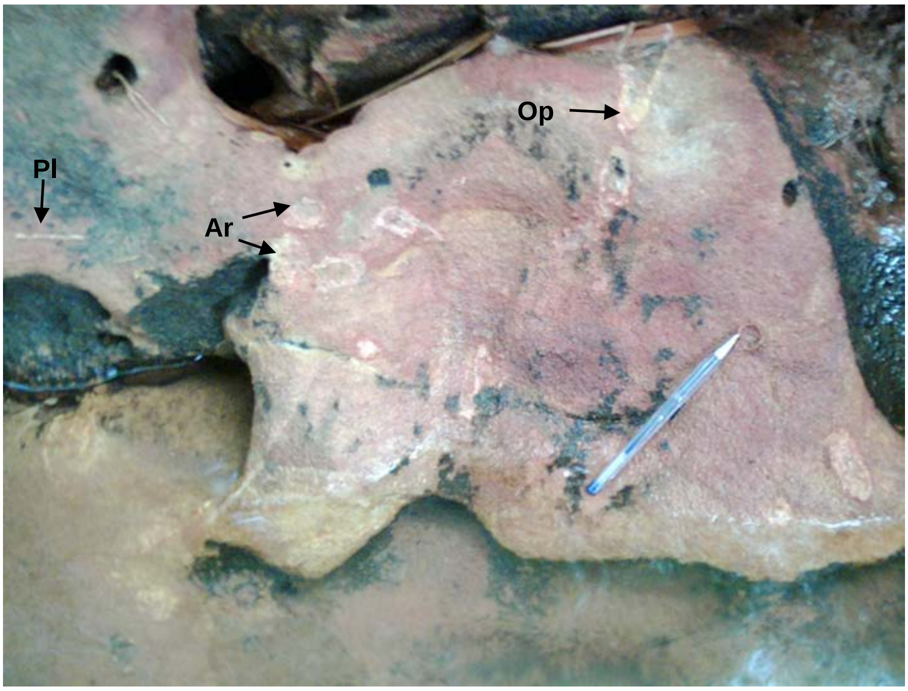


Figure 4.14. *Skolithos* ichnofacies assemblages (Facies Association 3) showing, *Arenicolites* (Ar) (paired burrows), *Planolites* (Pl) and *Ophiomorpha nodosa* (Op) (observed as a stream cut in Amowbia).

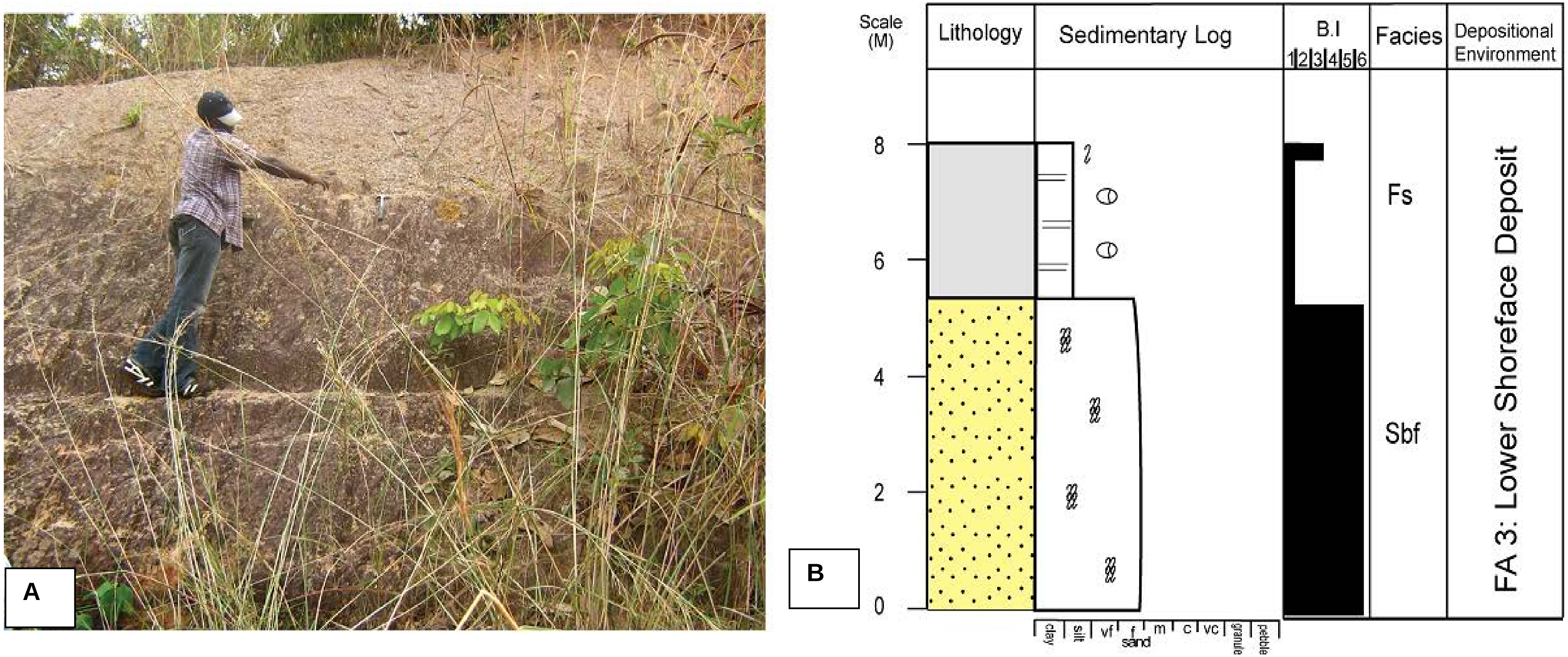


Figure 4.15. (A) Bioturbated micaceous sandstone (Sb), overlain by grey colour shale with iron-rich concretions, observed as a road cut at Isinyi Nando (Facies Association 3). (B). Lithostratigraphic log profile of Isinyi Nando Section

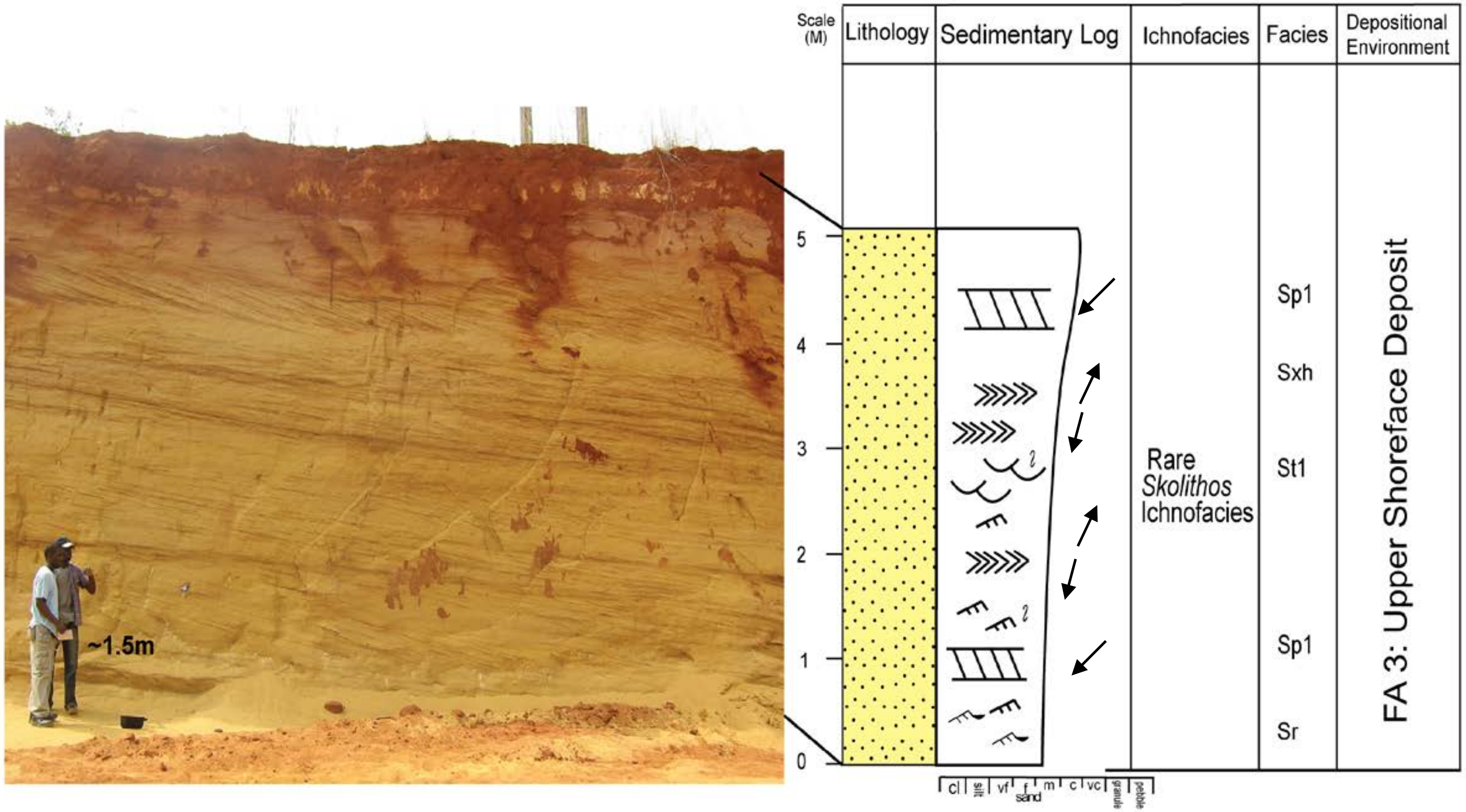


Figure 4.16. (A) Outcrop section of the coarsening upward (medium grained to pebbly) cross-bedded sandstone facies in Ikem Nando (Facies Association 3). (B) Lithostratigraphic log profile of Ikem Nando Section

FA 4 (Fluvial Deposit)

Deposits of facies association 4 commence the upper Sandstone Member of the Imo Formation. FA4 is characterised by structureless, coarse to medium grained sandstone facies (Sm). The sandstone facies sharply overlays a black shale facies along Bende-Abam road (Figure 4.17). This sandstone unit is unbioturbated and poorly exposed.

Fluvial deposits with similar characteristics have been described by Buatois et al., (2005), where they discussed fluvio-estuarine and open marine deposits of the lower Marrow Sandstone, southwest Kansas.

FA 5 (Shelf Deposit)

Facies association 5 comprises the uppermost part of the Imo Formation and is made up of siliciclastic and carbonate sediments. Dominant facies include marl facies (Fc), fossiliferous shale facies (Fl1); and structureless calcareous sandstone (Sm1) with subordinate structureless non-calcareous sandstone (Sm2), bioturbated sandstone (Sb) and non-fossiliferous dark grey shale facies (Fl1) (Figure 4.17). A cross-section along the Bende-Abam road exposes outcrops of the upper Imo Formation (Figure 4.2B) in the Umuahia axis from Okputong-Bende (SED 4) to Idima Abam (SID 4). FA5 exhibits alternations of fossiliferous shale and marl with limestone, bioturbated sandstone and fossiliferous, calcareous sandstone with limestone. Mudstone increases upwards and grades into marl indicating a sea level rise during a period of minimal sediment input. The marl is associated with thinly bedded (22 cm thick) fossiliferous limestone (see Chapter 3; Figure 3.23) which probably indicates a condensed section. Fossiliferous black shale characterised by fossil remains of rays, shark teeth, ambers, coquina, shells (gastropods, bivalves) and limestone concretions overlies the marl unit. The abundance of fauna suggests aerobic conditions in the water column above that led to favourable ecosystem for marine organisms to thrive. The black shale is interbedded with a fine grained, calcareous, well sorted sandstone that exhibits undulatory lamination that probably represents hummocky-swaley cross stratification; two fossiliferous limestone layers in the sandstone reflect late stage waning of episodic storm events (Oboh-Ikuenobe, et al., 2005). Further shoaling, resulted in the deposition of very fine grained, micaceous wave rippled sandstone which grades to a fine grained, micaceous fossiliferous calcareous structureless sandstone and finally into a strongly bioturbated fine grained sandstone, with bioturbation index of 5-6. Monospecific *Thalassinoides paradoxicus* dominates this unit.

This facies association is not well developed in the Awka axis, about 40 cm thick shale was observed at the Umuawulu location, but Arua, 1980 documented about 1m thick limestone interval underlain by calcareous sandstone and overlain by shales (Fig. 4.18). This outcrop was observed at Umuawulu town about 9 km south of Awka.

Borehole ditch cuttings from Umunze (Bh-A) consist of calcareous sandstone, that is dominantly medium to coarse grained and moderately sorted (Appendix B4.3). The sedimentary structures in this facies association suggest retrogradational shelf sedimentation. Oboh-Ikuenobe et al., (2005) and Lubeseder et al., (2009) documented and interpreted similar facies. Lubeseder et al., (2009) described mixed siliciclastic carbonate shelf sequence of the SW Anti-Atlas, Morocco, as a deposit of rhythmic alternation of lime mudstone /marls and massive shelf sandstone.

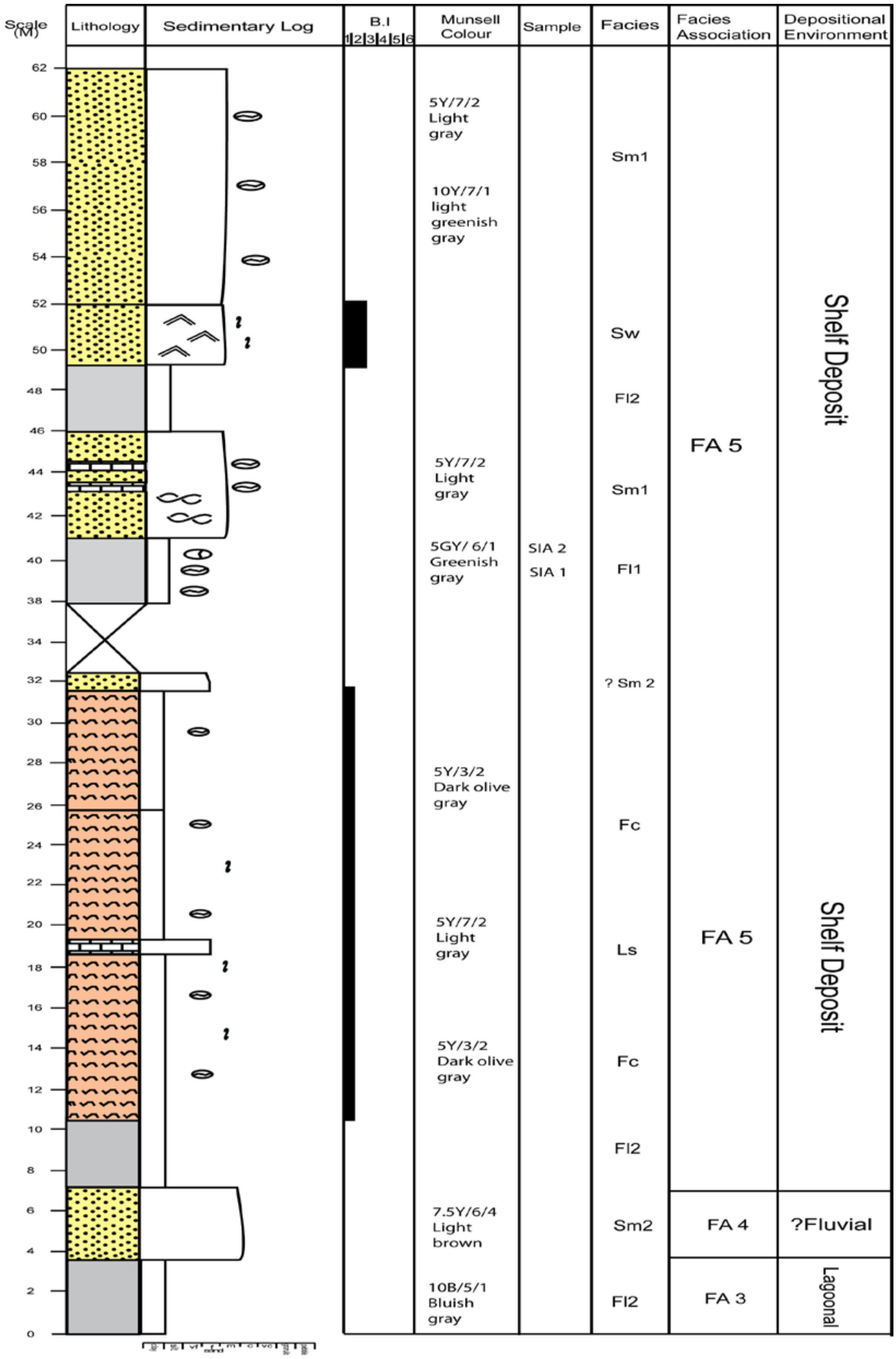


Figure 4.17. Lithostratigraphic composite log profile of Ameke-Abam Section

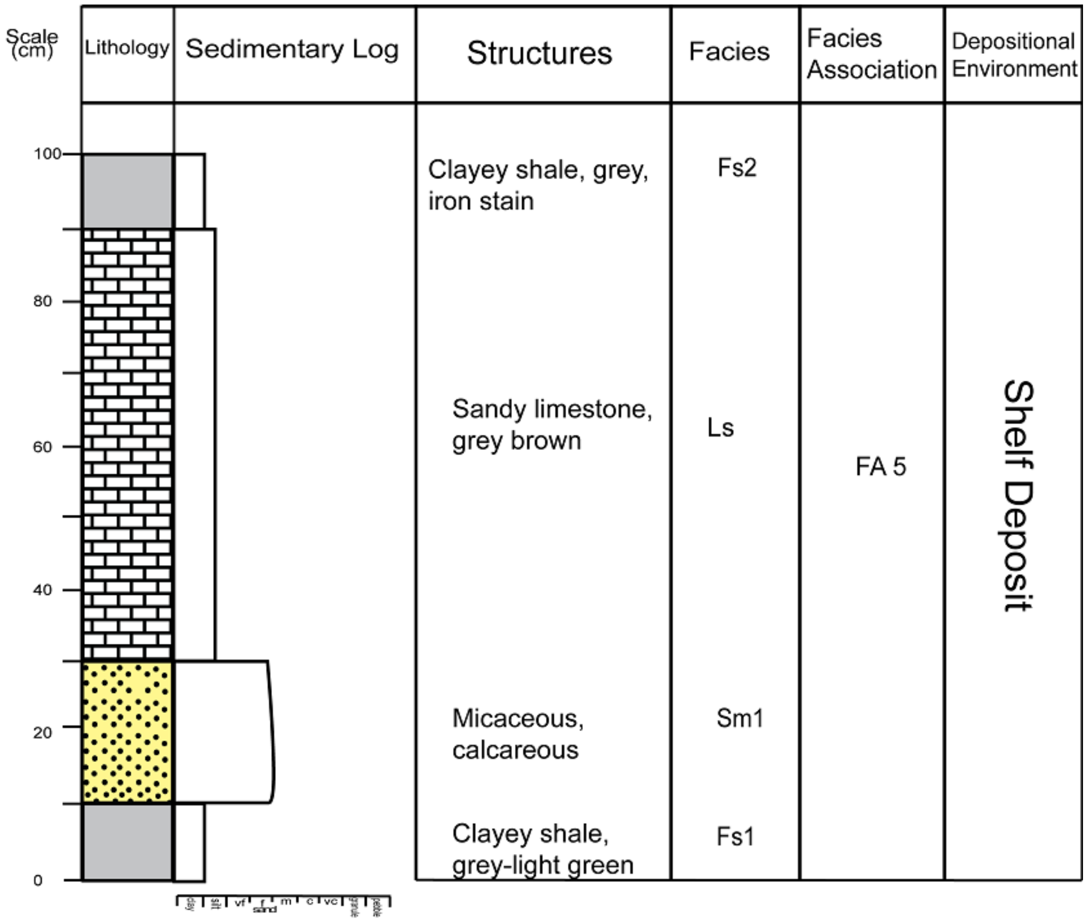


Figure 4.18. Lithostratigraphic log profile of Umuawulu (reviewed outcrop) (redrawn and modified after Arua, 1980).

4.3.2 Clay Mineralogy

Introduction

Mudrock samples from the Imo Formation (Figure 4.19), obtained from the lower (Ebenebe section (SEB-1), and Ndi Ojugwo Abam (SNA-2)), medial (Idoyi-Abam (SAA-4)) and upper part of the formation (Idima Abam (SIA-2), Umuawulu (SUU-1)) were characterised by a high to moderate content of nontronites-15Å, illite, palygorskite and kaolinite (Table 4.1). Non-clay minerals present in high proportion are quartz and microcline. Other minerals such as k-feldspar, calcite, pyrite and stilbite were detected in traces (Appendix B4.4 A-F). Sample (SEBC1) was analysed again to confirm the presence of smectite clay. Glycol was added to the sample and warmed. Blue is original trace while black is with glycol. The peak at around 6° shifts to 5° - this is a clear example of expansion of the lattice and is characteristic of smectite clays.

Nontronites are Fe^{3+}-rich smectites (dioctahedral swelling clays) and are associated with the weathering of basalt and volcaniclastic sedimentary rocks (Sudo and Shimoda, 1978; Ehrmann et al., 1992). They are also known to occur as authigenic clay minerals in recent submarine sediments (Deer et al., 1992) and can be derived from volcanism, hydrothermal activity or diagenetic processes (Hillier, 1995). Smectites are found in marine regions where volcanic activity is high and sedimentation rates and input of terrigenous material are low (Ehrmann et al., 1992). Illite is also common in marine sediments and is derived from more acidic rocks. High concentrations of kaolinite are common in temperate and tropical regions where intense chemical weathering of granitic source rocks and lateritic soil formation occur (Ehrmann, 1998). Palygorskite is a magnesium-rich clay mineral common in arid, semi-arid or evaporitic environments (Velde, 1985). It usually occurs in association with carbonate or dolomite (Sudo and Shimoda, 1978) and it can be found in wide range of environments (marine, lacustrine sediments, soils, paleosols and calcretes), but rarely in large amounts (Deer et al., 1992).

Results

The results (Table 4.1) show a gradual change in clay mineral type and composition in the sediments of the Imo Formation from the lower to upper member of the Imo Formation. The principal clay minerals present in the lower Imo Formation are nontronite, kaolinite, illite and palygorskite. Palygorskite occurs in relatively high concentration in shales found in the Umuahia axis. Kaolinite concentration is highest (more than 38.5%) in the sediments of the lower Imo Formation, the concentrations of nontronite-15A and illite are also relatively high (more than 21.6%), whereas the concentration of palygorskite is lowest (4.5%). In the upper Imo Formation, kaolinite and illite concentration are relatively high (within the range of 16.9% and 37.6%), whereas nontronite and palygorskite show moderately high concentration, within the range of 6.4% to 18.6%. Steady increase is observed in the proportion of illite from the lower to the upper Imo Formation, whereas a decrease in nontronite concentration is observed from the lower to the upper Imo Formation. The concentration of palygorskite is highest in the upper Imo Formation. Results of the middle Imo Formation show slight changes in the content of the clay minerals. The concentration of kaolinite and illite is very high (28.1% to 50.3%) from samples of the middle Imo Formation, whereas that of nontronite and palygorskite is very low (1.4% to 1.6%). Table 4.1 shows the distribution of clay minerals in the Imo Formation. Non-clay microcline has a relative high concentration of 11.8%.

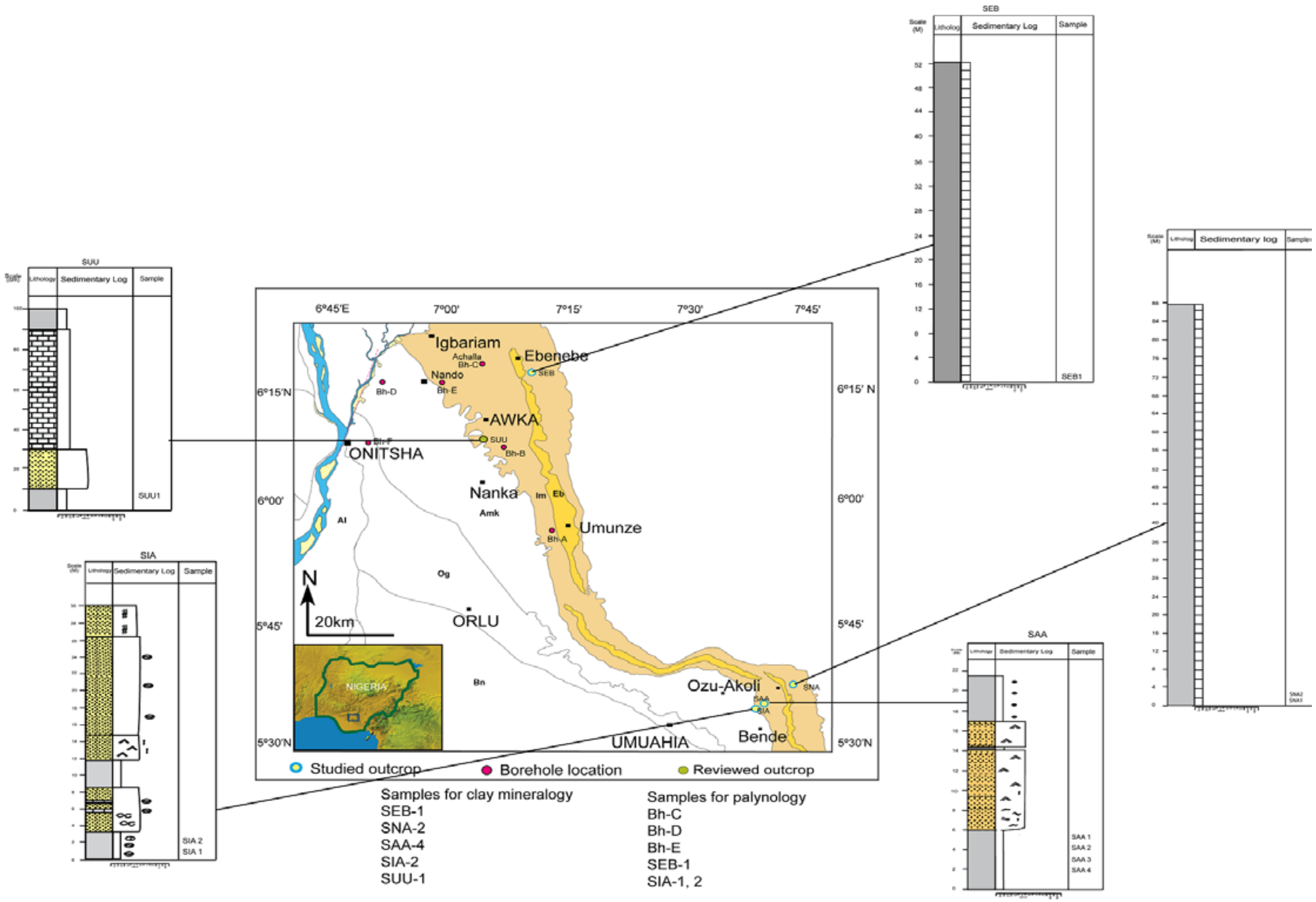


Figure 4.19. Outcrop location of selected samples from Imo Formation for clay mineralogy and palynologic analysis

Table 4.1. Rietveld quantification of the analysed whole rock showing the clay minerals in percentage.

Formation	**Lower Imo Shale**		**Medial**	**Upper Imo Formation**	
Sample no	**SEBC-1**	**SNA-2**	**SAA-4**	**SIA-2**	**SUU-1**
Nontronite-15 A	17.3	21.6	1.6	11.2	18.6
Kaolinite	65	38.5	50.3	33	34.1
Illite	2.1	17.4	28.1	37.6	16.9
Palygorskite	0	4.5	1.4	6.4	15
Goethite	0	0	0	0	0
Chlorite	0	0	0	0	0
Quartz 2%	14.3	11	5	3.1	5.2
Microcline	0	5.8	11.8	5.3	8.7
Orthoclase	0	0	0	0	0
Albite	0	0	0	0	0
Calcite 1%	0.1	0.1	0.3	0.3	1
Gypsum	0	0	0.1	0	0.2
Rutile	0	0	0	0	0
Graphite	0	0	0	0	0
Pyrite	0.4	0	0.1	3.3	0
Stilbite	0	1	1.3	0	0.1
Siderite	0	0	0	0	0
Anatase	0	0	0	0	0

Clay Minerals   Non-clay Minerals

Interpretation

The high occurrence of kaolinite in the analysed samples implies that continental clay minerals were transported to the ocean (Aoki and Kohyama, 1991) during deposition of the Imo Formation. Kaolinite has also been noted by Agumanu and Enu (1990) as the most abundant clay mineral in the pre-Cenomanian and post-Santonian sediments. They suggested that the pre-Albian and Santonian tectonic movements could have rejuvenated the source-land resulting to high supply of kaolinite rich sediments. This implies that high content of kaolinite in the upper Cretaceous sediments may have resulted to the increase of kaolinite content in the Paleogene sediments. Kaolinite is unstable in marine environment, because of the presence of K^+ and Mg^{2+} and easily absorbs these ions to transform to illite and/or Mg rich chloride (Agumanu and Enu, 1990); this probably account for the high content of illite in shallow marine sediments of the study area.

The occurrence of nontronite in the Imo Formation is possibly due to authigenesis within the basin, at the water/sediment interface during early diagenesis under very low sedimentation rates (Thiry, 2000). Aoki and Kohyama (1991), from their studies on clay mineral composition and chemical characteristics of smectite from sediment cores in the southern part of the Central Pacific Basin, also suggested that nontronite (Fe-smectite) are formed authigenically in submarine environment. Notably, palygorskite is common in the fossiliferous rich shales in the upper Imo Formation (Table 4.1). Velde (1985) demonstrated that the reactions of supersaturated marine solutions with aluminous silicate results in palygorskite.

4.3.3 Palynological assemblages in the Imo Formation

Introduction

The quantitative distribution of the palynomorphs encountered in both borehole and outcrop samples of the Imo Formation (Figure 4.19) are tabulated in appendix B4.5 and B4.6. They are further summarised into average percentage valves as shown in Table 4.2. Moderate to low counts of freshwater algal cysts, spores, structured/unstructured phytoclasts and flowering plant pollen occur in the borehole whereas very low counts are observed in the outcrop samples. Dinoflagellates, acritarchs and foraminiferal linings vary from zero to moderate amounts. The composition and distribution of the palynomorphs in the sediment are interpreted following Batten (1996) and Quattrocchio et al., (2006). This has resulted in the identification of four assemblage types for the Imo Formation.

Table 4.2. Summary of the counted components of the palynological assemblages in the Imo Formation.

Sample	Borehole sample		Outcrop sample	
Member	Lower Sst. Member	Middle Sst. Member	Lower Sst. Member	Upper Sst. Member
Sample No	Achalla	Nando/ Umuleri	Ebenebe	SIA
Assemblage	1	2	3	4
Pollen and spores	23-34%	42-70%	Barren	28-38%
Freshwater algal cysts	16-32%	14-31%	Low count	10-21%
Dinoflagellates	2-12%	<4%	Barren	10-21%
Acritarchs	2-10%	<3%	Barren	<5%
Forminiferal linings	1-5%	Barren	Barren	3-5%
Fungal	5-10%	3-7%	Low count	<14%
Phytoclasts (structured, unstructured and resin)	15-26%	10-20%	Low-moderate count	17-28%
AOM	low	low	low	abundant
Pyrite	common	low	low/common	abundant

Sst-Sandstone

Result and Interpretation

Assemblage type 1

The type 1 assemblage is present in Achalla borehole samples (Bh-C) of the mudrocks in the lower Sandstone Member of the Imo Formation. It is typified by the presence of amorphous organic matter (AOM), debris, cuticles and palynomorphs (Figures 4.20A-K). Pollen and spores vary from approximately 33% - 42%; freshwater algal cysts 34% - 37%; dinoflagellate cysts and acritarchs 13%; foramineral linings 1% - 4%; and fungal remains 8% - 10%.

The presence of pollen, spores and freshwater algae suggests terrestrial input and the occurrence of acritarchs and dinoflagellates, which are marine phytoplankton, indicate a marine influence (Oboh-Ikuenobe et al., 2005; Raymer, 2010). Foraminiferal test linings are good indicators of marine coastal and shallow shelf conditions (Ibrahim, 2002; Quattrocchio et al., 2006). A shallow marine environment is thus suggested for sediments containing assemblage type 1.

Assemblage type 2

The assemblage type 2 occurs in the Umuleri and Nando borehole samples (Bh-D, Bh-E) in the middle Sandstone Member of the Imo Formation. It is typified by palynomorphs, abundant debris and cuticles (Figure 4.21A-K; 4.23B,C); pyrite is common (Figure 4.23D). The palynomorphs are dominated by pollen, spores (50%-70%) and freshwater algal cysts (15%-40%). Foraminiferal test linings were not observed and very low counts of dinoflagellate cysts and acritarchs (0–5%) were encountered (Appendix B4.5; Table 4.2).

The abundance of spores, pollen and algal cysts suggest high influence from terrestrial with some marine input indicated by the presence of pyrite and dinoflagellates.

Sediments containing this palynofacies have been described as deposits of foreshore-shoreface environment.

Assemblage type 3

Ebenebe outcrop samples (Table 4.2) are almost barren of palynomorphs, but contain remnants of amorphous organic matter (Figure 4.22A, B). This could result from biodegradation by microbial activity, oxidation or weathering of outcrop samples.

Assemblage type 4

The outcrop samples SIA-1, 2 (Appendix B4.6) characterise the upper Sandstone Member of the Imo Formation and typically contain debris, amorphous organic matter and pyrite (Figure 4.23E-F). Palynomorph counts are generally moderate with minimal diversity. Spores, pollen, freshwater algal cysts, dinoflagellates, acritarchs and foraminiferal linings are present.

The presence of dinoflagellates and pyrite may suggest low energy, partially anoxic marine condition (Quattrocchio et al., 2006). Pyrite is usually associated with anoxic bottom-water conditions, where available iron minerals are converted to pyrite (Tyson, 1995). The abundant AOM can be formed as a result of degradation of organic materials such as algal remains (Oboh-Ikuenobe et al., 2005) and is likely in a marine realm due to large numbers of phytoplankton. Abundant AOM and dinoflagellate indicate marine condition. Sediments of type 4 palynofacies are considered to be deposited in a shelf environment.

Conclusions

Four palynological assemblages (1-4) encountered in borehole and outcrop samples were established for the Imo Formation. Assemblage 1 characterises the lower Sandstone Member of the Imo Formation and it has the highest counts of identifiable palynomorphs; the occurrence of dinoflagellates, acritarchs cysts and foraminiferal linings suggest most probably shallow marine conditions. The presence of fresh water algal cysts, pollen and spores indicate terrestrial influence on the shallow marine environment. Assemblage 2 occurs in the middle Sandstone Member of the Imo Formation. It is characterised by mixed terrestrial and inner neritic or nearshore marine condition. Paucity or low counts of palynomorphs in outcrop samples such as the Ebenebe samples of assemblage 3 could be as a result of weathering or oxidation. Biodegradation by microbial activity reduces palynomorphs count especially in shales deposited in marine environment. Assemblage 4 consists of moderate palynomorphs counts, with very high AOM and pyrite counts, which signifies a shallow marine environment. The occurrence and distribution of palynomorphs, phytoclasts, AOM and pyrite are consistent with the interpretation of the depositional facies in the study area.

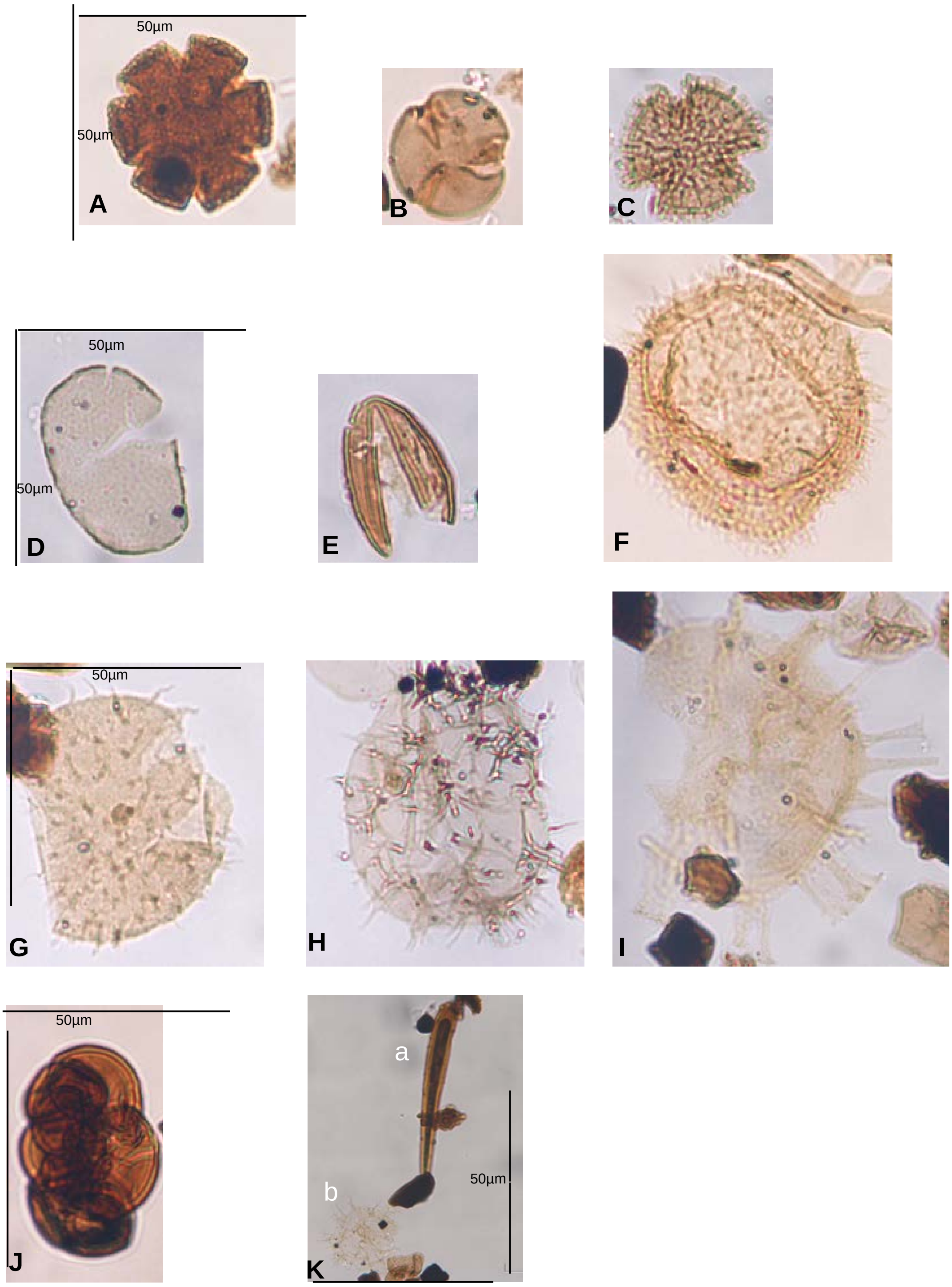


Figure 4.20. Palynomorphs from Achalla (borehole) samples (130-160), assemblage 1 (lower member of the Imo Formation). A. Reticulate hexacolpate pollen J36/1,3. B. Trizonocolpate pollen N35/1. C. Trizonocolpate pollen W36. D. Fresh water algae type-1 W36/4. E. Fresh water algae type-3 P36/4. F. Acritarch type-1 M35/1. G. Dinoflagellate type-1. H. Dinoflagellate type-1. I.Dinoflagellate type-2 W37. J. Foraminiferal lining. K. (a) Fungal remain; (b) Dinoflagellate type-1 X32/3.

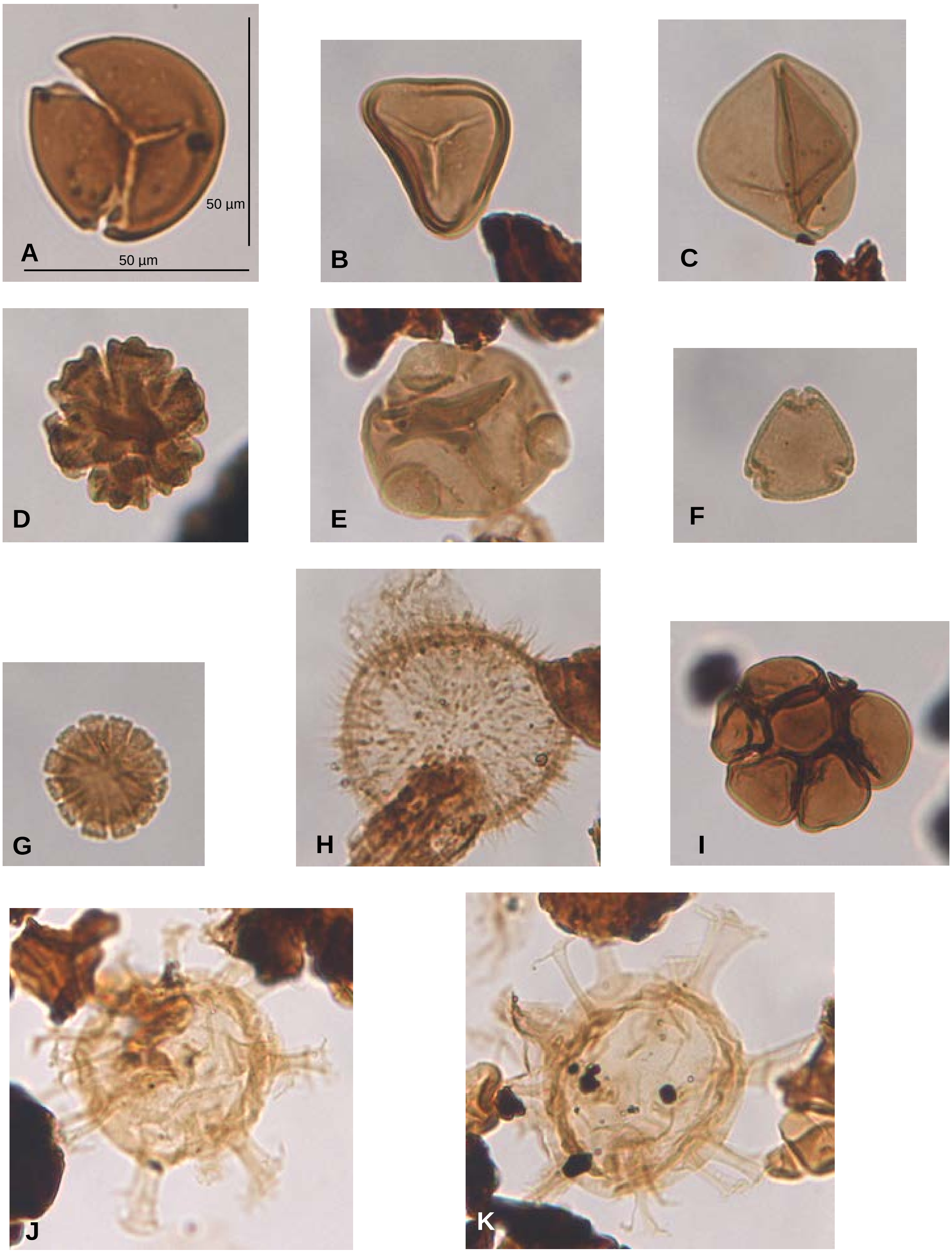

50 µm
A
50 µm
B
C
D
E
F
G
H
I
J
K

Figure 4.21. Palynomorphs from assemblage 2 (lower member of the Imo Formation). A. Trilete spore R34/4 Umuleri samples (230-260ft). B. Trilete spore U28 Umuleri samples (260-280ft). C. Trilete spore D35/2 Umuleri samples (230-260ft). D. Hexacolpate C35/4 Umuleri samples (230-260ft). E. Triporate pollen U37/4 Umuleri sample (260-280ft). F. Triporate pollen N31 Umuleri samples (230-260ft). G. Polyzonocolpate T38 Nando samples (190-220ft). H. ? Acritarch type 1 R31/3 Nando samples (190-220ft). I. Foraminiferal lining F29 Umuleri samples (230-260ft). J. Dinoflagellate type-1 M25 Nando samples (190-220ft). K. Dinoflagellate type-1 R40/3 Nando samples (190-220ft). Scale bar applies to all images.

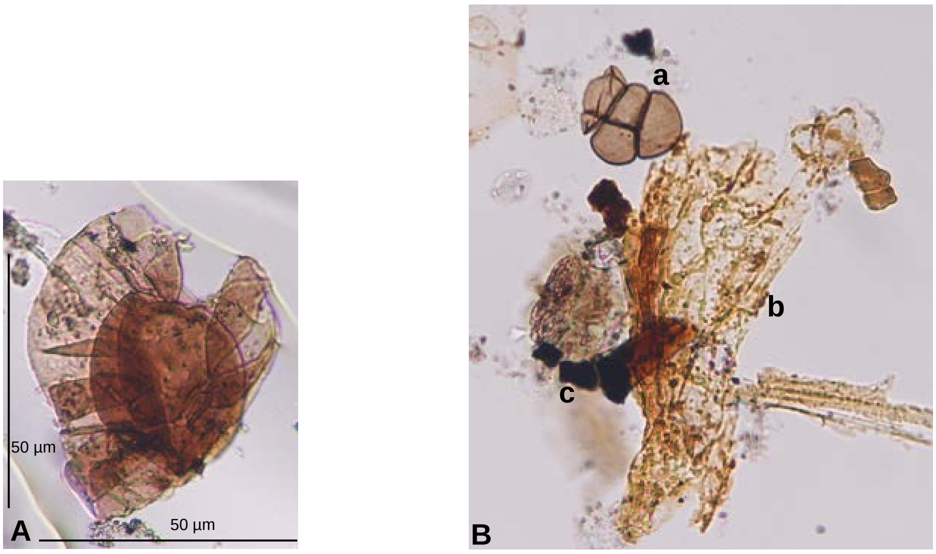
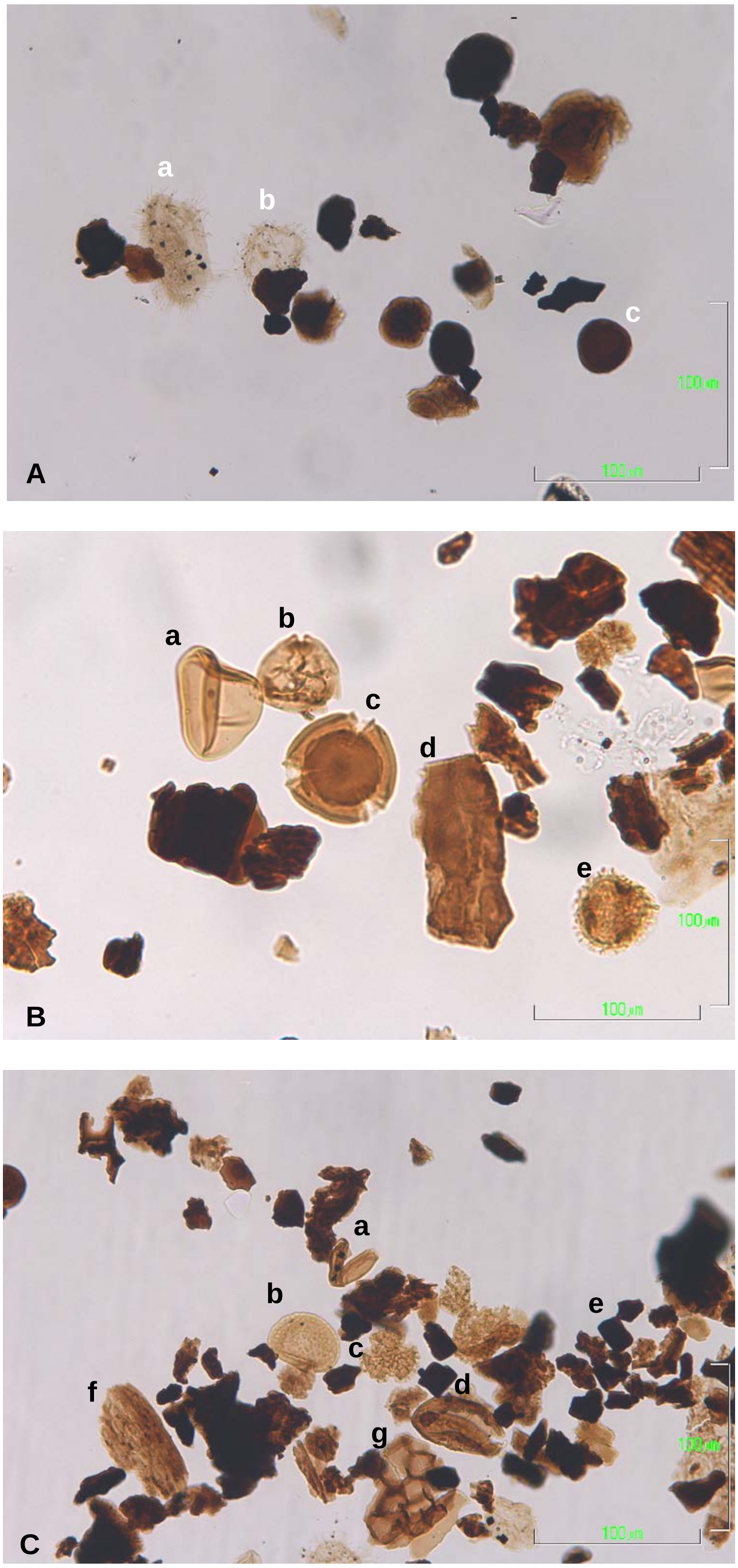
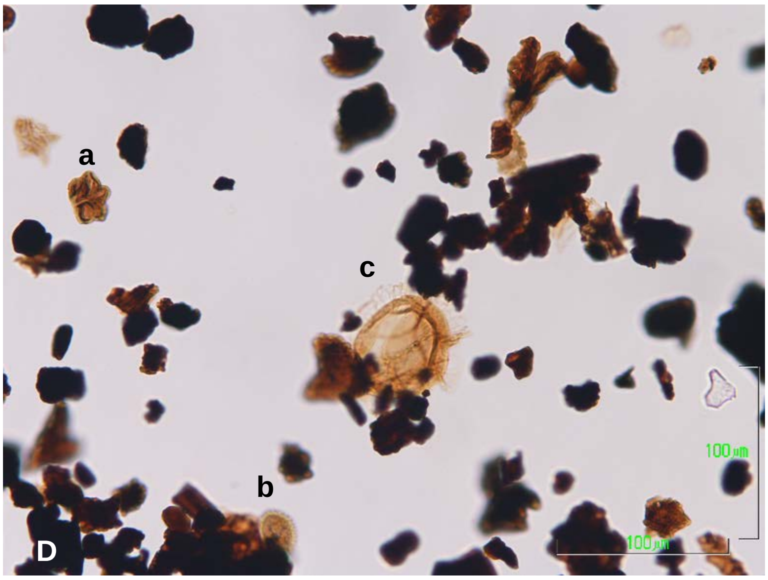
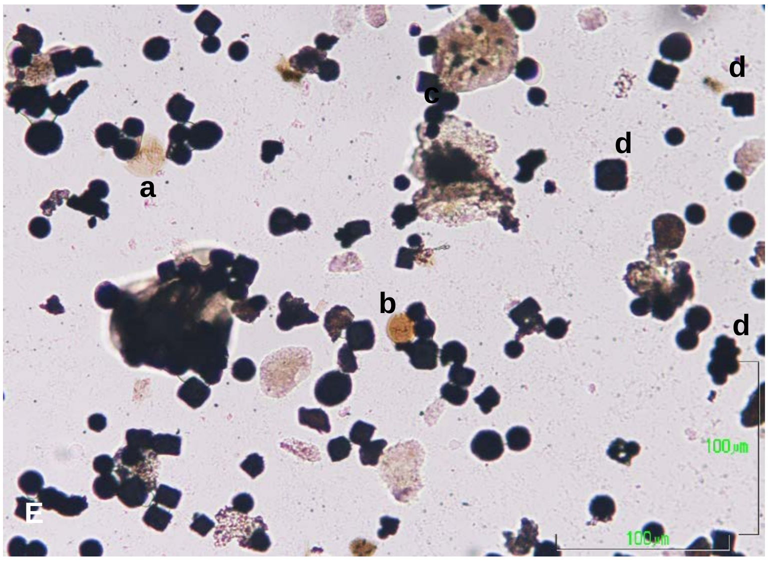


Figure 4.22. Palynomorphs from Ebenebe outcrop samples, assemblage 3 (lower Sandstone Member of the Imo Formation). A. ?Pollen. B. (a) Fungal (b) phytoclasts (c) pyrites.


a
b
c
100 μm
100 μm
A
a
b
c
d
e
100 μm
100 μm
B
a
b
c
d
e
f
g
100 μm
100 μm
C


a
c
b
D
100µm
100µm


d
c
d
a
b
d
E
100µm
100µm

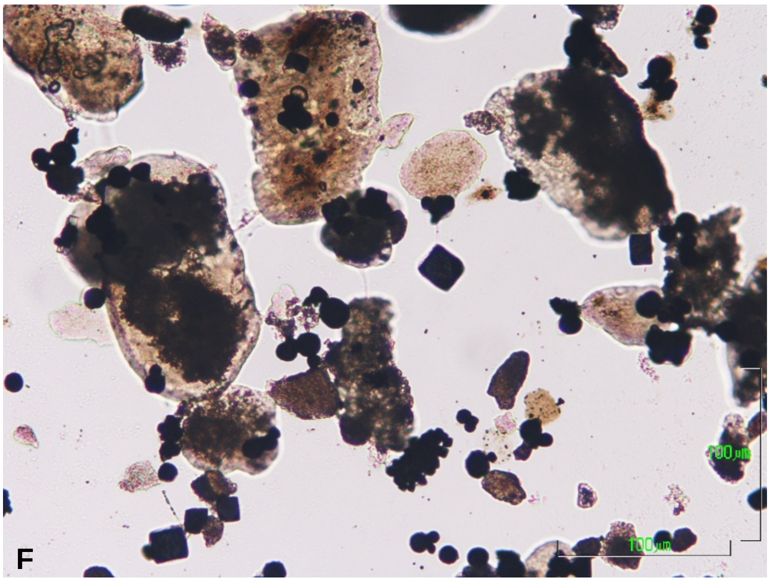


Figure 4.23. Content of the palynological assemblage types found in the Imo Formation. A. (a) Acritarch, (b) pollen, (c) resin. Achalla samples 130-160ft: assemblage 1.

B. (a) Trilete spore, (b-c) pollen, (d) unstructured phytoclast (e) pollen. Nando samples 110-150ft: assemblage 2.

C. (a) FW alga type-3, (b) FW alga type-1, (c) pollen (d) FW alga type-3, (e) pyrite, (f) phytoclast, (g) cuticle. Nando samples 110-150ft: assemblage 2.

D.(a-b) Palynomorphs, (c) dinoflagellate-type 1 with debris and pyrites. Umuleri samples 200-230ft: assemblage 2.

E. (a-b) Palynomorphs, (c) AOM, (d) pyrite (SIA 2 sample: assemblage 4).

F. Abundant pyrites and aggregated AOM (SIA 2 sample: assemblage 4).

4.4 DISCUSSION

The Imo Formation preserves a range of outcrops with structures that reflect the spatial distribution of sediments influenced by tide, waves and storm processes. In this section, simple conceptual models are proposed for the depositional environment and the stratigraphic and paleogeographic evolution of the study area.

4.4.1 Environmental Reconstruction

The facies interpretation presents evidence that sediments of the Imo Formation display a shelf to shoreface (shallow marine) depositional setting. The basal bluish to dark grey shale of the Imo Formation with a high organic content suggests a marine incursion which led to a major Paleocene transgression (Figure 4.24A). Evidence of a shelf environment is documented by the abundance of dinoflagellate cysts, acritarchs, pyrite and amorphous organic material (AOM) as observed from the palynological studies and other authors such as Oboh-Ikuenobe et al., (2005) and Raymer (2010), whereas the high proportion of phytoclasts suggest a terrestrial influx.

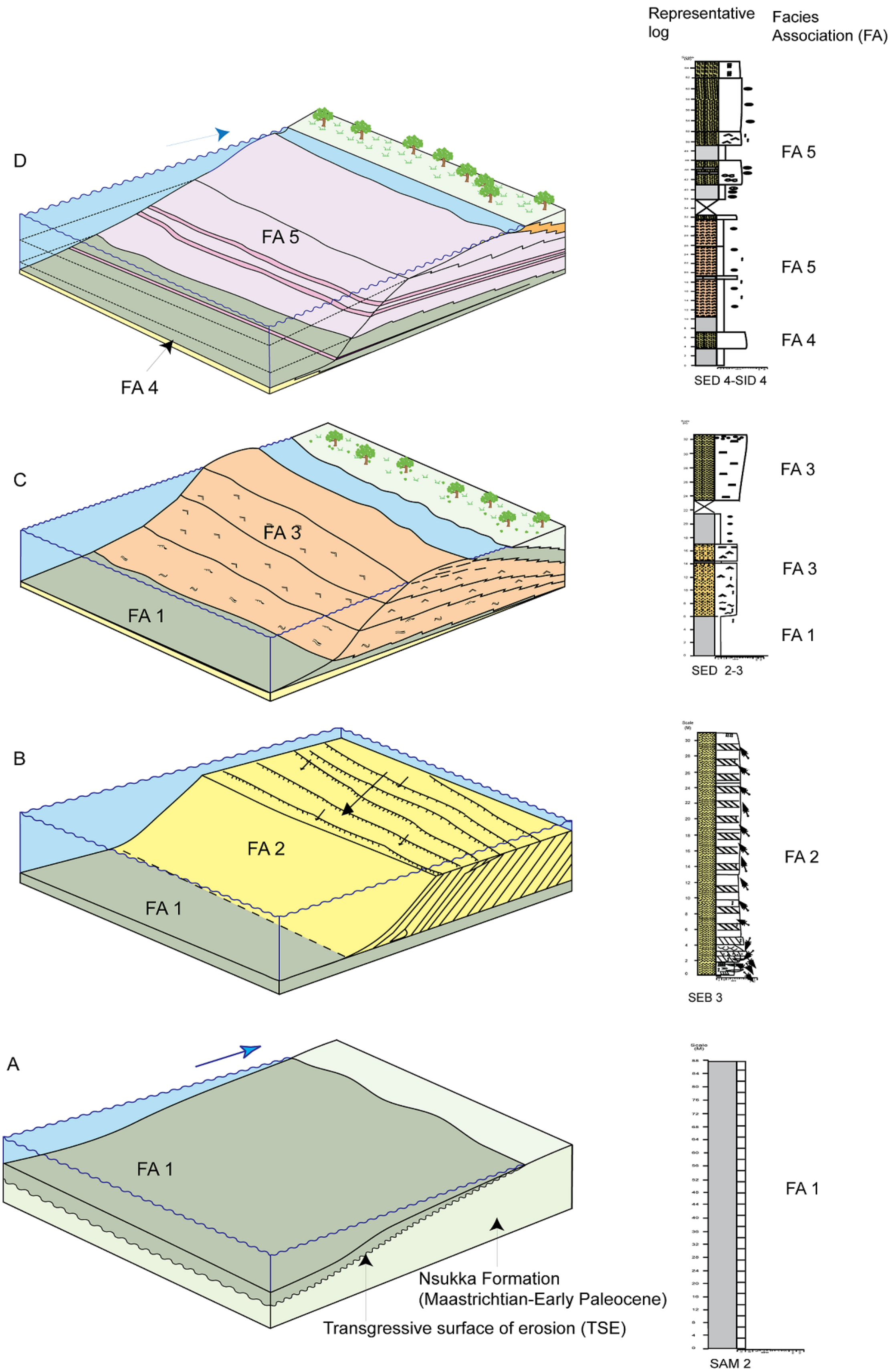
The terrestrial influence may have resulted in the deposition of the lens-shaped sand bodies interpreted as tidal sandwaves that occur in the shelf or proximal offshore environment. These sand bodies may have been formed when the relic of the fluvio-deltaic sands of the older sediments (Nsukka Formation) where eroded and reworked by strong tidal current during the subsequent sea-level rise. The sandwaves in the Imo Formation occur as three major sand bodies (Figure 4.24B), commonly referred to as the Ebenebe, Umuna and Igbaku sandstone members. These arenitic sand bodies (FA2) are characterised by large scale cross beds, with high dip angles of 15° to 40°, small scale herringbone structure, climbing ripples and counter ripples. The exposed sandstone bodies range from 15 to 25 metres thick. The dominance of unimodal paleocurrents suggests a significant unidirectional movement for the tidal current (Figure 4.24B). A drastic decrease in clastic input and tidal energy is evident with the occurrence of *Thalassinoides horizontalis* box-work burrows observed at the topmost part of the sandstone body (Figure 4.5). The slow clastic input led to the deposition of dark grey shale which seals the sandstone bodies.

Nichols (2009) documented types of tidal deposits in shallow marine environments and noted that sandwaves are formed at low to moderate tidal current velocities (50 to 100 cm s^{-1}. The migration of these sandwaves in the direction of predominant tidal direction generates a unidirectional cross-stratification that may be many metres thick and the sand bodies are lens-shaped. Tidal current on the shelf tend to follow regular patterns (rotary tides) that do not undergo the direct reversal seen in estuarine setting (Nichols, 2009).

Such large scale cross-stratified sandstone is also common in the delta front (foreset) of a Gilbert-type delta. Although the delta front sediments grades into finer grained sediments of prodelta, it is overlain by very coarse grains to gravels deposited by braided rivers (the delta top). This is not so for the sandstone bodies of the Imo Formation, as they are encased by shallow marine mudrocks, which confirms a tidal sandwave for lower Sandstone Member of the Imo Formation.

The effect of waves and storm is evident in the sediments of the middle part of the Imo Formation. The succession commences with a basal mudstone, followed by a well sorted, bioturbated, fine grained sandstone that denotes storm and post-storm events that form the proximal offshore environment. The preponderance of waves over storm processes is evident in the deposition of over 13 metres thick well sorted, wave rippled laminated sandstone. A backshore lagoonal fossiliferous mudstone topped the sequence (Figure 4.24C). The wave-ripple laminated sandstone suggests a fair-weather dominated environment.

The siliciclastic shelf (shoreface-offshore) is replaced by a mixed siliciclastic-carbonate shelf (Figure 4.24D). A minor regression probably led to the deposition of massive coarse to medium grained sandstone. The siliciclastic-carbonate deposits are restricted to the Umuahia axis (evident from outcrops) and part of the Ebenebe-Awka axis (based on borehole data). Increase in sea-level led to slow sedimentation rates but was punctuated by episodic storm event resulting in the deposition of black shale and bioturbated sandstone. This is thus typical of a shelf setting. Continuous slow sedimentation of clastics, shoaling and warming of the sea water probably increase deposition of marl and limestone (Dill et al., 1997) in the basin. The precipitation of carbonate in the basin was induced when the sea water became more alkaline. Progressive shoaling or coarsening-upward is represented by the presence of fossiliferous shale and calcareous sandstone. Aerobic conditions and possibility the introduction of freshwater resulted in abundant molluscs (bivalves and gastropods), amber, and coquina in the shale (Bermúdez-Rochas, 2009). The presence of black shale with shark teeth, rays and limestone concretions also reflect a marine environment. The occurrence of hummocky-swaley cross stratification and fossiliferous limestone layers, suggests a storm influence. Well sorted calcareous fine grained sandstone with isolated bivalves reflects a winnowing effect of waves.


Representative log
Facies Association (FA)
D
FA 5
FA 4
SED 4-SID 4
FA 5
FA 5
FA 4
C
FA 3
FA 1
SED 2-3
FA 3
FA 3
FA 1
B
FA 2
FA 1
SEB 3
FA 2
A
FA 1
Nsukka Formation
(Maastrichtian-Early Paleocene)
Transgressive surface of erosion (TSE)
SAM 2
FA 1

Legend

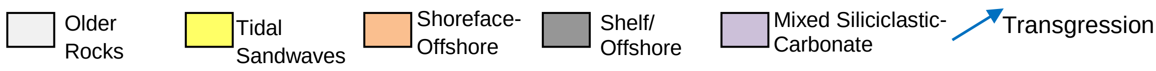


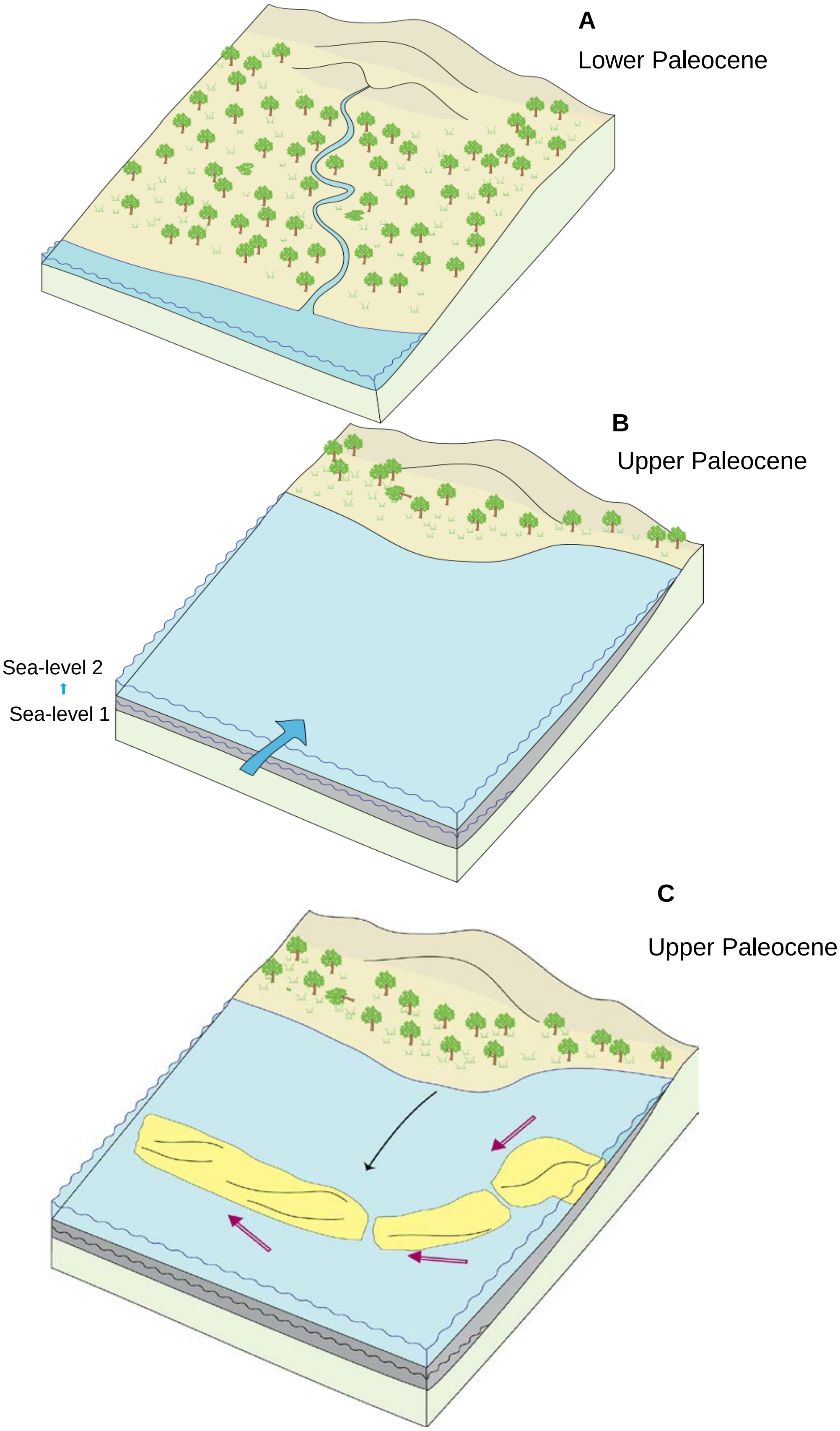
Figure 4.24. Depositional model of the Imo Formation (A) Marine environment is formed with the deposition of bluish shale (upper Imo Formation) during a major transgression in the Late Paleocene. (B) Tidal influence on the sea caused by a unidirectional tidal current resulted to tidal sandwaves in an offshore environment. (C) The preponderance of waves over tides led to the deposition of coarsening-upward succession characterised by wave-rippled laminated sandstone and horizontally bedded, medium to pebbly sandstone. A lagoonal deposit occurs at the backshore. (D) A return to transgression is obvious with the deposition of mixed siliciclastic–carbonate sediments in a shelf setting, which probably occurred during the early Eocene. Sedimentation is influenced by storm and wave processes.

4.4.2 Stratigraphic evolution of the Imo Formation

During the Paleogene, the sea-level changes, sediment supply and probably the basin bathymetry may have been the major controlling factors in the development of the sedimentary succession of the Imo Formation. A major Paleocene transgression resulted in sea-level rise (sea-level 1 to sea-level 2) and a landward shift in shoreline resulting in the marine conditions of the Imo Formation (Figure 4.25A,B). The marine shale has a sharp contact with the underlying older Nsukka Formation, and the contact marks an amalgamated the transgressive surface of erosion (TSE) and sequence boundary (SB). The contact is recorded as an unconformity (Avbovbo and Ayoola, 1981; Petters, 1991). The contact was observed in the study area along Okigwe-Umuahia express road and it is characterised by sharp contact between the underlying sandstone and overlying shale (Figure 4.26). *Thalassinoides* and *Ophiomorpha* burrows were observed at the topmost unit of the sandstone bed.

The high content of kaolinite and nontronite (Fe-smectite) and the presence of illite in the basal shale in Ebenebe and Abam sections further suggest marine environment with terrestrial influence. The presence and high proportion of nontronite (>17.3%) suggest that sediments were also probably derived from adjacent basement complex rocks of south-western Nigeria (mainly metamorphic rocks-gniesses and schists; others are metaigneous rocks, charnockite and older granite). Subaqueous tidal sandwaves deposited in the proximal shelf setting reflect a preponderance of tidal currents. Outcrops at Mkpa Junction and Akoli-Imenye (Umuna Sandstone) show a dominant south-west trend, while at Ozuitem, Ameke Abam (Igbaku Sandstone) and Ebenebe (Ebenebe Sandstone) the dominant trend is north-west (Figure 4.2A). The dominance of north-west direction implies a regional net sand transport direction (Figure 4.25C). The basal mudstone and the tidal sandwaves represent sediment deposited within the transgressive systems tract, with the maximum flooding surface (MxFS1) occurring with the dark grey shale which seals the sandstone bodies. The emergence of wave process resulted to development of shoreface and foreshore deposits (Figure 4.25D). This progradational succession led to a basinward shift in shoreline and a drop in sea-level (sea-level 2 to sea-level 3). This succession represents the highstand systems tract (HST1).

Backsteping from a progradational to a retrogradational pattern in the uppermost part of Imo Formation is marked by the deposition of a storm and wave-influenced shelf sediments of mixed siliciclastics and carbonates (Figure 4.25E). This transition from siliciclastics succession to mixed siliciclastics-carbonate sequence shows a significant shift from shoaling (progradation) of the shoreline to deepening (retrogradation) and is characterised by low sediment input, increase in accommodation and sea level rise (sea-level 3 to sea-level 4). The occurrence of a coarse to medium grained sandstone suggest, a further drop in sea-level, which probably marked the second sequence boundary (SB2). A flooding surface is noted by the deposition of mudstone which graded to marl and thin limestone beds may suggest a condensed section within a transgressive systems tract (TST2). The coarsening upward unit which commenced with bioturbated wave-rippled sandstone and graded into fossiliferous sandstone probably represents the highstand systems tract (HST2). The highstand sedimentary package terminated the Imo Formation deposition.


A
Lower Paleocene
B
Upper Paleocene
Sea-level 2
Sea-level 1
C
Upper Paleocene

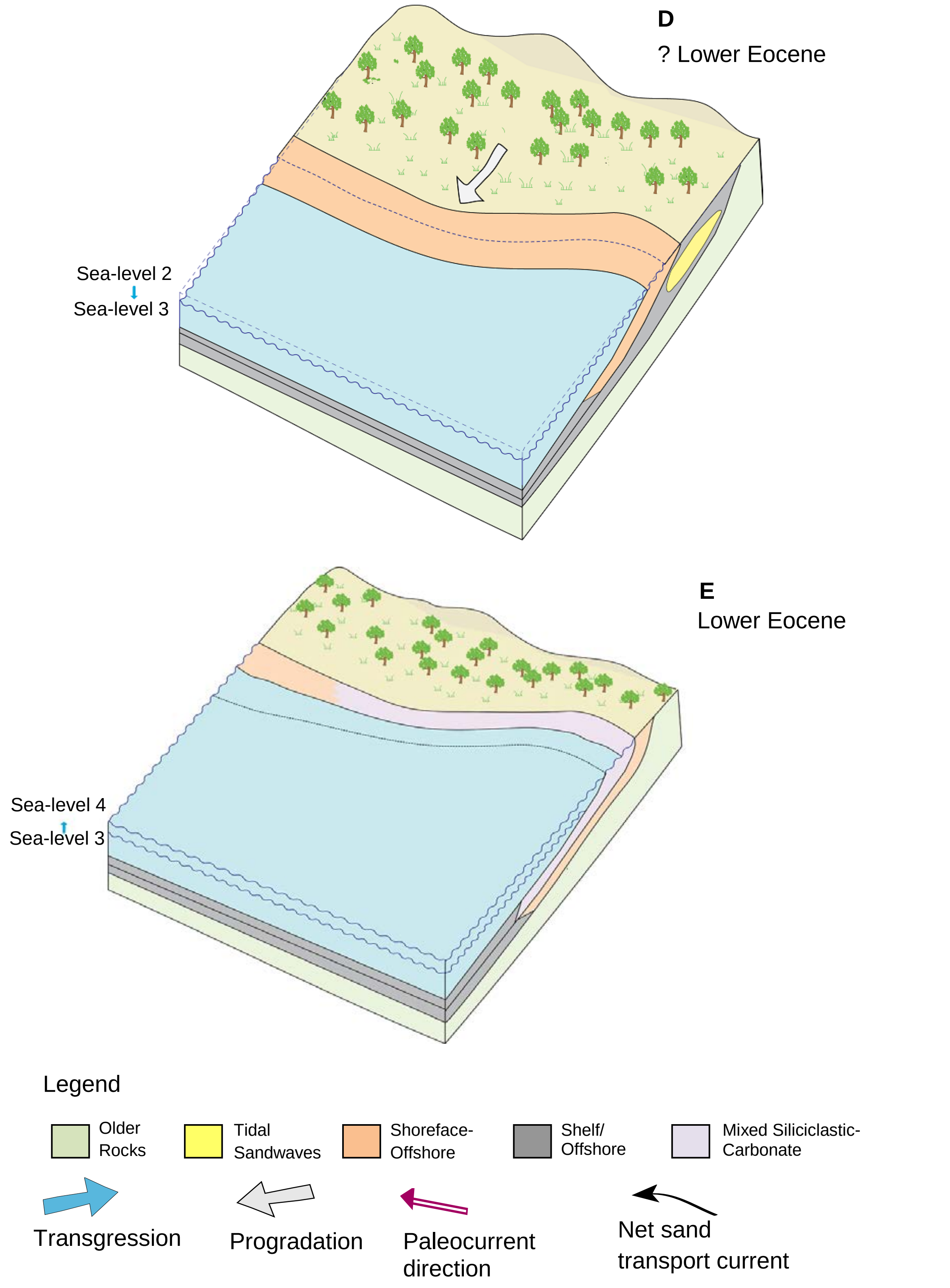

D
? Lower Eocene
Sea-level 2
Sea-level 3
E
Lower Eocene
Sea-level 4
Sea-level 3
Legend
Older Rocks
Tidal Sandwaves
Shoreface-Offshore
Shelf/ Offshore
Mixed Siliciclastic-Carbonate
Transgression
Progradation
Paleocurrent direction
Net sand transport current

Figure 4.25. Paleogeographic reconstruction of the Imo Formation during the Late Paleocene to Early Eocene. (A) Subaerial and minor transgression conditions prevailed during the deposition of the Nsukka Formation in the Maastrichtian to Lower Paleocene. (B) Sea-level rise led to a landward shift in a shoreline and a marine condition in the Imo Formation during the Upper Paleocene, resulting to a transgressive surface of erosion (TSE). (C) Sea-level remained fairly constant as unidirectional tidal current prevailed. (D) Progradation occurred probably during the Lower Eocene resulting to basinward shift in the shoreline and the deposition of shoreface sediments. (E) Renewed sea-level rise on the shelf, accompanied by decrease in siliciclastic input mainly in the eastern part of the study area (Umuahia axis) led to the deposition of mixed siliciclastic-carbonate sediments during the highstand system tracts.

Figure 4.26. Contact (white dotted lines) between Nsukka Formation and Imo Formation as observed along Okigwe-Umuahia express road.

4.5 CONCLUSIONS

Sedimentological studies, especially ichnological evidence, indicate that the Paleocene-Eocene Imo Formation is deposited in a shallow marine environment, influenced by tides, waves and storm processes. The stratigraphic sequence of the Imo Formation suggest periods of transgression with minor regression phases. The first major Paleocene transgression is evident in the deposition of thick shallow marine shales designated as part of the lower Sandstone Member of the Imo Formations. Clay mineral types (kaolinite, illite and nontronite) and palynomorph content suggest terrestrial influence in the shallow marine environment. Following that, there is a dominance in tidal process which resulted in the deposition from tidal sandwaves that formed as lens-shaped sandbodies (outcrops at Ebenebe are laterally extensive (>250 m) and geologic map (Figure 4.2) shows extensive lens-shape sandstone) that were further enclosed by shallow marine shales. The middle Sandstone Member reflects a period of minor progradation that led to a basinward shift in shoreline and development of shoreface and foreshore deposits. A predominance of waves prevailed with the deposition of wave-rippled laminated sandstone (shoreface deposit) during fair-weather conditions. The upper Sandstone Member reflects renewed transgression and the influence of both storm and waves that resulted in the deposition of mixed siliciclastic-carbonate sediments. The increasing proportion of palygorskite suggests the presence of carbonate sediments.

Two complete stratigraphic sequences were observed in the study area and are more pronounced in the Umuahia axis. The first sequence started with an initial shallow marine shale deposit which coincides with the transgressive surface of erosion (TSE) and sequence boundary (SB). The tidal sand bar was deposited during the transgressive systems tract, with the overlying shallow marine shale corresponding with the maximum flooding surface. The progradational shoreface corresponds to the highstand systems tracts. The second sequence commenced with probably a minor fluvial deposit, followed by a flooding surface is noted at the deposition of mudstone which graded to marl and thin limestone beds may suggest a condensed section within a transgressive systems tract (TST2). The coarsening upward siliciclastics-carbonate sediments probably represent the highstand systems tract (HST2). The changes in depositional environments suggest variation in sediments input, prevailing sedimentary processes and sea-level changes. The proposed depositional and paleogeographic models of the Imo Formation therefore document the evolution of the formation through time.

CHAPTER FIVE

TIDE DOMINATED ESTUARINE SYSTEM OF THE EOCENE AMEKI GROUP

SUMMARY

The Eocene siliciclastic sedimentary facies of the Ameki Group in the south-eastern Nigeria provide a record of the sedimentary response to an initial regression, followed by marine incursion into the Niger Delta basin. Detailed studies of several well-exposed sections of the Eocene Ameki Group within an outcrop area of over 1,800 km^2 show that deposition took place in a setting that was varying from coastal to shallow marine. This research indicates a tidally influenced estuarine system for the Ameki Group based on detailed sedimentological and ichnological studies. Seven facies associations (FA1 to FA7) are documented in the study area and the sediments are interpreted as fluvial channel, tidally influenced fluvial channel, tidal channel, tidal flats, supratidal, tidal sand bar and estuarine embayment deposits. Tidal depositional cycles which include semi-diurnal tidal rhythmites are recognised in tidal bundles, millimetre-centimetre scale heterolithic units whereas the occurrence of decimetre-metre scale cyclicity may indicate seasonal depositional cycles. The tidal deposits are associated with ichnofaunal assemblages of *Scoyenia*, *Skolithos, Cruziana,* mixed *Skolithos-Cruziana, Glossifungites*, *Psilonichnus* and *Teredolites* ichnofacies that show variation in intensity and diversity. A complete type-1 depositional sequence is encountered in the Ameki Group which consists of the lowstand-, transgressive- and highstand-systems tracts and transgressive surfaces. The depositional architecture of the Eocene Ameki Group was most probably controlled by relative sea-level changes, sediment supply, accommodation and regional tectonics consequent upon the location of the Niger Delta at the trailing edge of a continental plate.

5.1 INTRODUCTION

The Ameki Group consist of three formations which include the Nsugbe Formation (commonly referred to as Nsugbe Sandstone), the Nanka Formation (commonly referred to known as Nanka Sandstone) and the Ibeku Formation (formerly known as the Ameki Formation). The Ibeku Formation was first interpreted as an estuarine environment (White, 1926) based on faunal content. Arua (1986), Mode (2002) and Oboh-Ikuenobe et al., (2005) also suggested barrier ridge-lagoon complexes, open marine conditions and a wave dominated estuarine setting respectively for the Ibeku Formation. Nwajide (1980) suggested that the Nanka Formation may have been deposited in a tidally influenced marine shoreline environment. Less attention was given to the Nsugbe Formation.

The Ameki Group has been interpreted as a tide dominated estuarine complex in this research based on the criteria put forward by Darlymple (1992), also Kitazawa (2007) who distinguished a tide-dominated estuarine environment from a wave-dominated setting. The distinguishing factors are (a) the development of tidal sand bars and upper-flow regime sand flats instead of barrier and shoreface deposits, (b) the development of tidal meander deposits and salt marsh facies as opposed central basin deposits, (c) the absence of deposits representing a bay-head delta, and (d) a ravinement surface considered to have been formed by tidal currents instead of by waves (Dalrymple, 1992; Kitazawa, 2007). Similar characteristics of macrotidal tide dominated estuarine systems have been documented in research studies on both ancient and modern estuaries worldwide (Dalrymple et al., 1990; Dalrymple and Choi, 2007; Plink-Björklund, 2005; Pontén and Plink-Björklund, 2009; Yeo and Risk, 1981; Tessier et al., 2011).

The aims of this research are (i) to describe the sedimentological, clay mineralogy, palynological and ichnological characteristics of the Ameki Group, in order to refine the interpretation of the depositional system. (ii) to assess the key stratigraphic surfaces and the sedimentary packages within the sequence stratigraphic framework and establish the stratigraphic evolution of the Ameki Group, and (iii) to characterise the sandstone geometry, its spatial distribution, continuity in order to delineate the facies architecture and document reservoir heterogeneity.

5.2 METHODOLOGY

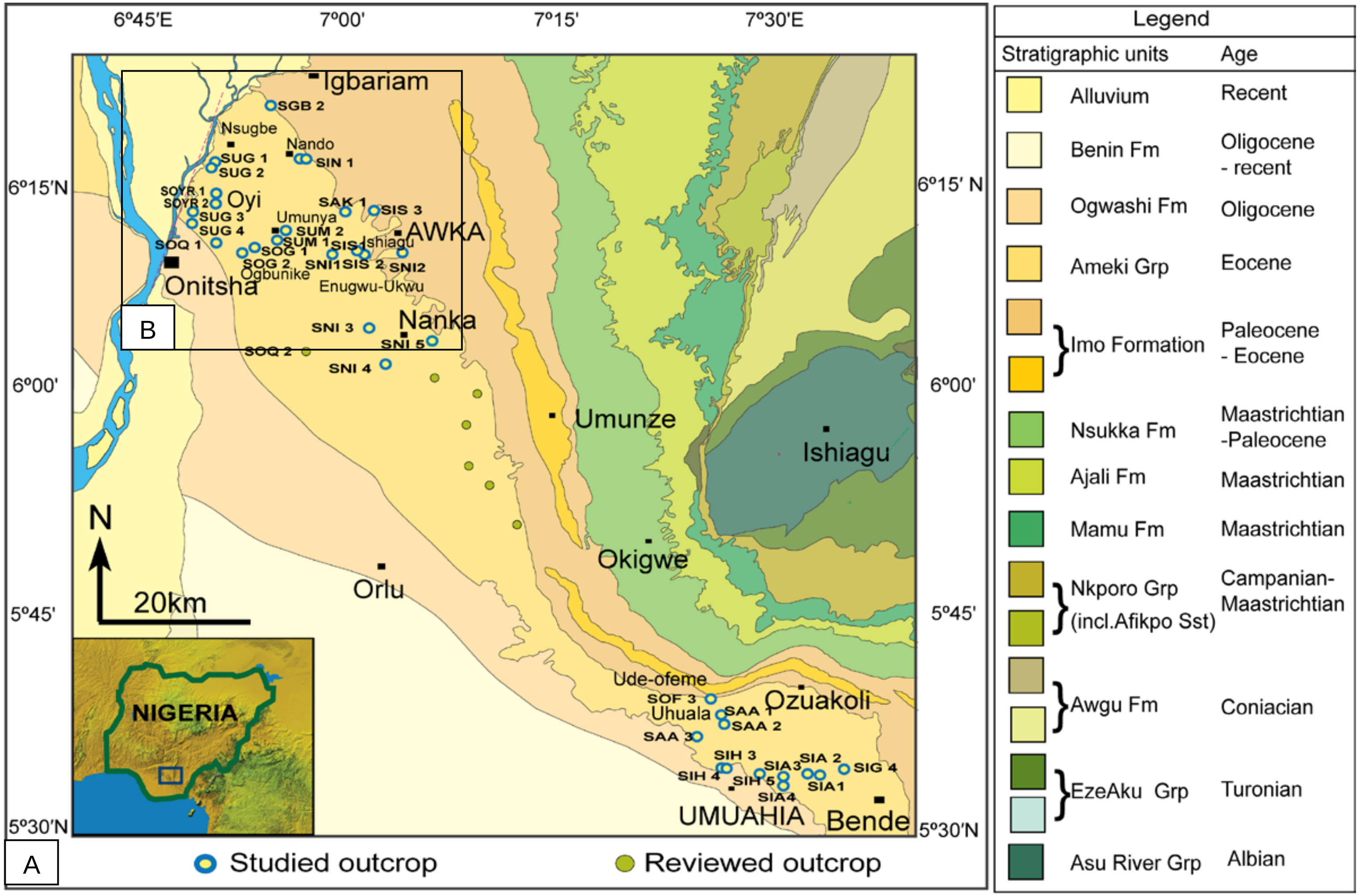
5.2.1 Field methodology

Systematic sedimentological and ichnological field descriptions were obtained from twenty-six outcrops in the study area (Figures 5.1, 4.2B; Appendix C5.1). The sedimentological approach follows the procedure discussed in chapter one. The size, distribution and strength of bioturbation (bioturbation index) were recorded and the taxonomic affinity of the trace fossils recognised by observing the burrow boundary or wall structure, the burrow fill and the branching characteristics. Observations from the field are used to describe and interpret the facies, facies associations and inferred depositional environments. Six representative outcrops were selected to determine the facies architectural elements of the Ameki Group. Figure 5.2 shows a correlation panel of studied lithologs and the spatial distribution of the depositional facies in the Ameki Group.

5.2.2 Laboratory studies

Clay mineral analysis (x-ray diffraction) was carried out at the Department of Earth Sciences, Royal Holloway, University of London as discussed in chapter one.

Palynological analysis was carried out partly at Global Energy, Lagos, Nigeria and at the Department of Earth Sciences, Royal Holloway, University of London.


6º45'E
7º00'
7º15'
7º30'E
6º15'N
6º00'
5º45'
5º30'N
Igbariam
Nsugbe
Nando
Oyi
Umunya
AWKA
Ishiagu
Onitsha
Ogbunike
Enugwu-Ukwu
Nanka
Umunze
Ishiagu
Okigwe
Orlu
Ude-ofeme
Uhuala
Ozuakoli
UMUAHIA
Bende
B
A
N
20km
NIGERIA
Studied outcrop
Reviewed outcrop
Legend
Stratigraphic units
Age
Alluvium
Recent
Benin Fm
Oligocene - recent
Ogwashi Fm
Oligocene
Ameki Grp
Eocene
Imo Formation
Paleocene - Eocene
Nsukka Fm
Maastrichtian -Paleocene
Ajali Fm
Maastrichtian
Mamu Fm
Maastrichtian
Nkporo Grp (incl.Afikpo Sst)
Campanian-Maastrichtian
Awgu Fm
Coniacian
EzeAku Grp
Turonian
Asu River Grp
Albian

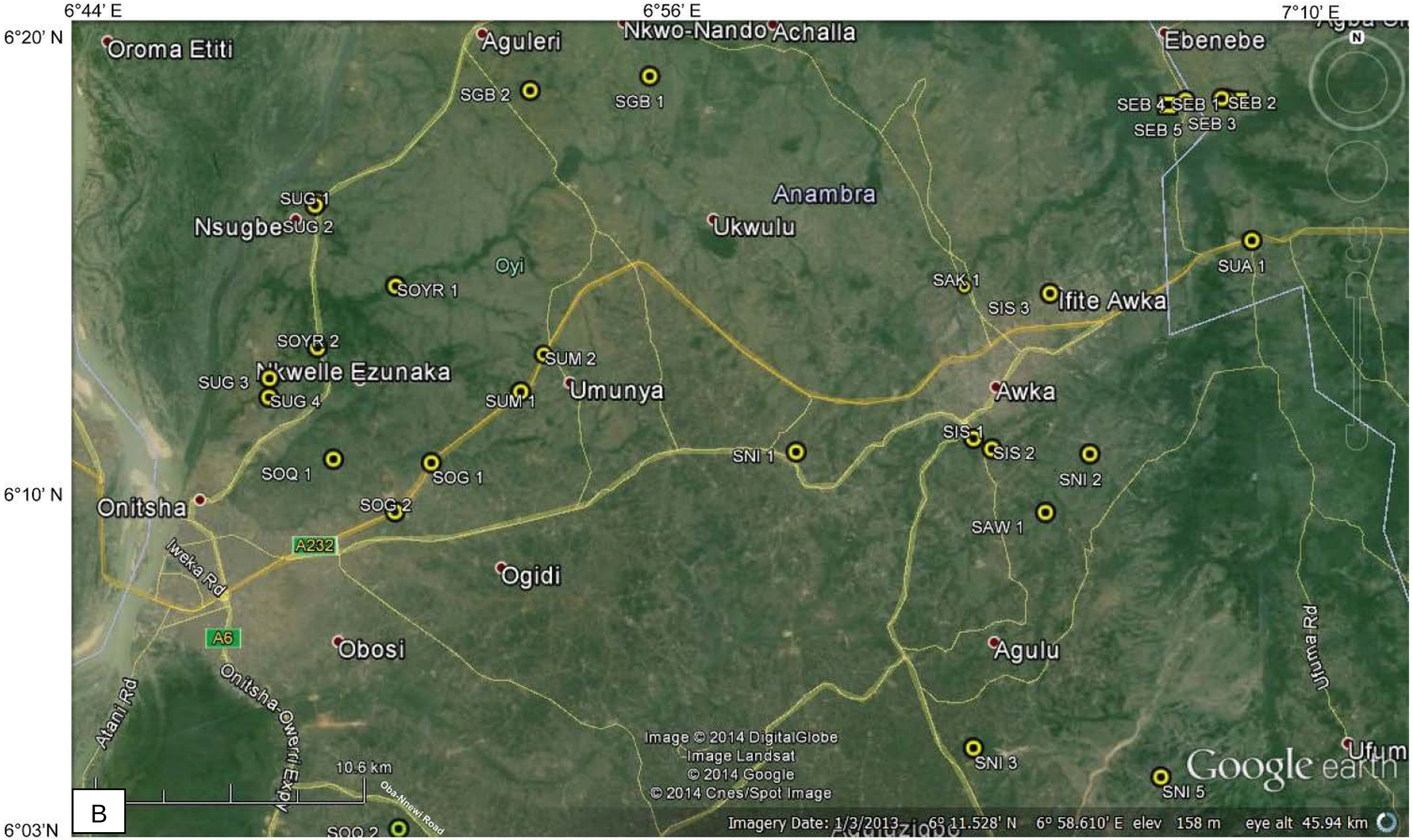
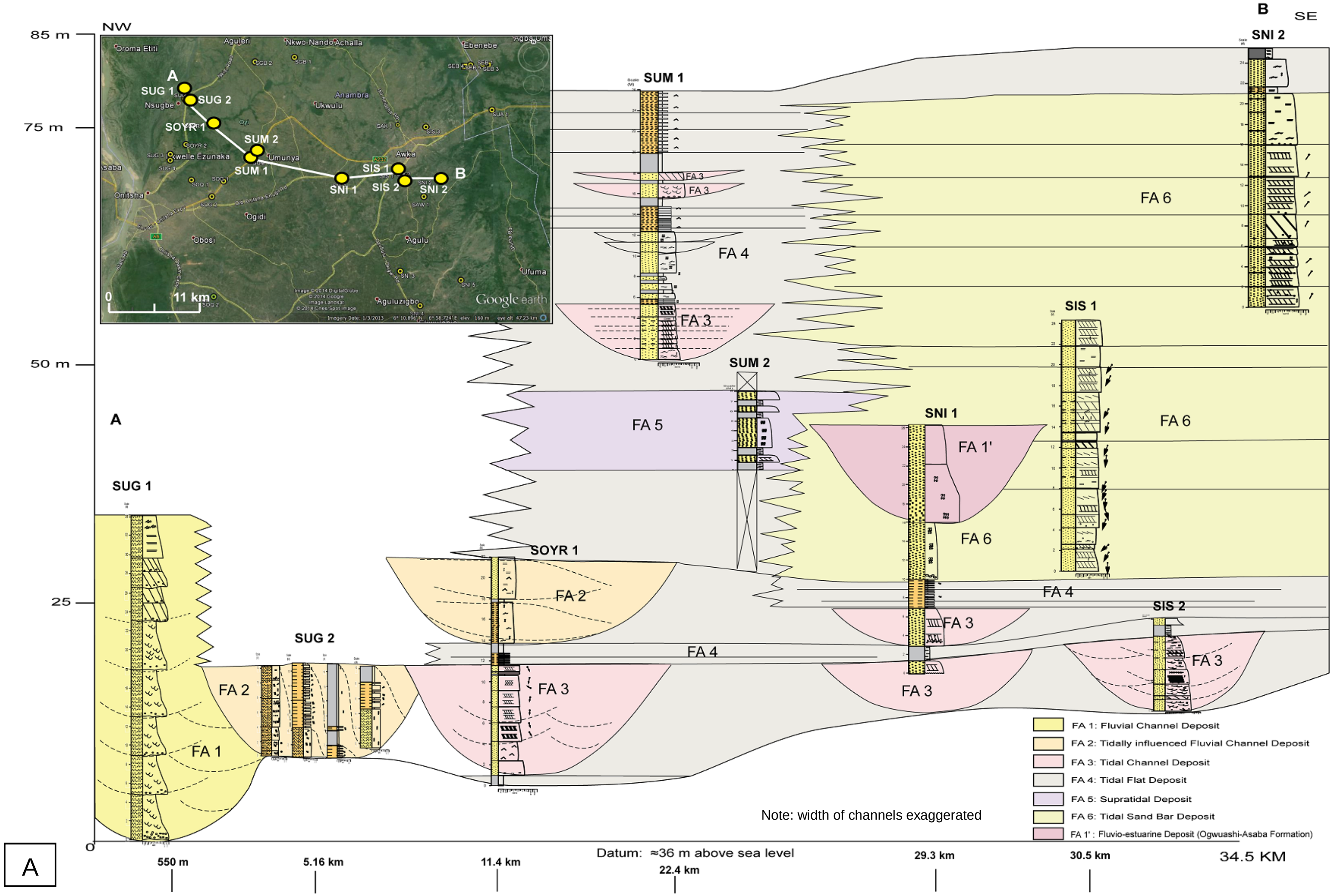
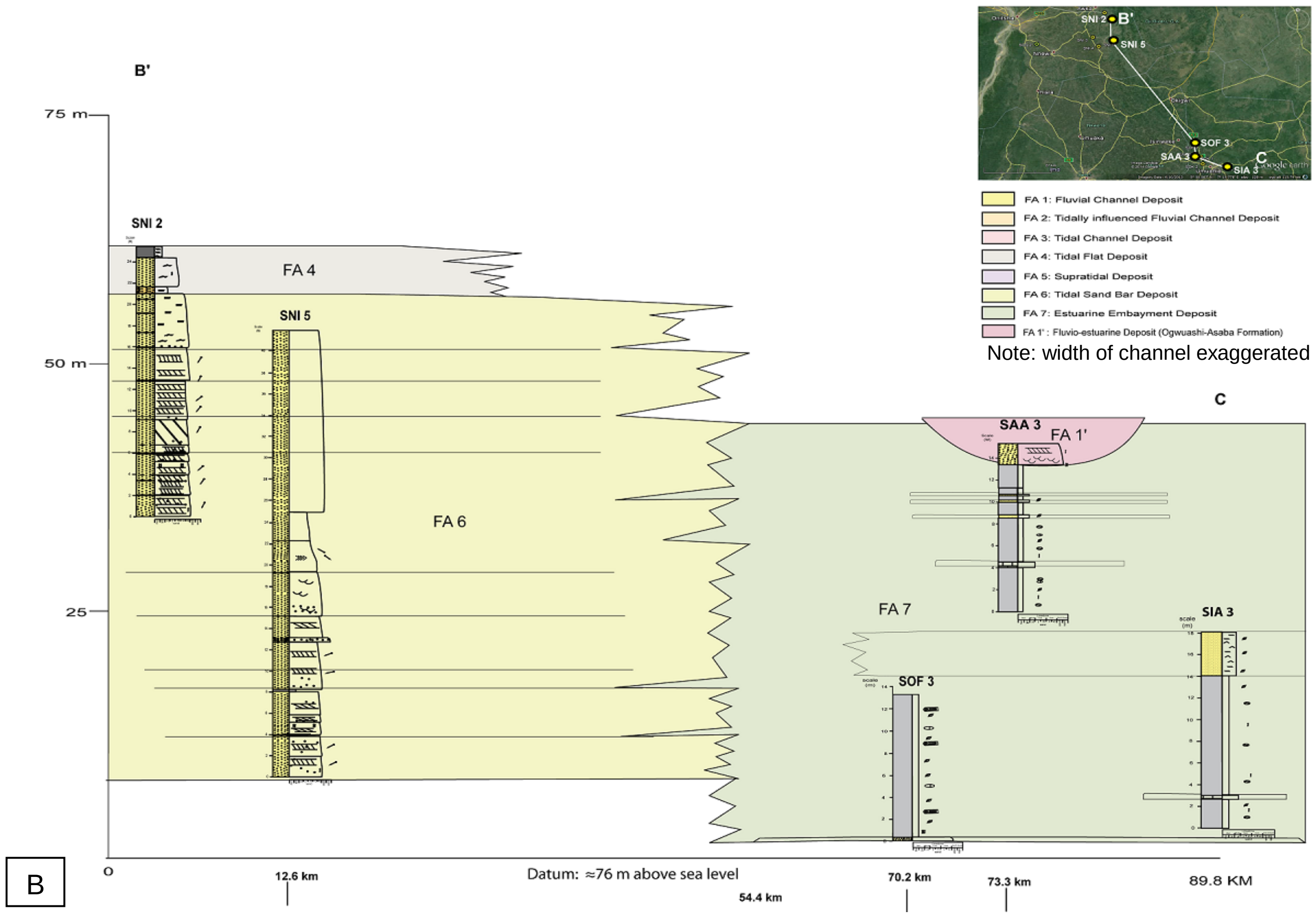


Figure 5.1 (A). Geologic map of the study area showing the outcrop locations of the Ameki Group (redrawn and modified after Nigerian Geological Survey Agency, 2009). (B). Accessibility map of the study area (Ebenebe-Onitsha axis) extracted from Google earth.


NW
SE
A
B
85 m
75 m
50 m
25
0
SUG 1
SUG 2
SOYR 1
SUM 1
SUM 2
SNI 1
SIS 1
SIS 2
SNI 2
FA 1
FA 2
FA 3
FA 4
FA 5
FA 6
FA 1'
Note: width of channels exaggerated
FA 1: Fluvial Channel Deposit
FA 2: Tidally influenced Fluvial Channel Deposit
FA 3: Tidal Channel Deposit
FA 4: Tidal Flat Deposit
FA 5: Supratidal Deposit
FA 6: Tidal Sand Bar Deposit
FA 1' : Fluvio-estuarine Deposit (Ogwuashi-Asaba Formation)
Datum: ≈36 m above sea level
550 m
5.16 km
11.4 km
22.4 km
29.3 km
30.5 km
34.5 KM
0
11 km
Onitsha
Nsugbe
Umunya
Awka
Agulu
Ogidi
Obosi
Ufuma
Aguluzigbo
Anambra
Ukwulu
Google earth

A



Process classification (after Ainsworth et al., 2011).

Tide-dominated elements – 85%

River-dominated elements – 12%

Wave-dominated elements – 3%

Figure 5.2 Schematic cross-sections of selected outcrops of the Ameki Group ((A) A- B cross-section and (B) B'-C cross-section) showing distribution of depositional facies.

5.3 RESULTS

5.3.1 Facies Association (FA)

The fourteen facies encountered within the Ameki Group were grouped into seven depositional facies associations. The internal characteristics, geometry and stacking pattern of the facies associations are utilised to determine the depositional environment. Each facies association represents particular environments of deposition that have been interpreted to occur in a tidally influenced estuarine system (Figure 5.3). These facies associations are similar to the facies associations recognised in the Amata Formation, Middle Devonian in the Baltic Basin (Pontén and Plink-Björklund, 2009), the Minas Basin and Cobequid bay of Salmon River estuary in Bay of Fundy (Yeo and Risk,1981; Dalrymple and Choi, 2007).

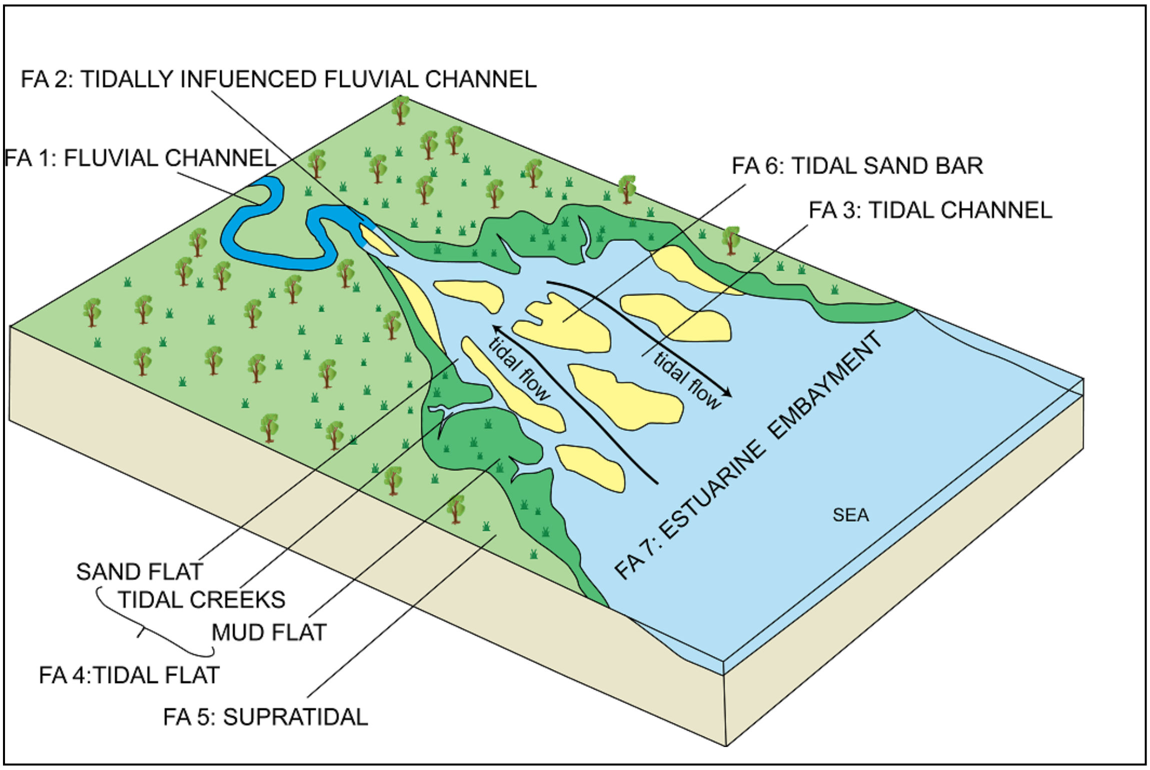


Figure 5.3. Schematic diagram of a tide-dominated estuarine system showing the distribution of the facies associations (FA) and their inferred depositional environments (redrawn and modified after Nichols, 1999).

FA 1 (Fluvial Channel)

Facies association 1 is restricted to the basal part of the Ameki Group and it is characterised by conglomerate facies (Gc), trough cross-bedded sandstone facies (St), planar cross-bedded sandstone facies (Sp), horizontally stratified sandstone facies (Sh), and current rippled laminated sandstone facies (Sr). The major outcrop is a 25 metre thick ferruginised sandstone, exposed at Ukwu-Nnadi quarry, Nsugbe (SUG 1) (Figure 5.4). Other similar sections were observed at Amumu Nsugbe and other parts of Nsugbe (SUG 3 and 4).

Ukwu-Nnadi Quarry Section

Ukwu-Nnadi quarry (SUG 1) occurs at Nsugbe (Figure 5.1B). The basal section of this sandstone unit is a scoured and erosional contact in filled by pebbles. The clasts are mostly quartz and range between 7 and 16 mm in diameter. The shape of the pebbles varies from spherical to ellipsoidal and they are subrounded to rounded. They represent the conglomerate facies (Gc3) which have been interpreted as channel lag (see Chapter 3). The clast-supported conglomerate facies (Gc1) was observed at Amumu Nsugbe, about 200 m from Ugwu-Nnadi quarry. It exhibits a sharp, erosive contact with the underlying mudstone (Figure 5.5). The conglomerate unit is massive, poorly sorted, with the basal part inversely graded. Overlying the Ugwu-Nnadi channel lag is the sandstone unit characterised by a multistorey channelised sandstone body, with each channel starting with pebble lags and fines upwards from coarse to medium grained sandstone (Figure 5.2). The pebbles are not poorly sorted, and are angular to subangular in shape. The sandstone is characterised by trough and planar cross-bedded sets and cosets (St1; Sp1), it is poorly to moderately sorted, strongly consolidated and ferruginised by iron-rich minerals (see figure 3.7). The cross beds have unimodal paleocurrent directions, oriented to the south-west (Figure 5.6A). The thickness of each bed varies from 1 to 6 m. Grains of feldspar and quartz dominate in the ferruginous matrix. The entire sandstone unit fines upward, exhibiting horizontal bedding (Figure 5.7) with parting lineations and climbing ripples.

The predominance of the unimodal paleocurrent patterns, poor to moderate sorting and the fining upward motif of the succession favours a fluvial channel interpretation (Miall, 1996; Collinson, et al., 2006; Ghazi and Mountney, 2009). The post-depositional transport of mineral-rich fluids within the sediments and the subaerial exposure of the sediments probably resulted to the ferruginised nature of the sediments, which is characteristic of most of the fluvial deposits in this Nsugbe region.

Interbedded siltstone and mudstone (Figure 5.8) is observed adjacent to a ferruginised channelized sandstone at Awka. It exhibits ripple lamination and horizontal bedding, and has a sheet-like geometry. The unit is about 4 m thick and contains abundant plant and carbonaceous materials. The heterolithic unit grades into thinly bedded, fine grained bioturbated (*Skolithos* isp.) sandstone interpreted as crevasse splay deposits. The sheet-like siltstone, mudstone and sandstone bed units suggest floodplain sedimentation resulting from overbank flood events (Jones and Hartley, 1993).

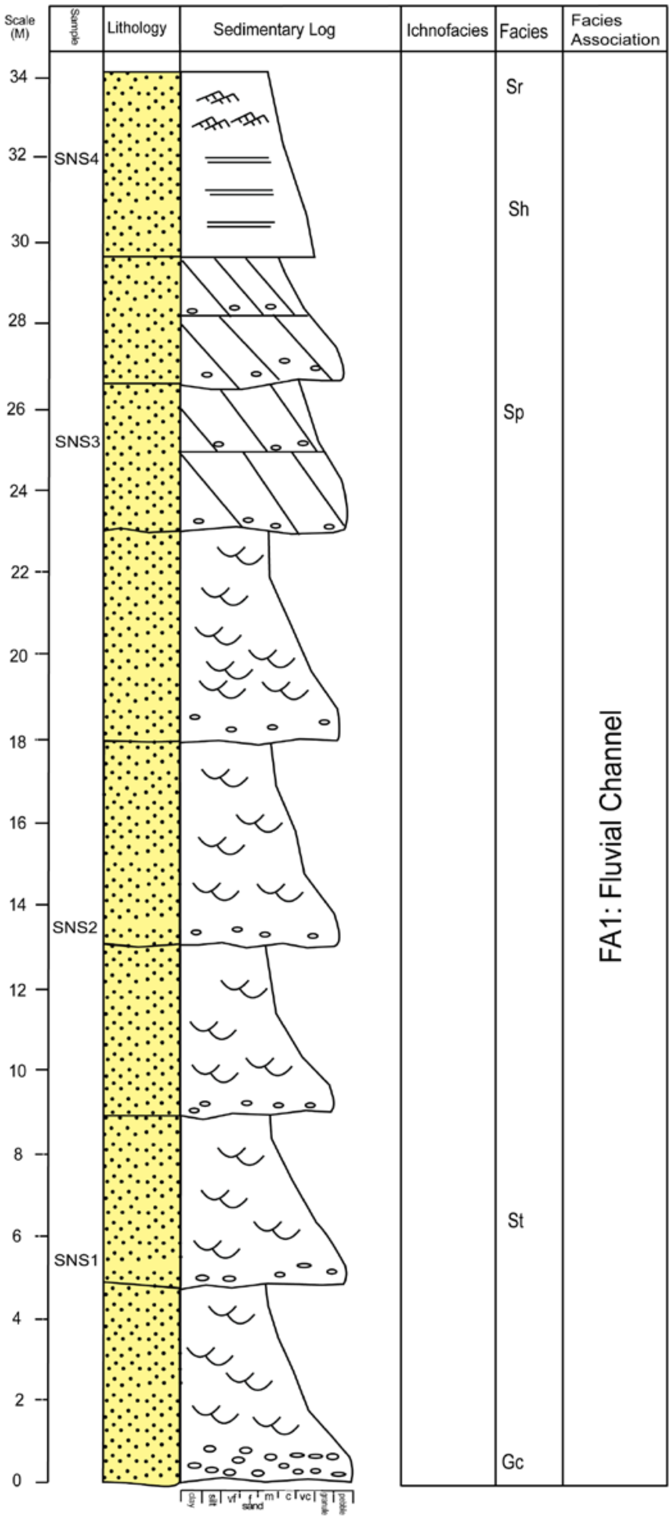


Figure 5.4. Lithology of Ugwu-Nnadi Sandstone Quarry Section in Nsugbe (Nsugbe Formation of Ameki Group).

Figure 5.5. Outcrop exposure at Amumu Nsugbe, exhibiting a sharp contact between clast-supported conglomerate facies (Gc1) and the underlying mudstone.

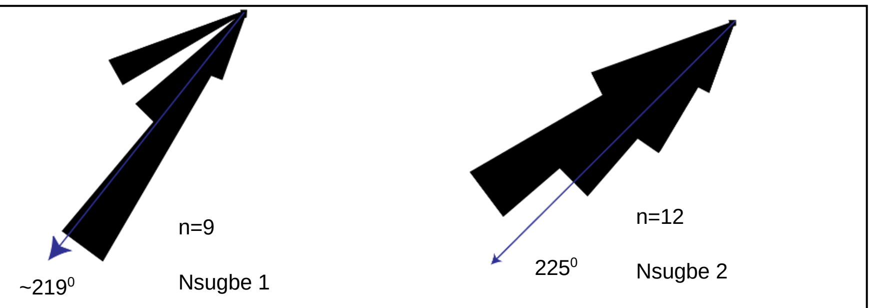


Figure 5.6A. Rose diagrams with paleocurrent data from Nsugbe sections (FA1).

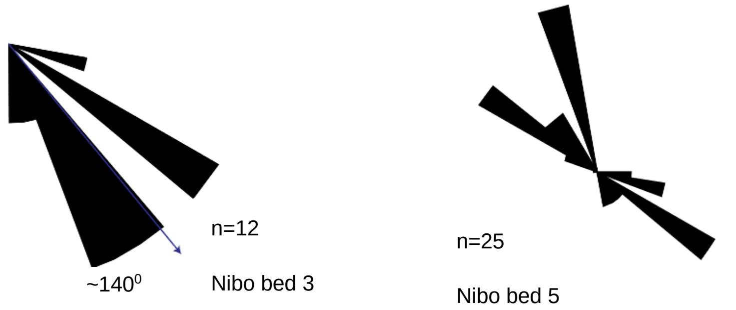


Figure 5.6B. Rose diagrams with paleocurrent data from Nibo section (FA 3).

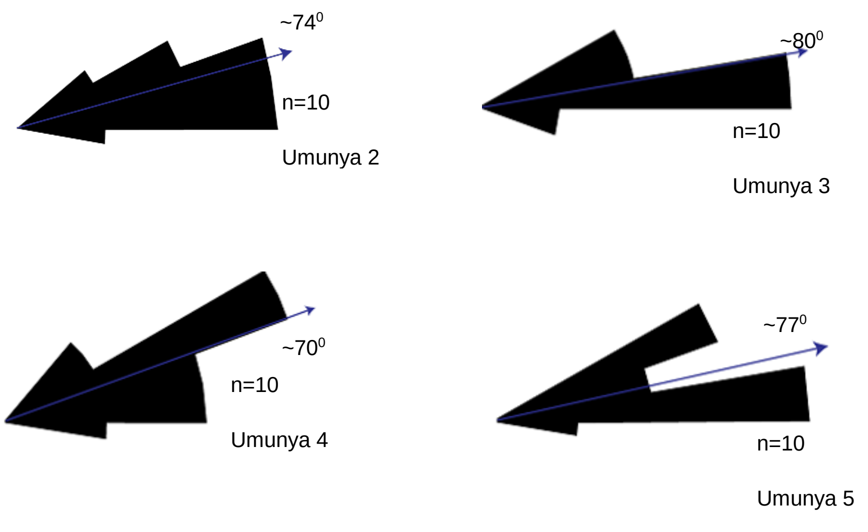


Figure 5.6C. Rose diagrams with paleocurrent data from Umunya section (FA 4).

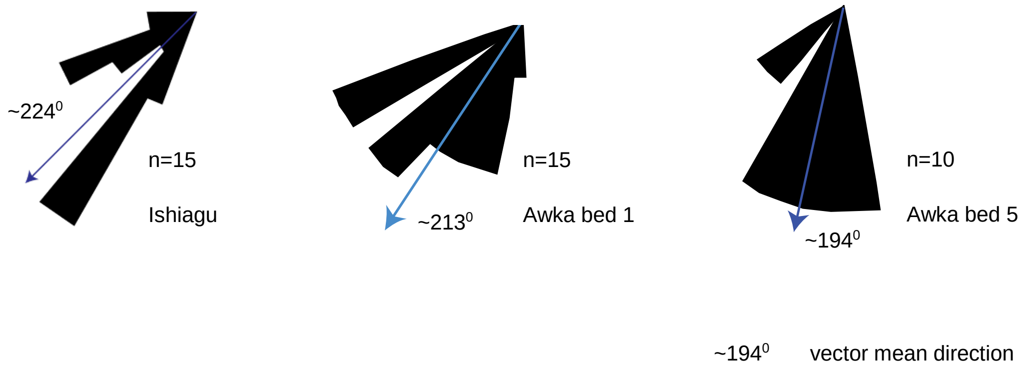


Figure 5.6D. Rose diagrams with paleocurrent data from Ishiagu and Awka sections (FA 6).

Figure 5.6 (A-D). Rose diagrams showing paleocurrent data from outcrop sections in the Nsugbe and Nanka formations of the Ameki Group.

Figure 2.7. Outcrop exposure at Ugwu-Nnadi sandstone quarry showing horizontal bedding (Sh) at the upper part of fining upward cross-stratified sandstone.

Figure 5.8. Outcrop exposure at Awka showing alternation of siltstone and mudstone that is characterised by ripple lamination and horizontal bedding, with carbonaceous materials interpreted as floodplain deposit (FA1).

FA 2 (Tidally-influenced Fluvial Channel)

Facies association 2 succeeds facies association 1 at Nsugbe area (SUG 2), which is its type locality. It occurs in other areas at the base of Nsugbe Formation; such as at Nando. FA2 is characterised by conglomerate facies (Gc4), sandy heterolithic facies (Sht), muddy heterolithic facies (Fmt), planar cross-bedded sandstone facies (Sp), herringbone cross-stratified sandstone (Sxh), mudstone facies (Fm) and bioturbated sandstone facies (Sb) (Figure 5.9). These facies vary laterally across the outcrop (Figure 5.10). The type section forms a fining upward succession with a maximum thickness of about 12 m and lateral extent of about 210 m. FA2 is sedimentologically and ichnologically diverse, exhibiting both *Skolithos* and *Cruziana* ichnofacies. The intensity and diversity of the ichnofauna varies within the various facies within FA2.

Ugwu-Nnadi Heterolithic Section

Facies association 2 occurs in Nsugbe (SUG 2) and it begins with sandy heterolithic beds that consist of non-inclined heterolithic units (sub-facies 1) and inclined heterolithic units (IHS) (sub-facies 2). Sub-facies1 of the sandy heterolithic facies is characterised by fine to medium grained sandstone with discontinuous wavy lamination, non-inclined clay laminae and flaser bedding. The horizontal clay lamination gradually becomes inclined, forming inclined sandy heterolithic facies. The non-inclined sandstone unit is characterised by moderate to intensely bioturbation intensities ranging from BI 3 to 5, and low-moderate diversity of opportunistic trace fossil suites dominated by *Thalassinoides, Skolithos,* and *Planolites*. Subordinate elements are *Arenicolites* and *Laminites.* Body-fossil assemblages (bivalves) in the unit are not diverse; and this is common with estuarine deposits which are dominated by euryhaline molluscs and inarticulate brachiopods (Buatois et al., 2005). The occurrence of these opportunistic trace fossils suggests an incursion of marine water and sudden environmental change. The presence of both *Skolithos* and *Cruziana* ichnofacies indicates normal marine water deposition (Pemberton et al.,1992; Gingras et al., 2002). The well-developed sandy heterolithic facies indicate that tidal sedimentation prevailed during the marine inundation.

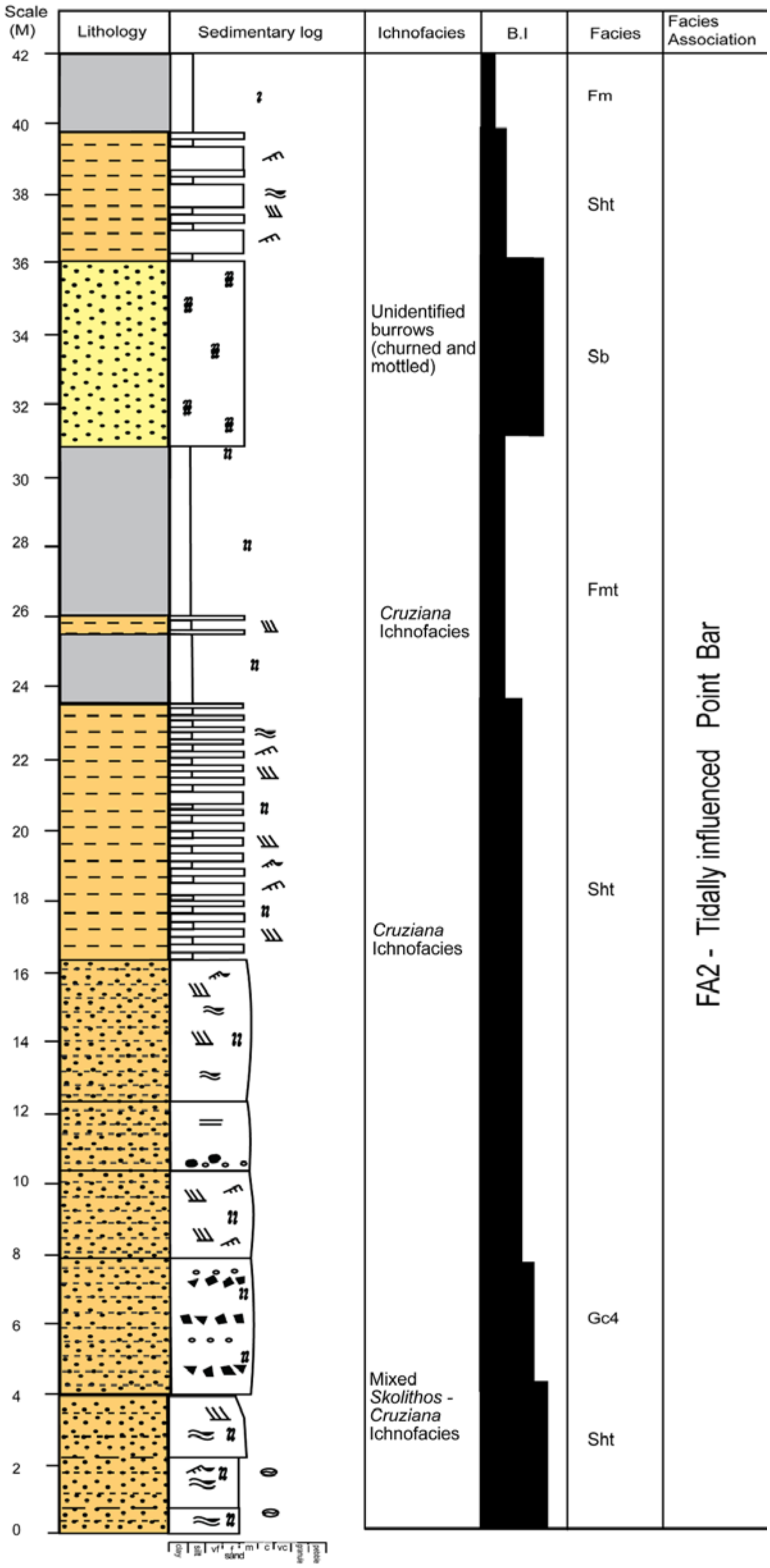


Figure 5.9. Composite litholog profile of Ugwu-Nnadi Heterolithic section at Nsugbe (Nanka Formation of Ameki Group).

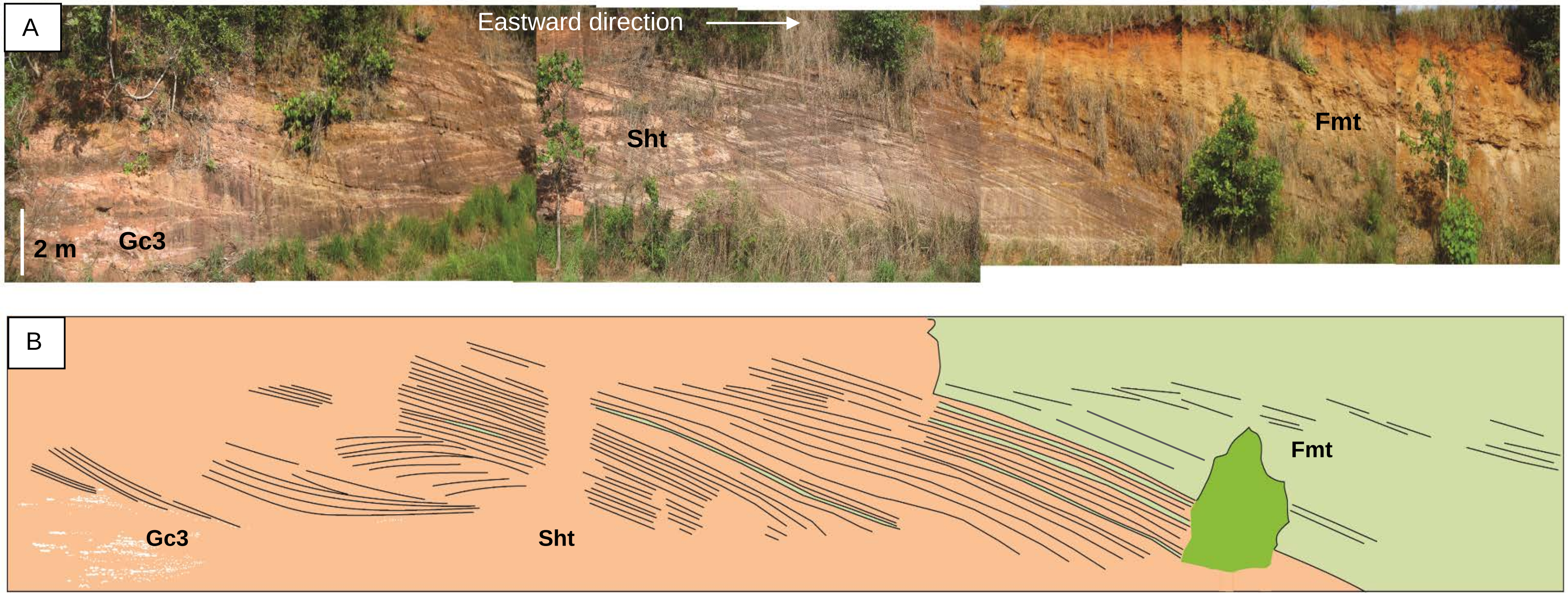


Figure 5.10. Outcrop photomosaic of the tidal influenced fluvial system showing lateral accretion deposit. (A) Dominate foresets orientate in a northward direction. (B) Schematic diagram outlining variation in facies change.

The sand-dominated inclined heterolithic facies (IHS) (sub-facies 2) begins with brecciated mudstone (Gc4) that occur in irregular centimetre-scale cycles in the fine grained sandstone (see figure 3.3A). The thickness of the brecciated mud clast units reduces upward, implying fluctuation in current energy, as consolidated muds were reworked by periodically strong currents and re-deposited. Some brecciated mud clasts and blocks slide down inclined surfaces (see figure 3.3B). Rebata et al., (2006b) suggested that mud clasts may be eroded during each rainy season, and the re-worked mud clasts were re-deposited at brecciated layers at the end of the rainy season. The centimetre-scale cycles of the brecciated mudstone can thus be interpreted as seasonal tidal cycles.

Laterally, the brecciated mudstone unit grades into amalgamated inclined heterolithic units bounded by a scoop-shaped erosional surface. The inclined heterolithic unit exhibits opposite dipping laminae (northward direction). This is then followed by southward dipping amalgamated to non-amalgamated inclined heteroliths. The amalgamated cyclic rhythmites exhibit millimetre thick interlamination of rippled sands, silts and muds couplets/triplets with sharp contacts, mud flasers, wavy lamination and sand-filled shrinkage cracks (Figure 3.15A, B). The non-amalgamated rhythmites consist of millimetres to centimetres thick sand, silt and mud heterolithic units with increasing upwards of mud/clay content. Laterally, the non-amalgamated rhythmites gradationally changed to muddy heterolithic facies (Fmt). The IHS is well burrowed with a moderate diversity of mixed *Skolithos* and *Cruziana* ichnofacies which includes *Thalassinoides, Planolites, Rhizocorallium, Paleophycus, Taenidium satanassi, Laminites, Skolithos, Arenicolites, Ophiomorpha* as well as sporadic small scale burrow mottling and robust articulated bivalves (Figure 5.11).

The muddy heterolithic facies (Fmt) is characterised by about 65 per cent mudstone, with mm-cm scale continuous and discontinuous sand/silt lamina, lenticular bedding and sand stringers forming both cyclic and non-cyclic rhythmites. Low diversity and impoverished monospecific *Teichichnus* dominate the unit with uncommon burrows such as *Planolites* and tiny *Thalassinoides* suites. This poorly diverse suite is typical of stressed conditions in estuarine environments (Pemberton et al., 1992; Buatois et al., 2002). The muddy heterolithic beds grade into a thick mudstone deposit which is overlain by bioturbated fine grained sandstone, which represents facies association 5. This succession of inclined heterolithic sandstone (IHS), muddy heterolithic facies and mudstone-bioturbated sandstone repeatedly occurs forming cycles.

The sandy inclined heterolithic beds (IHS) represent laterally accreting bars and are interpreted as point bar deposit in channel margin (Rebata et al., 2006b, Hovikoski et al., 2008). The inclined heterolithic units trend in a southwards direction (with low dip angle of 7°-10°) whereas the minor inclined heterolithic with above the brecciated mudstone show northward trending tidal currents. The amalgamated inclined heterolithic units overlying the brecciated mudstone-bearing sandstone is interpreted as a mid-channel, lower point bar deposit (Hovikoski et al., 2008).

The change of facies between the point bar deposits and the muddy deposits that fill the channel as a plug suggest abrupt abandonment, either by avulsion or cut-off (Ghazi and Mountney, 2009).

Nando Section

At Nando (SIN 1), tidally influenced fluvial channel succession begins with *Glossifungites* ichnofacies consisting of *Ophiomorpha, Planolites, Rhizocorallium*, and *Paleophycus.* The consolidated substrate also contains dispersed granules and pebbles. The sandstone consists of an erosively-based massive conglomeritic unit, within which no internal structure was observed. Overlying the conglomerate is coarse grained sandstone, which is characterized by large and small scale planar-tabular beds, herringbone cross stratification, reactivation surfaces, cut and fill structures and soft sediment deformation such as convolute lamination, and slump structures (Figure 5.12). The tabular sets of planar cross-beds dip steeply (17°-33°) towards the southeast direction (average of S145E). The herringbone cross-stratification records bi-directional of N298.5W and the opposing S128E, their dip angles vary from 12° to 24°. The sandstones are friable, they are light brown to purplish in colour and fine upwards into an immature paleosol.

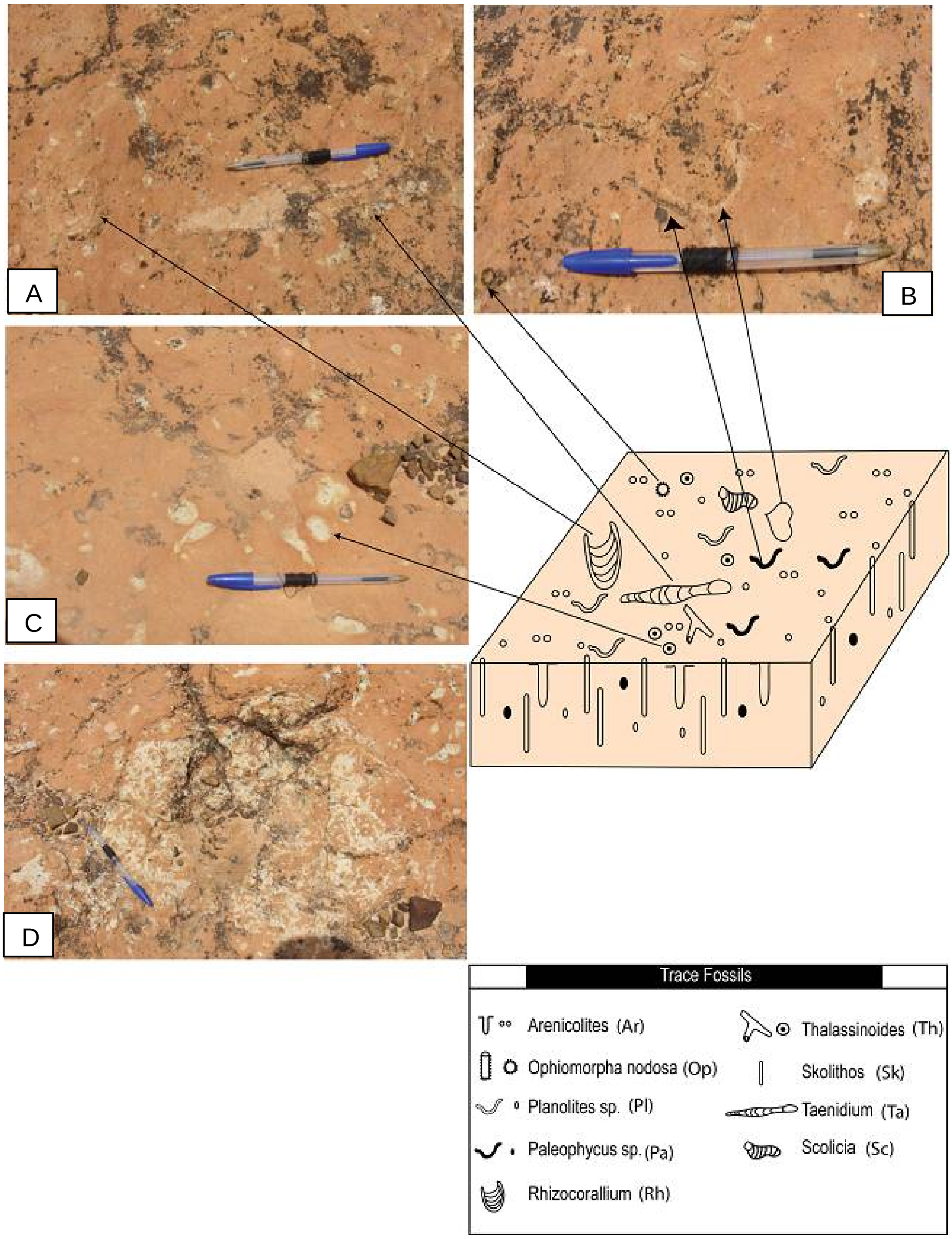


Figure 5.11. Mixed *Skolithos-Cruziana* ichnofacies occurring in the sandy heterolithic facies (Sht) at Ugwu-Nnadi in Nsugbe. (A. *Rhizocorallium, Taenidium*; B. *Planolites*, bivalve; C. *Thalassinoides*; D. Sporadic small scale burrow mottling).

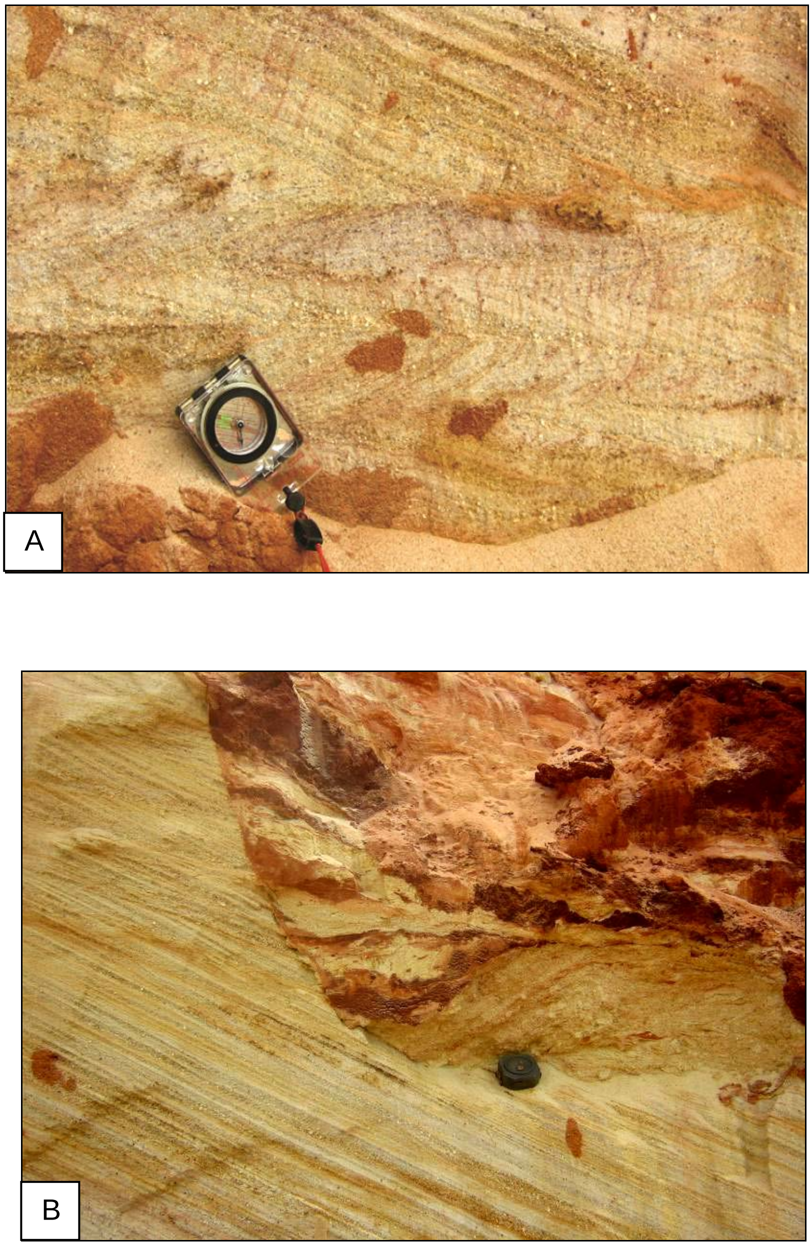


Figure 5.12. Cross-stratified sandstone from Nando Section exhibiting (A) herringbone cross-beds and (B) large scale planar cross-beds with cut and slump fill structure.

FA 3 (Tidal Channels)

Facies association 3 is one of the most dominant facies in the study area. It comprises tabular cross-bedded sandstone sub-facies (Sp), mud-draped tabular cross-bedded sandstone sub-facies (Sp2), trough cross-bedded sandstone facies (St), bioturbated sandstone facies (Sb), sigmoidal cross-stratified sandstone facies (Sx), herringbone cross-stratified sandstone facies (Sxh), variegated facies (Fms) and mudstone facies (Fm) (Figure 5.13). This facies association is characterised by very coarse to fine grained sandstone with a fining-upward trend. The dominant trace-fossil assemblages are mixed *Skolithos-Cruziana* ichnofossils. This outcrop section is observed at Umunya, Ogbunike, Okpuno-Awka, along Onitsha-Awka express road.

Nibo Section

The observed section at Nibo (SIS 2) is about 8 m thick (Figure 5.13) and has at its base a coarse grained sandstone, with sets of unidirectional large scale trough-cross stratified sandstone (St2) with thick mud lenses, and mud clasts; mud drapes are rare in this unit. These cross-stratified sets were deposited during the migration of sinuous crested 3D dunes that may be present on the outer part of the point bars at the base of the subtidal channel (Fenies and Faugères, 1998). The mud lenses may suggest deposition in channels within the turbidity maximum zone, where rapid accumulation of suspended fines are deposited as fluid mud (water-rich mud) during slack-water periods associated with high and low tides (McIlroy, 2004; Pontén and Plink-Björklund, 2009).

The sandstone unit is moderately burrowed, with the presence of large horizontal tunnel and vertical shafts of *Ophiomorpha,* and negative epirelief burrows of *Conichnus.* Other common burrows are mud-filled *Thalassinoides, Planolites, Gyroliths* and *Paleophycus.* The low diversity nature of the mixed *Skolithos-Cruziana* burrows suggests estuarine conditions (MacEachern and Pemberton, 1994; Rossetti and Santos Júnior, 2004; Pemberton et al., 1992). The trough cross bed unit is succeeded by a moderately burrowed section, characterised by herringbone cross stratification, tidal bundles and tabular cross beds with tangential and planar contacts (see Figure 3.6C). This unit would have been deposited in an intertidal channel-fill setting where the effect of tides is high. The cross bedded sandstone grades into a cross-laminated medium grained, moderately burrowed sandstone. Overlying this is a medium to fine grained, intensively burrowed sandstone.

The sandstone has been reworked dominantly by small horizontal burrows of *Thalassinoides;* other common burrows are *Planolites, Paleophycus,* and small vertical burrows of *Ophiomorpha, and Arenicolites*. The bioturbated sandstone facies (Sbf) grades into a mudstone unit which caps the entire section. The mudstone is characterised by dark gray mudstone with silty partings and it is strongly to moderately bioturbated with low diversity, but high abundance of small *Thalassinoides, Planolites* and *Gyrolith* burrows. This unit represents a mudflat that commonly caps most tidal channel point-bars or channel bars (Gingras et al., 1999).

Awka Section

At Awka, about 50 m away from Awka Cross-stone quarry, the tidal channel-fill also exhibit a fining-upward profile (Figure 5.14A) and it is characterised by mud draped, large- and small-scale planar-tabular cross beds with burrowed foresets, herringbone structures, horizontal bedding, cross lamination, and mud lenses (Figure 5.14B). There is a low diversity of burrows of *Thalassinoides, Ophiomorpha, Planolites and Gyrolith*. Mud flat deposit with lenticular shaped geometry caps the tidal channel (Figure 5.14A).

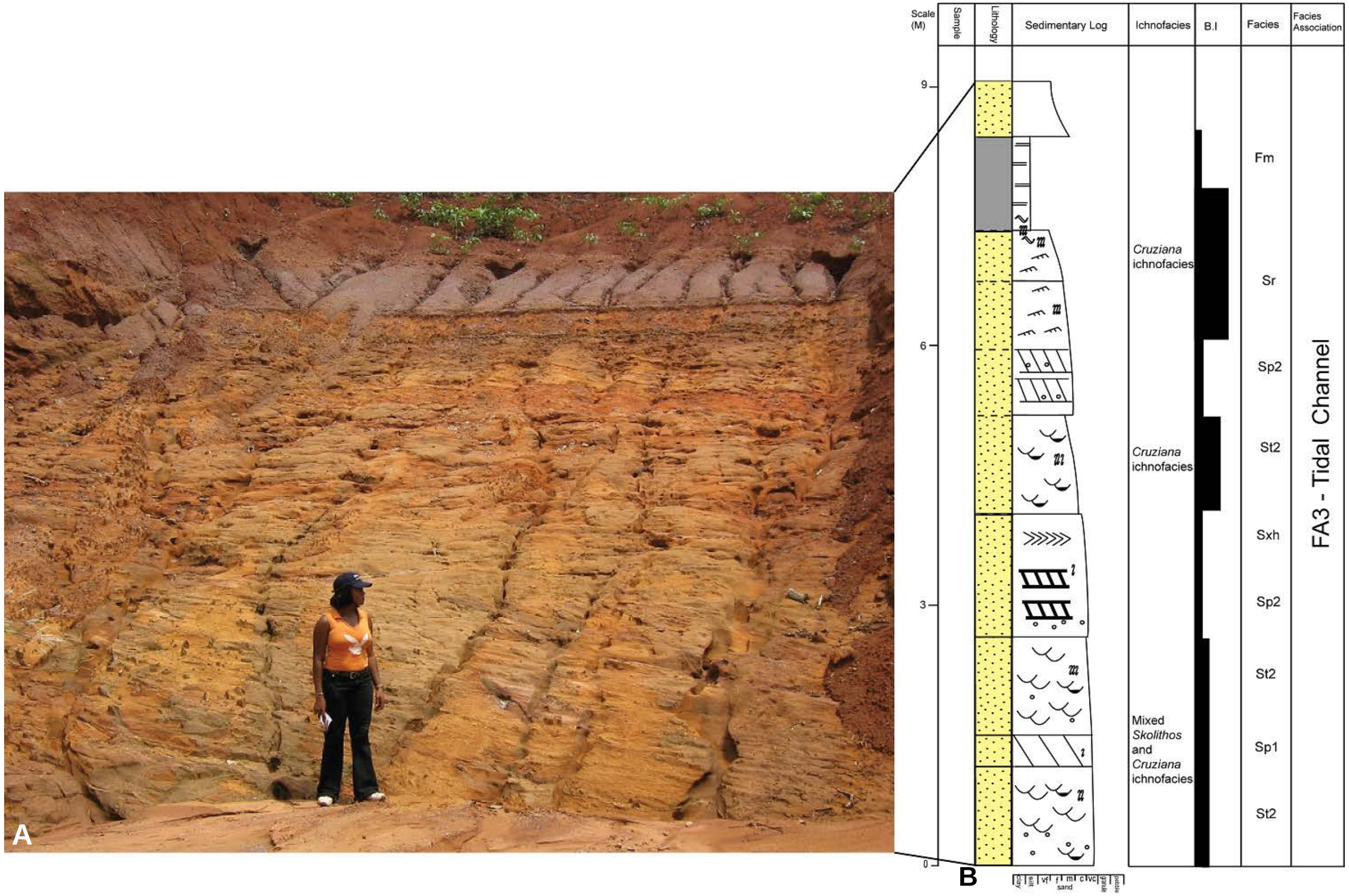


Figure 5.13 (A). Outcrop section at Nibo. (B).Litholog profile of the Nibo Section (Nanka Formation of Ameki Group).

Figure 5.14. Outcrop exposure of Awka section, (A) showing a fining upwards trend (f) typical of a tidal channel, with a lenticular shaped mudstone at the top. (B). Large scale mud draped cross-beds with some burrowed foresets.

Umunya Section

The lower unit of the Umunya section (SUM 1) is characterized by fine to medium grained sandstone, which is well to moderately sorted, clayey, micaceous, and poorly consolidated, light to creamy white on fresh surfaces and brownish on weathered surfaces. The sandstone unit is dominated by sigmodial and tabular cross-beds, with mud drapes, rippled asymptotic bottomsets, reactivation surfaces, and flaser and wavy bedding (Figure 5.15A). Each bed unit shows similar sedimentary structures from single to double mud draped sigmoidal, or tabular cross-beds with thick asymptotic bottomsets and cross lamination exhibiting wavy and flaser bedding. Some intervals shows gradual lateral changes from sigmoidal cross beds to co-flow cross lamination in a north eastern direction. The dominant trend in the cross beds is to the north-east (070°).

The beds vary in thickness from 30cm to 1m. The entire cross-stratified sandstone unit is about 4m thick. The sandstone unit is characterised by low-diversity, opportunistic burrows of mixed *Skolithos-Cruziana* ichnofacies such as *Ophiomorpha, Planolites, Skolithos, Arenicolites, Paleophycus* and concentric vertical burrows of *Cylindrichnus* (Figure 3.12).

The mud-draped sigmoidal and tabular cross beds form tidal bundles which occurred during the neap-spring cycles. Cyclic variation in thickness of bundles was observed (Figure 5.15A), thicker bundles are known to form during stronger spring tides and thinner bundles occur during neap tides (Kreisa and Moiola, 1986; Dalrymple, 1992). The average number of the tidal bundles is 27; suggesting semi-diurnal tidal cycles (Figure 5.15B).

Lateral change in sedimentary structures from sigmoidal cross beds to co-flow cross lamination suggests decrease in flow strength in the north-easterly direction. The lack of counter current ripples suggests the absence of vortices in the dune troughs. The dominant occurrence of tidal bundles and thick bottomsets is diagnostic of a subtidal sub-environment or inshore tidal domain (Dalrymple, 1992; Martinius and Van den Berg, 2011).

FA 4 (Tidal Flats)

Facies association 4 is the most commonly occurring facies association in the study area and it occurs in exposures several metres wide (Figure 5.2). Facies association 4 occurs also at the top of major tidal channels and tidal sand bars; it encases, interfingers with and/or encloses laterally some minor tidal channels (Figure 5.2). Sediments of facies association 4 are interpreted as tidal flats and they extend from the supratidal zone, through the intertidal zone and into the shallow portion of subtidal zone (Dalrymple, 1992).

Facies association 4 encompasses current rippled laminated sandstone facies (Sr), wave-rippled laminated sandstone facies (Sw), mud-draped tabular cross-bedded sandstone sub-facies (Sp2), siltstone facies (Sl), bioturbated sandstone facies (Sb), and mudstone facies (Fm). The dominant trace-fossil assemblages are both *Skolithos* and mixed *Skolithos-Cruziana* ichnofossils. The diversity and abundance of these ichnofacies vary across the facies from low to high. The outcrop sections are at Umunya, Ogbunike, Enugwu-Ukwu, Awka, Sandaff quarry, about 3 km from 3-3 junction in Onitsha, Ifite-Awka, Ishiagu and Nkwelle Ezunaka along the Onitsha -Awka express road (Figure 5.1B).

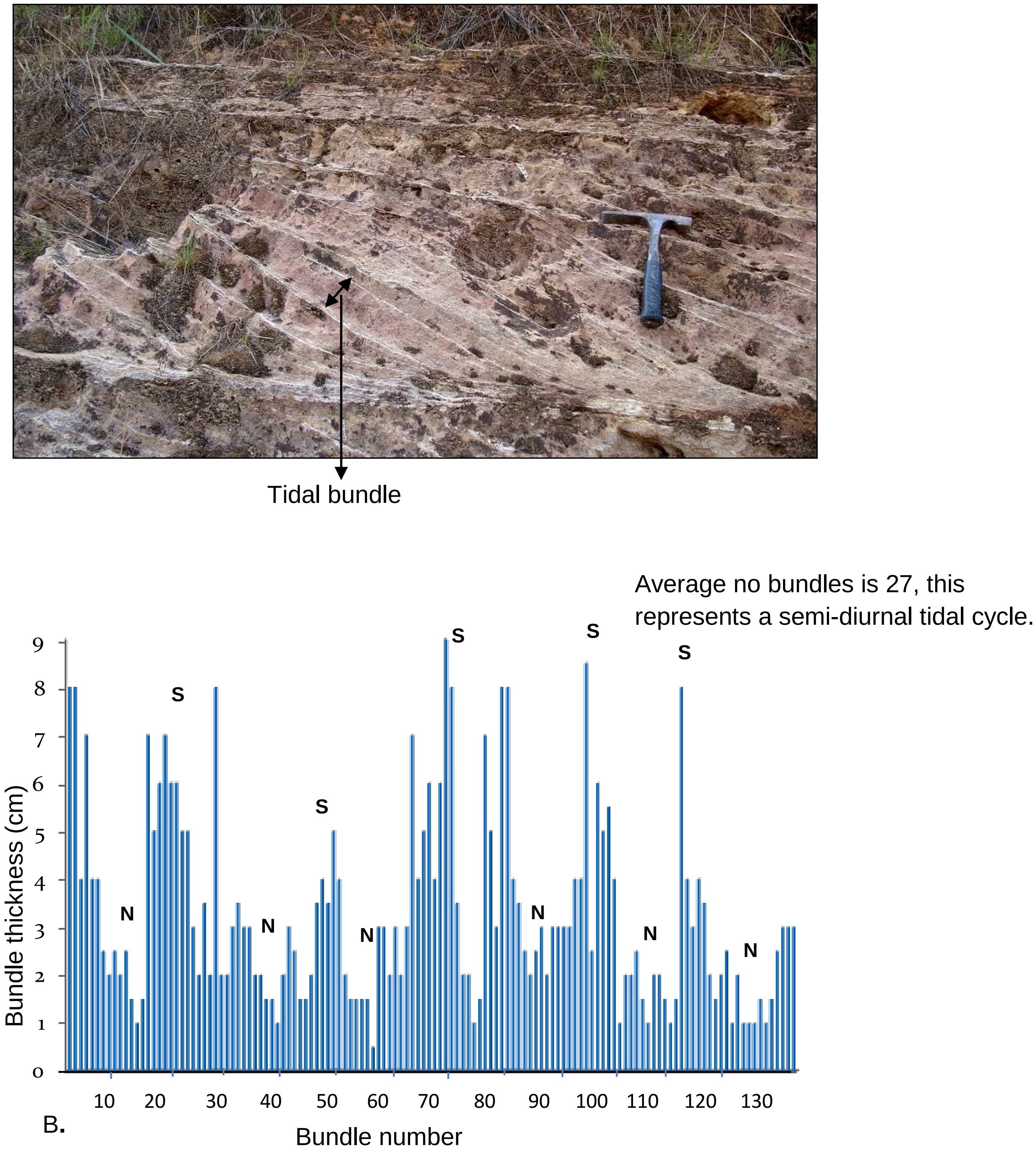


Figure 5.3. Tidal bundle in the Umunya section. (A). Outcrop photograph showing variation in the thickness of the tidal structure. (B). The neap-spring-neap tidal bundle has an average number of 27, reflecting a semi-diurnal tidal cycle.

Umunya Section

The Umunya section (SUM 1) (Figure 5.16) is an excellent example of a tidal flat environment, as it exhibits well preserved sedimentary structures that characterise deposits in subtidal and intertidal zones, mixed flats, mudflats, tidal creeks and minor tidal channels. The characteristic of the tidal flat is similar to those of the modern intertidal sediments of the Minas Basin, a macrotidal estuary at the head of Bay of Fundy (Yeo and Risk, 1980).

Sand Flat

The sand flat is characterised by cross-bedded unit that grades into alternations of fine to very fine grained sandstone and thin burrowed mudstone. The sandstone exhibits mud-draped planar cross bedding, flaser and wavy bedding. The burrowed mudstone varies from 5-35 cm thick, with increasing thickness upward whereas the sandstone beds vary from 35 cm-4 m thick. *Thalassinoides* burrows dominate the mudstone beds. The succeeding units are strongly burrowed, fine grained, micaceous, clayey sandstones, characterised by the presence of mud flasers, and wavy bedding, with low diversity ichnofacies which includes abundant large *Ophiomorpha nodosa*, Thalassinoides, *Planolites, ?Asterosoma, Protovirgularia,* and *Teichichnus* burrows. This sandstone unit is characteristic of sand flats where the cross bedded sandstone forms at high current velocities while the ripple cross lamination occurred when the current velocity is lower (Dalrymple, 1992). Upward increase in mud content resulted in wavy bedding and high bioturbation in the sand flat. These sand flat deposits interfinger with the deposits of the overlying mixed flat setting, reflecting local environmental changes.

Tidal Gullies

Scour and fill channels occur cross the sand flat. The lower channel fill is about 2 metres thick and 8 metres wide. It comprises fine grained to silty sandstone, with cross-laminated and concentric fill. The upper channel fill is characterised by lateral accreting heterolithic units that consist of interbedded lensoidal shaped silts/sandstone and mudstone, probably influenced by tidal currents and waves. The heterolithic channel-fill increases seaward in a southwards direction from 80 cm to 1.8 m thick and more than 15 m across (Figure 5.16A). Succeeding the channel-fill heterolithic unit is white coloured parallel laminated claystone with silt stringers that are slightly burrowed with *Planolites* burrows.

A sudden change from cross laminated to concentric fill indicates fluctuation in energy from relatively higher flow velocity and migration of ripples to lower flow energy. The concentric deposit represents vertical aggradation within a slowly migrating tidal creek (Dashtgard and Gingras, 2005).The laterally accreted heterolithic units represent tidal creek point bar deposition associated with channel migration (Dashtgard and Gingras, 2005). They are also referred to as tidal gullies (Dalrymple, 1992), and they increase in depth and width seawards. The heteroliths are less burrowed because deposition is more rapid than in the surrounding mud flats.

Mixed Flat

The mixed flat setting is characterised by fine-grained, rippled sandstone and heterolithic beds with wavy and flaser bedding. It interfingers with sand flat deposits and overlies the light grey claystone interpreted as mud flat deposits. Mixed flats are common in intertidal environments (as observed at Umunya, Paully Petrol station 1 and 2 sections, Ogbunike in Figure 5.17).

The heterolithic beds range in thickness from 1 to 6 m and show rhythmic alternation of cm–mm scale mudstone and fine grained rippled sandstone. The sandstone may be wave-rippled (symmetrical) laminated and highly micaceous as observed at Umunya section. On the bedding planes, the wave ripples show interference ripples with sinuous bifurcating crestlines (Figure 3.18B). Convolute lamination, slumping and other soft sediment deformation were observed within the heterolithic beds.

The alternation of sand and mudstone layers is interpreted to reflect fluctuations in tidal currents (Nio and Yang, 1991; Chakraborty, et al., 2003). In each sand-mud couplet, the sand represents deposition from higher flow velocities followed by suspension fallout of mud during the stillstand slack water period: this reflects a single tidal fluctuation in a diurnal or semidiurnal system (Archer, 1995). The wavy and flaser bedded heterolithic mudstone and sandstone suggest deposits in wave-influenced relatively low energy mixed flat environment (Tirsgaard, 1993). The influence of waves suggests shallow water deposition.

Mud Flat

The mud flat is characterised by laminated claystone or mudstone with thin continuous to discontinuous silty stringers. The thickness can vary from 50 cm to 3.5 m.

At Umunya, the claystone of about 3.5 m thick is dissected by coarse to medium grained sandstones (35 to 70 cm thick) with a scoured base. Mud chips, rip-up clasts and pebbles occur at the base of the sandstone beds. The sandstone beds may be structureless, planar or trough cross-stratified. The sandstone bodies occur as a lens in the claystone with a length from about 20 to 50 m long. The laminated claystone represents mud flats in an intertidal flat. Tidal currents are relatively weak in the mud flats, thus, the deposit is muddy. The sandstone beds with scoured bases represent minor tidal channels in the mud flats. At Nibo and Awka, the mud flat occurs on top of tidal channels as dark grey mudstone. The mudstones may be bioturbated as observed at Nibo, or contain fossil moulds as observed as Awka.

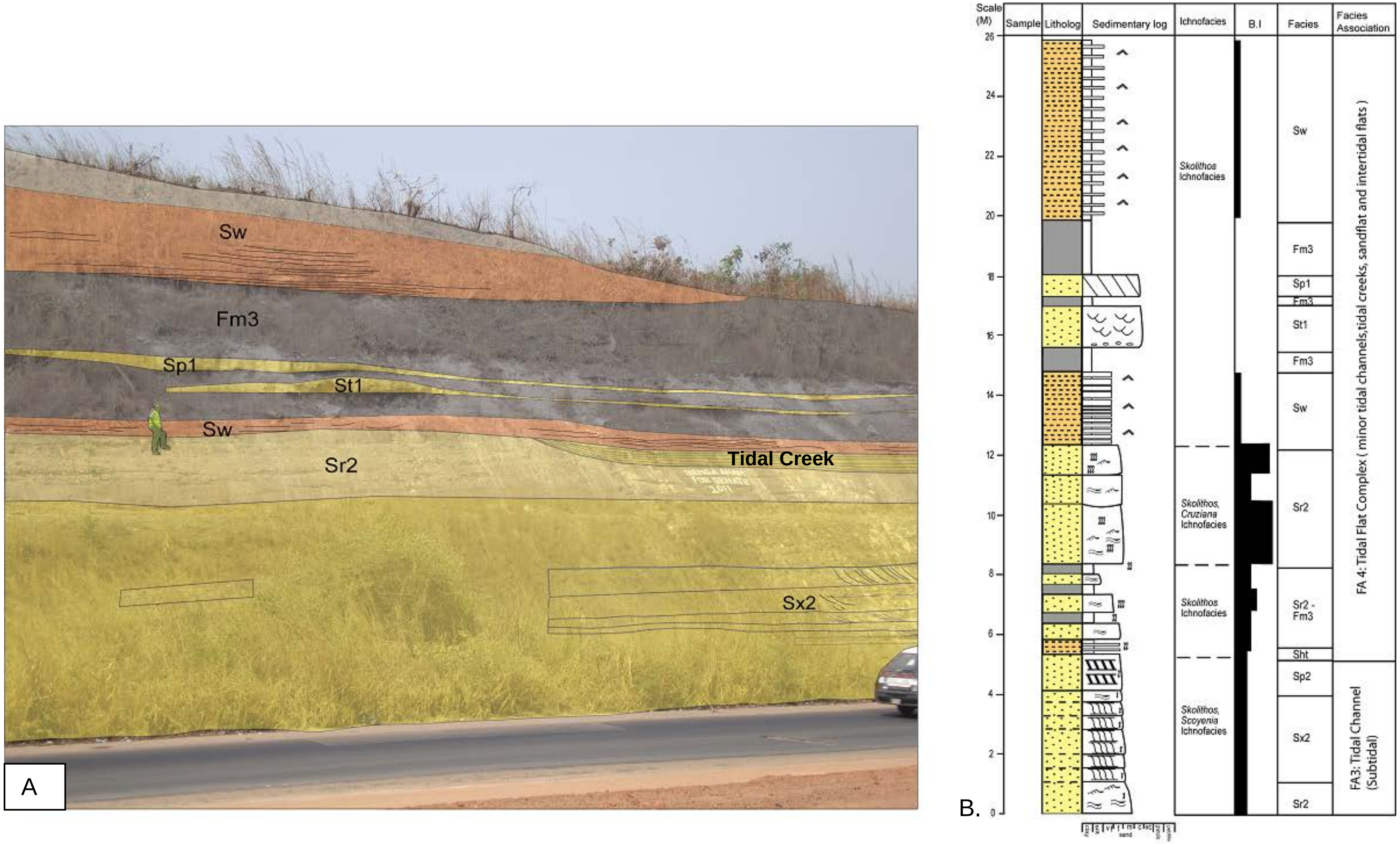
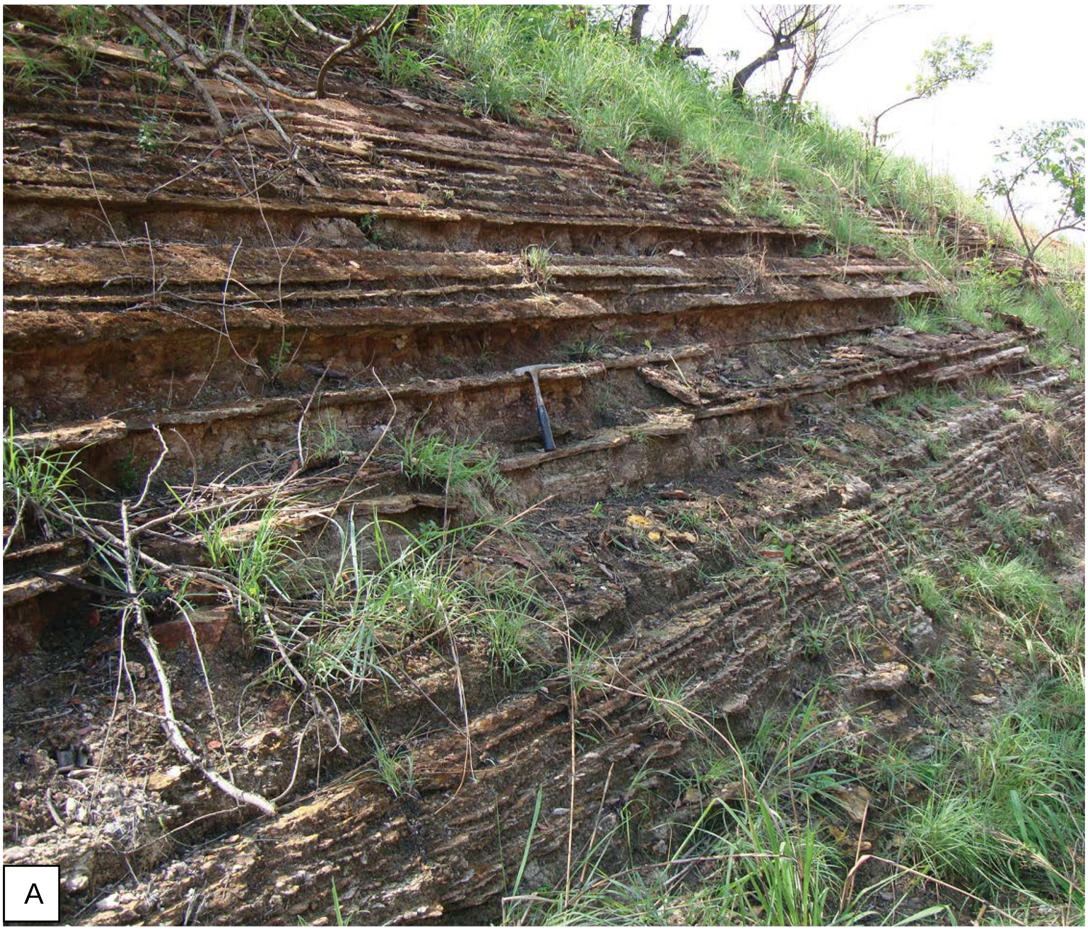


Figure 5.16 (A). Road-cut exposure at Umunya, exhibiting the various lithofacies geometry. (B). Litholog of Umunya section.


A


Subtidal
Intertidal
B

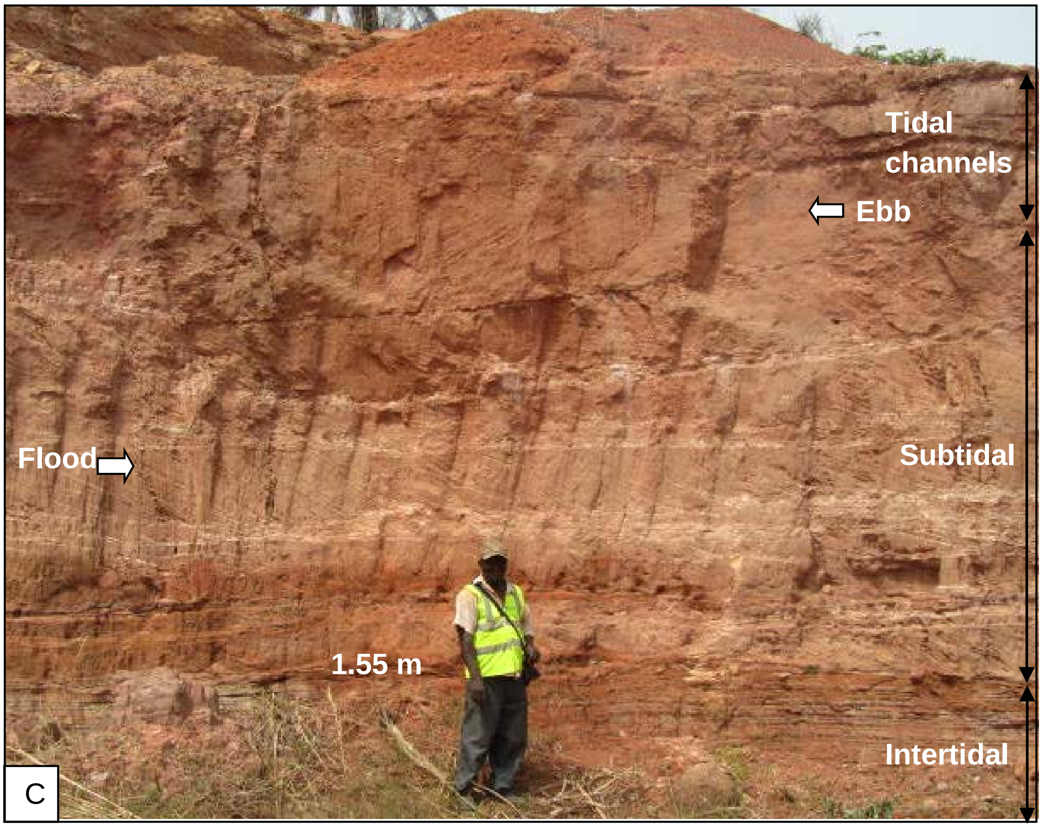

Tidal
channels
Ebb
Flood
Subtidal
1.55 m
Intertidal
C

Figure 5.17. Intertidal flat deposit occurs as mixed flat and displays rhythmic alternation of mudstone and rippled sandstone. Observed in the uppermost unit of Umunya section (A) and in the lower units of Paully petrol station 1 (B, C) and 2 (D) sections.

FA 5 (Supratidal Deposit)

Facies association 5 consists of variegated facies (Fms) and mudstone facies (Fm). The dominant trace-fossil assemblages are *Skolithos* and *Psilonichnus* (mainly plant-root penetration) ichnofacies. This outcrop section is observed at Ezi-Umunya, Ogbunike (SUM 2).

Ezi-Umunya section

The variegated facies (Figure 5.18) is best seen at Ezi-Umunya, at a road cut along Akuzu-Umunya express road. The facies comprises reddish-brown clayey sandstones with branching tubes (rhizoliths) and scattered carbonaceous matter (see Figure 3.24A). The sandstone is fine to medium grained and is about 3 to 6 m thick. The mud-filled tubes are elongate, branch downward and laterally, and they have a yellowish-brown rim. The tubes also contain carbonaceous materials and shrinkage cracks. The vertical dimensions of the tubes vary from 3 to 90 cm while the horizontal length is between 1 and 50 cm. The diameter of the tubes varies from 2 mm to 10 cm.

Paully Petrol Station 2 Section

Dark grey mudstone facies about 3 m thick is observed behind Paully petrol station 2 in Ogbunike (SOG 2). The basal part of the mudstone consists of silty lenses and stringers forming lenticular bedding. Dark brown colouration and dark organic particles are observed in the mudstone. Monospecific sparse bioturbation of *Planolites* was observed.

Most rhizoliths have both vertical and horizontal orientation indicating that they are formed *in situ* (Owen et al., 2008). The observed fossil root system is grouped into three based on Klappa's (1980) rhizolith classification: (i) root cast: this is the infilling of root mould by sediment or cement; (ii) root mould: this is a tabular void left after roots have decayed in partly or wholly lithified sediment; (iii) root petrification: this is the replacement and impregnation of organic matter by mineral matter without total loss of root features. Most of the root networks are root cast filled with clay and silty clay. Rhizoliths are indicators of paleosols in a subaerial vadose environment. Kraus and Hasiotis (2006) suggested that the elongate grey mottles (rhizohaloes) with yellow-brown (goethite) rims and the presence of carbonaceous root fossils with rhizoliths reflect poorly drained paleosol. The presence of Fe concentration in the matrix around rhizohaloes indicates surface-water gleying caused by a perched water table (Kraus and Hasiotis, 2006). The presence of organic-rich mudstone, plant fragments and roots, where sediments are reworked by pedogenic processes suggest supratidal parts of tidal mud flats and marshes (Plink-Björklund, 2005).

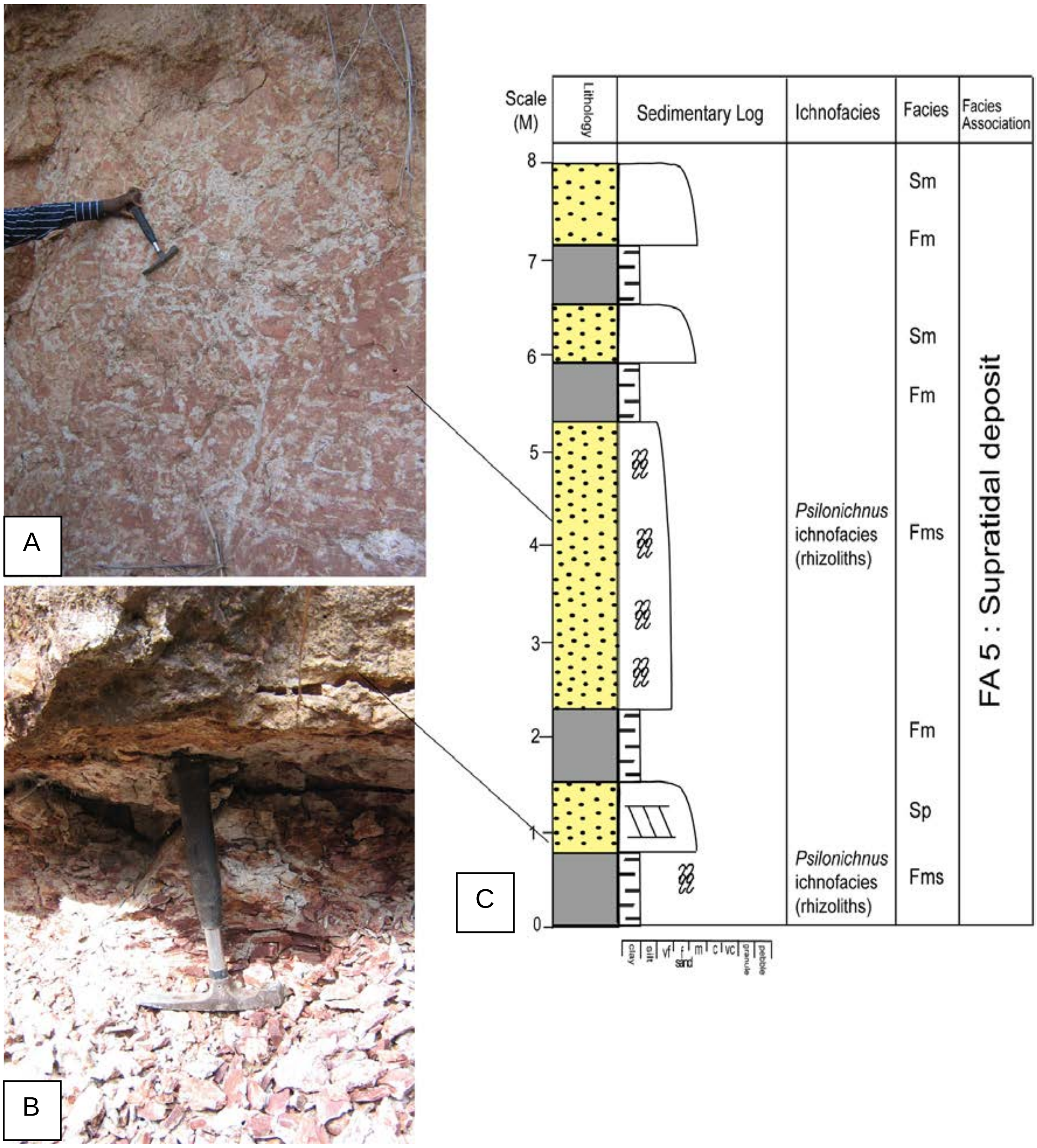


Figure 5.18 (A, B). Outcrop exposures of variegated facies observed at Ezi-Umunya. (B). Shows the contact between the mottled mudstone below and sandstone unit above. (C) Litholog of Ezi-Umunya Section (Nanka Formation of Ameki Group)

FA 6 (Tidal Sand bar)

Facies association 6 is the thickness facies association in the study area. The facies association 6 consists of tabular cross-bedded sandstone facies (Sp), current rippled laminated sandstone (Sr), bioturbated sandstone facies (Sb), sigmoidal cross-stratified sandstone facies (Sx) and variegated sandstone facies (Fmc). It has low to high diversity and abundance of *Skolithos* and *Cruziana* ichnofacies. The outcrop sections of the outer estuarine sand bars are observed at Ishiagu (Figure 5.19) Awka (Awka cross-stone) (Figure 5.20) and Ifite-Awka (Figure 5.21). The lateral extents of the exposed sandstone bodies vary from 150 m to 400 m, (with maximum extent of up to 1,500 m from topographic map) and their dimensions vary from 70 m to 360 m. This facies association is characterised by high energy sand deposits and a very low suspended sediment concentration; the best examples of the tidal sand bars are in the Ishiagu section (outer estuarine tidal sand bar deposit) and the Ugwu-Akpi quarry section (inner estuarine tidal sand bar deposit).

Outer estuarine tidal sand bar

Ishiagu Section

The outcrop occurs in a sandstone quarry at Ishiagu (SNI 2), which is about 6km from Amowbia. It is an amalgamated sandstone body about 25 metres thick (Figure 5.19). The sandstone is characterized by large-scale planar tabular cross-beds, low-angle cross-beds, sigmoidal cross-beds, trough cross-beds and reactivation surfaces, with sharp bounding surfaces. Cosets of small-scale planar cross-beds with tangential toesets are common. Less common are mud draped foresets and mud flasers in the trough, forming flaser bedding. The cross-beds all trend in a south-west direction with an average of about 220° (within 180°-250°) and a dip angle of 10° to 20°. Some of the sandstone beds have few mud clasts at the base of the bed unit.

Certain horizons are sparsely to moderately burrowed with mainly *Skolithos* ichnofacies such as *Diplocraterion, Skolithos, Arenicolites, Paleophycus* and escape traces. The sandstone consists of quartz-rich grains, well to moderately sorted, medium to very coarse grained, and creamy to light brown coloured with scattered pebbles of extraformational clasts (such as plant fragments). The upper part of the sandstone is medium to coarse grained and characterized by wavy bedding, mud bands, horizontal bedding and liesengang structures. It fines to very fine rippled sandstone with pinstripe bedding, slightly burrowed with *Diplocraterion,* and *Planolites* burrows, and capped by mudstone with siltstone lenses at the base to form lenticular bedding. A normal fault is observed at the topmost segment of the outcrop.

The sharp bounding surfaces, planar cross-beds, reactivation surfaces, medium to coarse grain-size grains, well to moderately sorted sands, sparse trace fossils, as well as the height and length of the sandbodies suggests deposition as tidal sand bars in a subtidal environment (Dalrymple et al, 1990; Plink-Björklund, 2005; Pontén and Plink-Björklund, 2009; Yeo and Risk, 1981). These large tidal bars are common at the seaward end of macrotidal estuaries (Dalrymple et al., 1990; Plink-Björklund, 2005). The dominant seaward (ebb dominated) paleocurrents of cross beds, high dip angles of cross beds in the sandbodies suggest a headward migration of swatchways which is common in the central channel and its steep flanks (Dalrymple et al., 1990). Trace fossils are sparse throughout the sand bars deposits, and this is most probably due to rapid migration of the large bedforms (Yeo and Risk, 1981; Dalrymple et al., 1990). Mud deposition formed as mud drapes and mud chips/pebbles are minimal on the sand bars probably due to limited slack water periods (Dalrymple et al., 1990) and high migration rates of the bedforms (Plink-Björklund, 2005).

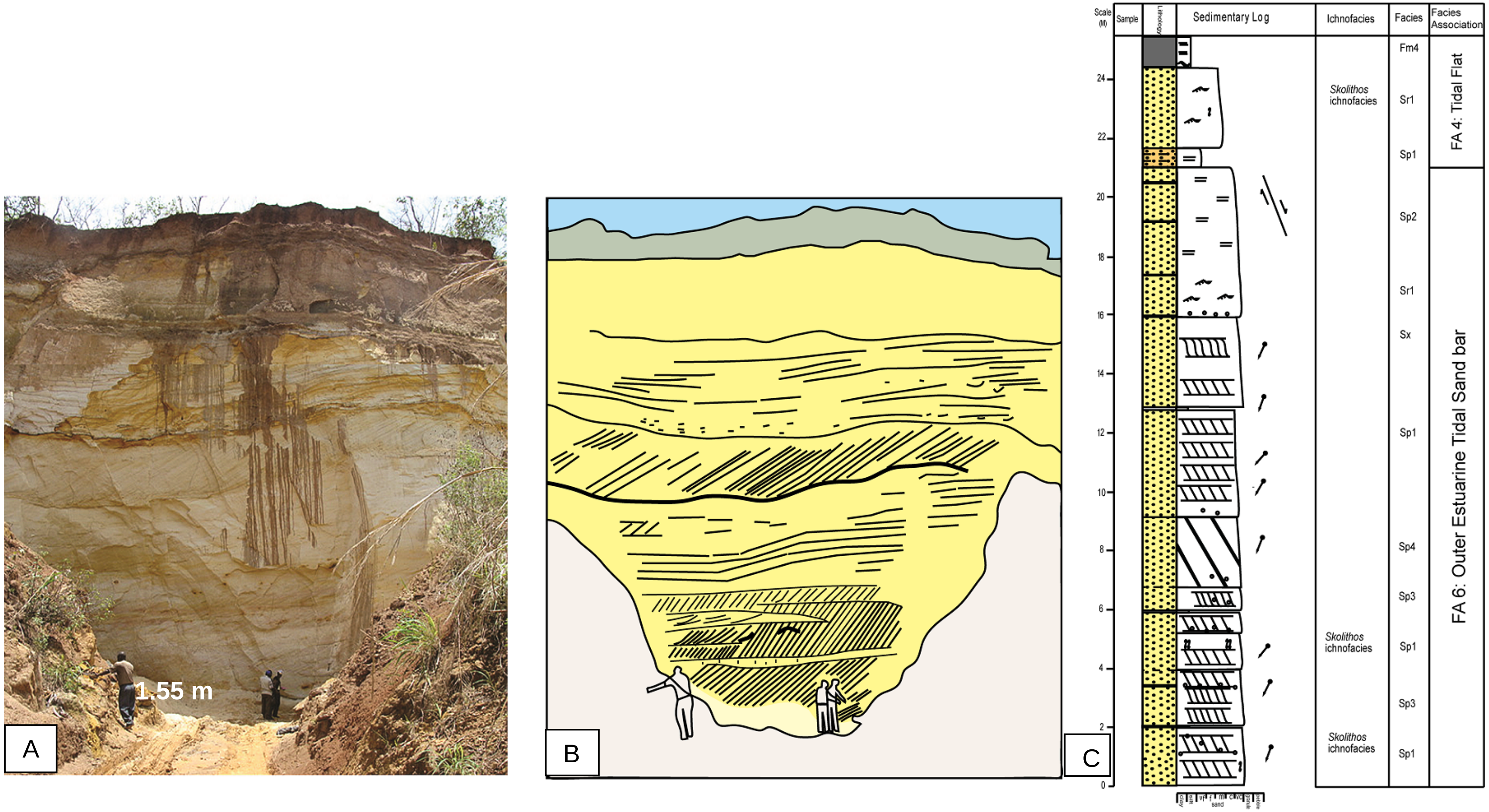


Figure 5.19 (A). Outcrop photograph of an amalgamated sandstone body observed in Ishiagu. (B). Schematic diagram showing the cross-stratified sandstone interpreted as an outer estuarine tidal bar deposit. (C) Litholog profile of the Ishiagu Section (Nanka Formation of Ameki Group).

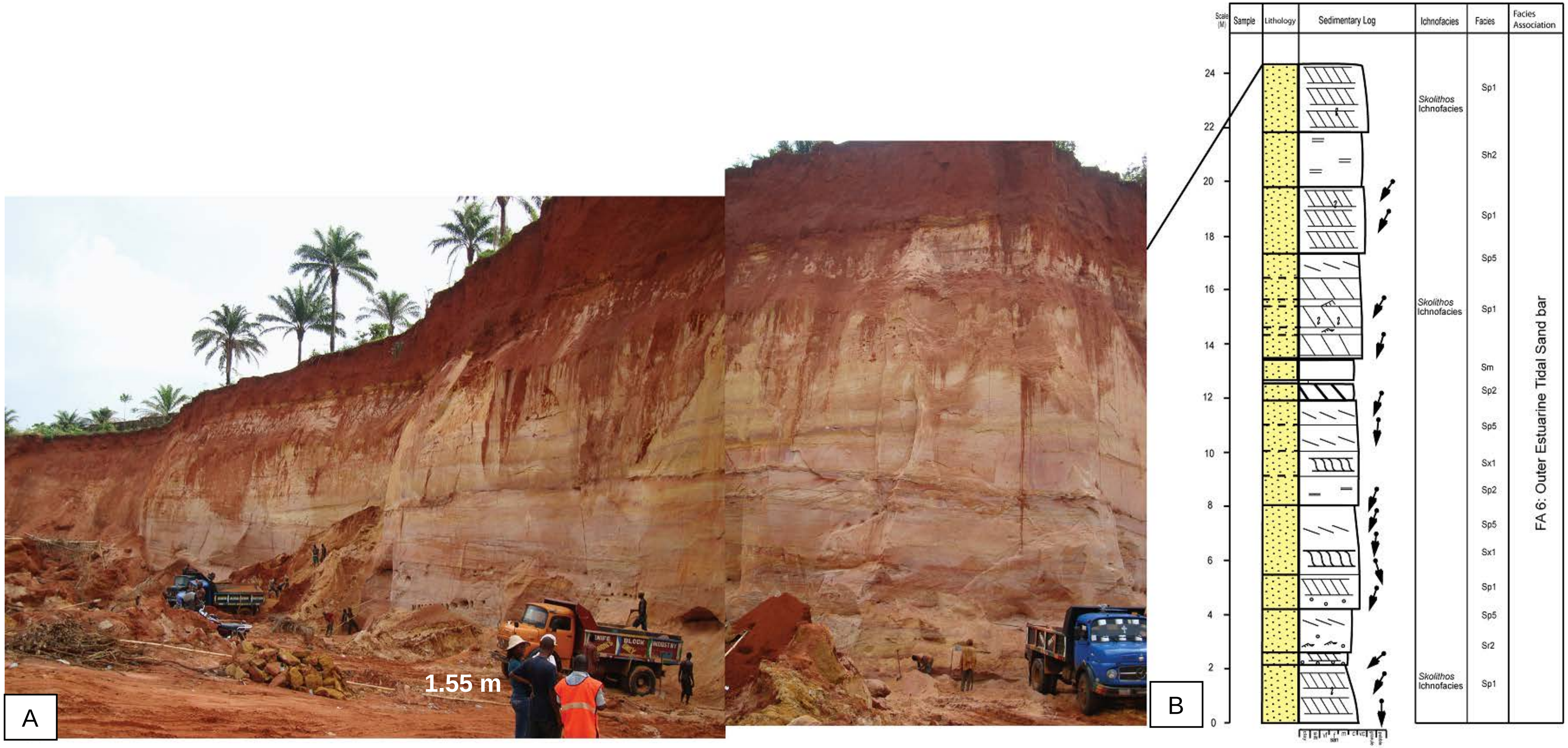


Figure 5.20 (A). Outcrop photograph of an amalgamated sandstone body observed at Awka. (B). Litholog profile of the Awka Cross-sand Section (Nanka Formation of Ameki Group).

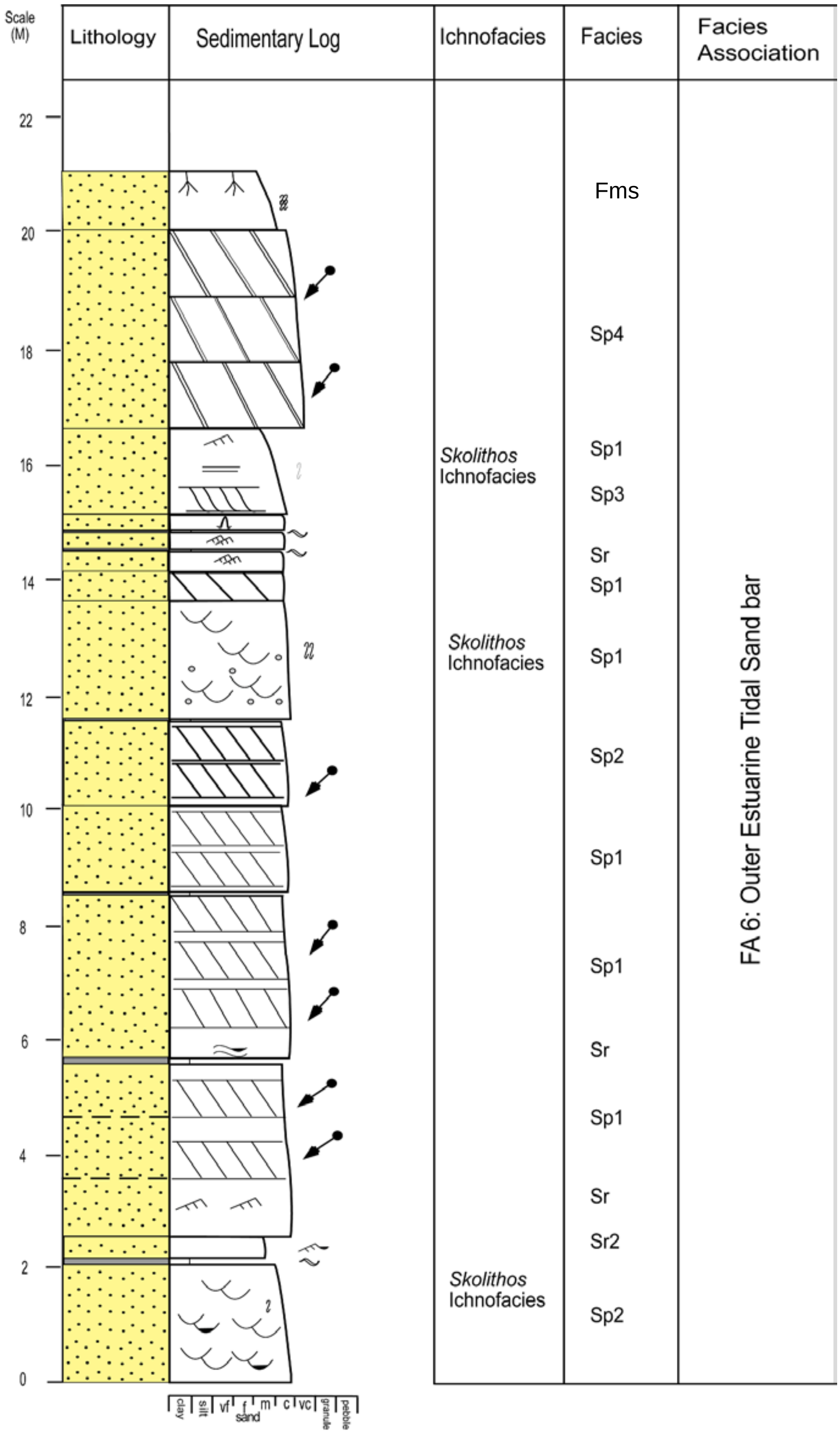


Figure 5.21. Litholog profile of Ifite-Awka section (Nanka Formation of Ameki Group).

Inner estuarine tidal sand bar

Facies association 5 is consists of massive sandstone (Sm), bioturbated sandstone facies (Sb) and current rippled laminated facies (Sr). It is observed at Ugwu-Akpi quarry, Enugwu-Ukwu (SNI 1) (Figure 5.22).

Ugwu-Akpi quarry II Section

Overlying the fining upward sandstone unit (interpreted as tidal channel deposits), are heavily mineralized sandstone, with ferruginised ironstone and liesegang bands (reddish coloured), that have disrupted the original sedimentary fabric of the sandstone (Figure 5.23). This sandstone unit is light brown to deep yellowish brown coloured with grain size varying from fine to medium grained. The sandstone unit is well burrowed and the burrows continued to the succeeding pebbly unit characterised by quartz pebbles and mud clasts. The pebbles are generally aligned in a NW-SE direction, and they vary in size from subrounded to angular. This pebbly horizon is interpreted as a transgressive lag reflecting a tidal ravinement surface of erosion. The sandstone is clayey, poorly sorted, slightly consolidated and moderately to strongly burrowed, with a bioturbation index of 4-6. The physical sedimentary structures are completely obliterated (Figure 5.24). Recognisable burrows are the horizontal tunnels and vertical shafts of *Ophiomorpha nodosa, Planolites, Skolithos, Arenicolites, Paleophycus.* This high density of Ophiomorpha burrows is typical of a shallow, protected area (Frey et al., 1978; Pearson et al., 2012) and suggests marine influence.

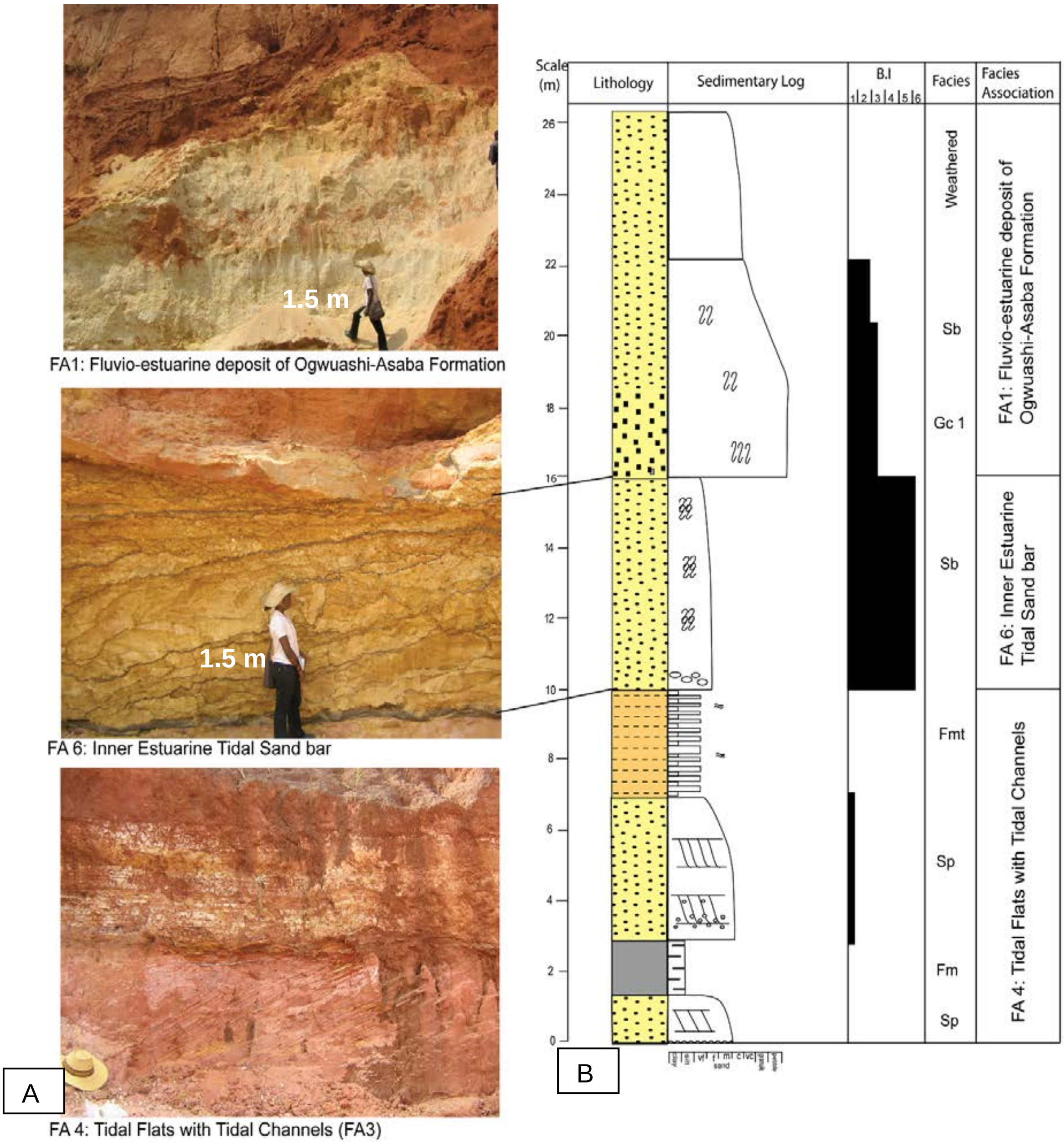


Figure 5.22 (A). Outcrop exposures at Ugwu-Akpi quarry. (B). Composite log of Ugwu-Akpi.

Figure 5.23. Bioturbated fine grained sandstone, completely disrupted by mineralisation to form ferruginised ironstone and liesegang bands.

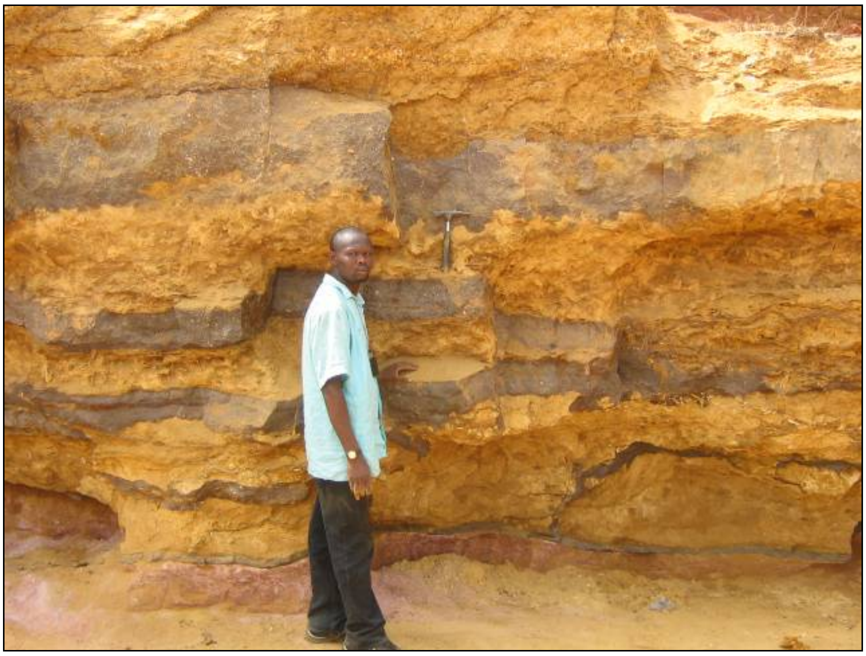


Figure 5.24. Bioturbated fine grained sandstone, completely obliterated by *Skolithos* ichnofacies.

FA 7 (Estuarine Embayment)

Facies association 7 is restricted to the south-eastern part of the study area and forms the Ibeku Formation (formerly known as Ameki Formation). It is characterised by mudstone, shale, siltstone and nodular mudstone facies. The mudstone and shale facies cover an areal extent of about 100km^2 and contains abundant body fossils and microfossils. This facies association has very low diversity and low to moderate abundance of trace fossils. Outcrops were observed at Ameke, Ajata-Ibeku, Ohuhu Umuahia, Ude-Ofeme, and Umuezeoma-Uhuala (Figure 4.1B).

The type localities of this facies association have been described extensively by Arua (1991), Arua and Rao (1987) and Oboh-Ikuenobe et al., (2005). In this research, the lithofacies are classified into fossiliferous mudstone and shale, gypsiferous shale, tide to wave reworked siltstone, claystone and nodular mudstone.

The fossiliferous mudstone/shale facies forms extensive deposits in the Ibeku Formation. Outcrop sections at Ajata-Ibeku (SIA 3) (Figure 5.25) and Umuezeoma-Uhuala (SAA 3) (Figure 5.26) are characterised by sparsely burrowed, micaceous dark grey shale and mudstone with abundant body fossils such as well ornamented gastropods and bivalves, shark teeth and phosphate deposits. Low diversity of depauperate *Cruziana* ichnofacies which include diminutive *Teichichnus* and *Planolites* were observed in the lower part of shale unit at Ajata-Ibeku.

The dominance of the ornamented gastropod (*Turritella*) and bivalves (*Glans*) suggest a shallow marine setting (Arua, 1986). Arua (1986) and (1991) also noted the presence of foraminifera, ostracods, corals and scaphopods in this lithofacies which indicate warm, tropical, normal to near normal shallow marine. Limestone concretions about 30 cm thick occur in the fossiliferous shale. The limestone is micritic and contains no trace fossils. The micritic nature of the limestone may imply a diagenetic origin.

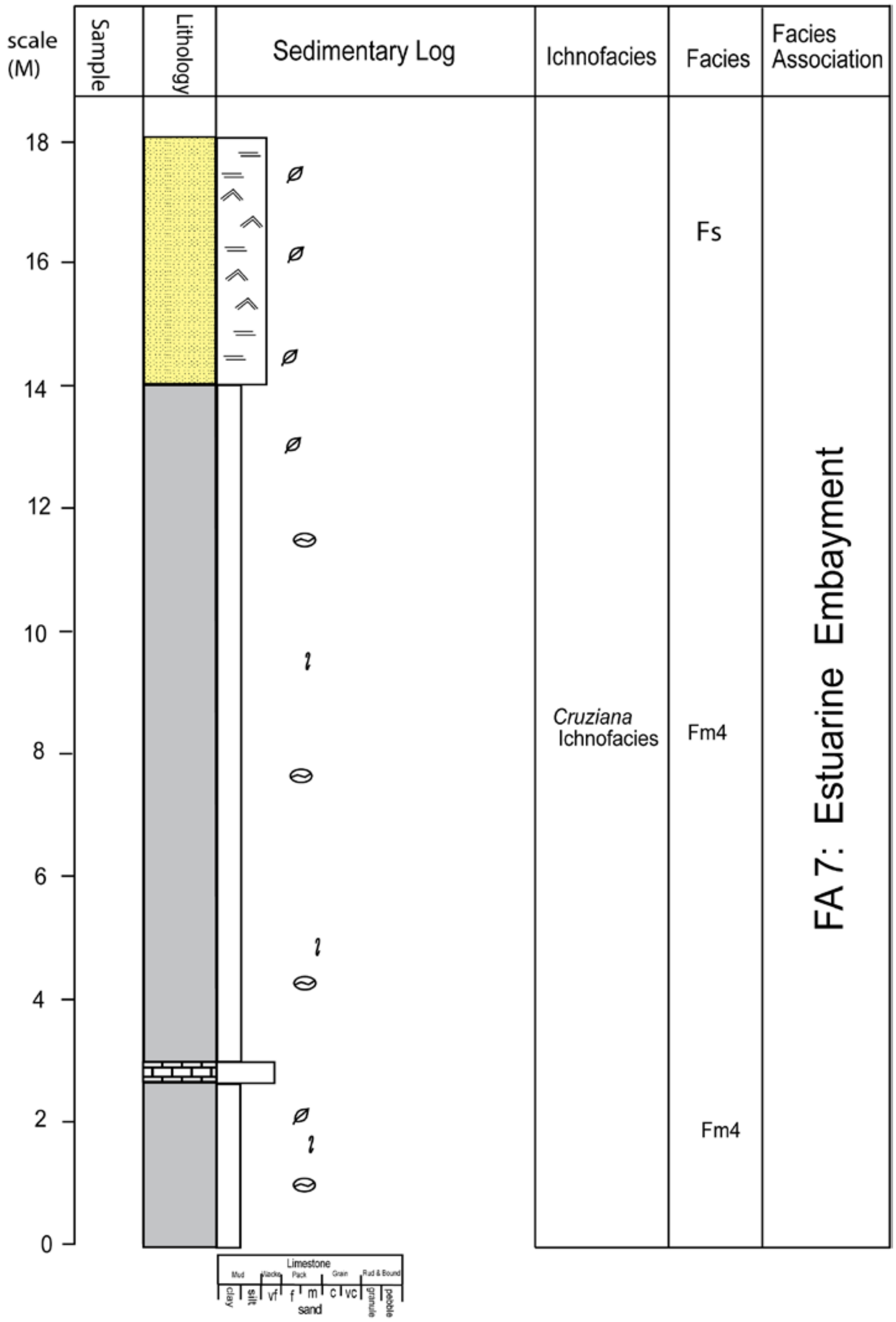


Figure 5.25 Litholog of Ajata-Ibeku Section (Ibeku Formation of Ameki Group).

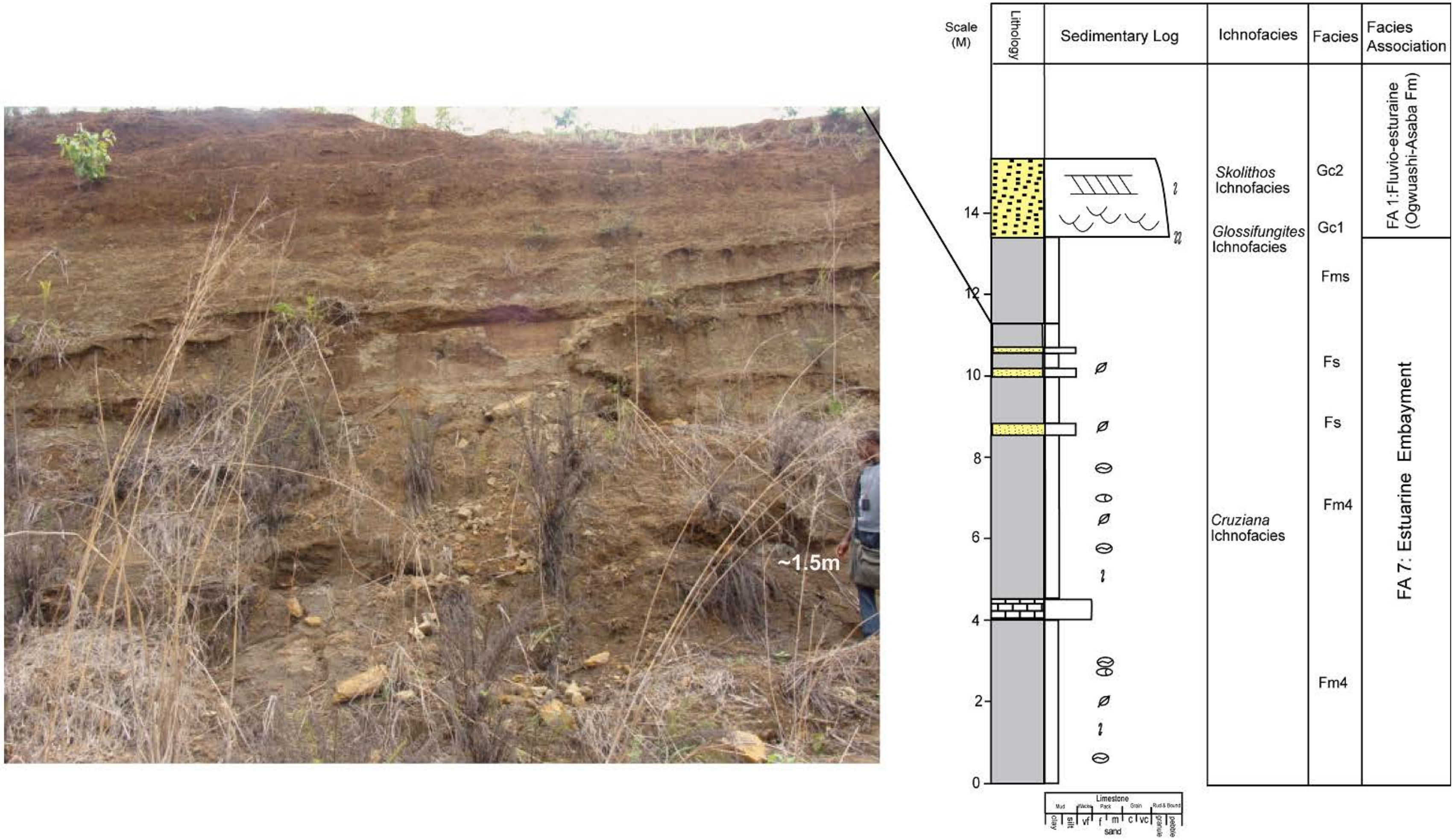


Figure 5.26 (A) Outcrop section at Umuezeoma-Uhuala. (B) Litholog of Umuezeoma-Uhuala Section (Ibeku Formation of Ameki Group).

Arua (1991) discovered a trace fossil (*Teredolites longissimus*) in calcareous concretions which occur abundantly in lower fossiliferous shale facies at Umuahia, along the Umuahia Bende road.

Gypsiferous shale facies occurs in Ude-Ofeme (SOF 3), where it is characterised by diagenetic gypsum crystals, large petrified logs, lignite fragments, amber, and bored wood fragments with *Teredolites* ichnofacies (Figure 3.22). The gypsiferous shale is greyish black to brownish black in colour and it is underlain by pebble lag, interpreted as a transgressive ravinement surface; followed by about 50-80 cm mottled mudstone probably resulting from intense bioturbation. The presence of petrified logs, bored woods, lignite and amber fragments suggest affinity to an estuarine environment and a mangrove-rich environment such as tidal creeks, tidal flats and hinterland margins (Woodroffe et al., 1988; Arua, 1991).

The siltstone facies consists of a rhythmic alternation of well-sorted micaceous greenish coloured silts, light grey finer silt and dark grey organic-rich laminae. The rhythmites are millimetre-to-centimetre scale and exhibit parallel lamination. Wave reworked undulating lamination is observed at some intervals in the Ohuhu Umuahia section (SAA 1) along the Umuahia-Okigwe expressway. This siltstone facies also occurs in Ajata-Ibeku and in Umuezeoma-Uhuala, at the uppermost part of the outcrops where it succeeds the dark gray fossiliferous shale. The silty layers indicate deposition during combined flood and high-tide periods in a rainy season when suspended-sediment load was high, whereas the organic laminae represent marsh vegetation which formed in the dry season and was gradually covered as sedimentation from suspension continued (Gibson and Hickin, 1997). The interlamination of siltstone and organic-rich laminae is interpreted as tidal flat deposits within an estuarine embayment.

Nodular mudstone caps the Ibeku Formation at Umuezeoma-Uhuala. The 80-120 cm thick mudstone is variegated in colour (grey, purple, yellow and reddish brown) and shows no definite internal structures. The nodular mudstone grades downward into a light grey coloured claystone. The claystone is structureless indicating homogeneous, continuous and probably rapid deposition of clay particles from suspension (Backert et al., 2010). The claystone probably reflects deposition on a mud flat within a tidal flat.

The nodular structure of the mudstone suggests bioturbation by roots and the variegated nature indicates subarieal exposure. This implies that the nodular mudstone represents a paleosol within a supratidal setting.

Although Arua (1991) interpreted the Ameki Formation (now Ibeku Formation) as the deposits of a lagoonal environment; she acknowledged the presence of estuarine and mangrove elements which may have drifted into the lagoon. Arua and Rao, (1987) also suggested that the dark grey shale was probably deposited in a restricted embayment under partly stagnant conditions of the inner lagoon. Detailed facies analysis suggests a tide-dominated estuarine setting for the Ameki Group which rules out a lagoonal setting and it is alternatively suggested that the setting was an estuarine embayment in the transgressive Ibeku Formation deposit.

5.3.2 Facies Architecture

Five major depositional architectural elements are identified in the fluvial-estuarine strata based on the grain textures, sedimentary structures, geometry, palaeocurrents, and lateral and vertical arrangement of lithofacies (Miall, 1985, 1986). These architectural elements include channel deposits, lateral accretion deposits, gravel bars, sandy cross-stratified and heterolithic deposits (Figures 5.2; 5.27). Internally, these elements are segmented by lower-order bounding surfaces that separate individual lithofacies units (Taylor and Ritts, 2004).

Channel deposits

Channel deposits are observed in a number of outcrops in the study area and are usually associated with fluvial or tidal channels and tidal flat environments (Figure 5.2); they exhibit different internal architectural elements in these environments. The channel deposits include isolated channel and amalgamated channel bodies.

Isolated channels occur either as minor tidal channels or tidal creeks incised into or enclosed by tidal flat deposits or subtidal deposits. The minor tidal channels are enveloped by tidal mud flat deposits. They occur as simple, single-storey sandstone bodies and contain no internal scour surfaces. They are characterised by planar cross-beds (Sp1 and Sp2), structureless sandstone facies (Sm), and trough cross beds (St1). They have maximum thickness of 80cm and pinch-out laterally, ranging from 20 to 50 m wide. Basal bounding surfaces are erosional, gently curved and concave-up whereas upper bounding surface are sharp and planar (Figure 5.27). A high W/T ratio of more than 15 (Friend, 1983) defines them as sheet-like bodies with a broad lenticular geometry. The characteristics of these single-story channelized sandstone bodies suggest a single episode of sedimentation whereby the channel was plugged by sand transported during relatively high stage flow and sand spilled laterally a few metres to from wings (Friend et al., 1979).

The tidal creek deposits are characterised by symmetrical and asymmetrical shaped concave-up sandstone bodies with concentric and asymmetrical infill. Sediment infills are fine grained bioturbated sandstone or heterolithic sand/silt/mud. The thickness ranges from 60 cm to 1 m, whereas the widths vary from 8 to 15 m. Basal bounding surfaces are sharp, concave-up and the upper bounding surface may be planar or convex. The sand-filled tidal creeks can be defined as fixed channel bodies with a low W/T (>5) implying a narrow ribbon geometry (Gibling, 2006).

Concentric fills reflect the progressive filling of a channel by deposition on the channel floor and accretion on the banks, reducing the cross-sectional area (Gibling et al., 1998; Gibling, 2006). The heterolithic units suggest sediment deposited by vertical aggradation at the base of tidal creeks either as a response to relative sea level rise or from changing hydraulic conditions related to channel cutoff (Dashgard and Gingras, 2005).

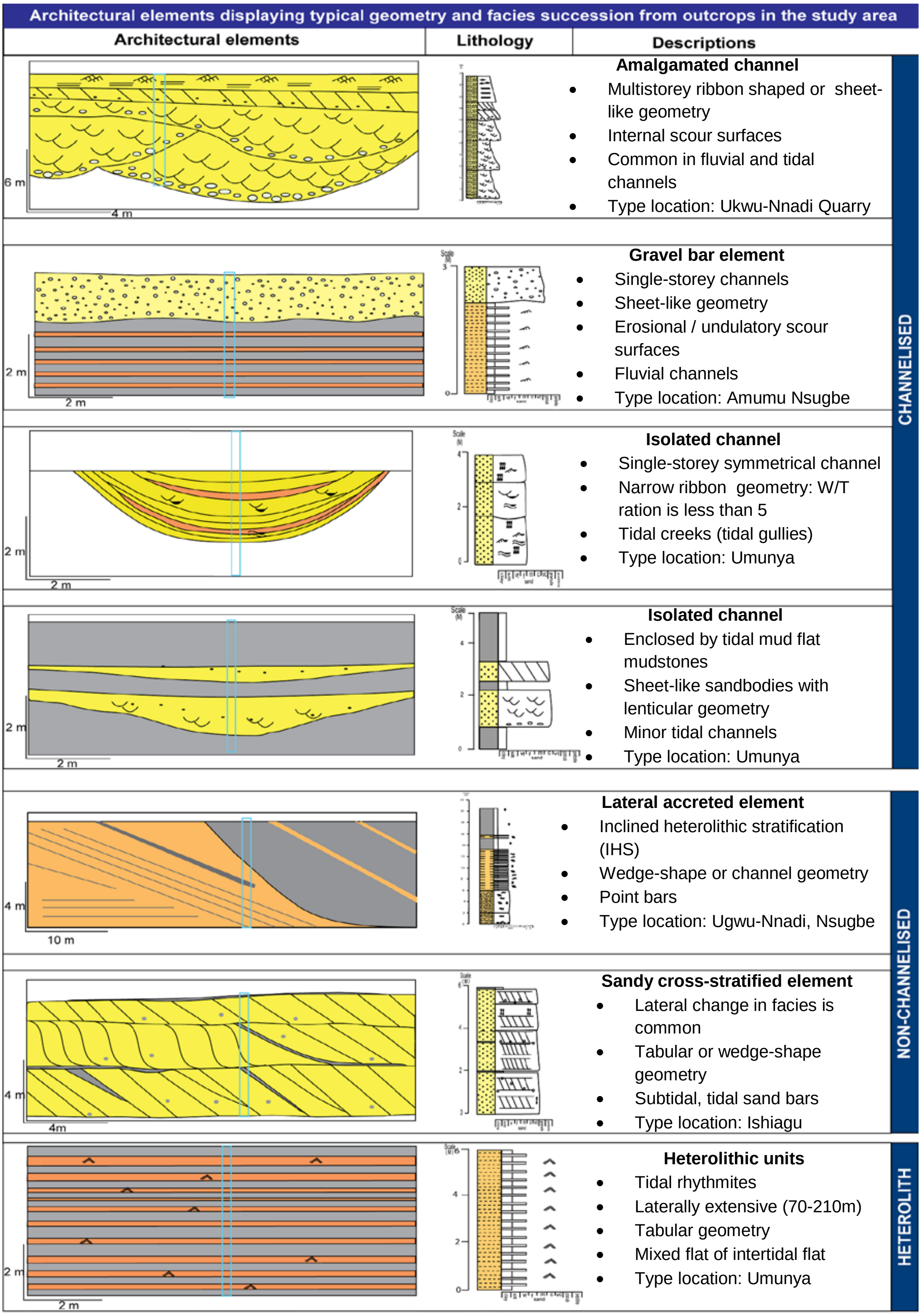


Figure 5.27. Architectural elements from the Ameki Group indicating the sand body geometry and their corresponding facies associations.

Amalgamated channels are prominent in both fluvial deposits and in tidal channel deposits. They occur as multichannel sandstone units with internal scoured surfaces. Individual sandbodies vary in thickness from few centimetres (20 cm) to few metres (4 m) thick. They are amalgamated to form channel complexes with minimum thicknesses of 2 m and maximum thicknesses of about 30 m. Wings are well preserved and observed mainly in the tidal channel deposits (Figure 5.27). The multi-storey sandstone bodies are composed of stack sets, arranged into fining-upward packages and characterised by trough cross-beds (St1), planer cross beds (Sp1), horizontal beds (Sh) and ripple lamination (Sr). The lateral extent of the exposed sand bodies ranges from 60 to 170 m. Basal bounding surfaces are sharp, erosional and may contain a channel lag. Upper bounding surfaces are usually sharp and eroded when overlain by other channels or sharp and planar when overlain by non-channelized deposits. The individual sandstone facies within the amalgamated sandstone complex are bounded by lower-order bounding surfaces.

The fluvial channel complex deposit exposed at Ugwu-Nnadi has a W/T ratio 4.5 and is thus classified as a multistorey ribbon. The tidal channel deposit at Ogbunike toll gate is has a sheet-like geometry with W/T ratio >15. Amalgamated channel element represents the vertically stacked fills of a major channel belt (Friend, 1983; Ghazi and Mountney, 2009). The multistorey channels have been built by a succession of channel scour episodes, this may be as a result of a series of scour and fill events (Friend et al., 1979).

Lateral accretion (LA) deposits

The lateral accretion elements are characterised by mud breccias, mud blocks, non-inclined rippled heterolithic units and inclined heterolithic stratification that exhibits mm-dm thick sand and silt couplets and sand, silt and clay triplets. The entire succession shows a fining-upward pattern. The individual facies have sharp concave or convex basal and upper bounding surfaces. The inclined foresets of the inclined heterolithic stratification (IHS) dip at 10° to 15° in a direction perpendicular to the channel axis. Thickness varies between 5-15 m and lateral dimension ranges between 80-120 m. The lateral accretion elements have wedge-shaped or sheet-like geometry (Figure 5.2; 5.27).

The lateral accretion deposits with the inclined heterolithic stratification are interpreted to represent point bars (Ghazi and Mountney, 2009; Rebata et al., 2006) within tidally influenced fluvial systems (Thomas et al., 1987; Nouidar and Chellai, 2001). The occurrence of the low angle inclined foresets perpendicular to the channel axis or transport direction supports a point bar origin (Nouidar and Chellai, 2001).

Gravel bar deposits

The gravel bar deposits occur at Amumu Nsugbe within a single-story channel with maximum thickness of 1 m and lateral dimension of over 100 m. No obvious stratification is observed in the clast-supported conglomerate (Figure 5.5). The basal bounding surface is characterised by an erosional and undulatory scour surface. The gravel bar element has a high W/T ratio >15 indicating a sheet-like geometry.

The gravel bar deposit may have been formed as a result of stream channel migration or switching of a single major channel scour (Miall, 1985). It is interpreted to represent a longitudinal bar forming sheet-like bodies that is characterised by traction-carpet sedimentation (Collinson et al., 2006).

Sandy cross-stratified deposits

The sandy cross-stratified deposits are most common in the subtidal zone and in tidal sand bars deposits. They are characterised by a fining upward motif, exhibiting coarse to fine grained sandstone and isolated sets or cosets of planar-cross beds (Sp1, Sp2), sigmoidal cross-beds (Sx1, Sx2), horizontal beds and ripple laminated facies in a variety of vertical successions. These tidal bar sand deposits are characteristically coarse grained and reactivation surfaces are common. Lateral changes of structures from sigmoidal cross beds to ripple lamination are observed in the subtidal deposits.

Paleocurrent data shows a unidirectional trend for the sand bodies and the orientation of the cross-beds is parallel the paleoflow direction (Figure 5.4C,D). The thickness of the sandy cross-bedded element varies between 4 to 20 m, while the individual bed-sets is 0.4 to 1.2 m thick. The lateral extent of the sandy bedform element varies between 80 to 250 m. These elements are characterised by tabular-, sheet-like or wedge-shaped sandbodies and their W/T ratio exceeds 15. Basal and upper bounding surfaces are sharp and erosive. Lower order bounding surfaces that segment individual bed-sets are sharp and either erosive or non-erosive.

These elements represent the migration of dune-scale bedforms on either mid-channel bars in the fluvial deposits (Ghazi and Mountney, 2009) or middle-upper estuarine environments for the tidal deposits. Lateral changes from cross bedding to ripple lamination reflect a reduction in the scale of the cross bed sets, which probably signify a local decrease in flow velocity and channel depth. The tabular- or wedge-shaped geometry of the sandy cross-stratified elements probably signifies the presence of straight-crested dunes deposited during high discharge events (Ghazi and Mountney, 2009).

Heterolithic units

The heterolithic units are tabular and relatively extensive, extending laterally for between 70 and 210 m. The internal architecture consists of thin (2 mm to 50 cm thick) continuous to discontinuous sheets of micaceous fine grained sandstone alternating with mm-scale discontinuous lenses of mudstone and mud laminae, which stack vertically to produce a maximum of about 6 m thickness heterolithic units. Basal and upper bounding surfaces may be sharp and ferruginised or gradational. The element exhibits wave-ripple lamination, current-ripple lamination, parallel lamination and flaser bedding.

The occurrence of repetitive alternation of mm-scale to cm-scale fine grained sandstone with mm-scale mudstone is interpreted as tidal rhythmites in both modern and ancient tidal sediments and is typical of an intertidal flat environment (Fan and Li, 2002; Fenies and Tastet, 1998; Hori et al., 2001; Stupples, 2002; Kvale et al., 1995).

5.3.3 Clay Mineralogy

Introduction

The fourteen mudrock samples analysed from sedimentary rocks of the Ameki Group (Figure 5.28) show variations in whole mineral contents. Clay and non-clay minerals are listed for the Nsugbe Formation, Nanka Formation and Ameki Formation. Samples from Nsugbe and Nanka formations exhibit a high content of kaolinite and relatively moderate content of illite (Appendix C5.2). Palygorskite is negligible in the Nanka Formation; montmorillonite is completely absent in the samples. Goethite is only limited to samples SUMY-2 and SUMY-4, though in minute quantities. The non-clay minerals present are dominated by quartz. Nanka Formation samples show low concentration of microcline and siderite. Pyrite, gypsum and orthoclase presence are negligible. Table 5.1 shows the summary of the clay and non-clay mineral suites in the Ameki Group. Appendix C5.3 shows the X-ray patterns of representative samples, exhibiting clay minerals as well as other non-clay minerals.

Samples from Ibeku Formation show relatively high occurrence of kaolinite; montmorillonite and mixed layer illite are well represented, though they are very low in some samples (Appendix C5.2). Palygorskite is also negligible in the Ameki Formation. The non-clay minerals vary in occurrence with the dominant mineral being quartz. Other minerals such as pyrite, microcline, orthoclase, albite, gypsum and graphite vary in occurrence and distribution from moderate to very low mineral counts. Calcite, stilbite and siderite concentrations are negligible.

Results

The results (Table 5.1; Appendix C5.2) show the variation in the clay mineral type and distribution in the Nsugbe Formation, Nanka Formation and Ibeku Formation. Only two

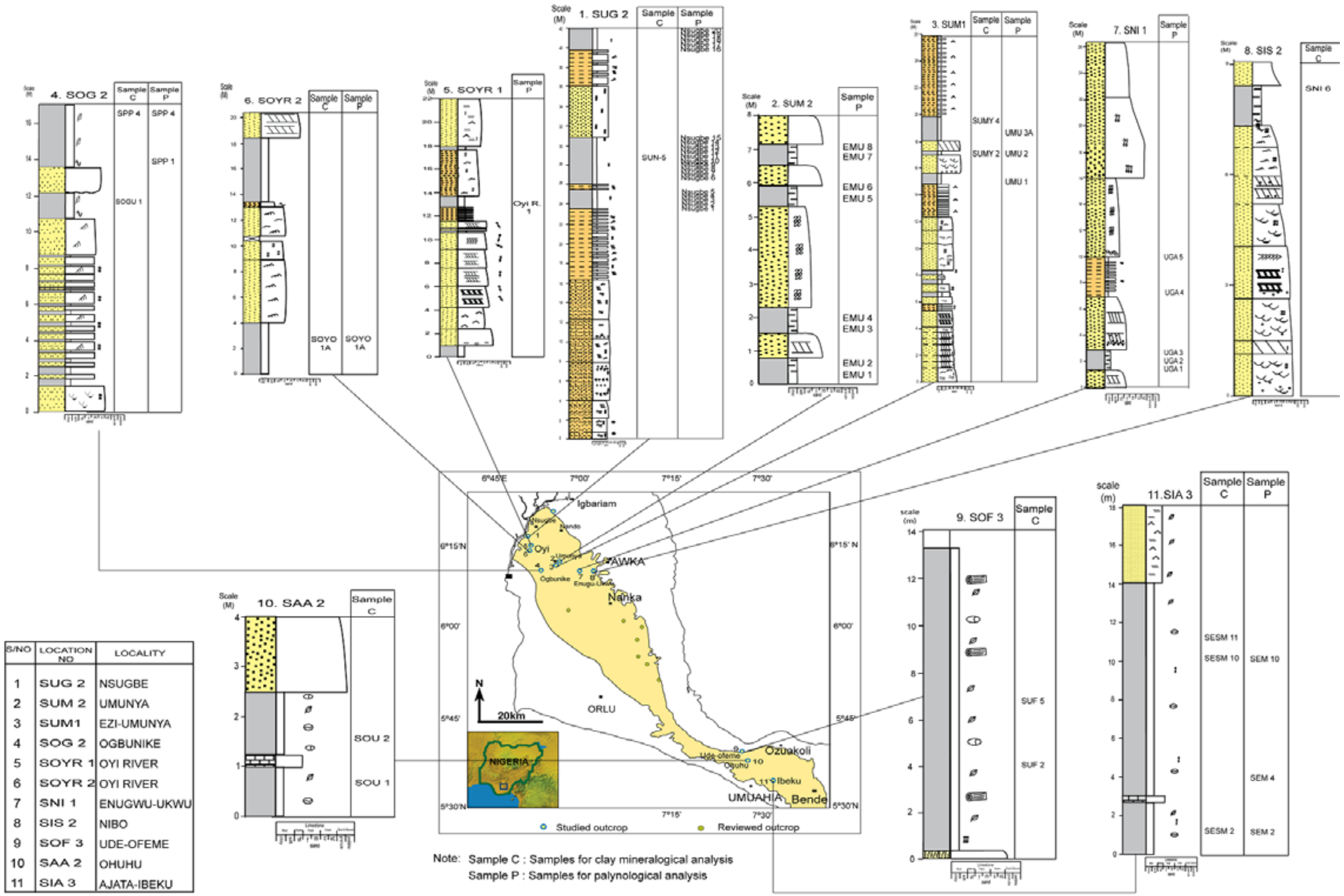


Figure 5.28. Outcrop location of selected samples from Ameki Group for clay mineralogy and palynologic analysis.

clay minerals were observed in the Nsugbe Formation; the principle clay mineral is kaolinite (50.8%), followed by mixed layer illite (16.5%). The main occurring mineral in the Nanka Formation is also kaolinite ranging from 66% to 79% in concentration. This is followed by mixed layer illite with a low range of 3% to 8%. Goethite and palygorskite are negligible, occurring below 1.1%. Clay minerals such as montmorillonite and chlorite are obviously absent in Nanka Formation.

Kaolinite still remains the primary clay mineral in the Ibeku Formation though in a lower concentration than the Nanka Formation. The kaolinite concentration varies between 36% and 57%. The concentration of montmorillonite and mixed-layer illite in the Ibeku Formation varies from 0 to 12%. The non-clay minerals present are diverse, though the result (Table 5.1; Appendix C5.2) shows they are not distributed though out the formation. The concentration of quartz mineral is high (6.5% to 22%). Other non-clay minerals such as microcline, orthoclase, albite, gypsum and graphite are well represented, whereas siderite, stilbite, chlorite, rutile and calcite are poorly represented.

Interpretation

The common occurrence of kaolinite in the Paleogene sediments indicates the stability of the mineral. Kaolinite occurs more in than Nanka Formation Formation of Ameki Group than in the Ibeku Formation; this probably signifies more input of terrestrially derived materials in the sandstone members. The predominance of kaolinite minerals over illite and chlorite suggest a tropical climate condition (Ehrmann et al., 1992) during the Paleogene period similar to today in the study area (Hoque, 1977; Obi, 2000). The high abundance of kaolinite and mixed layer illite in the Nanka Formation most probably suggests a terrigenous input (Thiry and Jacquin, 1993). The presence of illite with chlorite occurring in minor amount may suggest an influence of marine waters in Ibeku Formation; as kaolinite easily transforms to illite and/or chlorite in marine conditions (Agumanu and Enu, 1990). Velde (1985), Ehrmann (1998), Ehrmann et al., (2005) and Weaver (1989) noted that the clay minerals such as kaolinite and illite are indicative of source areas. High concentration of kaolinite signifies intense chemical weathering of commonly granitic rocks, basic rocks and lateritic soils. Illite is common in pelitic sediments, altered acidic volcanic rocks, hydrothermal alteration of acidic rocks, soils and physical weathering products of these rocks.

The occurrence of montmorillonite is more restricted to the Ibeku Formation (Appendix 5.2), though in low concentrations. Montmorillonite is Al-rich smectite; it is formed commonly by alteration of eruptive or basic igneous rocks or occurs in sedimentary product derived from igneous rocks (Deer et al., 1992). Thiry and Jacquin (1993) suggested that the presence of smectite and mixed layer clays suggest open marine conditions. Therefore, the presence of montmorillonite and mixed layer illite suggests a strong influence of marine conditions in the Ibeku Formation.

The clay mineral composition and distribution in the tidal dominated estuarine system in the study area is similar to those of the estuaries along the east coast of the United States, though the abundance of the clay minerals differ (Weaver, 1989). The seaward portion of the estuaries has increasing illite and chlorite content from continental shelf due to the action of tidal currents while the southern estuaries are dominated by mixtures of kaolinite and montmorillonite from the drainage basin (landward).

Table 5.1. Summary of the clay and non-clay mineral assemblages in the Ameki Group.

Mineral (%)	Nsugbe Ss.	Nanka Formation	Ibeku Formation
Nontronite-15 A	0	<2.2	<6.7
Kaolinite	50.8	49-79	36-57
Illite	16.5	3-28.5	<11.6
Palygorskite	0	<0.5	<0.7
Goethite	0	<1.1	0
Chlorite	0	0	<1.2
Quartz 2%	32.6	9.5-25.5	6.5-21.6
Microcline	0	<2.5	<13.7
Orthoclase	0	<0.5	<18
Albite	0	0	<9.1
Calcite 1%	0	0	<0.8
Gypsum	0	<0.4	<12.4
Rutile	0	<0.2	<3.9
Graphite	0	0	<7.6
Pyrite	0	<2.2	<16
Stilbite	0	0	<4.2
Siderite	0	<2.6	<0.4
Anatase	0	0	0

Legend

Clay minerals (rows Nontronite-15 A to Chlorite)

Non-clay minerals (rows Quartz to Anatase)

Ss. Sandstone

5.3.4 Palynological assemblages in the Ameki Group

Introduction

Outcrop samples from the Ameki Group (Figure 5.28) show very low counts of palynomorphs (Appendix C5.4; Table 5.2). Negligible to low counts of freshwater algal cysts, flowering plant pollen, spores and fungal remains occur in samples SPP-1, 2 and SOYO-1A, but phytoclasts and resins are abundant. SESM samples from the Ibeku Formation show low counts of dinoflagellates, acritarchs and foraminiferal linings (Table 5.2). Fresh water algal cyst, spores, pollen and fungal also occur in very low counts. Other components are pyrite, AOM, unstructured phytoclasts with some resin and structured phytoclasts.

Two distinct palynofacies are identified in the Ameki Group based on the presence and distribution of the palynomorphs.

Results and Interpretation

Assemblage type 1

The assemblage type 1 is very similar to palynological assemblage type 3 of the Imo Formation (Chapter 4) in terms of palynomorph counts, but the palynomorph species differ. The type 1 is recognised from sediments (SPP 1-4; SOYO-1A; Oyi River, UGA 1-5) in the Nanka Formation of the Ameki Group. Most samples have low counts of palynomorphs. The presence of freshwater algae, pollen, spores, fungal remains, cuticles, wood debris, foraminiferal lining and structured/unstructured phytoclasts (Figures 5.29; 5.31A, B) indicate strong terrestrial influence on the strata.

Table 5.2. Summary of the counted components of the palynolgical assemblages in the Ameki Group.

	Outcrop sample	
Formation	Nanka Sst	Ibeku Fm
Sample No		
Assemblage	1	2
Pollen and spores	<29%	16-51%
Freshwater algal cysts	<16%	<10%
Dinoflagellates	Barren	<10%
Acritarchs	<3%	9-13%
Forminiferal linings	<17%	6-16%
Fungal	<8%	<9%
Phytoclasts (structured, unstructured and resin)	<48%	20-47%
AOM	barren	abundant
Pyrite	common	abundant

Sst-Sandstone
Fm-Formation

Assemblage type 2

Type 2 recognised from SESM-2, -4 and -10 are typified by the presence of pyrite, AOM, unstructured phytoclasts with some resin and structured phytoclasts (Figures 5.30; 5.31C-E). Though the palynomorph count is low, the presence of dinoflagellates, acritarchs and foraminiferal test linings indicate marine influence. The relatively high abundance of spores with a low occurrence of pollen and fresh water algal cysts indicates terrestrial input. The marine setting is further supported by the presence of pyrite, AOM and unstructured phytoclasts.

Sedimentary facies analysis of this palynological assemblage considered the deposit to be of estuarine embayment (see section 5.3.1), where there is strong influence of marine condition and an influx of terrestrial material.

Conclusions

The two palynological assemblages (type 1 and 2) observed in the Ameki Group record relatively low counts of palynomorphs (Appendix C5.8). Some samples from the Nanka Formation are essentially barren while other samples show relatively low counts of freshwater algal cysts, flowering plant pollen, spore and fungal remains, with abundant resins. This palynological assemblage indicates terrestrial influence on the strata interpreted to be a tide dominated estuarine environment. The palynological assemblage 2 is limited to the Ibeku Formation. It is characterised by low counts of dinoflagellates, acritarchs and foraminiferal test linings with a high occurrence of pyrite, AOM and unstructured phytoclasts, which typifies marine conditions. The relatively high occurrence of spores with low counts pollen and fresh water algal cysts indicates terrestrial input into the estuarine embayment.

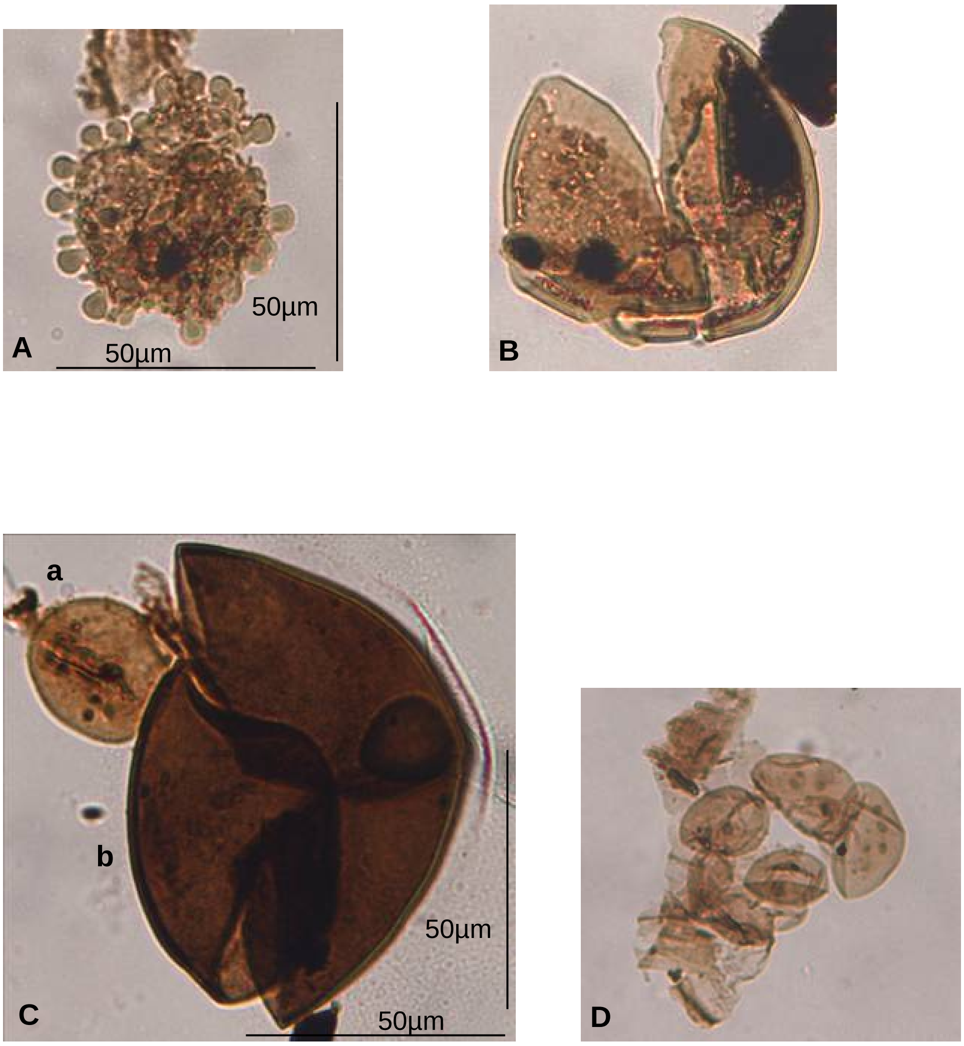


Figure 5.29. Palynomorphs from assemblage 1 (Nanka Formation Member of Ameki Group). A. Gemmate pollen. K45. SPP4 sample. B. Freshwater alga. S41/2. SPP-1 sample. C. (a) Fresh water alga type-1. Q34. SPP-4 sample. (b) Trilete spore. Q34/1. SPP-4 sample. D. Foraminiferal lining. F39/3. SPP-4 sample.

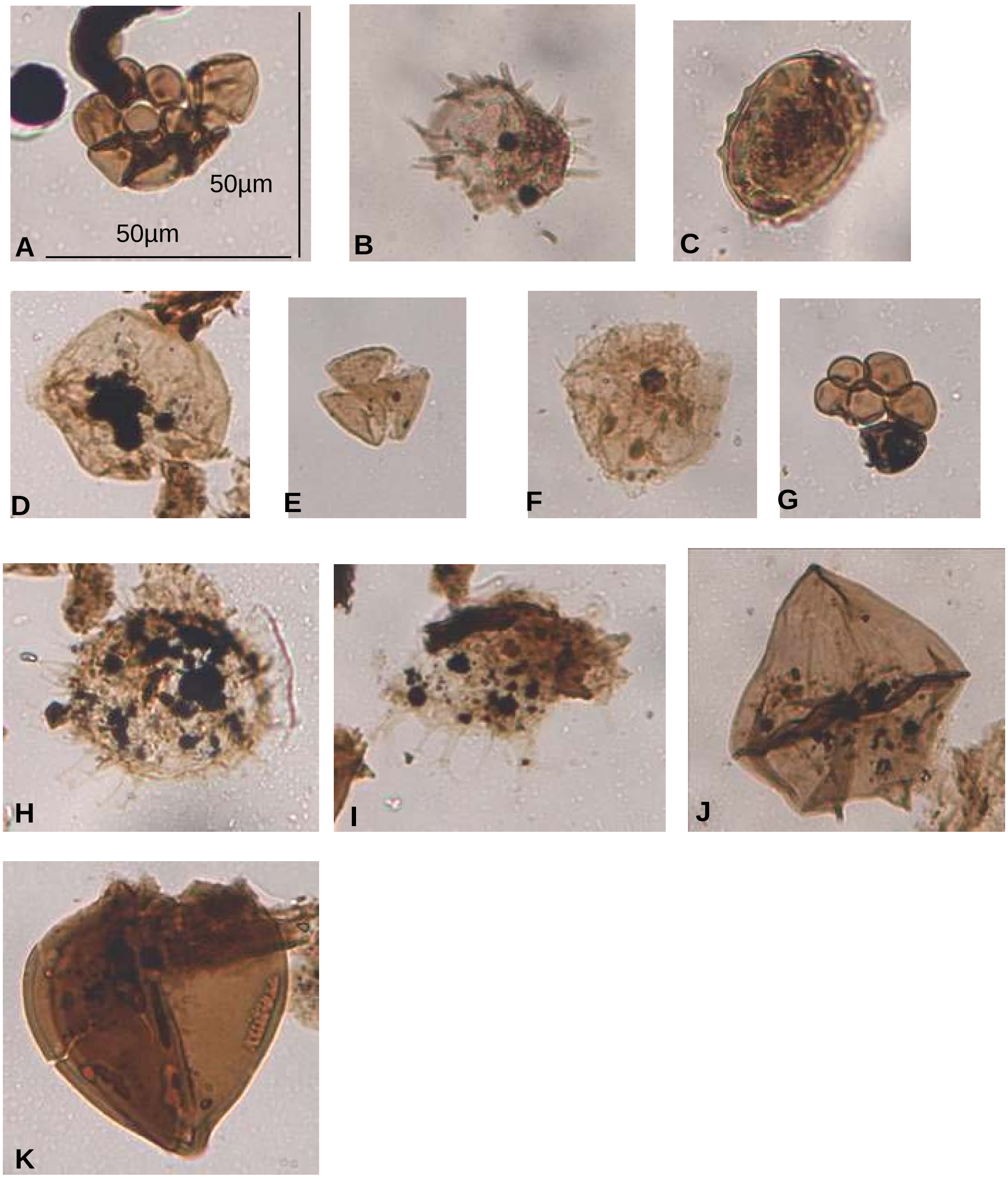
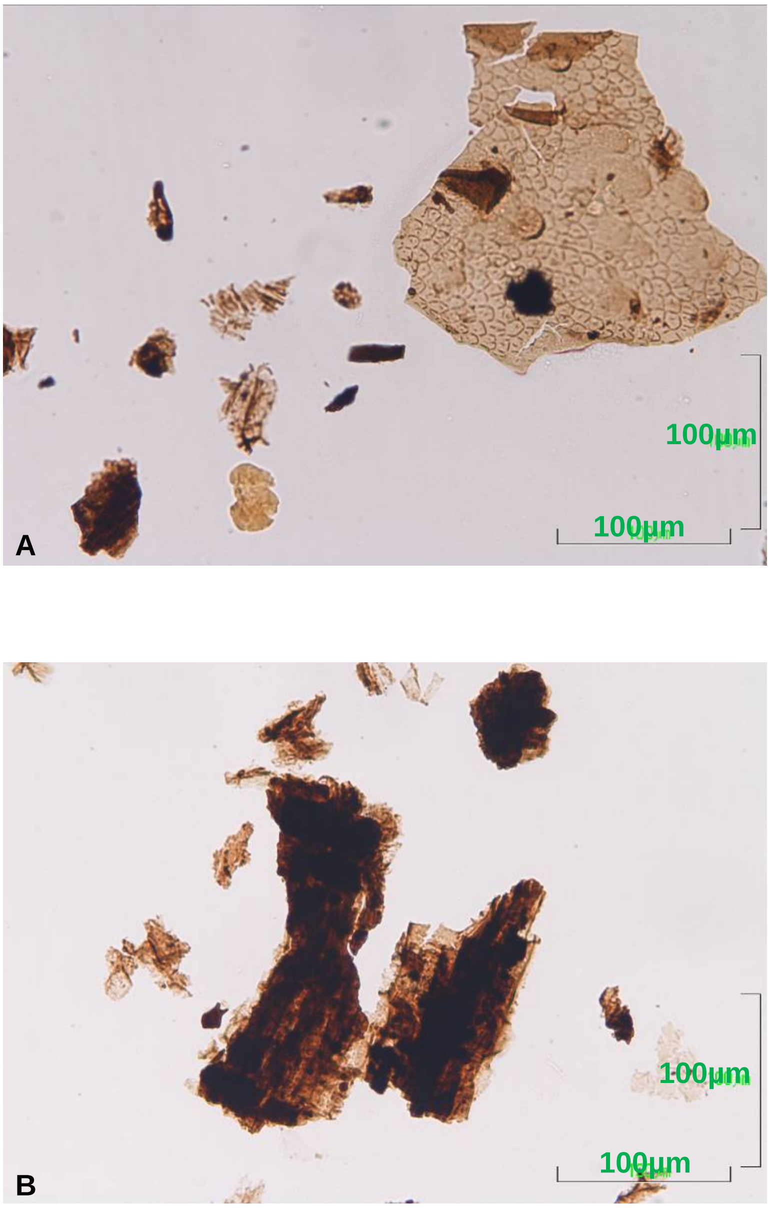
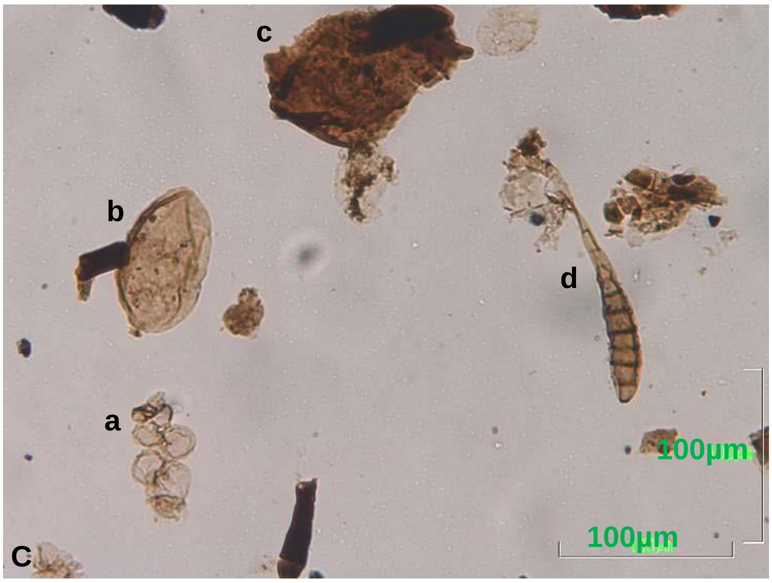
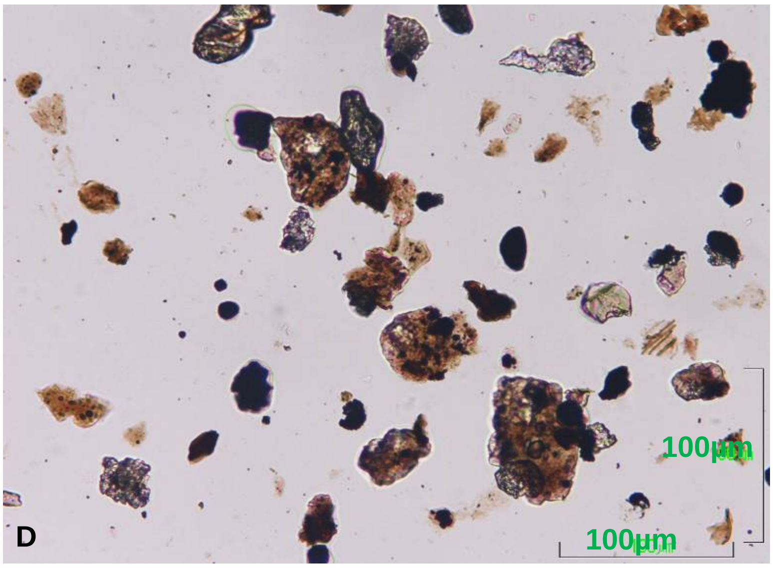


Figure 5.30. Palynomorphs from assemblage 2 (Ibeku Formation of the Ameki Group). A. Foraminifera lining. B. Echinate pollen H36 SESM 10. C. Monolete spore G35 SESM 4. D. Fresh water alga K37 SESM 4. E. Trizonocolpate pollen R46/3 SESM 2. F.? Acritarch type 1 M47/1 SESM 4. G. Foraminifera lining K42/3 SESM 4. H. Dinoflagellate type-1 K37 SESM 4. I. Dinoflagellate type-1 S44/3 SESM 2. J. Dinoflagellate type-3 J42/3 SESM 10. K. Trilete spore-1 H32/2 SESM 2.


100µm
100µm
A
100µm
100µm
B


c
b
d
a
100µm
C
100µm


100µm
D
100µm

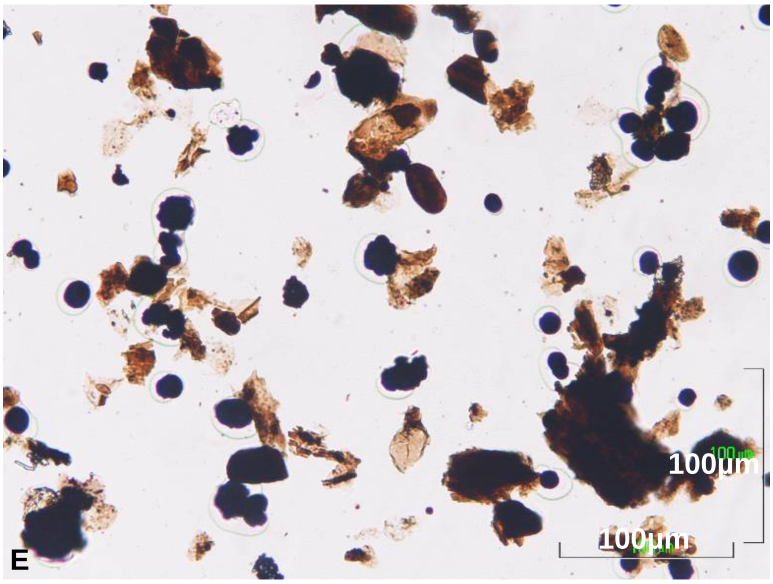


Figure 5.31. Content of the palynological assemblage types found in the Eocene Ameki Group strata.

A. Cuticle (SPP sample: assemblage 1).

B. Wood debris (SPP sample: assemblage 1).

C. (a) Foraminiferal lining, (b) FW alga, (c) unstructured phytoclast, (d) fungal (SESM samples: assemblage 2).

D. Pyrite, AOM, unstructured phytoclasts (SESM samples: assemblage 2).

E. Pyrite, AOM, Black debris, resin and algal remains (SESM samples: assemblage 2).

5.4 DISCUSSION

5.4.1 Lateral and vertical variations

Sediments of the Ameki Group can be subdivided into fluvially-dominated units, estuarine complexes and estuarine embayment associations (Figure 5.32; Appendix C5.1). Facies distribution in the Ameki Group is similar to that of Cobequid Bay-Salmon River estuarine complex of Bay of Fundy (Dalrymple et al., 1990).

In the north-eastern area the Ameki Group is mainly represented by the Nsugbe Formation. This is fluvially-dominated and it is represented by fining upwards fluvial deposits (FA1). These facies associations are restricted to the northern part of the study area, and they are incised into the underlying sediments of the Paleocene-early Eocene Imo Formation.

In the central area outcrop is more extensive and it is referred to as the Nanka Formation. This consists of estuary mouth sand bodies and includes

(1) low sinuosity tidally influenced fluvial channel deposits (FA2);

(2) extensively occurring subtidal and tidal flat deposits (FA4) with a dominant north-eastern paleocurrent direction (Figure 5.6C) indicating flood tide currents;

(3) deposits of tidal sand bars (FA6) that are very common in the central area; they occur as thick (about 25 m thick) sandstone bodies and show both coarsening and fining upward profiles and are usually capped by tidal flat deposits

(4) fining-upward tidal channels (FA3) are characterised by both northwards and southward paleocurrent directions (Figure 5.4B) which suggest the action of both flood and ebb tidal currents in the central estuary; the tidal channels are usually capped by low-energy mixed flat and mud flats, which reflect a shallowing upward trend from tidal channel to tidal flat.

Deposits in the south-eastern area of the Ameki Group are referred to as the Ibeku Formation, which comprises the estuarine embayment association (FA7). Sediments shallow-upwards from transgressive lag deposit to fossiliferous mudstone and shale / gypsiferous shale (diagenetic) to tide to wave reworked siltstone and claystone - nodular mudstone. This succession (FA7) may or may not occur together, but is restricted to the southern part of the study area. The occurrence of well ornamented gastropods and bivalves, shark teeth and phosphate deposits in the fossiliferous shale/ mudstone implies a shallow marine setting. The presence of petrified logs, lignite fragments, ambers, and bored wood fragments in shale suggest the action of ebb flow and/or longshore currents along the embayment. Lateral and vertical variations of sediments in the Ameki Group show some influence of river action, a dominant tidal influence and a subordinate wave action.

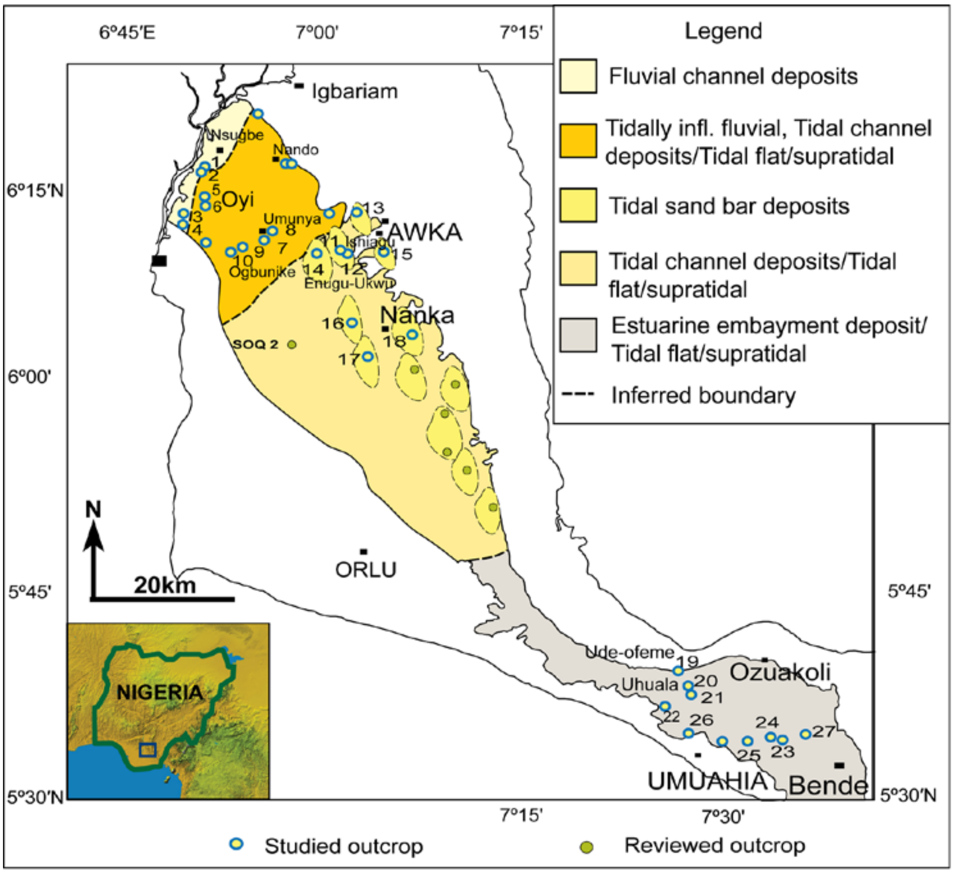


Figure 5.32. Variations in facies distribution and depositional environment of the Eocene Ameki Group.

5.4.2 Tidal range

The intertidal deposit commences from the base of sand flats to the top of mudflats and it varies from 4 m thick (as observed at Ogbunike in a tidal flat to 15.5 m thick (as observed at Umunya in the tidal flat successions). At Ogbunike, the mixed flat succession is 4 m thick, whereas at Umunya the mixed flat succession is 6 m thick. At Umunya, the sand flat is about 6 m thick and the mudflat is more than 3.5 m thick. The thickness of the intertidal flat reflects the tidal range (Darlymple, 1992; Kitazawa, 2007), and based on Davies (1964) classification, the tide-dominated estuarine is defined as macrotidal. The tidal range is similar to the average semidiurnal tidal range of 11.5 m in the Minas Basin (Yeo and Risk, 1980) and the maximum range of 16.3 m in the Cobequid Bay located at the head of the Bay of Fundy (Dalrymple et al., 1990). The presence of the deposit of tidal flats, supratidal flats, tidal channels and tidal bars further support a tide-dominated macrotidal estuary setting (Dalrymple et al., 1992; Kitazawa 2007; Pontén and Plink-Björklund, 2005; Tessier et al., 2011).

5.4.3 Sequence stratigraphic interpretation

One complete stratigraphic sequence defines the Eocene Ameki Group. The major stratigraphic surfaces encountered are a type-1 sequence boundary (SB), an initial transgressive surface (ITS), a maximum flooding surface (MxFS) and a transgressive ravinement surface (TRS). The stratigraphic sequence consists of an initial lowstand systems tract (LST), followed by an extensive transgressive systems tract (TST) and then, a highstand systems tract (HST). This sequence stratigraphic framework is similar to that of the modern Gironde estuary, France, interpreted as a mixed wave- and tide-influenced estuarine system (Allen and Posamentier, 1993). Though the Gironde incised valley was formed during the Würm glacio-eustatic fall, it is bounded by type-1 sequence boundary and filled with diverse assemblages of lithofacies that were grouped into lowstand, transgressive and highstand systems tracts (Allen and Posamentier, 1993).

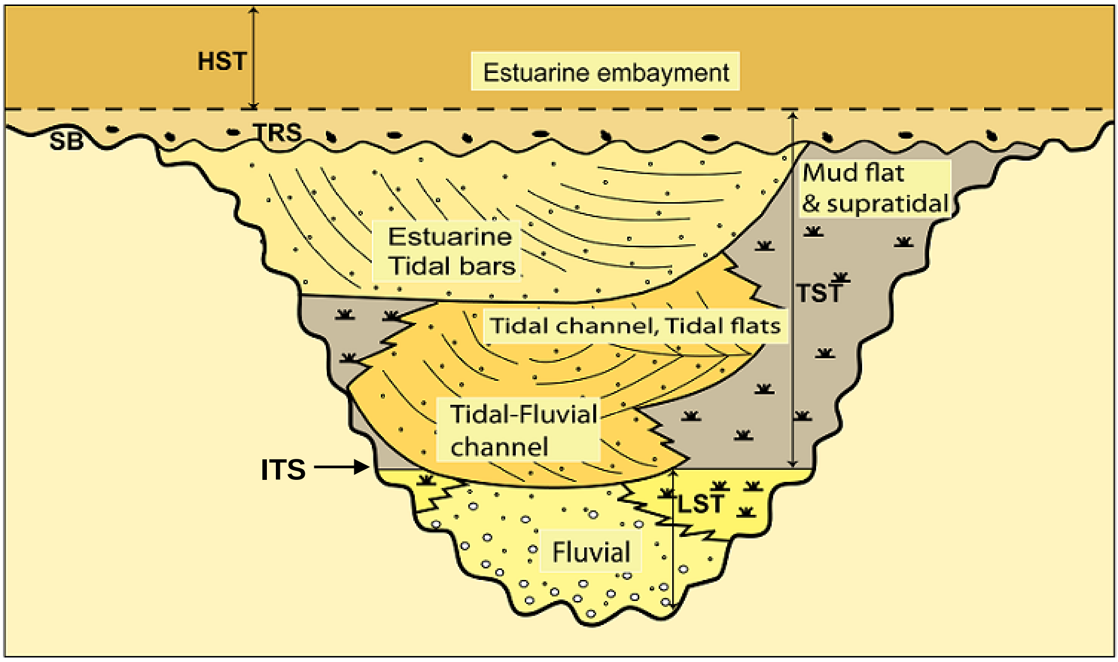
Sequence boundary (SB)

The stratigraphic framework of the Ameki Group (Figure 5.33) is defined based on the Darlymple and Choi (2006) illustration of a tide-dominated estuary within an incised valley. The type-1 sequence boundary is represented by an unconformity (Van

Wagoner el al, 1990). The SB is observed at the base of the fluvial deposit (FA1) at Ugwu-Nnadi, Nsugbe and is characterised by a deep erosive scoured channel and channel lag which may represent a lowstand deposit (Figure 5.34A). This marks a seaward facies shift of the shoreline. The sequence boundary is formed during the fall of relative sea-level to its lowest position (Bhattacharya 1993, Plink-Björklund, 2005). The sequence boundary can also merge with the transgressive surface as observed at Nando. The north-eastern part of the Ameki Group represents the upper part of the incised valley.

Lowstand systems tract (LST)

The lowstand systems tract is bounded by a subaerial unconformity at the base and initial transgressive surface (Figure 5.34A) at the top. The LST is formed during the early stage of sea level rise, when the rate of sediment supply is greater than the rate of rise (Catuneanu, 2002). In the study area, the LST is represented by an amalgamated fluvial deposits belonging to the Nsugbe Formation Member of the Ameki Group, which exhibits a fining-upward profile. The fluvial lowstand strata are well developed and preserved; they are overlain by the tidally influenced fluvial channel deposits of the estuarine complex (Figure 5.34A). This corresponds to the Catuneanu, (2002) description of the lowstand systems tract characterised by fluvial deposits and overlain by estuarine facies.



Not drawn to scale

Legend

LST - Lowstand systems tract

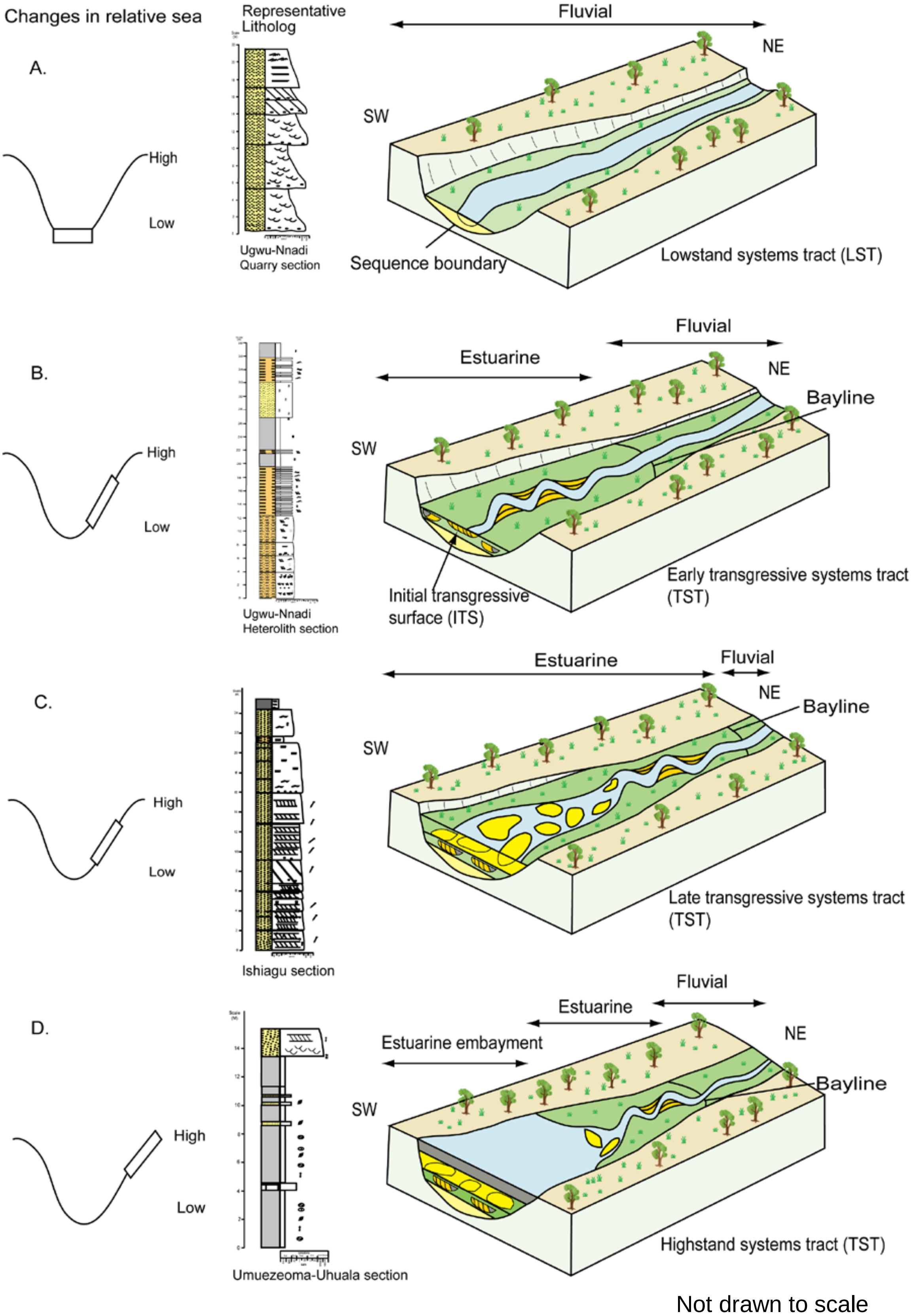
ITS - Initial transgressive surface

TST - Transgressive systems tract

TRS - Transgressive ravinement surface

HST - Highstand systems tract

Figure 5.33. Schematic vertical section of a tide dominated estuary with an incised valley (see map view in figure 5.3) showing the 2-D view of the systems tracts and the depositional environments (redrawn and modified after Dalrymple and Choi, 2007).


Changes in relative sea
Representative Litholog
A.
High
Low
Ugwu-Nnadi Quarry section
Fluvial
NE
SW
Sequence boundary
Lowstand systems tract (LST)
B.
High
Low
Ugwu-Nnadi Heterolith section
Fluvial
Estuarine
NE
Bayline
SW
Initial transgressive surface (ITS)
Early transgressive systems tract (TST)
C.
High
Low
Ishiagu section
Estuarine
Fluvial
NE
Bayline
SW
Late transgressive systems tract (TST)
D.
High
Low
Umuezeoma-Uhuala section
Fluvial
Estuarine
Estuarine embayment
NE
Bayline
SW
Highstand systems tract (TST)
Not drawn to scale

Fluvial channels

Tidally influenced fluvial channels

Tidal sand bars and tidal channels

Overbank deposits/ Tidal flat deposit

Abandoned channel plugs/ Embayment mudstones/shales

Figure 5.34. Sequence stratigraphic evolution of the tide-dominated estuarine system of the Ameki Group. A. LST is formed during the early stage of sea level rise resulting to deposition of fluvial channel system. B. ITS represents abrupt increase in marine water and a basinward shift in bayline, which resulted to the deposition of tidally influenced fluvial deposits. C. As the sea level continues to rise, accommodation space increases, and due to availability of sediments both from river and sea; thick sequences of tidally influenced channel deposits, tidal flats, tidal sand bars are deposited. Deposition of the thick sequence of sediments must have been influenced by subsidence. D. HST represents deposition in an estuarine embayment where siliciclastic input is minimal, resulting to deposition of mudstone, shale and siltstone (modified from Plink-Björklund, 2005).

Initial transgressive surface (ITS)

The initial transgressive surface represents an abrupt increase in marine influence, whereby the bayline moved landward from regressive to transgressive (Cattaneo and Steel, 2003; Plink-Björklund, 2005). This resulted in deposition of finer sediments of the tidally influenced fluvial channel and it is characterised by strong bioturbation. Thus, the transgressive surface records an abrupt change from fluvial to tidally-estuarine sand deposit (Figure 5.22B) as proposed by Allen and Posamentier (1993).

At Ugwu-Nnadi, the initial transgressive surface is typified by the presence of both *Skolithos* - depauperate *Cruziana* ichnofacies and body fossils (Figure 5.11). At Nando, the ITS coincides with the SB and it is characterised by a firmground defined by *Glossifungites* ichnofacies and a thin pebbly channel lag. Here, strata of the ITS directly overlie sediments of the Imo Formation. This occurrence is similar to that of the Gironde estuary (Allen and Posamentier, 1993), where the transgressive surface merges with the sequence boundary on the valley wall. The initial transgressive surface occurs at the base of the transgressive systems tract.

Transgressive systems tract (TST)

The transgressive systems tract commences with the initial transgressive surface or coincides with sequence boundary and ends at the base of the high stand systems tract. In this tide-dominated estuary, the TST consists of the transgressive tidally influenced fluvial channel deposits, the tidal flats and also (high energy) tidal sand bars and transgressive marine sandstone (Figure 5.34C). The transgressive marine sandstone overlies the transgressive ravinement surface, within the transgressive systems tract. The transgressive deposits volumetrically dominate the depositional sequences; this could be as a result of increasing accommodation and high sediment influx. The major reason for the accommodation may be subsidence, which created more space for sediment accumulation and the constant supply of sediments from both river and sea (observed from paleocurrent directions of outcrop sections) resulted in thick sediment deposition during the transgressive systems tract.

Early transgression due to initial sea-level rise, led to the deposition of tidally influenced fluvial channel deposits typified by sandy-muddy-silty heterolithic beds and mud lenses. The influx of sediments in the estuary during the transgression led to development and deposition of tidal channels and tidal flats resulting from a landward transgression. As sediment influx increases, upward coarsening and thickening successions of tidal sand bars dominate, indicating increasing tidal currents with continuing transgression (Kitazawa, 2007). This results from the seaward progradation of the estuary (Dalrymple et al., 1990).

Transgressive ravinement surface (TRS)

Transgressive ravinement surface or tidal ravinement surface is the term used for the landward-migrating, channel-generated tidal erosion surface formed during transgression whereby the ravinement surface incises into alluvial or estuarine deposits and is overlain by tide influenced deposits (Cattaneo and Steel, 2003). TRS may occur in estuarine coastal areas or tidal inlets or tidal channels or proximal tidal sand bars (Cattaneo and Steel, 2003; Hori et al., 2002; Kitazawa, 2007). The TRS occurs within (toward the top) the TST in the study area.

The TRS observed at Ugwu Akpi in Enugwu-Ukwu is characterised by a landward dipping layer of quartz and mud pebbles (pebble lag) (Figure 5.35A). The TRS incised into the tidal channel / tidal flat in the seaward area of the estuary mouth and is overlain by strongly bioturbated fine to medium grained sandstone (Figure 5.35B) which suggested that the sands are of marine origin (inner estuarine tidal sand bars). The TRS also occurs at the base of the estuarine embayment at Ude-Ofeme, where it occurs also as a pebble lag, overlain by mottled mudstone (marine deposit).

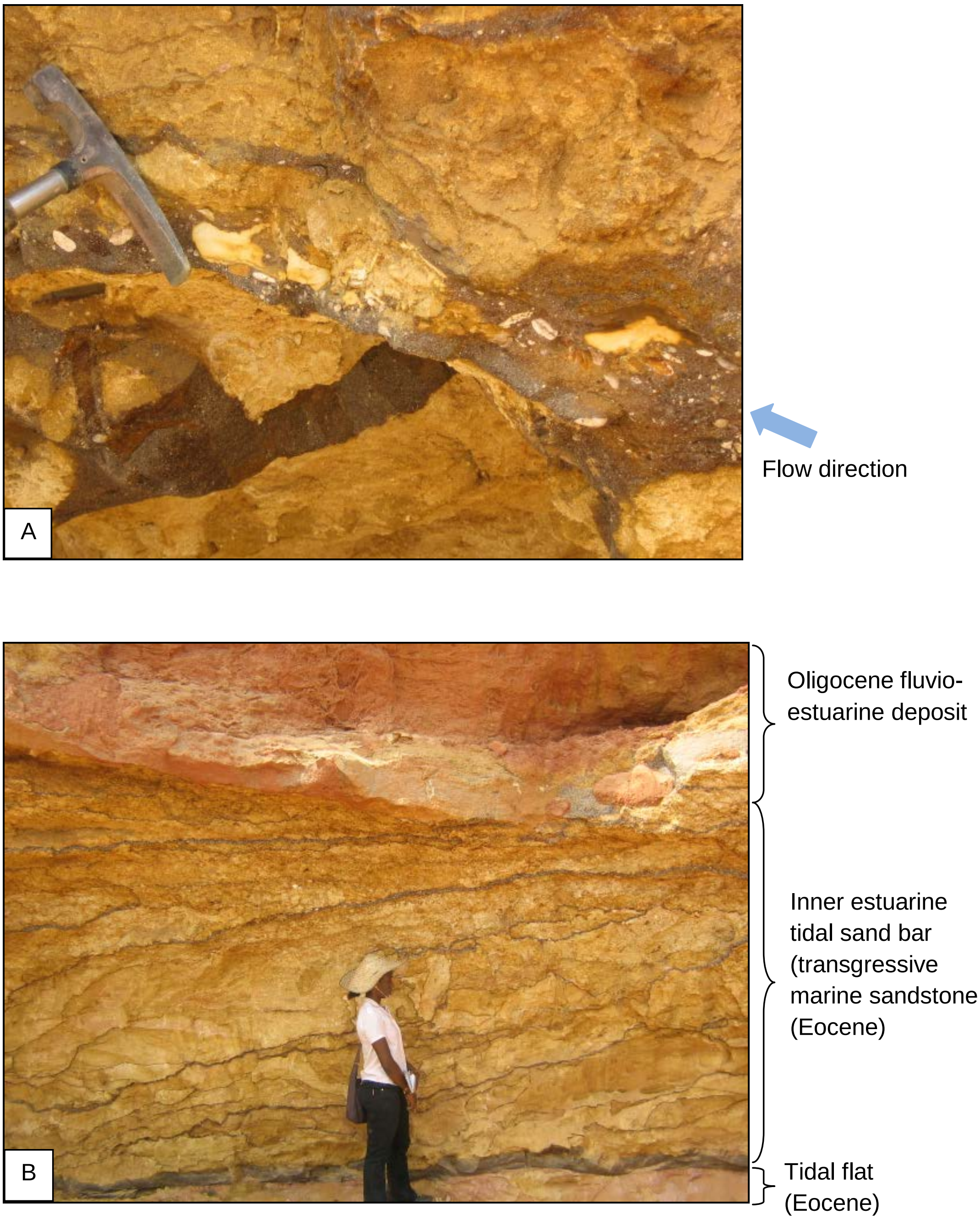


Figure 5.35. Outcrop photographs at Ugwu-Akpi quarry showing transgressive marine sandstone interpreted as outer estuarine tidal sand bar. (A) Landward dipping mud and quartz clasts in the lower horizon of the bioturbated marine sandstone. (B) The transgressive sandstone is underlain by tidal flat and overlain by erosive fluvio-estuarine deposit of Oligocene Ogwuashi-Asaba Formation.

Maximum flooding surface (MxFS)

The maximum flooding surface is the point of maximum flooding in a basin; it is commonly an extensive surface in the rock record (Posamentier and Allen, 1999) and represents the maximum water depth in a vertical succession (Cattaneo and Steel, 2003). The maximum flooding surface marks the end of shoreline transgression (Pearson et al., 2012). In the study area, the MxFS occurs above the tidal sand bars and the tidal ravinement surface; it is located within (upper part) the Ibeku Formation. The MxFS in the Ibeku Formation may be associated with a condensed section; this is characterised by authigenic minerals such as siderite, limestone concretions (Arua, 1990). It is extensive and has been located in various localities within the Ibeku Formation.

High stand systems tract (HST)

The HST is bounded by the MFS at the base and by a subaerial unconformity (sequence boundary) at the top. It corresponds to a late stage of sea level rise resulting in lower rate of creation of accommodation and deposition in the estuary and open-marine (Figure 5.34D). The HST is represented by the estuarine embayment facies association and it displays a weak coarsening upward profile (progradation) from dark gray shale/ mudstone facies with more shallow marine fauna to dark gray to brownish shale facies with more land-derived materials and capped by organic rich tidal flat and supratidal deposits. This indicates that overall succession of the tide-dominated estuarine system within an incised-valley is transgressive.

5.4.4 Reservoir Potential

The reservoir potential of the tide-dominated estuary complex is based on the description of the internal architecture of the sandstone bodies. The heterogeneities observed in the estuarine system are due to the varying amounts of mud present, occurring in the form of mud clasts, mud balls, mud drapes, mud lenses and mud laminae.

Strata of the amalgamated channels, particularly the fluvial deposits, lack mud deposits within the channels resulting in low heterogeneity. The thickness and amalgamation of the channels would produce vertically- and laterally-connected sand body complexes. This would imply good connectivity and high lateral continuity and low vertical compartmentalization (Taylor and Ritts, 2004). Major tidal channels consist of bedsets that are heterogeneous reservoir units, due to the presence of mud draped planar and trough cross-beds, mud plugs, and mud chips within the sands. These may act as small scale permeability barriers or create flow baffles (Fenies and Tastet, 1998; Taylor and Ritts, 2004). The presence of sand-filled vertical trace fossils or open-burrow systems can act as conduits in the sandbodies connecting layers (Egbu et al., 2009; Gingras et al., 2004) and horizontal burrows can also aid lateral connectivity (Tonkin et al., 2010). Mud filled borrows can likewise act as baffles to fluid flow. Isolated channels bounded below and above by tidal mud flat deposits may result in poor lateral continuity and high vertical compartmentalization. Isolated channels with fine grained infill, heterolithic units, and mud clasts would have poor vertical connectivity. Outer estuarine tidal sand bars have low proportions of mud laminae and mud chips; this suggests moderate to high connectivity between the sand bodies and low compartmentalization. The heterolithic beds consist of alternating sand-silt-mud and the sands are rippled with mud flasers and mud laminae. These internal heterogeneities would result to poor lateral continuity and high vertical compartmentalization. The alternation of sand-silt-mud would act as flow barriers and the mud flasers and laminae within the sandy intervals will act as flow baffles.

The best reservoirs with the tide dominated estuarine complex of the Ameki Group are rocks of the fluvial deposit and the inner estuarine tidal sand bars due to their good connectivity and lateral continuity (Figure 5.2).

The lateral variability of the transgressive shales and muds (dominate in the estuarine embayment) may enhance the likelihood of stratigraphic traps and may act as both seal and source rocks (Cattaneo and Steel, 2003).

5.5 CONCLUSIONS

This research documents the characteristics of a well preserved sedimentary infill of an ancient tide-dominated macrotidal estuarine complex. The depositional successions of the Eocene Ameki Group exhibit a complete sequence stratigraphic framework which consists of a lowstand fluvial deposit (referred to as the Nsugbe Formation), a transgressive estuarine systems tract (referred to as the Nanka Formation) and a highstand estuarine systems tract deposits (referred to as the Ibeku Formation). The transgressive estuarine deposit is the most voluminous succession of the systems tracts consisting of tidally influenced fluvial channels, tidal channels, tidal flats, supratidal and tidal sand bars. The availability of accommodation may have been generated by subsidence and the interplay of sedimentary processes such as tide, current and waves contributed to the influx of sediments. The highstand systems tract is preserved as an estuarine embayment which has minor clastic input, resulting to accumulation of dominantly mudstones and shales that was capped by the deposits of tidal flats and supratidal flats.

CHAPTER SIX

TIDALLY INFLUENCED COASTAL PLAIN DEPOSITS OF THE OGWASHI FORMATION, SOUTH-EASTERN NIGERIA

SUMMARY

The Oligocene Ogwashi Formation is interpreted as a tidally influenced coastal plain deposit based on the detailed outcrop description of exposures and facies analysis. Other studies which include clay mineralogy, heavy mineral analysis and petrology were used to support the interpretation. The facies associations comprise strata interpreted to be the deposits of the following environments: fluvio-estuarine channels, tidally influenced fluvial channel, tidal flats, coastal plain channels, and coastal floodplain/ mire. The fluvio-estuarine channels deposit are characterised by high energy conglomerate and coarse grained sandstone that are strongly to weakly bioturbated by *Skolithos* ichnofacies and include mud layers. The tidally influenced fluvial channel includes mud chips, mud lenses (at the base) and mud draped planar and trough cross beds. The tidal flat deposit exhibits sandy heteroliths that is strongly burrowed. The coastal plain channel deposits are mud-filled channels, with sand sheets interpreted as splay deposits and variegated sandy claystone which has undergone pedogenic alteration. The floodplain and mire deposits are light grey coloured mudstone and dark grey carbonaceous mudstone with plant remains and lignite.

The depositional succession shows a change from marine to non-marine conditions, interpreted to be a result of relative sea level changes. The sedimentary rocks of the Ogwashi Formation may be eustatically and tectonically controlled coastal plain deposits. The coastal plain succession is grouped into channelized and floodplain deposits. The channelized elements occur either as isolated or multistorey channel deposits. The sequence stratigraphic interpretation reveals one depositional sequence with a type-1 sequence boundary and a series of transgressive surfaces of erosion indentified by the occurrence of *Glossifungites* ichnofacies with sharp, erosive contacts.

6.1 INTRODUCTION

The Ogwashi Formation was formerly called the Lignite Series because of the occurrence of lignite-rich beds found in the southern part of Nigeria and popular referred to as Ogwashi Formation. The Ogwashi Formation overlies the Ameki Group conformably (Reyment 1965) and covers an areal extent of 4,900km^2 (Figure 1.1). The formation consists of a sequence of coarse grained sandstone, light grey claystone and carbonaceous mudstone with lignite seams (Kogbe, 1976; Ogala et al., 2012). The lignite deposits (Figure 1.1) in Nigeria extend from Orlu in the south-east though Nnewi to Ogwuashi-Uku (Okezie and Onuogu, 1985). The Ogwashi Formation is considered to be Oligocene-Miocene age (Reyment, 1965).

Published works on the Ogwashi Formation mainly concern the occurrence, geochemistry, petrology and mineralogical studies of the lignite deposits (Nwadinigwe, 1992; Okezie and Onuogu, 1985; Adedosu et al., 2007; Ogala et al., 2012; Orajaka et al., 1990) which is of economic interest. Lignite reserves of over three hundred million tons have been proven, providing Nigeria with the largest lignite reserves in Africa (Orajaka et al., 1990). There are few published works on the sedimentology of the Ogwashi Formation (Akpoborie et al., 2005; 2011).

No detailed research has been carried out regarding the facies analysis, facies architecture and sequence stratigraphic framework of the Ogwashi Formation. This research gives a new perspective to the stratigraphy of the Ogwashi Formation, by integrating sedimentology, sandstone petrology, X-ray diffraction, and heavy mineral analyses to reconstruct the depositional environment and decipher the various facies associations.

6.2 METHODOLOGY

The field and laboratory methods used are as discussed in chapter one. The study area covers an areal extent of about 1,200 km^2 (Figure 6.1). The Ogwashi Formation is poorly exposed or outcrop on the surface, less than 40% of the estimated thickness for Ogwashi Formation was encountered in the study area. The representative outcrops studied occur in Enugwu-Ukwu, Okaiga-Umuahia, Umuezeoma-Uhuala and Umuogo-Ubakala, and along Umuahia–Aba Expressway as quarries and road cut exposures. The exposed outcrops are very accessible, detailed and well preserved.

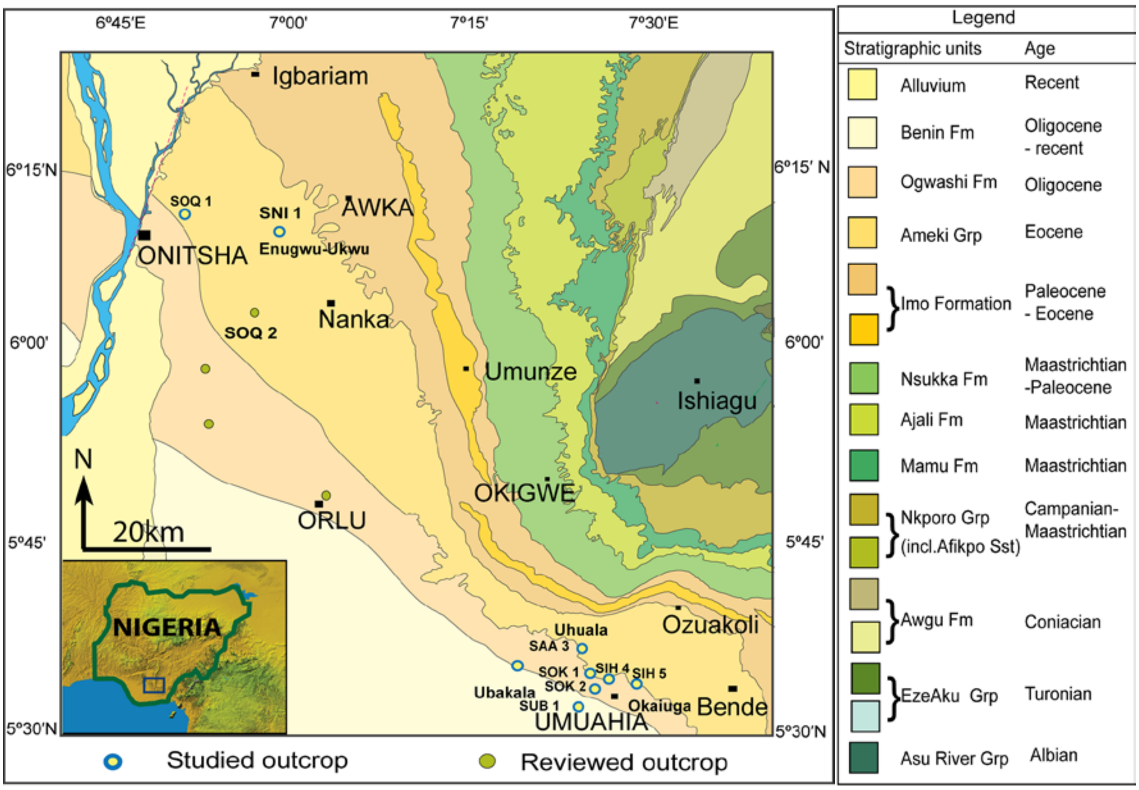


Figure 6.1. Geologic map of the study area showing representative outcrops of the Ogwashi Formation (redrawn and modified after Nigerian Geological Survey Agency, 2009).

6.3 RESULTS

6.3.1 Facies Associations (FA)

Nine lithofacies and three subfacies were documented from the Ogwashi Formation. The lithofacies were further assembled into five facies associations based on the sedimentary structures, grain textures, bedding contacts, and geometries. The facies associations are discussed in ascending order of their occurrence in the formation.

FA 1 (Fluvio-estuarine deposit)

Facies association 1 is the basal part of the Ogwashi Formation; it outcrops in several places within the study area and beyond. Although the type locality lies outside the study area, excellent outcrop sections occur within the study area in Enugwu-Ukwu, Okaiga-Umuahia, Ogbunike, Ehitte-Obowo and Umuezeoma-Uhuala. Facies association 1 consists of conglomerate facies (Gc), trough cross bedded sandstone facies (St), planar cross bedded sandstone facies (Sp), herringbone cross stratified sandstone facies (Sx), bioturbated sandstone facies (Sb), and current rippled laminated sandstone facies (Sr).

Enugwu-Ukwu Section

At Ugwu-Akpi quarry in Enugwu-Ukwu (SNI 1), a single channel deposit about 10 m thick is incised into underlying Ameki Group (Figure 5.2A). The channel-fill unit has a scoured base, with a thick (30 cm) ferruginised layer at the base. The channel fill is conglomeritic (Gc), clayey, strongly bioturbated and poorly sorted, it fines gradationally into a coarse, clayey sandstone. The internal structure of the conglomerate is obliterated due to intense bioturbation, although no individual burrows were identified (Figure 3.1). The conglomerate exhibits relics of crude horizontal bedding while low angle cross stratification occurs in the coarse grained sandstone. Lignite fragments are observed in the conglomeratic unit (Figure 6.2). Within the sandstone there are vertical shafts of *Ophiomorpha nodosa* and *Diplocraterion* burrows and horizontal burrows of *Paleophycus* and *Planolites*. Slump structures were also observed. Though the overall vertical thickness is about 20 m, about 10 m was accessible while the rest was inaccessible due to intense weathering.

Figure 6.2. Lignite fragments in the conglomeritic unit in Enugwu-Ukwu section.

Umuezeoma-Uhuala Section

A similar basal unit is observed at Umuezeoma-Uhuala (SAA 3), the conglomerate is clast-supported and shows planar, inclined to trough cross-stratification (Figure 6.3); large clasts occur aligned along the foresets. At Umuezeoma-Uhuala, the conglomeratic (Gc) bed has a sharp erosive contact with a basal strongly burrowed (roots penetration) mottled nodular mudstone of the Ameki Formation (Figure 6.3), which have been interpreted as supratidal flat (chapter 5, p. 241). The paleosol signifies the end of a depositional cycle, while the conglomerate indicates the onset of a new sedimentation cycle during the Oligocene. Low diversity and low abundance *Glossifungites* ichnofacies including *Thalassinoides, Ophiomorpha, Arenicolites* and *Planolites* burrows were observed at the contact (Figure 6.4). Mud chips, and mud pebbles and altered feldspar grains are common in this unit. The pebbles are mostly subrounded to well rounded and are aligned in a preferred orientation ranging from 072° to 094°NE. The foresets of planar cross-beds trend in a north-west direction of 300° to 312° at dip angles of 10°-15°.

The nature of channel incision, the presence of lignite fragments and thickness of the infill suggest a fluvial origin, but the intense bioturbation of both the conglomerate and the sandstone and the occurrence of dominantly *Skolithos* ichnofacies suggest that the fluvial channel was drowned and invaded by marine water during transgression. In this way, brackish water conditions were created in the channel. This confirms to MacEachern and Hobbs (2004) statement that marginal marine conglomerates are associated with fluvial conglomerates where fluvial system supply coarse sediments to the coastline.

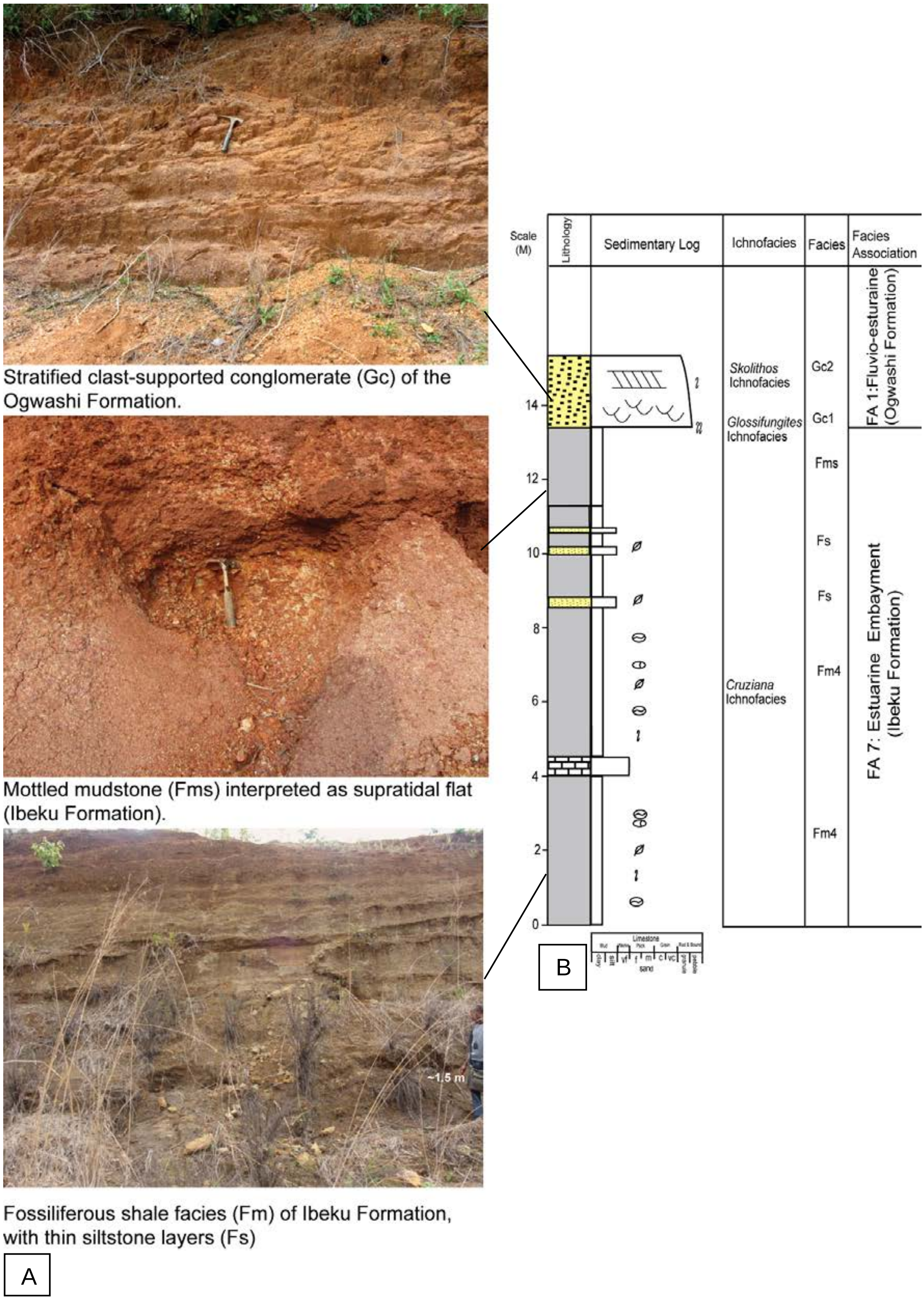


Figure 6.3. (A) Outcrop exposures at Umuezeoma-Uhuala. (B) Litholog of Umuezeoma-Uhuala section.

Figure 6.4. Outcrop section at Umuezeoma-Uhuala the poorly bioturbated contact between the conglomerate (overlying) and the mottled mudstone (underlying) (black arrow points at *Thalassinoides suevicus* and white arrow signifies vertical burrows probably *Arenicolites* isp.). The contact is interpreted as a sequence boundary.

Okaiuga Section

At Okauiga-Umuahia (SOK 1) (Figure 6.5), an extensive amalgamated sandstone channel succession is observed (Figure 6.6). Vertical and lateral variations in facies are observed on the outcrop section. The basal unit is characterised by orthoconglomerates (Gc) which shows a clast- to matrix- supported framework with a clay-rich matrix and some imbricated pebbles (Figure 3.2). The succeeding unit of the Okaiga-Umuahia section is a strongly bioturbated, very coarse to medium grained sandstone (Sb) of about 8 m in thickness. The sandstone is clayey with mud lenses and carbonaceous matters (Figures 6.6; 6.7). Planar-tabular cross beds with foresets trending in a northwest direction of 300° and dip amount of about 17° are observed at the base of the unit where the internal structure is obliterated completely by suite of dominantly *Skolithos* ichnofacies (Figures 3.13A; 6.8). Vertical shafts and horizontal tunnels of thick-walled *Ophiomorpha nodosa* dominate, while *Planolites beverleyensis*, *Skolithos* and *Paleophycus heberti* are common. *Arenicolites, Thalassinoides and Diplocraterion* occur as opportunistic burrows. These ichnofabric increases in intensity upwards, resulting in reworking of the clayey sandstone units. The bedding plane of the lower bed is bounded by mud drapes. A clayey granular unit of 10 cm thickness is observed within the bioturbated interval and is less burrowed. The bioturbated sandstone unit has a sharp erosive contact with the overlying pebbly sandstone unit that is interpreted as tidal channel (Figure 6.9).

Towards the NW direction, the outcrop commences with basal conglomerate (Gc) of about 1 m thick which grades into coarse to medium grained sandstone (1.2 m) with low angle planar cross-beds (Sp) trending in a southeast direction (mean 170˚). The upper horizon of the sandstone unit consists of cut and fill structures, with a pebbly infill. This grades into a clast supported conglomerate (Gc). The pebbles are partly aligned in a northeastern direction (mean 90^0). Mud flakes, mud pebbles and mica grains are common in this unit. The conglomerate is sharply overlain by medium to coarse grained opposite dipping cross bedded sandstone (5 cm to 13 cm thick). This bed is characterised by escape burrows, *Conichnus, Planolites* and *Ophiomorpha nodosa* burrows in the upper horizon (Figure 3.17). There is a sharp contact with the overlying bed, which is very coarse to fine grained, and includes of herringbone cross bedding (Sxh) at the base, followed by cross laminated sandstone (Sr) (with a dominant southeast palaeoflow direction (mean 164^0)). Mud clasts, *Ophiomorpha nodosa* and *Planolites* burrows are common in this unit. The succeeding unit shows increasing bioturbation (Figure 6.10), with poorly sorted, very coarse to fine grained sandstone (Sb). The lower part of the unit shows planar cross-beds (Sp) with north-eastern paleocurrent directions (mean 320^0). The dominant trace fossils are vertical *Ophiomorpha nodosa, Skolithos, Arenicolites* and *Planolites.* Remarkable equilibrium and escape structures (fugichnia) are common.

The presence of cross-beds formed by 2-D and 3-D dune migration, internal scours, mud draped foresets, mud clasts, mud lenses and coarse grain sizes suggest tidal influence and a high energy regime during sediment deposition (Pearson et al., 2012). The low-diversity, sporadic distribution and occurrence of the *Skolithos* ichnofacies is consistent with a stressed, brackish coastal depositional environment (Corbett et al., 2011).

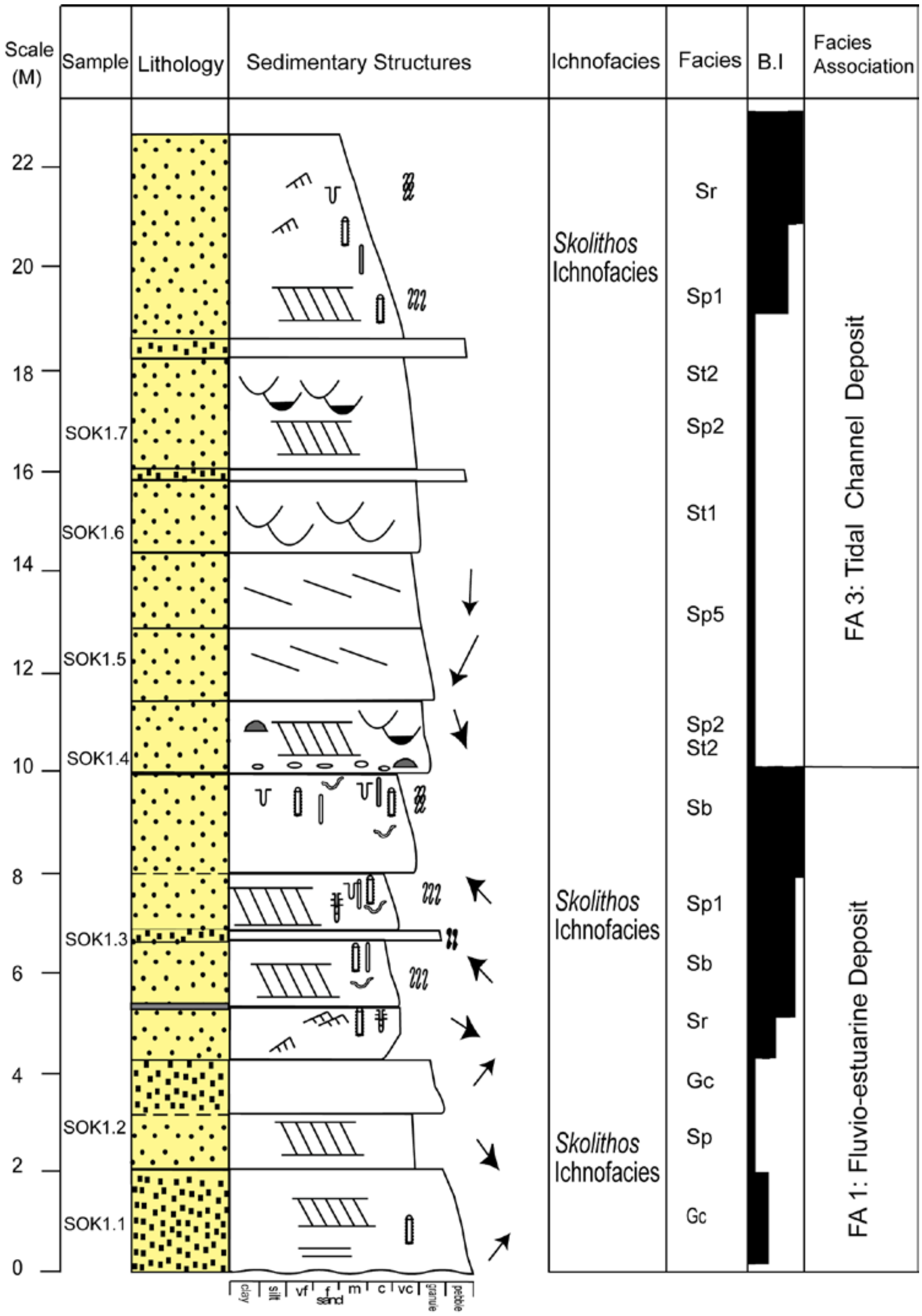


Figure 6.5: Litholog profile of Okaiuga Section showing a typical bioturbated sandstone deposit of the Ogwashi Formation.

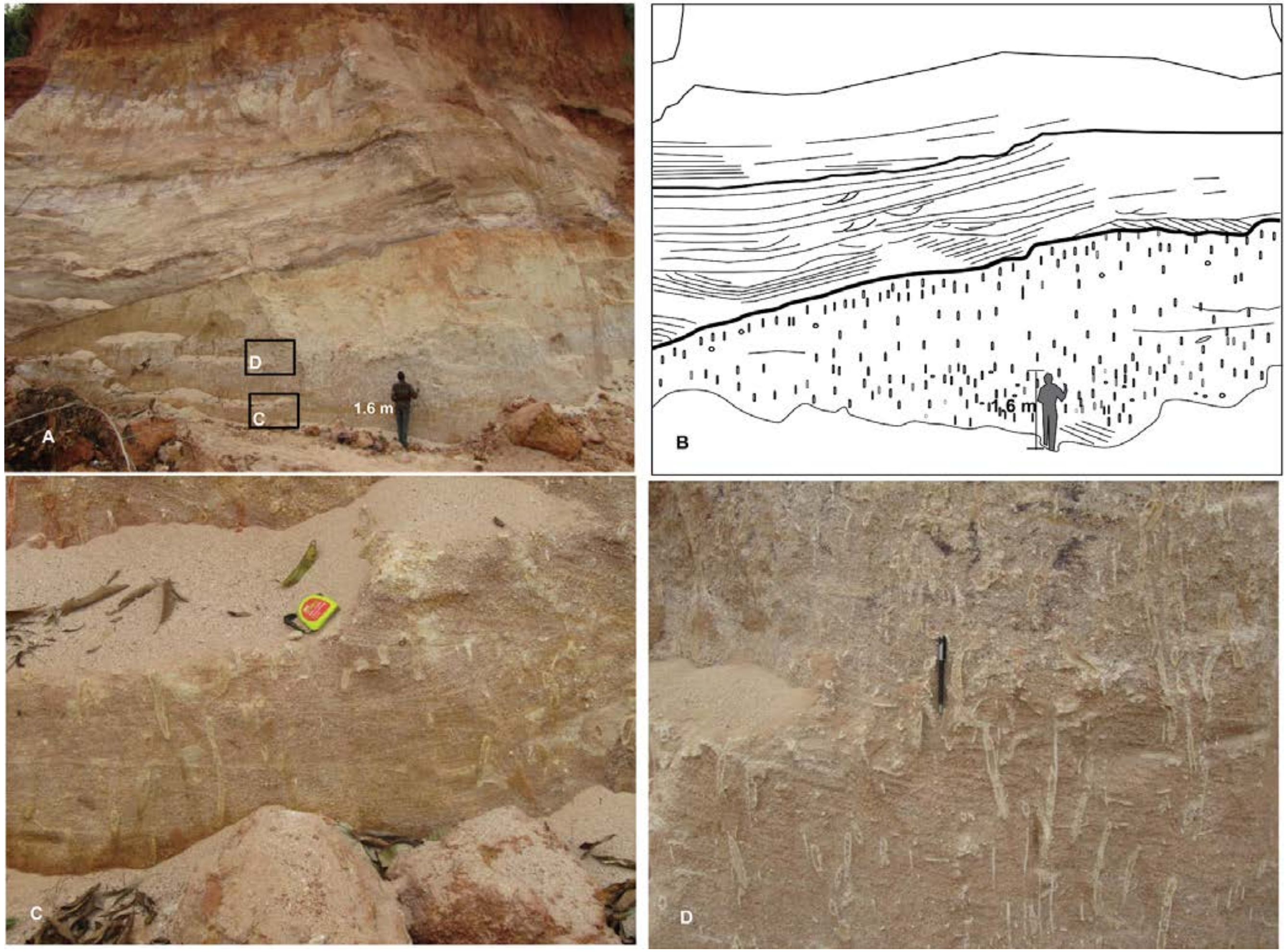


Figure 6.6: Outcrop exposure of the Okaiuga Section, exhibiting bioturbated sandstone facies of the Ogwashi Formation.

Figure 6.7. Bioturbated sandstone at Okaiuga section, exhibiting mud lenses (A) and carbonaceous matters, as well as mottled and cross-cutting structures (A,B).

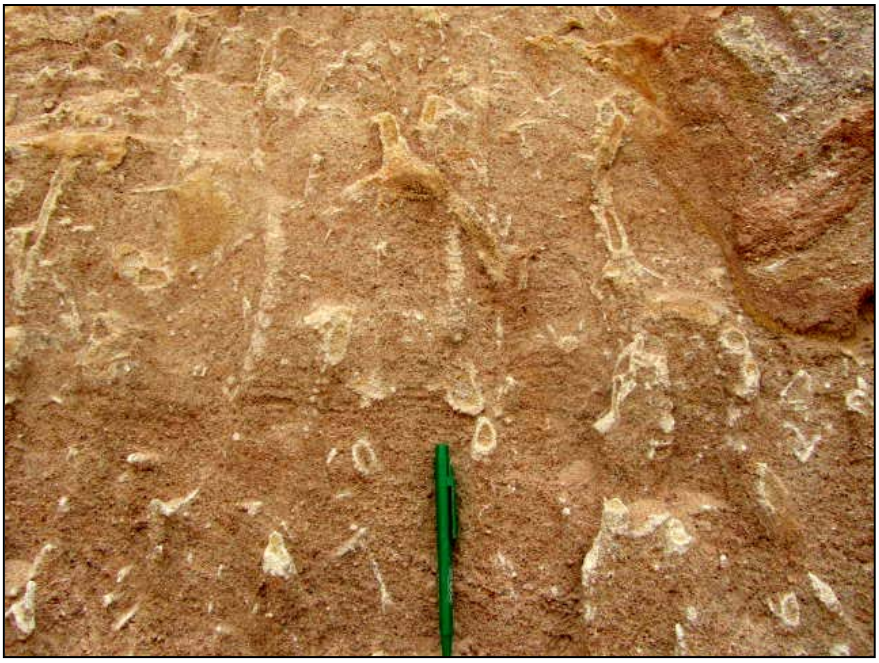


Figure 6.8. Bioturbated sandstone at Okaiuga section, exhibiting *Skolithos* ichnofacies.

Figure 6.9. Erosive contact between the bioturbated sandstone (below) and pebbly sandstone unit (above). This sharp contact suggests abrupt change in environmental condition. The bioturbated horizon (hammer) probably indicates a Maximum Flooding Surface (MxFS).

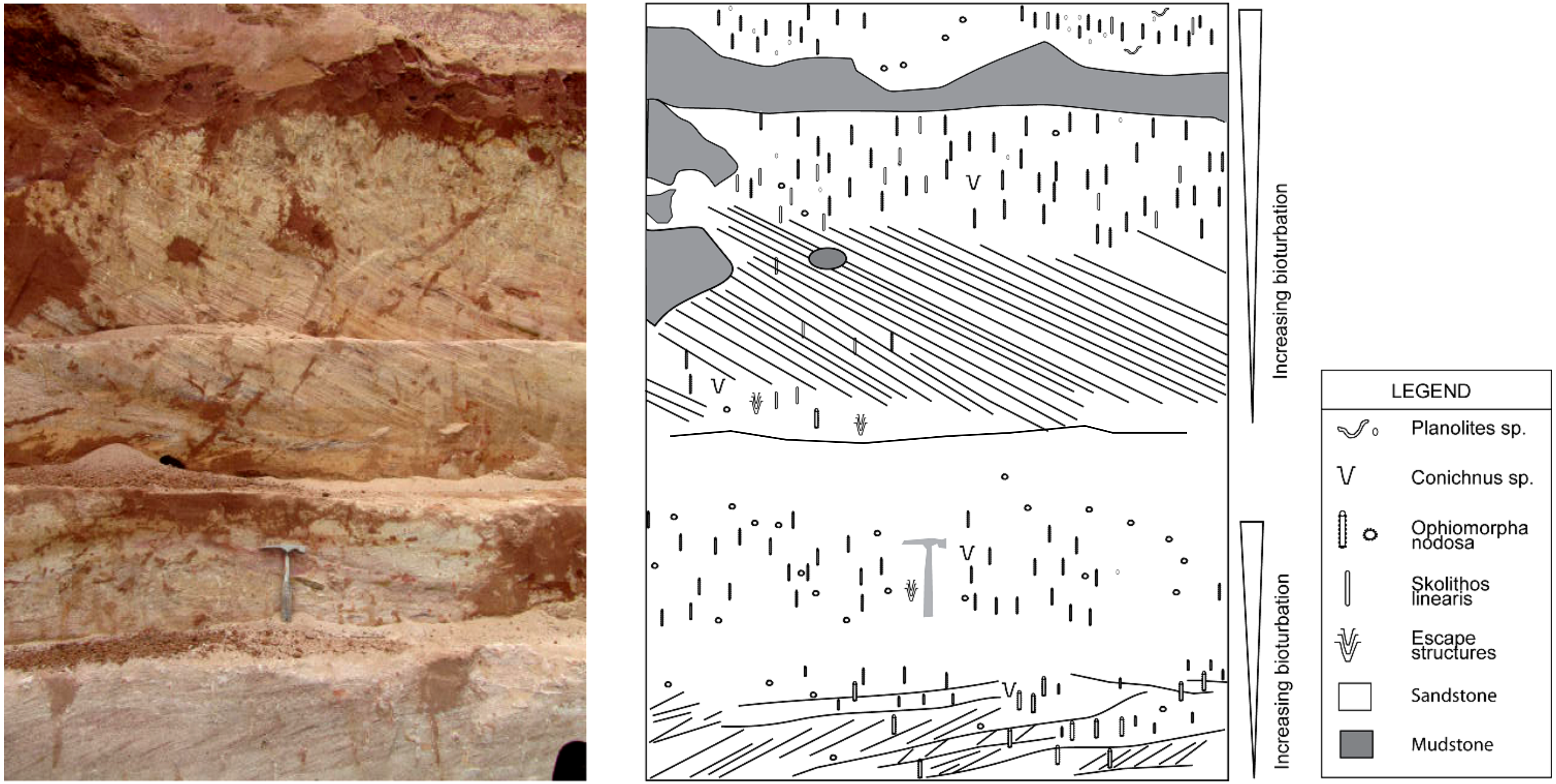


Figure 6.10. Outcrop and schematic diagrams showing low diversity and sporadic occurrence of *Skolithos* ichnofacies in the Okaiuga section.

Ogbunike Quarry Section

The sandstone section (SOQ 1) is about 14 m thick sandstone deposit and it is capped by intertidal deposit (Figure 6.11). The lower part of the sandstone deposit is characterized by fine grained massive sandstone, and medium to coarse grained sandstone that exhibits planar–tabular, trough, and herringbone cross-stratification. The cross beds are rarely mud draped and they trend in a dominant north-east paleocurrent direction. Convolute lamination was also observed within the cross-bedded unit. The sands are well to moderately sorted, heavily mineralized, and shows variation in colour from light brown to yellowish brown and brown. Low to Intense bioturbation occurred in the section, although the some burrows tend to concentrate within the bounding surfaces. The lower section of the sandstone deposit exhibits low diversity and low density ichnofossils which includes *Skolithos, Lockeia, Rosselia* while *Ophiomorpha, Paleophycus* and *Planolites* are less common. The ichnology of the Ogbunike quarry is discussed in chapter 7.

The succeeding unit is intensively bioturbated, some bed units are completely churned and reworked and their internal structures are obliterated. The sands are coarse grained, poorly to moderately sorted, friable and also shows variation in colour from yellowish brown to reddish brown and dark brown. *Ophiomorpha nodosa boxwork* is abundant and other common ichnofossils are *Skolithos, Cylindrichnus, Rosselia, Conichnus, Arenicolites, Paleophycus* and *Planolites*. *Conichnus* occur as escape burrows. There is lateral variation in the bioturbation and this relates to increase in burrow density seaward. Bioturbation in the fluvio-estuarine deposit ranges from low to complete (bioturbation index 1-6), with moderate ichnodiversities. Individual burrows could not be discerned in beds with complete bioturbation due to biogenic homogenisation of the sediments (Pearson et al., 2012). Bed with complete bioturbation suggests salinity change to normal marine salinity. The abundance of *Ophiomorpha nodosa* boxwork suggests a lower energy environment, an area that is shallow, quiet and protected (Frey et al., 1978), although the salinity and current energy may be moderately high in sandy substrate. The strong marine influence on the fluvio-estuarine deposit suggests that the sediments are mouth-bar deposits in the coastal plain (Pemberton and Gingras, 2005).

FA 2 (Tidal Flat)

Facies association 2 is less common and only observed in Ogbunike quarry (SOQ 1). But, it has been observed in Asaba region were Ogwashi Formation outcrops (Akpoborie et al., 2011). The facies association 2 consists mainly of sandy heterolithic facies (Sht), bioturbated sandstone facies (Sb), and current rippled laminated sandstone facies (Sr) (Figure 6.11).

FA 2 is heterolithic and it is characterized by interbeds of varying proportion of sands and mud forming flaser bedding, wavy bedding and lenticular bedding. The sands are fine grained and whitish to brown coloured. This unit is strongly to moderately burrowed and dominated by *Lingulichnus* isp. Commonly occurring burrows are *Paleophycus, Skolithos* and *Thalassinoides*. The heterolithic unit is interpreted as intertidal flat and the characteristic presence of *Lingulichnus* isp. is documented in other intertidal flats such as the Keuper Marl of Cheshire of England and the upper Buntsandstein of South Germany (Buatois et al., 2005; Pollard, 1981).

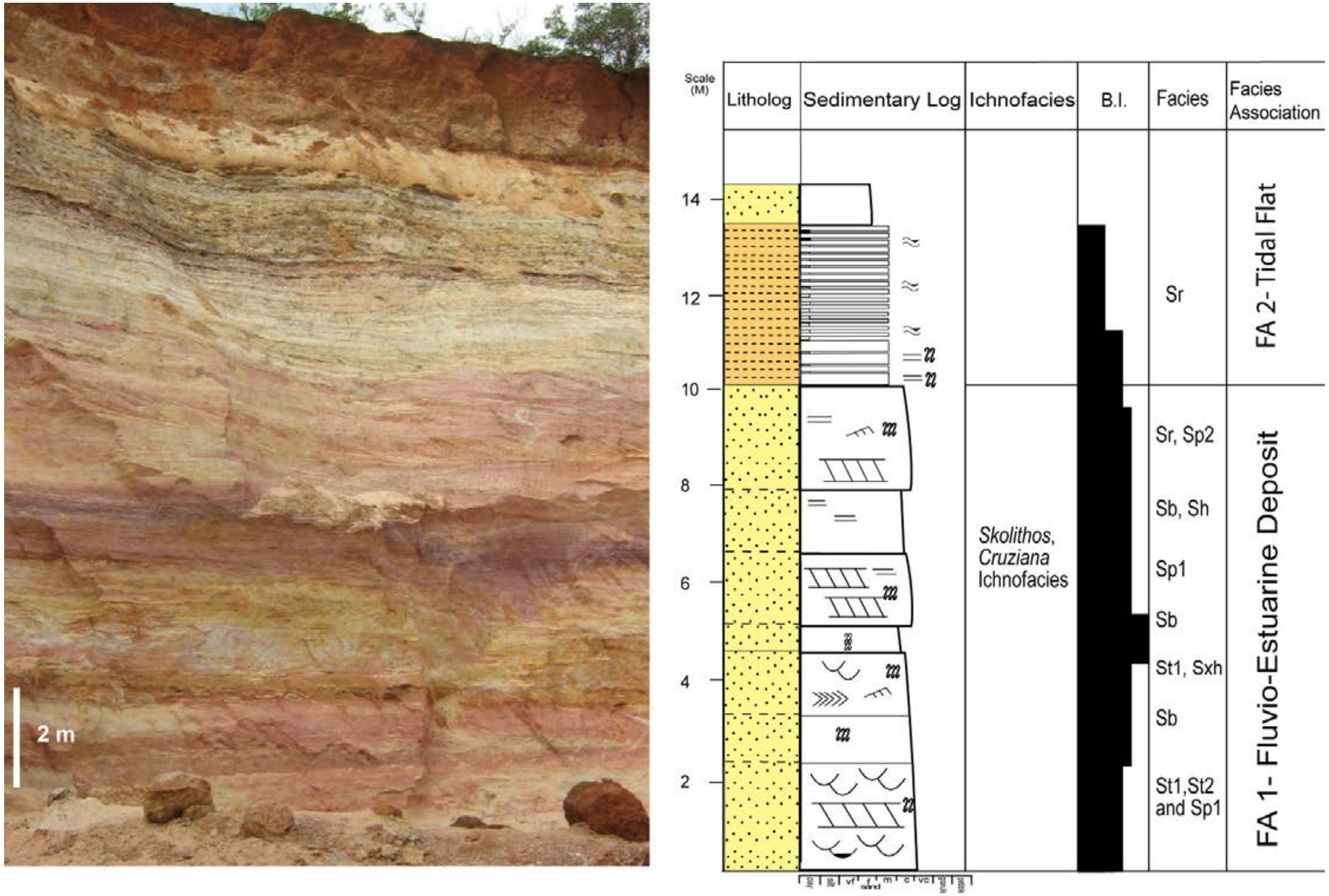


Figure 6.11: Litholog profile of Ogbunike Quarry section showing a typical bioturbated sandstone deposit of the Ogwashi Formation.

FA 3 (Tidal channel deposit)

Facies association 3 is observed in Okaiuga-Umuahia (SOK 1). It occurs as a multistorey channel, which incised into bioturbated conglomerate-coarse grained sandstone. Facies association 3 is composed of trough cross-bedded sandstone facies (St), planar cross-bedded sandstone facies (Sp), bioturbated sandstone facies (Sb), and current rippled laminated sandstone facies (Sr).

The channel fill consist of pebbly to very coarse sandstone, with pebble lags at the base of the channel and also aligned to the foresets. This unit is characterised by sets of low angle planar-tabular cross-beds (Sp5) with large scale sets of up to 4 m (Figure 6.12). The cross-beds trend in a south-east direction of about 150˚. Large scale clay lenses of 40 cm by 30 cm in diameter are common. Succeeding bed units exhibit sets of amalgamated small-scale mud draped planar cross-beds (paleocurrent direction is about 210˚), reactivation surfaces and wavy thick mud bands that form wavy bedding (Sr). This is then overlain by sharp-based large scale trough cross-beds (St), that trend in a south-western direction (240˚) and small scale planar to trough cross-beds, with mud in the troughs forming flaser bedding (Sr). A thick lensiodal pebbly bed (40 cm thick) occurs locally. A pebbly to fine grained burrowed sandstone caps the Okaiuga-Umuahia section. *Ophiomorpha nodosa* and *Paleophycus heberti* dominate the unit. This channel fill vary from 9 m to 13 m thick and the lateral extent is about 70 m to 150 m.

At about 3 km away from the quarry site in Okaiuga-Umuahia, is a road exposure along the Umuahia Expressway which shows a channelized sandstone and claystone fills. The sandstone units show fining upward profile from coarse to fine grained, slightly burrowed, and mud draped planar–tabular cross-beds (Sp), with paleocurrent trend are in south-west direction (264°). A sharp, burrowed (*Planolites beverleyensis)* contact is observed between the sandstone and the overlying claystone (Figure 6.13).

Figure 6.12. Large set of low angle planar cross-beds (Sp5) overlain by small sets of planar cross-beds.

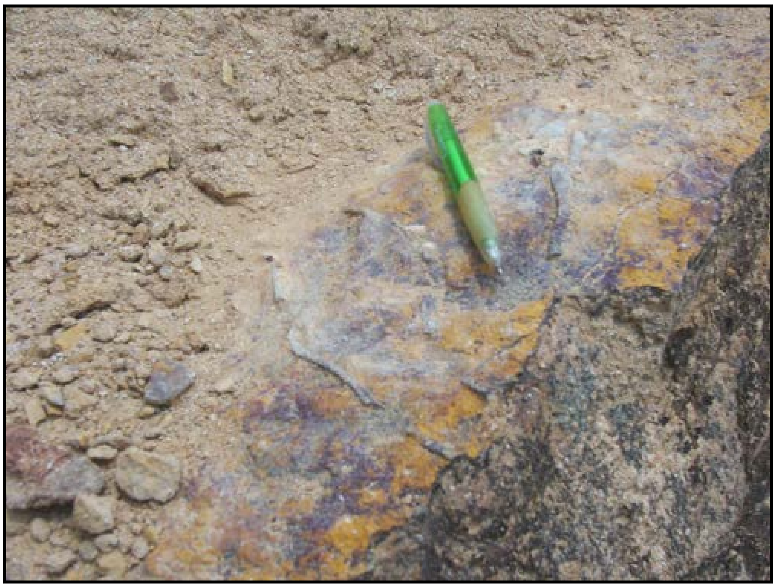


Figure 6.13. Sharp, burrowed (*Planolites beverleyensis)* contact between the sandstone (below) and the overlying claystone.

FA 4 (Coastal plain deposit)

Facies association 4 is dominated by mudstone facies (Fm) and includes massive fine grained sandstone (Sm) and variegated facies (Fms). It is observed as light grey to white coloured claystone-fill channel deposit (Figure 6.14).

Umuahia Expressway Section

The facies association is observed at Umuahia (SOK 2) along the Umuahia expressway and characterised by multistorey mud-fill and fine grained sand-fill channels (of about 10 m thick) (Figure 6.14).

The basal channel axis trends in a south-west direction (230°). Two prominent channels are filled mainly with light grey claystone (Fm), and the infill varies in thickness from 50 cm to 3 m and lateral extent also varies from 40 to 70 m wide. The claystone is massive with no internal scoured surfaces. It is rarely burrowed, but a distinctive network-like sand-fill burrows in one horizon. The overlying succession shows an alternation of slightly concave base, fine grained sandstone channel-fill, light grey claystone and variegated colour gritty claystone-filled channels.

The mud-filled channels suggest channel abandonment (Hopkins, 1985) or incision related to fall in base level (Kraus and Bown, 1993) or channel avulsion (Kraus and Davies-Vollum, 2004). The fine grained channel fill is interpreted as crevasse feeder channels with avulsion deposits (Kraus and Davies-Vollum, 2004). The occurrence of massive claystone with no internal scour surfaces suggests rapid deposition of the claystone. The absence of pedogenic activity in the two major channels and the light grey colour of the claystone are attributed to rapid filling of sediment and a high water table that prohibited pedogenic action (Kraus and Davies-Vollum, 2004). The variegated colour gritty claystone suggests weak pedogenic modification and the alternation of light gray claystone and variegated colour gritty claystone indicates episodic subaerial exposure of the floodplain. The paleosol is similar to the modern entisol or incipient soil.

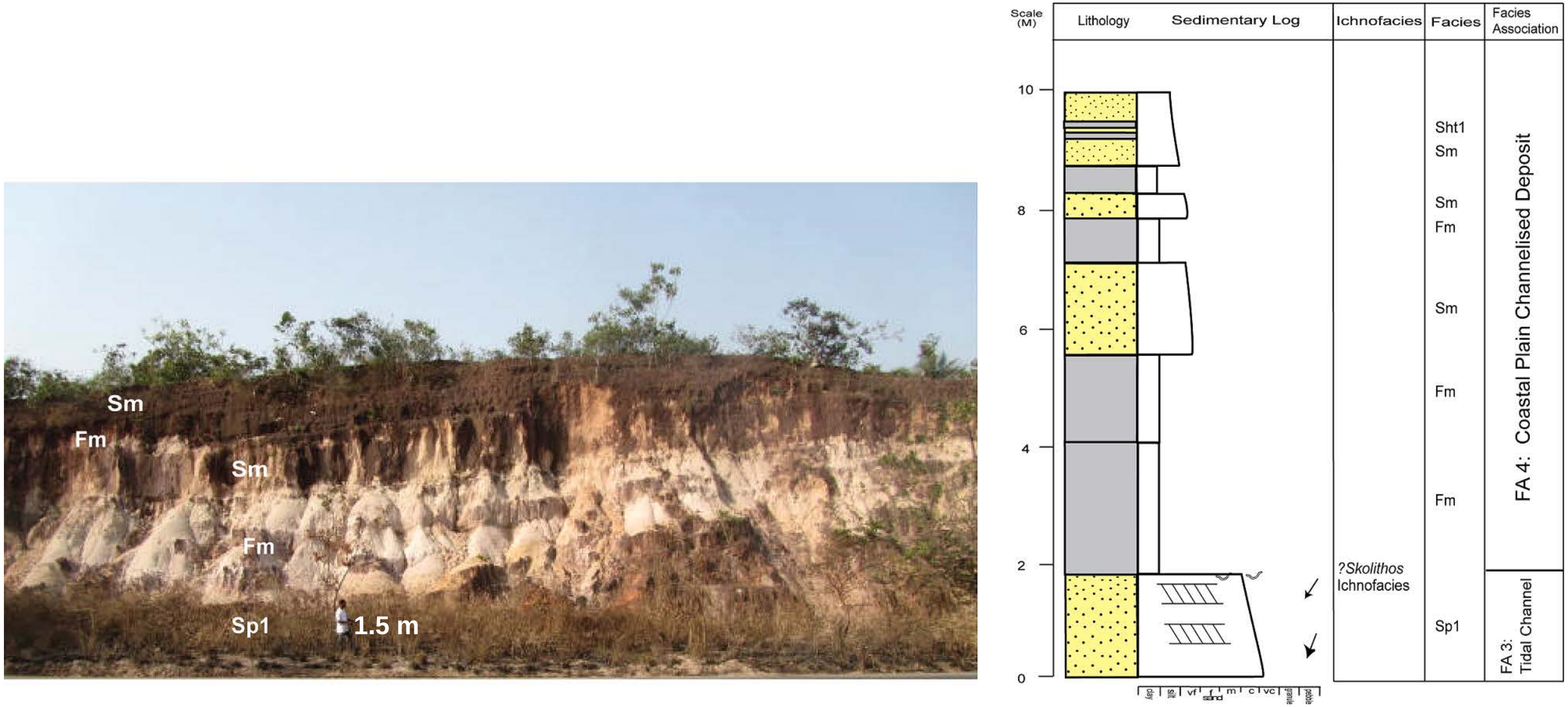


Figure 6.14. (A) Outcrop exposure at Umuahia along the Umuahia expressway exhibiting the claystone-fill channels. (B) Litholog profile of Umuahia Express road section showing the claystone-fill channel deposit of the Ogwashi Formation.

FA 5 (Coastal floodplain/mire)

Facies association 5 is characterised by mudstone facies (Fm), with subfacies (Fm1-carbonaceous mudstone), (Fm2-claystone), (Fm3-gritty claystone) and massive sandstone facies (Sm) (Figure 6.15). This section is the lignite-bearing unit in the study area, with two prominent dark grey carbonaceous horizons that contains lignite fragments (Figure 3.20C).

Ubakala Section

At Umuogo-Ubakala (SUB 1), along Umuahia–Aba Expressway, a claystone quarry exposes about 10 m thick of sediments comprising an alternation of horizontally continuous thick claystone (2 - 6 m thick), and thin lignite rich carbonaceous mudstone (about 60-30 cm thick), with thin micaceous lens-shaped fine grained sandstone layer and gritty claystone (Figure 6.15A). The claystone is greenish grey in colour and finely laminated whereas the lignite rich carbonaceous mudstone is dark grey coloured and comprises lignite, petrified leaves and plant fragments (Figure 3.20).

The horizontally continuous claystone deposits are probably formed in a poorly drained floodplain depression on the coastal plain where mud was deposited from suspension (Falcon-Lang, 2006). This wetland (floodplain) would have contained localised vegetated peat mires where the carbonaceous mudstone, lignite and plant remains accumulated. This interpretation is similar to recent work of Ogala et al., (2012) which is based on analytical study of the lignite samples from the Ogwashi Formation. They suggested the lignite originated from peat (from herbaceous plants and/or tropical angiosperm trees) that accumulated in topogenous mire located in a continental basin. The thin lensiodal sandstone horizon suggests splays formed during high stage flow events in nearby channel (Corbett et al., 2011).

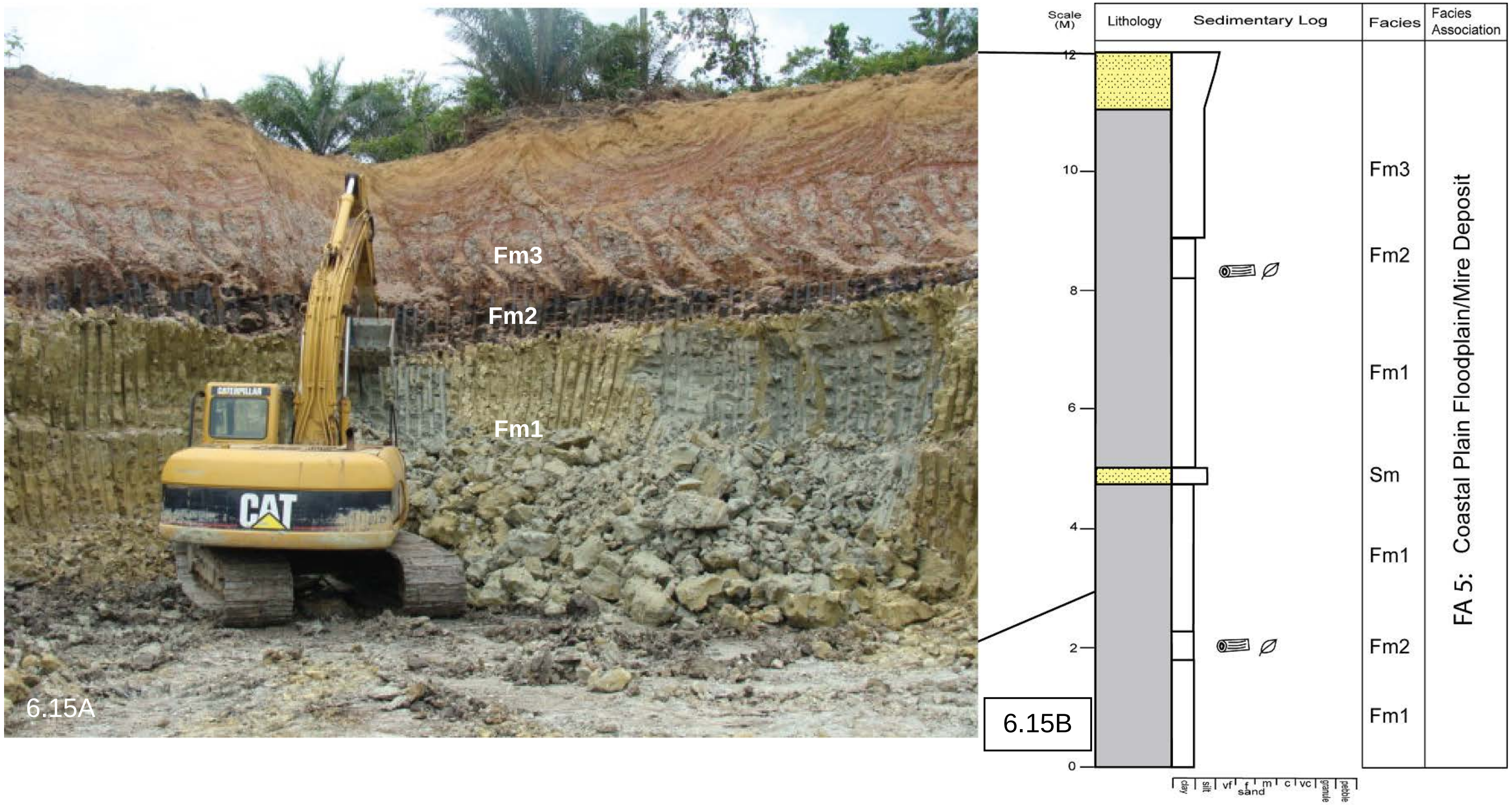


Figure 6.15 (A). Outcrop exposure of Ubakala section. (B). Litholog profile of Ubakala section showing claystone deposit with lignite bearing layers.

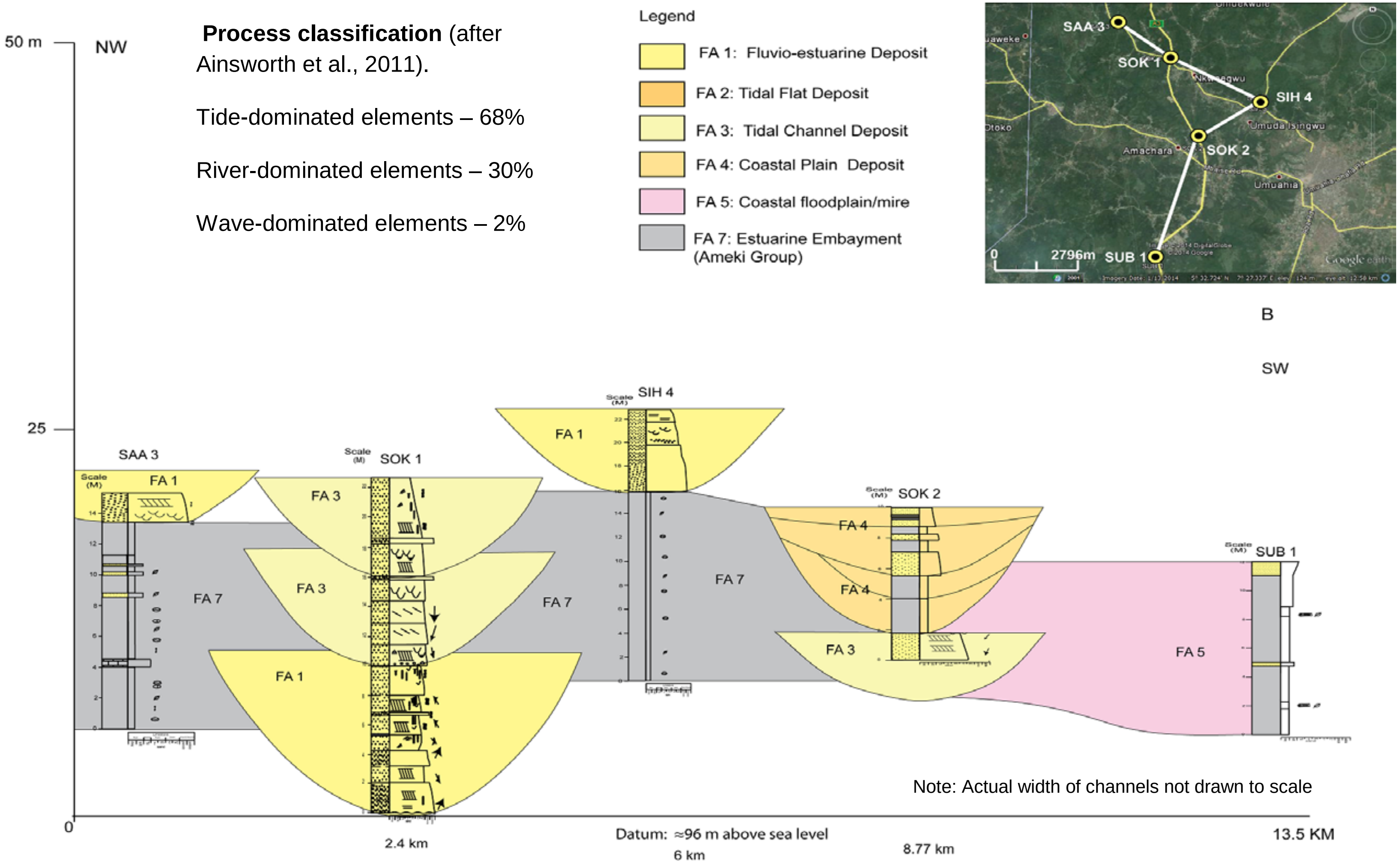


Figure 6.16. Schematic cross-sections of selected outcrops of the Ogwashi Formation showing distribution of depositional facies.

6.3.2 Coastal Plain Architecture

The coastal plain architecture of the Ogwashi Formation comprises of four major elements based on the grain texture, facies geometry, lateral and vertical changes of facies successions, lateral extent of sandstone bodies, spatial distribution and bounding surfaces. The four major elements can be grouped into channelized deposits (which include isolated channels, multistorey channels), non-channelized deposit such as sandy cross-stratified deposit and floodplain deposits (Figure 6.16).

Channelized Element

The channelized elements in the study area are either sand-fill or mud-fill and they may occur as the fill of either isolated channels or multistorey channels.

Isolated Channel deposits are single channel elements that are common in the fluvio-estuarine environment. They occur in Enugwu-Ukwu at Ugwu-Akpi quarry (SNI 1), with a scoured, lower bounding surface (see Figure 5.2A). The channel incised into the underlying distal tidal sand bar deposit of the Eocene Ameki Group. At Umuezeoma-Uhuala, the lower bounding surface is sharp, erosive, rich in quartz and mud pebbles and characterised by *Glossifungites* ichnofacies (Figures 6.3; 6.4). It underlain by the supratidal flat deposits associated with the estuarine embayment of the Eocene Ibeku Formation. The channel fills at Ugwu-Akpi quarry in Enugwu-Ukwu exhibit a fining-upward sequence from strongly bioturbated conglomerate at the base to well burrowed coarse grained sandstone at the top. The channel fills at Umuezeoma-Uhuala consist of cross-stratified conglomeratic units, with internal scour surfaces. Bioturbated is low in these units. The conglomerate to sandstone bed sets vary from 1.5 to 4 m thick, with a maximum exposed outcrop thickness of 9 m and their lateral extent vary from about

15 to 40 m wide. A low width/depth ratio less than 15 indicates a ribbon shaped geometry (Friend, 1983).

Multistorey Channels are associated with the coastal plain channels, fluvio-estuarine and tidal channel environments. They consist of more than one channel, incised and stacked into one another, bounded at the base by scoured, erosive lower bounding surfaces (Miall, 1985). At the Umuahia expressway section individual channels are dominantly mud-fill with subordinate fine grained sand-fill and gritty claystone-fill. Artificial exposure created by road cuts allows the internal geometries and fill of the channels to be observed (Figure 6.17). Lower bounding surfaces are concave-up, sharp and erosive. The channel-infill varies in thickness from 50 cm to 3 m with lateral extent of about 70 m wide. Width/depth ratios of the mud-fill and sand-fill channels are greater than 15 indicating a sheet like geometry (Friend, 1983). Erosional surfaces in the multistorey channels may suggest repeated erosion and infilling (Komatsubara, 2004). Hopkins (1985) noted that mud-fill channels on delta-plain may result from rapid abandonment of channels whereas sand in-fills may result from progressive abandonment of channels. The concave-up multistorey mud-fill channel may have been deposited by vertical aggradation during sudden abandonment whereby the channel is abandoned by diversion of all discharge (Hopkins, 1985).

Large channel fill complexes were observed at Okaiuga-Umuahia in the sandstone quarry as three storey channel fills (Figure 6.18). The first channel fill has a maximum thickness of about 8 m and the exposed lateral extent is about 95 m wide. Although basal contact was not exposed, the lower segment is conglomeratic suggesting an erosive, scoured basal bounding surface. The channel consists of several internal scoured and sharp surfaces bounding the bed units. The beds vary in thickness from 60 cm to 4 m thick and exhibits planar cross-beds cosets, planar, trough cross-beds, massive beds due to bioturbation, herringbone cross-beds and ripple laminated sandstone units. These sedimentary structures change laterally across the bed units due to changes in flow strength. Mud chips, mud balls, mud plugs and mud laminae are common. The mud lenses can be as thick as 7 cm by 53 cm in dimension. Bioturbation varies from low to very intense, with a low diversity of trace fossils. Dominant burrows are vertical shafts of *Ophiomorpha nodosa;* others include *Skolithos, Planolites, Diplocraterion* and *Arenicolites.*

The second channel incised into the first channel, with an incision depth of 3.5 m thick. The basal bounding surface is erosive, scoured, (Figure 6.6) with abundant mud clasts/chips, and pebbles. The base may coincide with a transgressive ravinement surface, which is characterised by the presence of mud clasts/chips, and pebbles, thick mud laminae and intense bioturbation within and below the horizon (Cattaneo and Steel, 2003; Murakoshi and Masuda, 1992). The channel infill has a maximum thickness of about 7.5 m. It consists of low angle planar and trough cross-beds, pebbly to coarse grained sandstone with some mud drapes on foresets. The low angle planar cross beds changes to trough cross bed in a southward direction as the flow velocity increases. The paleocurrent direction is about 240˚ SW. The internal bounding surfaces are sharp and planar. The third channel is strongly oxidised, the accessible section is about 4 m thick. It consists of planar cross bedded sandstone with mud drapes on some foresets. The paleocurrent also trend in about 200˚ SW direction. Internal bounding surfaces are also sharp and planar. The multistorey channels have width/depth ratio less than 15 and have a lenticular ribbon shaped geometry (Friend, 1983).

Sandy cross-stratified deposits

The sandy cross-stratified deposits are observed in Ogbunike quarry (Figures 6.11; 6.19). It consists of isolated sets or cosets of planar cross-beds (Sp1), trough cross-beds (St1), herringbone cross-beds (Sxh), bioturbated sandstone facies (Sb) and current ripple laminated facies (Sr). The element is dominated by unidirectional planar cross-stratified sandstone that trend in the north-east direction. This landward directed cross stratification suggests tidal influence. The thickness of the sandy cross-bedded element varies between 5 to 15 m, while the individual bed-sets are 0.2 m to 1.5 m thick. The lateral extent of the sandy bedform element varies between 80 to 150 m tabular-shaped sandbodies and their W/T ratio exceeds 15. Basal and upper bounding surfaces are sharp and may be planar or undulatory. The single sets and co-sets cross-stratification suggest deposition due to migration of simple and compound (superposed) dunes of variable sizes (Gani and Bhattacharya, 2007).

Floodplain Element

The floodplain element is predominantly represented by claystone, thin discontinuous sandstone laminae and carbonaceous mudstone with lignites. This grades into a brownish coloured gritty claystone, that suggest poorly developed paleosol, and it is similar to modern entisol (incipient soil). Entisols are known to occur commonly on young geomorphological surfaces such as floodplain (Retallack, 2001). The floodplain deposit varies in thickness from 4 to 13 m. It is laterally extensive, covering tens of metres and thus, infers to as a sheet-like geometry. The tidal flat deposit also occurs as a sheet-like geometry.

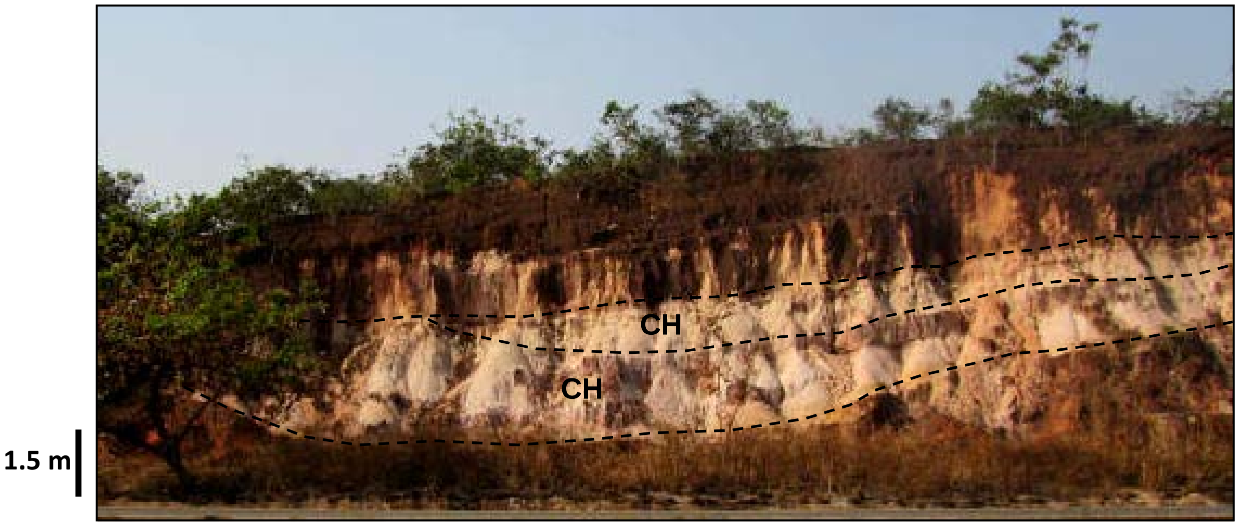


Figure 6.17. Road cut exposure at Umuahia section exhibiting the geometry of the claystone-fill channels (CH).

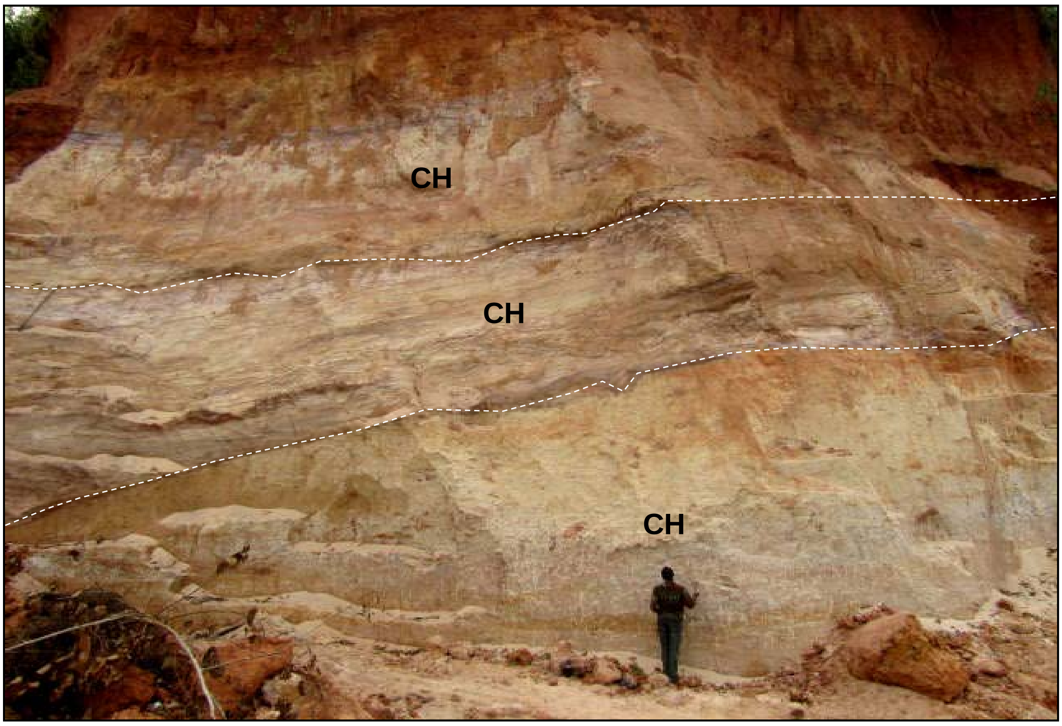


Figure 6.18. Sandstone quarry exposure at Okaiuga-Umuahia showing sandstone-fill channels (CH).

Figure 6.19. Sandstone quarry exposure at Ogbunike showing sheet-like geometry.

6.3.3 Clay Mineralogy

Introduction

Three representative mudrock samples analysed from Ogwashi Formation show the clay and non-clay minerals present. The two major occurring minerals are kaolinite and illite (Table 6.1), with nontronite present as traces. The non-clay minerals present are dominated by quartz. Microcline, siderite and anatase presence are negligible. Appendix D6.1 shows the X-ray patterns for the clay minerals as well as other non-clay minerals.

Results

Results (Table 6.1) show clay mineral type and distribution in the Oligocene Ogwashi Formation. The main occurring mineral is kaolinite ranging from 45% to 83% and illite with a range of 7% to 12%. The non-clay minerals present are limited to quartz, microcline, siderite and anatase (Table 6.1). The concentration of quartz mineral is high (22% to 37%). Other non-clay minerals such as microcline, siderite and anatase are poorly represented, with low count of less than 7.3%.

Interpretation

Kaolinite is the most commonly occurring clay mineral in the Paleogene sediments indicates high input of terrigenous debris and tropical humid climatic condition during the Oligocene. The occurrence of kaolinite and mixed layer illite as the only clay mineral present in Ogwashi Formation signifies dominance of terrigenous input (Thiry and Jacquin, 1992).

Table 6.1. Rietveld quantification of the analysed whole rock samples of the Ogwashi Formation showing the clay minerals in percentage.

Formation	Ogwashi		
Sample no	**SOK2.1**	**SUB-4**	**SUB-7**
Nontronite-15 A %	0	0	0.3
Kaolinite %	62.6	45.1	83.2
Illite %	12	7.9	10.7
Palygorskite %	0	0	0
Goethite	0	0	0
Chlorite	0	0	0
Quartz 2%	22.3	37.3	2.6
Microcline %	1.9	2.1	1.2
Orthoclase	0	0	0
Albite	0	0	0
Calcite 1%	0	0	0
Gypsum %	0	0	0
Rutile	0	0	0
Graphite	0	0	0
Pyrite %	0	0	0
Stilbite	0	0	0
Siderite	1.2	7.3	1
Anatase	0	0.2	0.9

6.4 DISCUSSION

6.4.1 Sequence stratigraphy and Ichnological significance of key surfaces

The sequence stratigraphic framework of the Oligocene Ogwashi Formation suggests a single depositional sequence for the formation. The major stratigraphic surfaces encountered are the sequence boundary (SB), the maximum flooding surface (MxFS) and transgressive surfaces of erosion (TSE). About three TSE occur in the formation representing repetitive transgression within the stratigraphic sequence. The depositional sequence consists of incomplete systems tracts which consist of transgressive systems tract and highstand systems tract with several top truncations. These incomplete systems tracts may have formed under direct or indirect influence of glacioeustatic sea level changes (Catuneanu et al., 2009), or associated with subsidence.

Amalgamated sequence boundary (SB) and marine flooding surface (FS)

The base of the depositional sequence (sequence boundary) is marked by an abrupt, scoured, erosional contact between the Ameki Group and the overlying Ogwashi Formation as revealed in Ugwu-Akpi quarry, Enugwu-Ukwu. The sequence boundary is also evident by the presence of *Glossifungites* ichnofacies, typically dominated by *Thalassinoides, Ophiomorpha, Arenicolites* and *Paleophycus* observed in Umuezeoma Uhuala. *Glossifungites* ichnofacies occurs in semi-lithified or firm substrates formed either by subaerial exposure or by burial and subsequent exhumation (Pemberton and Frey, 1985; MacEachern et al., 1992; Pemberton et al., 1992; 2004). They are usually associated with erosional discontinuities such as sequence boundary (SB), transgressive surface of erosion (TSE), amalgamated sequence boundary and marine flooding surface (FS/SB) and regressive surface of erosion (RSE) (Pemberton et al., 1992; 2004). The underlying Eocene Ameki Group at Umuezeoma Uhuala terminated with thick sequence of shale, limestone concretions, siltstone layers and finally mottled mudstone. The mottled mudstone is interpreted as supratidal flat which signifies paleosol resulting from subaerial exposure at the period the relative sea-level was low. The Oligocene period was initiated with probably an uplift that resulted to numerous incisions and deposition of conglomerate characterised by plant debris and lignite fragments. Subsequently, the relative sea-level rise ensued in the incursion of marine water, which resumed burrowing in the mottled mudstone. The presence of low-diversity *Skolithos* ichnofacies in the conglomeritic channel fill and the occurrence of firmground *Glossifungites* ichnofacies at the basal contact suggest that the marine flooding surface (FS) occur contemporaneous with the SB which resulted in the marine reworking of the initial fluvial deposits. This corresponds to Pemberton et al., (2004) explanation of the amalgamated SB and FS which also occur in coastal plain and delta plain settings were initially subaerial surfaces subsequently get flooded and eroded during transgressive influx of brackish to marine water.

Maximum flooding surface (MxFS)

The conglomerate fines upward into very coarse to coarse grained sandstone that is typified by episodic occurrence of trace fossils. The topmost unit of the basal channel at Okaiuga-Umuahia quarry is intensely bioturbated with uniformly distributed distal *Skolithos* ichnofacies consisting of *Ophiomorpha*, *Skolithos, Diplocraterion, Arenicolites, Planolites* and *Cylindrichnus.* Due to the intense bioturbation, the horizon is almost biogenically homogenised (Figure 6.9). The lateral continuity of this high-density bioturbation horizon implies evidence of fully marine conditions. This probably records the most landward extent of marine incursion or maximum flooding surface

(MxFS) (Rodriguez-Tovar and Uchman, 2006). The maximum flooding surface also coincides with the second transgressive surface of erosion (Catuneanu et al., 2009) and is characterised by sharp erosive contact, sandy substrate *Skolithos* ichnofacies, mud plugs, and mud rip-up clasts. The erosional discontinuity is obvious due to abrupt change of the abundance and diversity of the *Skolithos* ichnofacies.

Transgressive systems tract (TST)

The transgressive systems tract consists of the interval between the sequence boundary and the maximum flooding surface. The subaerial exposure may have occurred during relative sea-level lowstand and probably deposited fluvial sediment. These deposits may have been partially eroded and reworked during early transgression resulting to marginal-marine conditions that led to deposition of aggradational fluvio-estuarine sediments. The fluvio-estuarine deposit are characterised by crudely horizontally bedded conglomerate, cross stratified conglomerate, cross stratified sandstone and bioturbated sandstone. Paleocurrent data for these sediments show a partial pebble imbrications in NE direction, while the stratified conglomerate exhibits both NW and SW directions. The cross stratified sandstone likewise shows SE and NW directions. These suggest a strong marine reworking (tide) of the initial fluvial deposits.

Highstand systems tract (HST).

The highstand systems tract overlays the transgressive systems tract and it is represented by thick succession of strata interpreted as tidal channel, coastal plain channel and floodplain/mire deposits. These deposits are common features of the HST (Shanley et al., 1992; Corbett et al.,2011). The base of the mud-fill coastal plain channel is interpreted as a minor transgressive surface of erosion. This is evidence from the presence of firmground *Planolites* that reflects *Glossifungites* ichnofacies (Figure 6.13). The stacked channels of the coastal plain and the extensive floodplain represent late highstand deposits as available accommodation is filled and relative base level begins to fall.

6.5 CONCLUSIONS

The Oligocene Ogwashi Formation outcropping in the study area is re-interpreted as tidally influenced coastal plain deposit, due to strong influenced of marine incursion (which resulted to intense bioturbation of low diversity *Skolithos* ichnofacies) and associated tidal processes. Facies architecture suggests dominance of channelized sediments that exhibit isolated and multistorey channel bodies. Floodplain/mire deposits occurred in the flooded overbank plains and interfluves. The sequence stratigraphic interpretation reveals a type-1 sequence boundary that incised into the underlying Eocene Ameki Group. An incomplete depositional system that consists of transgressive systems tract and highstand systems tract typifies the coastal plain succession. This is due to fact that no fluvial sediment was observed; though the incision and an initial fluvial deposit may have occurred during the lowstand systems tract, this was reworked by tides creating a fluvio-estuarine condition. The tidally influenced coastal plain setting was thus formed during the intermittent transgression of the shoreline. Sea level changes, as well as availability of siliciclastic sediment, accommodation and geomorphology (low elevation and low relief) may have contributed to the stratigraphic succession of the Ogwashi Formation.

CHAPTER SEVEN

ICHNOLOGY OF THE PALEOGENE STRATA, SOUTH-EASTERN NIGERIA

7.1 INTRODUCTION

Trace fossil analysis is an important tool used in determining depositional settings and identifying the characteristics of a sedimentary environment such as the depositional energy, sedimentation rates, substrate cohesiveness, salinity and other chemical parameters (Bromley, 1990; Pemberton et al., 1992; Taylor et al., 2003; McIlroy, 2004; Gingras et al., 2011). Ichnology is also important in recognising and delineating key strata surfaces in stratigraphic sequence (Goldring, 1995; MacEachern et al., 1992; Pemberton et al., 2004; Taylor and Gawthrope, 1993; Taylor et al., 2003).

The main ichnological methods employed in this study in order to obtain a high-resolution sedimentary analysis are trace fossil identification (systematic ichnology) and ichnofacies analyses. Trace fossil analysis records the behaviour of the organisms/plants as a response to subtle changes in environmental parameters such as substrate consistency, salinity, energy conditions and oxygenation (Buatois et al., 2002). Ichnofacies analysis uses the ethological grouping of trace-fossils, based on the temporal and spatial recurring suites that are commonly associated with depositional conditions (Gingras et al., 2011; Pemberton et al., 1992). Published works on the trace fossils assemblages limits the Paleogene ichnofacies to only *Skolithos* and *Cruziana* ichnofacies (Anyanwu and Arua, 1990; Nwajide and Hoque, 1979).

This research aims at using the analysis of trace fossils by integrating systematic ichnology and ichnofacies studies to: infer depositional and biogenic processes operating during basin fill; identify discontinuities using substrate controlled ichnofacies; identify physiological stressful conditions that affected the diversity of trace fossils;

identify and document the ichnofacies assemblages found within the Paleogene rocks and provide ichnologically constrained facies control for the Paleogene strata.

7.2 METHODOLOGY

Systematic sedimentological and ichnological field descriptions were obtained from the study area. The sedimentological approach has been discussed in chapter one. The trace-fossil size, ethological diversity, trace-fossil distribution and strength of bioturbation were recorded. The taxonomic affinity of the trace fossils is recognised by observing the burrow boundary or wall structure, the burrow fill and the branching characteristics. Observations from the field are used to describe the trace fossils and to consider the ichnofacies assemblages present. Information from the trace fossil studies is synthesized for the interpretation of depositional environments.

7.3 RESULTS

7.3.1 Systematic Ichnology

The trace fossil distribution in the Paleogene sedimentary rocks is characterised by high to low ichnodiversity and abundance. The low ichnodiversity is associated with physiologically stressful conditions such as salinity stress, low water oxygenation and nutrients stress (Buatois et al., 2005; MacEachern et al., 2007). Higher ichnodiveristy and abundance indicates less stressful conditions in which the environment is more hospitable for the organisms (Phillips et al., 2011). The Imo Formation exhibits moderate to low diversity and an abundance of trace fossils. The distribution of trace fossils in the Ameki Group varies from high to low ichnodiversity and abundance depending on the facies association. The Ogwashi Formation contains a high degree of bioturbation, but with a monospecific to low diversity of ichnofossils. A systematic description of the trace fossils identified in the study area is discussed below in alphabetical order:

Ichnogenus: Arenicolites Salter, 1857

Type Ichnospecies: *Arenicolites* isp. (Figure 7.1A, B)

Description: *Arenicolites* occur as simple U-shaped tubes. They are preserved in convex epirelief (Figure 7.1A) as paired circular openings on the bedding plane and as a complete full relief on a vertical section (Figure 7.1B). Burrows are small and have a diameter of 5-20 mm and height of about 80 mm. The burrow lining is thin; the burrow fill is finer than the surrounding substrate. Mud fill is observed in Figure 7.1A.

Occurrence: *Arenicolites* is observed in the basal unit of the sandy heterolithic beds (Sht) at the Ugwu-Nnadi Heterolithic section (chapter 5). The heterolithic facies are interpreted as tidal point bars of the (Nanka Formation) Ameki Group. Arenicolites also occur in the upper unit of the bioturbated sandstone facies (Sb) of the Ogbunike Quarry section (chapter 6), which is interpreted as fluvio-estuarine deposit of Ogwashi Formation. It is considered to be a dwelling and feeding burrow (domichnia) of suspension-feeding (polychaete) annelids (Pickerill, et al., 1992; Buatois, et al., 2005).

Ichnogenus: ?Asterosoma von Otto, 1854

Type Ichnospecies: ?*Asterosoma* isp. (Figure 7.1C)

Description: *Asterosoma* isp. is observed in cross-section as a small oval-shaped burrow with a subcircular inner tube. The burrow infill is massive with clayey fine grained sandstone. The burrow length is about 50mm and the width has a maximum diameter of about 40 mm that tapers downward to 10 mm.

Occurrence: Asterosoma occur in very low abundance in fine grained sandstone beds of a bioturbated sandstone facies (Sb) of the upper unit of the Umunya Section (chapter 5), Nanka Formation of the Ameki Group interpreted as intertidal sandflat. It is commonly referred to as a deposit feeder of decapod crustaceans (Neto de Carvalho and Rodrigues, 2007). The ichnospecies could not be identified due to poor definition of the general morphology and the absence of a view of the external surfaces of the bulbs and the associated shafts.

Ichnogenus: Beaconites Vialov, 1962

Type Ichnospecies: *Beaconites antarcticus* Vialov, 1962 (Figure 3.12C)

Description: *Beaconites antarcticus* exhibits subhorizontal, tabular, unbranched, thick walled, meniscate backfilled burrows. The burrow wall is smooth, unornamented and clayey. The packed menisci merged into the wall lining. Burrow infill meniscates are homogeneous packets of unequal thickness. The burrows are small and vary in length from 50 to 80 mm long and 10 to 30 mm wide.

Occurrence: *B. antarcticus* is preserved in fine to medium grained sandstone of sigmoidal cross-stratified sandstone facies (Sx) interpreted as subtidal zone of tidal channel. This occurs in the lower unit of the Umunya section, Nanka Formation of the Ameki Group. The burrows are produced by simple excavation or during locomotion (Keighley and Pickerill, 1994); they are referred to as locomotion structure (Buatois and Mángano, 1993) produced by arthropods or vertebrates (Graham and Pollard, 1982). Although the burrows are common in terrestrial environments (Buatois and Mángano, 1993; Bruck et al., 1985), they have also been reported in marginal marine environments (Bridge and Droser, 1985).

Ichnogenus: Conichnus Myannil, 1966

Type Ichnospecies: *Conichnus conicus* Myannil 1966. (Figure 7.1B)

Description: This occurs as a vertical conical structure or a cone-in-cone structure. It is usually perpendicular to bedding. The inner central burrow fill is structureless and similar to the surrounding matrix. The upper part of the cone is about 80mm wide and tapers downward to less than 40 mm wide. The length is about 250 mm long.

Occurrence: *Conichnus* is observed in medium to coarse grained sandstone of the Ogbunike Quarry section (upper unit) interpreted as fluvio-estuarine deposit of the Ogwashi Formation. *Conichnus* isp. is associated with resting and adjustment structures (Gerard and Bromley, 2008).

Ichnogenus: Cylindrichnus Howard, 1966

Type Ichnospecies: *Cylindrichnus concentricus* (Figure 3.12D)

Description: *Cylindrichnus concentricus* is observed as vertical to oblique, slightly curved burrows with conical and concentric lined shafts (Figure 3.12D). The conical shaped burrow may thicken upward and tapers downward. The burrows are passively filled and up to 80 mm long with diameter varying between 5–15 mm.

Occurrence: *Cylindrichnus* occurs in fine to coarse grained sandstone. It is observed in the sigmoidal cross-stratified facies of subtidal channel in the lower unit of the Umunya section, Nanka Formation of the Ameki Group and the non-inclined heterolithic facies of intertidal flat deposit of Paully petrol station section (chapter 5), Nanka Formation of the Ameki Group. *Cylindrichnus* isp. is also found in the planar cross-stratified sandstone of a medium to coarse grained sandstone in the lower and upper units of the Ogbunike Quarry section interpreted as a fluvio-estuarine deposit in the Ogwashi Formation. The structure is interpreted as a dwelling burrow (domichnia) of filter feeding organisms or polychaete annelids (Goldring, 1996). The domichnian burrow also indicates sufficient bottom-water circulation and oxygenation at the sea floor (Ekdale and Lewis, 1991).

Ichnogenus: Diplocraterion Torell, 1870

Type Ichnospecies: *Diplocraterion parallelum* Torell, 1870 (Figure 7.1D, E,F)

Description: *Diplocraterion parallelum* is observed in the study area as a vertical U-shaped burrow with protrusive or retrusive spreite (back-fill laminae). The burrows have a passive fill and vary in length from 50 to 200 mm and the cumulative width is up to 20 mm.

Occurrence: *Diplocraterion* occurs as opportunistic burrows in the planar cross-stratified sandstone of the Ishiagu section (lower unit) interpreted as outer estuarine tidal sandbar facies (Nanka Formation of the Ameki Group) and also as monospecific burrows in silty intertidal deposits of the Ishiagu section (uppermost unit) Nanka Formation. *Diplocraterion* is useful for identifying tidally influenced environments such as tidal channels, tidal sandbars when associated with high energy deposition (Cornish, 1986). The trace fossil also characterises transgressive surfaces (Taylor and Gawthrope, 1993) and has been used to delineate sequence boundaries in the Kimmeridgian, Jurassic, Southern Spain (Olóriz and Rodríguez-Tovar, 2000).

The back-fill laminae (spreite) reflect movement of the burrow upwards or downwards in the substrate, which may occur in response to infaunal feeding and concurrent extension of the burrow downwards or in response to dynamic sediment conditions such as burial or erosional exhumation and concurrent shifting of the burrow either upwards or downwards (Fursich, 1974a). *Diplocraterion* isp. reflects activities of infaunal suspension feeders which include vermiform organisms and diminutive arthropods (Fürsich, 1974a; Cornish, 1986).

Type Ichnospecies: ?*Diplocraterion biclavatum* Miller, 1875 (Figure 7.1G)

Description: *D. biclavatum* is preserved in full relief, whereby the arms of the U-tube are observed (Figure 7.1) as they extend below the base of the deepest U to form blind pouches (Fürsich, 1974A). The spreite are not clearly observed most likely due to the coarse nature of the sediment. The burrow is about 70 mm long and 30 mm wide.

Occurrence: *D. biclavatum* occurs in the lower unit of very coarse grained bioturbated sandstone facies of Ugwu-Akpi section interpreted as the fluvio-estuarine deposit of the Ogwashi Formation.

Ichnogenus: Gyrolithes Saporta, 1884

Type Ichnospecies: *Gyrolithes davreuxi* Saporta, 1884 (Figure 7.1C)

Description: *Gyrolithes davureuxi* are coiled, helical-shaped burrows in an upright position. It occurs as circular cross sections of burrow segments. The coil diameter is about 20–50 mm wide and the length is about 60 mm. The burrow is passively mud-filled and different from the substrate which is fine grained sandstone. The burrow is unbranched and unlined but sharp walled.

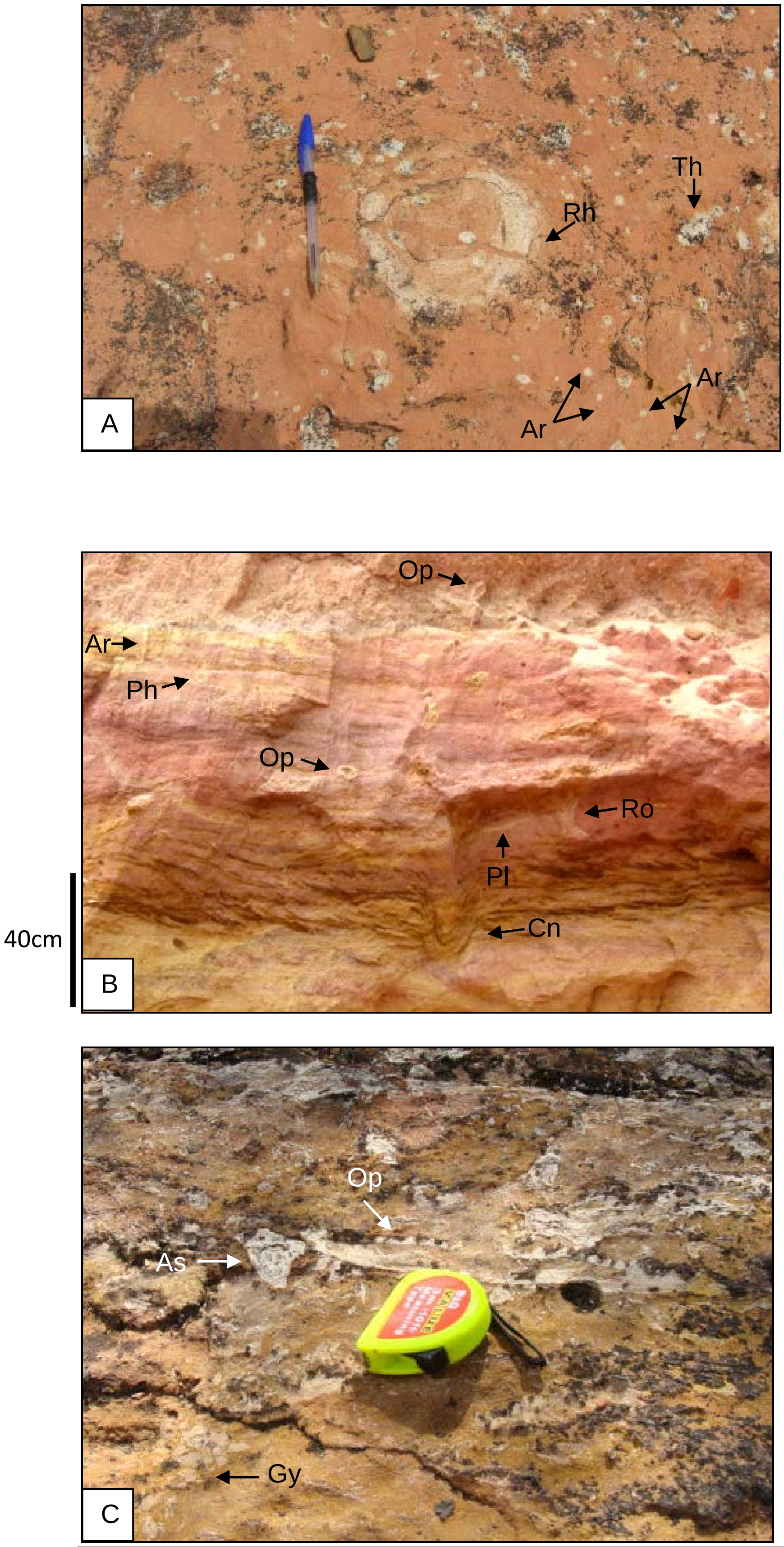
Occurrence: *G. davureuxi* occurs in bioturbated sandstone facies of Umunya section (upper unit) which is interpreted as the sandflat zone of an intertidal flat (Nanka Formation). *Gyrolithes* is known to occur exclusively in marginal marine and brackish water environments (Gernant, 1972; Netto et al., 2007; Pemberton and Wightman, 1992) and it represents a permanent dwelling burrow (domichnia) produced by thalassinidean shrimps-decapods (crustaceans) and caterpillar worms. *Gyrolithes* is known to reflect fluctuating salinity in estuarine setting (Buatois et al., 2005; Netto et al., 2007; Wetzel et al., 2010).

Ichnogenus: Laminites Ghent and Henderson, 1966.

Type Ichnospecies: *Laminites* isp. (Figure 7.1H)

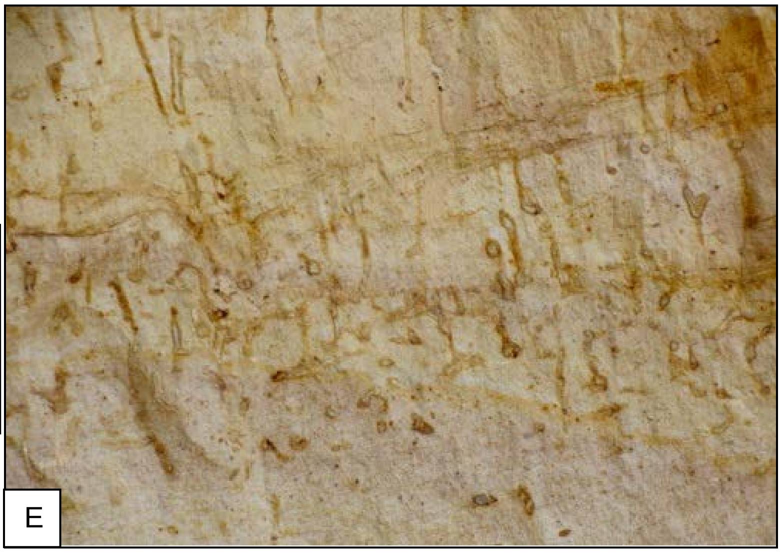
Description: *Laminites* isp. is observed in the study area as horizontal to inclined burrows with back-fill laminae. The miniature burrow is passively-filled, with length of 50 mm and width of about 10-15 mm.

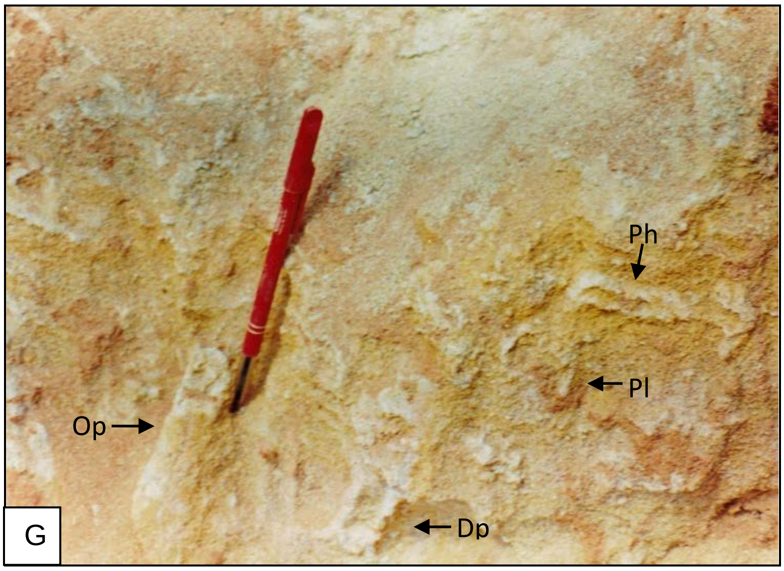
Occurrence: *Laminites* isp. occurs in fine to medium grained sandy heterolithic facies (Sht) at the basal unit of the Ugwu-Nnadi Heterolithic section, which is interpreted as tidally influenced fluvial deposit of the Nanka Formation. The occurrence of *Laminites* probably suggests an impoverished *Cruziana* ichnofacies (Rebata et al., 2006b) that occurs in low-energy heterolithic sandy units. *Laminites* is a variant of *Scolicia* and it is commonly observed in water with relatively salinity of >20 or 25 ppt (Rebata et al., 2006b). The presence of *Laminites* in the tidally influenced fluvial deposits indicates marginal marine conditions (Gingras et al., 2002b). *Laminites* is regarded as a grazing trace, produced by endobenthic and deposit feeding irregular echinoids (Gibert and Martinell, 1995).


Th
Rh
Ar
Ar
A
Op
Ar
Ph
Op
Ro
Pl
Cn
40cm
B
Op
As
Gy
C

40cm

40cm




Ph
Pl
Op
Dp
G


H

Figure 7.1.A-H: Eocene to Oligocene ichnofauna of the tide-dominated estuarine system of the Ameki Group and tidally influenced Ogwashi Formation. A: Tidally influenced fluvial deposit characterised by vertical and horizontal ichnofossils including *Arenicolites* isp. (Ar), *Rhizocorallium jenense* (Rh), *Thalassinoides paradoxicus* (Th). B: Fluvio-estuarine deposit (Ogwashi Formation) displaying *Arenicolites* isp. (Ar), *Paleophycus* (Ph), *Ophiomorpha* (Op), *Planolites montanus* (Pl), *Rosselia socialis* (Ro) and *Conichnus* (Cn). C: Strongly burrowed intertidal sandflat exhibit robust *Ophiomorpha nodosa* burrows, *Asterosoma* (As) and *Gyrolithes* (Gy). D-E: Opportunistic burrows preserved in outer estuarine tidal sandbar, prominent are *Skolithos, Arenicolites* isp., *Diplocraterion, Lockeia* isp. and escape burrows associated with *Lockeia*. F: Intertidal flat with *Diplocraterion* burrow. G: Oligocene ichnofauna of fluvio-estuarine deposit of Ogwashi exhibiting *Ophiomorpha nodosa* (Op), *Diplocraterion* (Dp), *Planolites montanus* (Pl) and *Paleophycus heberti* (Ph). H. Miniature *Laminites* isp. (black arrow) found in the sandy heterolithic facies of the tidally influenced fluvial deposit.

Ichnogenus: Lingulichnus Hakes, 1976

Figure 7.2 shows the schematic diagram of lingulide infaunal behaviour, which reflects the three ichnospecies - *L. verticalis, L. inclinatus, L. hamatus*, as observed at Ogbunike quarry section of the Oligocene Ogwashi Formation.

Type Ichnospecies: *Lingulichnus verticalis* (Figure 7.3).

Description: *L. verticalis* is a vertical, sediment-filled tube characterised by downward-deflected laminae or spreite. The pedicle trace is very conspicuous. Burrows are 5-10 mm wide and vary in length between 50 and 150 mm long.

Occurrence: The burrows occur in a sandy heterolithic facies at the upper unit of the Ogbunike Quarry section, which is interpreted as intertidal deposits, although they penetrate downwards into the underlying fluvio-estuarine deposit of the Ogwashi Formation. *L. verticalis* represents the dwelling structure of (domichnia) of a lingulide brachiopod (Hakes, 1976; Buatois et al., 2005; Zonneveld and Pemberton, 2003; Zonneveld et al., 2007); the common occurrence of long pedicles and the downward-deflected laminae reflect an equilibration structure, which suggests *L. verticalis* is a lingulide equilibrichnia.

Type Ichnospecies: *Lingulichnus inclinatus* (Figure 7.3).

Description: *L. inclinatus* is an oblique oriented, sediment filled tube, also produced by a lingulide brachiopod.

Occurrence: *L. inclinatus* is less common in the sandy heterolithic facies of the Ogwashi Formation. The presence of the burrow may be indicative of stressed conditions (oxygen, salinity, or population stress) Zonneveld and Pemberton (2003); Zonneveld et al., (2007).

Type Ichnospecies: *Lingulichnus hamatus* (Figure 7.3).

Description: *L. hamatus* is characterised by the wide, vertical U-shape and n-shape burrows. J- shaped burrows are also observed. The burrows may show downward-deflected laminae.

Occurrence: *L. hamatus* is common in sandy heterolithic units (intertidal flat) and the underlying fluvio-estuarine deposit of the Ogwashi Formation. The U-shaped burrow is said to be formed by an exhumed lingulide brachiopod; the J-shaped burrow is formed by a buried lingulide brachiopod (Zonneveld and Pemberton, 2003; Zonneveld et al., 2007); the n-shaped burrow may also be formed by buried lingulide brachiopod. *Lingulichnus* isp. are known to occur in variety of environment settings form shallow marine to marginal marine (Buatois et al., 2005; Zonneveld and Pemberton, 2003; Zonneveld et al., 2007).

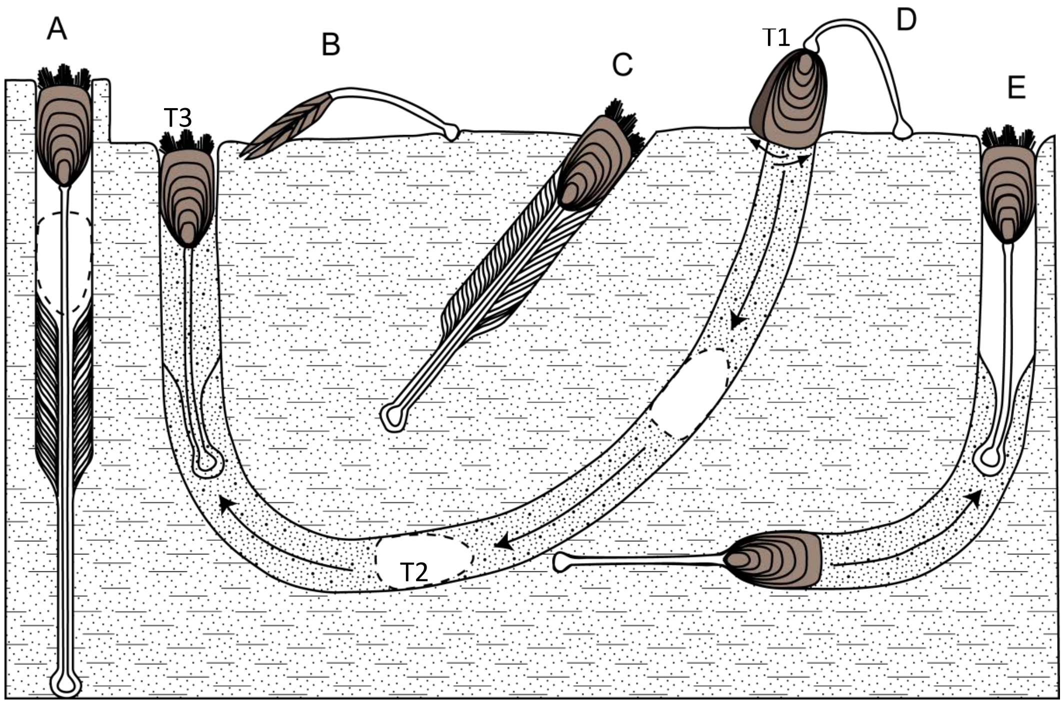


Figure 7.2. Schematic diagram of lingulide infaunal behaviour (redrawn and modified after Zonneveld et al., 2007). Ichnofossils reflecting these ethologies are preserved in the fluvio-estuarine deposit of Ogwashi Formation. The ichnospecies is derived from the lingulide behaviour. A: *Lingulichnus verticalis* is assigned to lingulide brachiopod in normal dwelling position. B: A lingulide in process of arching its pedicle, to initiate reburrowing after exhumation. C: *Lingulichnus inclinatus* is assigned to lingulide brachiopod in oblique position. D: *Lingulichnus hamatus* is formed by a U-shaped burrow of an exhumed lingulide brachiopod. Zonneveld et al., 2007 illustrated the downward movement of brachiopod from T1 to T2 and upwards to the surface (T3), in a vertical orientation. E: *Lingulichnus hamatus* is also referred to J-shaped burrow; it is produced by a buried lingulide brachiopod after exhumation, transport and burial.

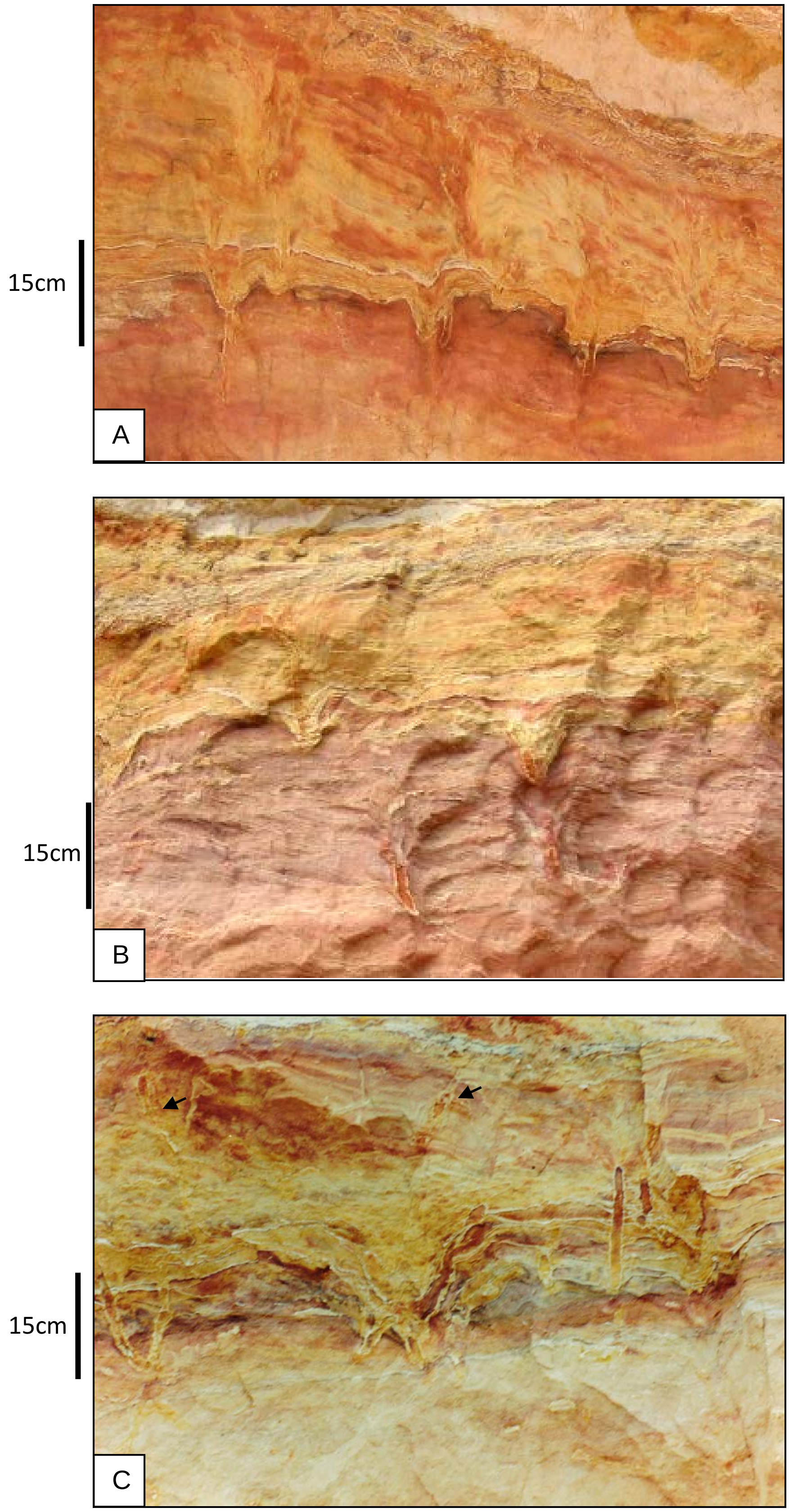

15cm
A
15cm
B
15cm
C

Figure 7.3. Oligocene ichnofauna in fluvio-estuarine deposit of the Ogwashi Formation. A: *Lingulichnus verticalis* in interstratified sandstone and mudstone heteroliths of intertidal deposit. B: *Lingulichnus hamatus* (J-shaped burrow) occurs in the underlying sediment. C: *Lingulichnus hamatus* (U-shaped burrow), *L. verticalis* and *L. inclinatus* (black arrow) occurring in the heterolith.

Ichnogenus: Lockeia James, 1879

Type Ichnospecies: *Lockeia* isp. (Figure 7.4A)

Description: *Lockeia* isp. is represented by a small bilaterally symmetrical trace, an almond–shaped burrow, preserved as positive and negative epirelief. The burrows are about 3-8 mm long and 3-5 mm wide. *Lockeia* isp. (Figure 7.1D,E) is associated with a bivalve escape structure (Radley et al., 1998).

Occurrence: The burrow occurs in medium to coarse grained planar cross-stratified sandstone facies of the Ogbunike Quarry section (lower unit), interpreted as outer estuarine tidal sandbar of the Nanka Formation. It also occurs in the trough cross-stratified sandstone facies of Okaiuga section (lower unit) interpreted as the fluvio-estuarine deposits of the Ogwashi Formation. The *Lockeia* isp. (Figure 7.4A) occurring as a resting trace (cubichnia) is referred to as *Lockeia siliquaria* (James, 1879; Seilacher and Seilacher, 1994). Mángano et al., (1998) noted that *L. siliquaria* also records vertical and oblique displacement through sediment and suggests stable domiciles rather than resting traces. The burrow is considered to be a dwelling structure of suspension feeders or fugichnial response to changing environmental conditions (Mángano et al., 1998).

Ichnogenus: Ophiomorpha Lundgren, 1891

Type Ichnospecies: *Ophiomorpha nodosa* (Figure 7.4 B-E) Lundgren, 1891

Description: *O. nodosa* exhibits simple to complex, single, isolated shafts or tunnel, Y-shaped and branched burrow systems. The burrow wall has exterior dense to sparse knobby pellets that are either regularly distributed discoid to ovoid in shape or are irregular polygonal in shape (Figure 3.12B). The knobbly wall varies in thickness from 2 to 10 mm and is commonly made up of argillaceous (clayey) material or sandy or clayey sand and may be ferruginised (Figure 3.13B). The internal burrow linings are rather smooth and thin; they are usually less than 2 mm thick. The burrow infill is structureless and similar to the surrounding rock.

Occurrence: *O. nodosa* occurs in a wide range of localities in the study area. It is observed in fine to very coarse grained sandstones as well as in conglomerate. The environments interpreted for these localities vary from tidal channels to flats, inner estuarine tidal sand bars, tidal sandwaves, shoreface, fluvio-estuarine channels and tidally influenced fluvial channels. Isolated shafts and tunnels of *O. nodosa* are observed in most of the depositional environments. The Y-shaped burrows (Figure 7.4B,C) are observed in trough, planar, and sigmoidal cross-stratified sandstone facies of the lower units of the Nibo section, Umunya section and Paully Petrol Station section at Ogbunike, Nanka Formation, which is interpreted as tidal channels. The three dimensional polygonal system (boxwork) of vertical and horizontal components as described by Chamberlain and Baer (1973) are dominant in fluvio-estuarine deposits of the Okauiga section (middle – upper units), Ogwashi Formation (Figure 7.4D,E). The vertical shafts are associated with higher energy environments (also observed at the lower unit of the Okauiga section and Ogbunike section, Ogwashi Formation) while boxwork and maze geometries are common in lower energy environments (Frey et al., 1978). *Ophiomorpha* is associated with escape and adjustment structures. *Ophiomorpha* are regarded as dwelling burrows of thalassinidean shrimp or other decapods (Frey et al., 1978).

Ichnogenus: Paleophycus Hall, 1847

Type Ichnospecies: *Paleophycus heberti* Saporta, 1872 (Figure 7.1H)

Description: *P. heberti* is characterised by horizontal or inclined to slightly curved, thickly lined cylindrical burrows, with mud wall linings which are light coloured and better sorted than the burrow fill (Figures 7.1H). Burrows form concentric circles with a thick wall lining in cross-section (Figure 7.1B). The burrow fill is structureless and identical to the host rock. The burrow wall is smooth and unornamented. Burrows are well preserved as full relief with diameter 4-15 mm and burrow length is about 100-120 mm long.

Occurrence: *P. heberti* occurs in variety of environments in the study area. They are found in tidal sandwave deposits of the Ebenebe section, Imo Formation (within the herringbone cross-stratified sandstone facies), in the trough cross-stratified sandstone facies of the subtidal zone of the tidal channel (lower and upper unit of the Nibo section) in the Nanka Formation, and in the fluvio-estuarine deposits (lower unit of the Umuahia Expressway section) of the tidally influenced coastal plain setting of the Ogwashi Formation. *Paleophycus* signifies passive sedimentation within an open dwelling burrow produced by predaceous or suspension-feeding organisms (Pemberton and Frey, 1982).

Type Ichnospecies: *Paleophycus tubularis* Hall, 1847 (Figure 5.8B, 7.4F)

Description: *P. tubularis* occurs as thinly lined, horizontal to gently curved cylindrical burrow with dark grey wall lining (Figure 7.4F). The burrow is unbranched, smooth walled and unornamented. The burrow fill is massive and similar to the surrounding substrate. Burrows are preserved as negative epirelief and full relief with a diameter that varies from 4–15 mm and burrow length that may vary between 60 and 400 mm long.

Occurrence: *P. tubularis* is observed as full relief in coarse grained planar cross stratified sandstone facies interpreted as fluvio-estuarine deposit of Ogbunike Quarry section (lower unit) of the Ogwashi Formation. It is also observed as concave epirelief in the basal unit of the Ugwu-Nnadi Heterolithic section characterised by fine to medium grained bioturbated sandy heterolithic facies interpreted as tidally influenced fluvial channel deposits of the Nanka Formation. Pemberton and Frey (1982) regarded the infills of *Paleophycus* as passive, gravity-induced sedimentation within open, lined burrows.

Ichnogenus: Planolites Nicholson, 1873

Type Ichnospecies: *Planolites montanus* Richter, 1937 (Figure 7.1B,G)

Description: *P. montanus* are preserved as unlined, smooth walled, curved to straight cylindrical, unbranched burrows. The burrow fill is structureless, light to dark coloured and different from the host rock. Burrows vary in size from miniature *Planolites,* with diameter of 3-5 mm and length of 40-70 mm. Large sized *P. montanus* have lengths of over 500 mm (Figure 7.4G).

Occurrence: The burrow is observed all level of the stratigraphic succession where it occurred. It is observed in fine to medium grained sandy heterolithic facies of tidally influenced fluvial channels, tidal channels, in the bioturbated sandstone facies of tidal flats and in the mudstone facies of estuarine embayment, all in the Eocene Ameki Group. *P. montanus* also occurred in the bioturbated sandstone and planar cross-stratified sandstone facies of the fluvio-estuarine deposit of the Ogbunike Quarry section (lower unit), Ogwashi Formation. *Planolites* generally represents active backfilling of sediments in an ephemeral burrow made by mobile vermiform deposit feeder (Frey and Howard, 1990; Pemberton and Frey, 1982).

Type Ichnospecies: *Planolites beverleyensis* Billings, 1862 (Figure 6.6)

Description: *P. beverleyensis* is an unlined, curved to straight cylindrical burrow, often large and has smooth burrow walls. The burrows are quite long, with a maximum length of about 250 mm. Burrow diameter is about 10 mm. Burrow infills merge with enclosing sediment. *P. beverleyensis* is usually preserved as convex epirelief on bedding plane (Figure 6.6).

Occurrence: *P. beverleyensis* occurs on the bedding surface of medium grained planar cross-stratified sandstone facies interpreted as tidal channels of a coastal plain environment (Ogwashi Formation) observed at basal unit of the Umuahia Expressway section.

Ichnogenus: Protovirgularia McCoy, 1850

Type Ichnospecies: *Protovirgularia* (Figure 7.4H)

Description: *Protovirgularia* isp. is observed as a straight to slightly curved, horizontal burrow with closely spaced chevron-shaped ornamentation along the structure. The chevron patterns are formed of muddy sediment. The trace is about 70 mm long and 10 mm wide.

Occurrence: *Protovirgularia* isp. occurs in a fine grained bioturbated sandstone facies (Sb) interpreted as intertidal sandflat at the upper unit of the Umunya section (Nanka Formation). It is regarded as a locomotion trace (repichnia) of a cleft-foot mollusc such as protobranch bivalves or scaphopods (Ekdale and Bromley, 2001; Seilacher and Seilacher, 1994).

Ichnogenus: Rhizocorallium Zenker, 1836

Type Ichnospecies: *Rhizocorallium jenense Z*enker, 1836 (Figure 5.6A; 7.1A)

Description: *R. jenense* is a short U-shaped spreiten burrow, parallel or oblique to bedding plane. Distance between the tubes varies between 100 and 180 mm, the tube diameter is within 5-30 mm, the tube length is 100-160 mm.

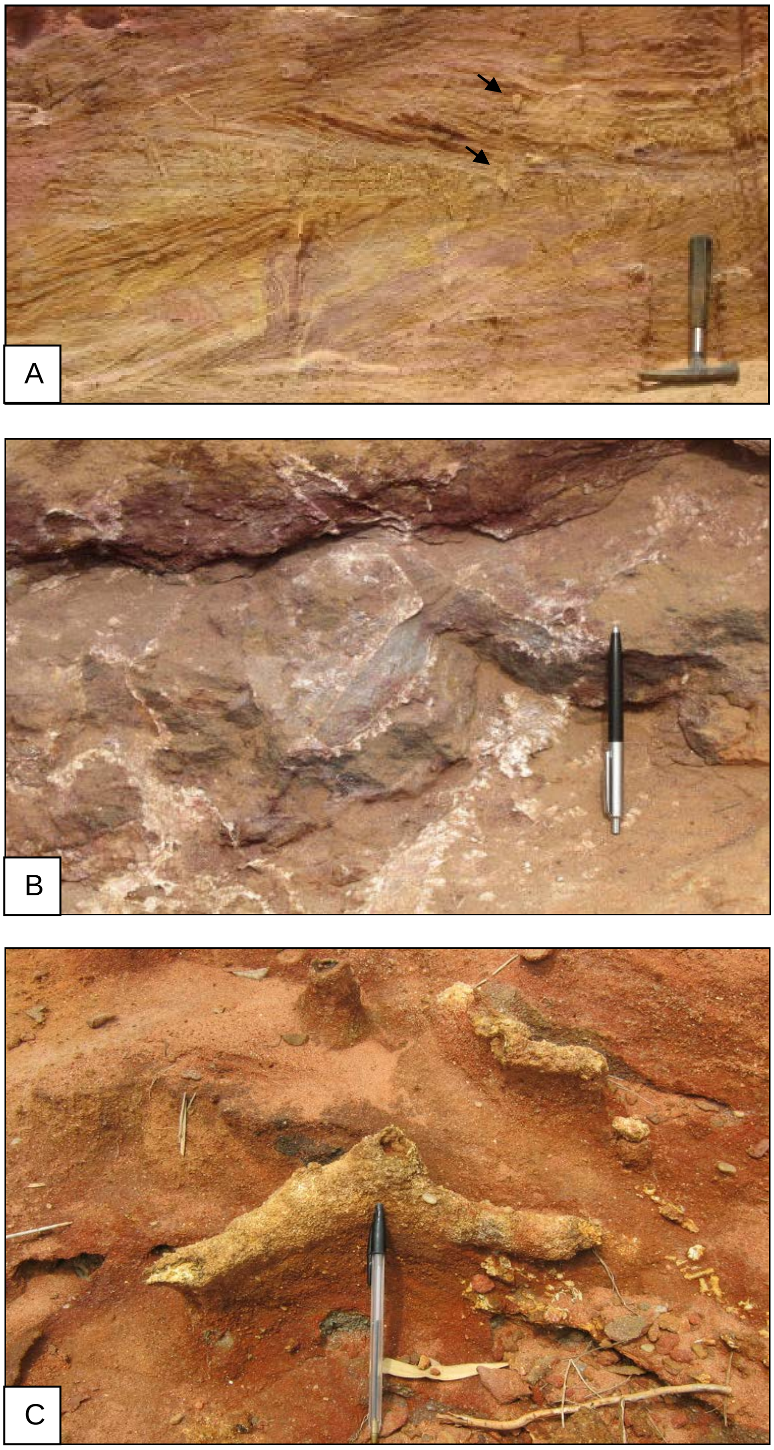
Occurrence: *R. jenense* is observed only in one locality (at the basal part of Ugwu Nnadi Heterolithic section; Nsugbe Formation). It occurs in the fine to medium grained sandy heterolithic facies (Sht) interpreted as tidally influenced fluvial channel deposits. *R. jenense* has been documented in various environments such as foreshore, shoreface, high energy shallow marine environment and deep marine environment (Fürsich, 1974b; Knaust, 1998; Uchmann, 1992; Worsley and Mørk, 2001). *R. jenense* is interpreted as domichnia of suspension feeder for the trace maker which may be crustaceans or annelids (Basan and Scott, 1979; Fürsich, 1974b; Rodríguez-Tovar and Pérez-Valera, 2008).

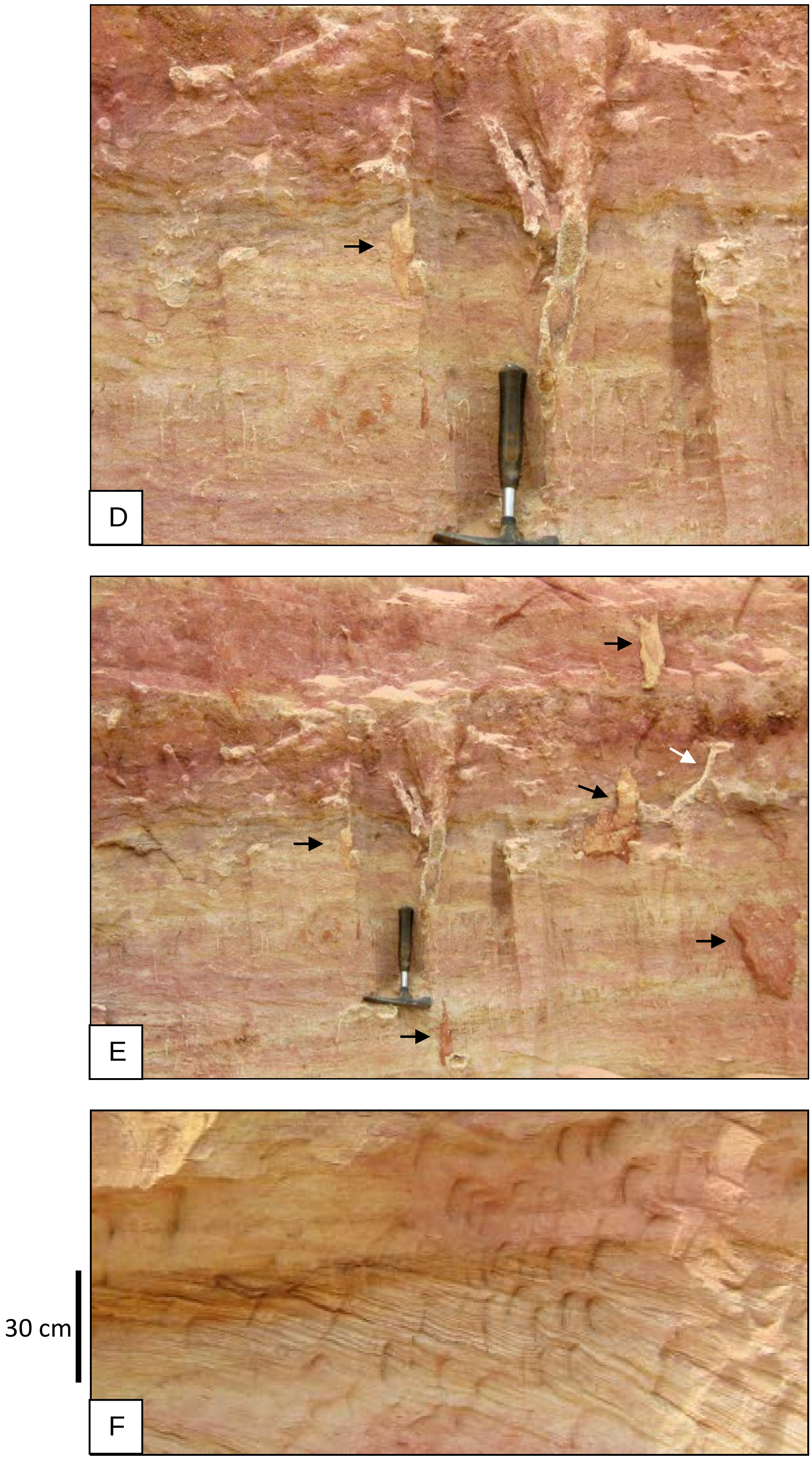
Ichnogenus: Rosselia Dahmer, 1937

Type Ichnospecies: *Rosselia socialis* Dahmer, 1937 (Figure 7.1B; 7.4D, E)

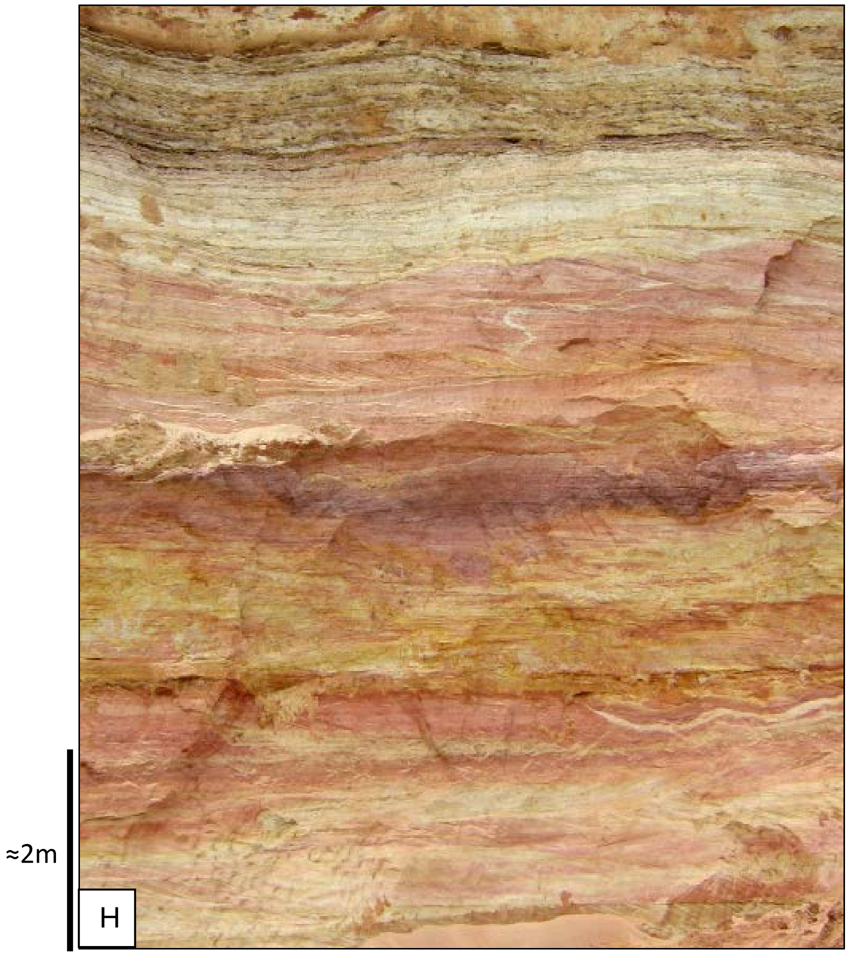
Description: *Rosselia socialis* occurs as a vertical structure with central passively filled burrow with funnel to spindle-shaped, concentric laminated lining (width varies from 50 to 300 mm). The burrow length is from 200 to 400 mm.

Occurrence: The burrows are observed in medium to coarse grained bioturbated sandstone facies of the Ogbunike Quarry section (mostly at the upper unit) interpreted as fluvio-estuarine deposits of Ogwashi Formation. *Rosselia socialis* is interpreted as a dwelling burrow of a terebellid polychaetes (Nara, 1995; 2002) common in a wide range of shallow marine environments including shoreface, tidal-flats, lagoon, bay, flood-tidal delta and estuarine (Nara, 2000).


A
B
C


D
E
30 cm
F


G


≈2m
H

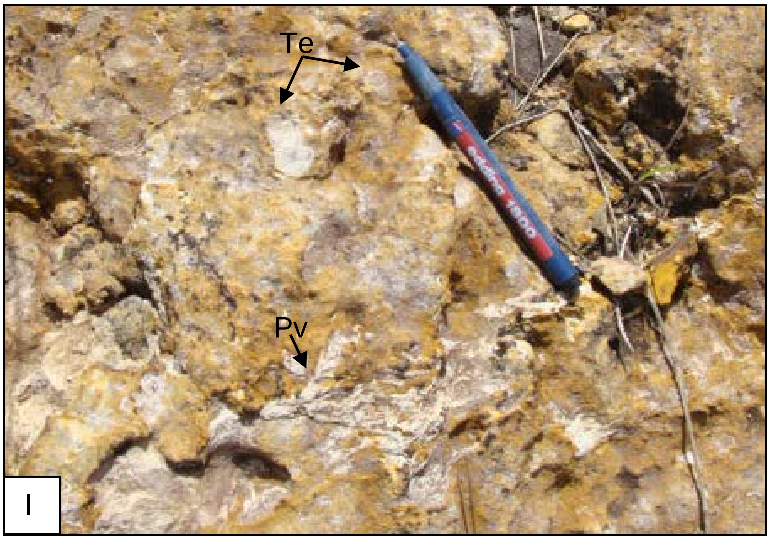


Figure 7.4. Ichnofauna in estuarine deposit of the Ameki Group and the fluvio-estuarine deposits of the Ogwashi Formation. A: Low diversity ichnofossils consisting of *Skolithos linearis* and isolated *Lockeia* isp. (black arrows) in the lower part of fluvio-estuarine deposit. B: Robust T-shaped *Ophiomorpha nodosa* preserved in the subtidal zone of a tidal channel in Ogbunike. C: Y-shaped *Ophiomorpha nodosa* observed at the subtidal zone of a tidal channel in Nibo. D: Pervasively burrowed sandstone in the middle part of the fluvio-estuarine deposit at Ogbunike, exhibiting medium-to-deep-tiers of *Skolithos linearis* and cross-cut by *Ophiomorpha nodosa* shafts. E: The three dimensional polygonal system (irregular boxwork) of *Ophiomorpha nodosa* occurs as a shallow-to-medium tier. Cross-cutting effect is observed by the shallow-to-medium tiers *Rosselia* isp. (black arrow) and *Cylindrichnus* isp. (white arrow). F: Isolated *Paleophycus tubularis* observed in lower part of the fluvio-estuarine deposit. G: Randomly distributed *Planolites montanus* in the fine to medium grained sandstone unit of subtidal zone of the tidal channel (Nanka Sandstone). H: Outcrop section of the coarse to fine grained sandstone interpreted as fluvio-estuarine showing large *?Planolites montanus* burrow. I: Fine grained sandstone, interpreted as intertidal sandflat deposit in Umunya; minute *Teichichnus rectus* ichnofossils and ?*Protovirgularia* isp. were also observed in the bioturbated sandstone.

Root Structures (Figure 3.24)

Description: Root structures are discussed in the description of variegated facies in chapter 3 (facies analysis). The root structures or rhizoliths are branched exhibiting vertical, horizontal or oblique patterns. The root cast-fill is commonly of argillaceous material.

Occurrence: Root structures are observed in fine to medium grained clayey sandstone and mottled mudstone regarded as variegated facies at the lower and middle units of Ezi-Umunya section (Nanka Formation) and Umuezeoma-Uhuala section (Ibeku Formation). The strata with the root structures are interpreted as supratidal deposits.

Ichnogenus: Skolithos Haldemann, 1840

Type Ichnospecies: *Skolithos linearis* Haldemann, 1840 (Figure 7.4A,D,E)

Description: *Skolithos linearis* is represented by simple vertical to steeply inclined, cylindrical, unbranched tubes. They are circular to elliptical in cross-section when viewed on a bedding plane. Burrow fills are passive and structureless. Burrows are lined by clayey sand (Figure 3.13A) and sand (Figure 7.4 A,D,E). *S. linearis* vary in size, burrow length is from 40 mm to up to 200 mm and the burrow width is between 4-8 mm.

Occurrence: *S. linearis* is common in medium to very coarse grained bioturbated sandstone facies and trough and planar cross- stratified sandstone facies interpreted as fluvio-estuarine deposits of the lower and upper units of Ogbunike Quarry section and Okaiuga section respectively, both of Ogwashi Formation. *Skolithos* are referred to as dwelling burrows of suspension feeding polychaetes (such as annelid and worms); indicative of a shallow water environment (Alpert, 1974; Pemberton and Frey, 1982).

Type Ichnospecies: *Skolithos verticalis* Hall, 1843

Description: *Skolithos verticalis* exhibits simple vertical to steeply inclined, small and short burrows that are preserved as convex epirelief. The burrows form holes in the sediments where they occur. The burrow diameter is an average of 3 mm.

Occurrence: *S. verticalis* is preserved in the fine grained bioturbated sandstone facies interpreted as crevasse splay deposits. This occurs in the Nanka Formation of the Ameki Group.

Ichnogenus: Taenidium Heer, 1877.

Type Ichnospecies: *Taenidium serpentinum,* Heer, 1877 (Figure 5.6)

Description: *T. serpentinum* is a simple, unwalled, meniscate backfilled burrow. The burrow is horizontal, unbranched, with a burrow length of about 250 mm and the diameter is about 50 mm. Although the burrow is poorly preserved as a concave epirelief, the nature of the meniscate is used to differentiate the type of *Taenidium* ichnospecies following the D'Alessandro and Bromley (1987) and Keighley and Pickerill (1994) distinguishing criteria for the ichnotaxa *Taenidium*.

Occurrence: *T. serpentinum* is observed in fine to medium grained sandy heterolithic facies of the Ugwu-Nnadi Heterolithic section (lower unit), interpreted as tidally influenced fluvial deposits of Nanka Formation. According to Keighley and Pickerill (1994), the ichnospecies has been confirmed in marine sediments. Bromley (1990) considered *Taenidium* with meniscate backfilling containing faecal pellets or meniscate packeting as fondinichnia and those without distinct faecal contents or meniscate packeting are regarded as repichnia.

Ichnogenus: Teichichnus Seilacher, 1955

Type Ichnospecies: *Teichichnus rectus* Seilacher, 1955 (Figure 7.4H).

Description: *T. rectus* is preserved as retrusive spreiten, U-shaped, small vertical burrows. In some cases, the burrow deflects sharply upwards to vertical near the burrow edge forming a J-shaped burrow. Burrows are not branched and the tubes are about 20-50 mm wide and 20-30 mm long.

Occurrence: *T. rectus* are observed in the fine grained bioturbated sandstone facies of the Umunya section (upper unit) interpreted as intertidal sandflat of the Nanka Formation of the Ameki Group; muddy heterolithic facies and mudstone facies of the mud dominated channel plug of the Ugwu-Nnadi Heterolithic section (upper unit), Nanka Formation. *T. rectus* displays traces made by worms or annelids (Crimes, 1977). The burrow is made by a deposit feeder that moves its burrow up and down in a vertical plane for systematic feeding. The vertical to curved nature of the tunnel suggests a near-surface, shallow burrowing habit of the trace-markers (Bhattacharya and Bhattacharya, 2007).

***Ichnogenus: Teredolites Leymerie,* 1842**

Type Ichnospecies: *Teredolites longissimus* Kelly and Bromley, 1984 (Figure 3.22C)

Description: *T. longissimus* exhibits straight to curved or sinuous subcylindrical boring in a xylic substrate. They are preserved in full relief as clusters of isolated tubes with thin wall linings. The width of the tubes is between 2 mm to 5 mm wide and the length varies from 10 mm to 20 mm.

Occurrence: *Teredolites* isp. occurs in wood fragments found in dark grey shale facies at Ude-Ofeme section (lower unit) interpreted as estuarine embayment deposit (Ibeku Formation of the Ameki Group). *T. longissimus* is regarded as the boring activities of wood digesting bivalves of the family Teredinidae (Savdra et al., 1993; Pickerill et al., 2003).

Ichnogenus: Thalassinoides Ehrenberg, 1944

Type Ichnospecies: *Thalassinoides horizontalis* Myrow 1995 (Figure 4.6)

Description: *T. horizontalis* is characterised by dominantly unlined horizontally to inclined branched tunnels forming polygonal networks of burrows. No vertical shafts or swelling at junctions were observed. The boxwork burrow forms mostly Y-junctions, though the branching is irregular. The burrow cross-sectional diameter is from 10 mm to 35 mm.

Occurrence: *T. horizontalis* are observed in fine grained (bioturbated sandstone facies at Ugwuoba section) substrate at the top of tidal sandwave deposit of Imo Formation. The interval is interpreted as a marine flooding surface, where offshore shale overlays shallow marine sandstone (Pemberton et al., 2004) of the tidal sandwave deposit. *Thalassinoides* isp. is constructed by a variety of marine organisms most especially decapod crustaceans. They are common in intertidal, shallow subtidal environments (Myrow, 1995) and also shelf environments (Gerard and Bromley, 2008).

Type Ichnospecies: *Thalassinoides paradoxicus* Woodward, 1830 (Figure 7.5A,B)

Description: *T. paradoxicus* exhibits both horizontal tunnels and vertically directed shafts. Bifurcations are T or Y shaped, and may or may not contain swellings at junctions. Burrow walls are smooth and unlined. Burrow infill is muddy and burrows occur in sandy substrate (Figure 7.5A) and silty substrate (Figure 7.5B). The burrow fill may be lighter or darker than the surrounding sediments. The cross-sectional diameter ranges between 10 and 55 mm.

Occurrence: *T. paradoxicus* is common. It occurs in the trough cross stratified sandstone facies (St) and planar cross stratified sandstone facies (Sp) of the subtidal tidal channel deposit of Nibo section (lower and upper units) and the bioturbated sandstone facies (Sb) of the intertidal tidal flat setting (upper unit of the Umunya section), both in the Nanka Formation. It is also observed in the fine to medium grained sandy heterolithic facies (lower units of the Ugwu-Nnadi Heterolithic section) interpreted as tidally influenced fluvial deposits of the Nanka Formation of Ameki Group. The vertical shaft acts as a ventilation channel through which the horizontal network of burrows connects to the surface (Bromley, 1990). *Thalassinoides isp*. are regarded as fodinichnial tunnels and shafts constructed by infaunal deposit-feeding crustaceans (Frey et al., 1978; Ekdale, 1992).

Type Ichnospecies: *Thalassinoides suevicus* Rieth, 1932 (Figure 7.5C,D)

Description: *T. suevicus* occur as dominantly horizontal, regularly branched, unlined burrow. The burrow fill is passive and different from the surrounding sediments. The cross-section diameters of the burrows have a wide range between 5 to 60 mm.

Occurrence: *T. suevicus* occurs in sandy and muddy substrates (Figure 7.5C,D). They were observed in the bioturbated coarse grained sandstone at Awka (lower unit) which is interpreted as subtidal tidal channel deposits (Nanka Formation) and heterolithic facies of the Nsukka Formation, along Okigwe-Umuahia express way. Ekdale and Lamond (2003) noted that *T. paradoxicus* appears earlier in fossil record than *T. suevicus*, inferring *T. paradoxicus* as a more primitive trace fossil and *T. suevicus* is more a derived trace fossil. *T. suevicus* is produced by detritus feeding / scavenging crustaceans.

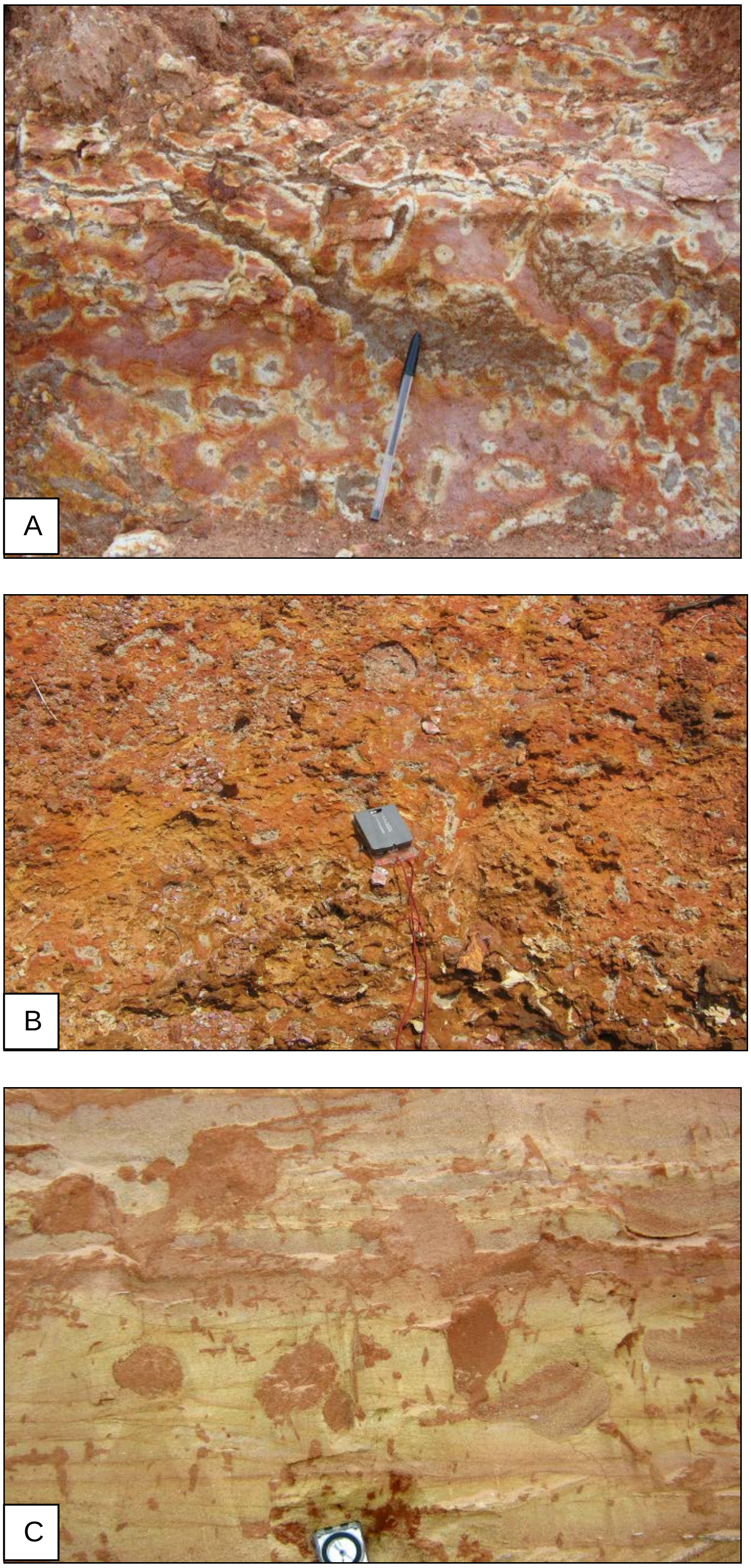

A
B
C

Figure 7.5. Paleocene - Eocene outcrop exposures exhibiting *Thalassinoides* ichnofossils. A: Monospecific *T. paradoxicus* observed in a fine grained sandstone in Idima Abam (Imo Formation). B: *T. paradoxicus* dominates the intertidal flat deposit in the Nibo Section (Ameki Group). C: *T. suevicus* dominates the subtidal zone of a tidal channel at Awka (Ameki Group). D: *T. suevicus* within the contact between the Imo Formation and the underlying Nsukka Formation; the outcrop was observed along Okigwe-Umuahia express way.

Table 7.1. Summary of the ichnofossils found in the study area, their tropic groups and depositional settings.

Ichnogenus	Trophic group	Paleoenvironment (in the study area)	Ichnofacies
Arenicolites	Suspension feeder	Tidal point bar, fluvio-estuarine	*Skolithos*
Asterosoma	Deposit feeder	Intertidal sandflat	*Cruziana*
Beaconites	Deep deposit feeder	Subtidal channel	*Scoyenia*
Conichnus	Resting trace/ adjustment structure	Fluvio-estuarine	*Skolithos*
Cylindrichnus	Deposit feeder	Subtidal channel, intertidal flat, fluvio-estuarine	*Cruziana*
Diplocraterion	Suspension feeder	Outer estuarinetidal sandbar, intertidal deposit	*Skolithos*
Gyrolithes	Suspension feeder	Subtidal channel, intertidal sandflat	*?Cruziana*
Laminites	Deposit feeder	Tidally influenced fluvial channel	*?Cruziana*
Lingulichnus	Suspension feeder	Intertidal flat	*Skolithos*
Lockeia	Suspension feeder/ fugichnial	Tidal sand bar, fluvio-estuarine	*Skolithos*
Ophiomorpha	Suspension feeder	Numerous environments	*Skolithos*
Paleophycus	Deposit feeder	Fluvio-estuarine, tidally influenced fluvial deposit, tidal sand bar, sandwave deposit	*Cruziana*
Planolites	Deposit feeder	Numerous environments	*Cruziana*
Protovirgularia	Crawling trace (locomotion activity)	Intertidal sandflat	*Cruziana*
Rhizocorallium	Deposit feeder	Tidally influenced fluvial channel	*Cruziana*
Rosselia	Suspension feeder	Fluvio-estuarine	*Cruziana*
Root structures		Supratidal flat	*Psilonichnus*
Skolithos	Suspension feeder	Tidally influenced fluvial channel, tidal sandbars, tidal channel	*Skolithos*
Taenidium	Deposit feeder	Tidally influenced fluvial channel	*Scoyenia*
Teichichnus	Deposit feeder	Sandflat (intertidal), tidally influenced fluvial deposit, offshore deposits	*Cruziana*
Teredolites	Deposit feeder	Estuarine embayment	*Teredolites*
Thalassinoides	Deposit feeder	Tidal channel, tidal flats, offshore deposits, tidally influenced fluvial deposit	*Cruziana*

7.3.2 Ichnofacies classification

The twenty individual ichnogenera and twenty-seven ichnospecies observed in the study area are further grouped into five recurring ichnofacies (Table 7.2) namely *Scoyenia*, *Psilonichnus, Skolithos, Cruziana, Glossifungites* and ?*Teredolites* (Seilacher, 1967; Bromley et al., 1984; Frey et al., 1984). These ichnofacies contain suites of identical fossils occurring in similar or different substrates. These ichnofacies reflect adaptations of trace-makers to environmental factors such as food supply, hydrodynamic energy, substrate consistency, salinity and oxygen levels (Frey et al., 1990; Pemberton et al., 1992).

Scoyenia ichnofacies

The *Scoyenia* ichnofacies is represented in the study area by low diversity and abundance of meniscate backfilled trace fossils (Frey et al., 1984) produced by mobile deposit feeders. The two meniscate traces identified are *Beaconites antarcticus* and *Taenidium serpentinum. Scoyenia* ichnofacies characterises low-energy continental deposits (Buatois and Mángano 2004; Frey and Pemberton, 1987; Pemberton et al., 1992), but they have been recorded in marginal marine environments (Bridge and Droser, 1985). In the study area, they occur in association with *Skolithos* and depauperate *Cruziana* ichnofossils in the tidally influenced fluvial channel and the subtidal tidal channel deposits of the Nanka Formation of the Ameki Group.

Psilonichnus ichnofacies

The *Psilonichnus* ichnofacies in the study area is dominated by root penetrations found in fine grained sediments (variegated facies) interpreted as supratidal flat deposits of the Nanka Formation and the Ibeku Formation of the Ameki Group (Figure 3.24). Plant types may include intertidal halophytes that are tolerant of saltwater (Pemberton et al., 1992). The soil type represents an ultisol (a base poor forest soil with no calcareous material), which is common in humid, warm and tropical regions (Soil Survey Staff, 1999).

Skolithos ichnofacies

The study area is dominated by *Skolithos* ichnofacies which is characterised by vertical, inclined, cylindrical or U-shaped burrows considered mostly as dwelling burrows of suspension feeders (Seilacher, 1967; Pemberton et al., 1992). *Skolithos* ichnofacies occur in low diversity, though the trace fossils may be abundant. The most abundant of the suites are *Ophiomorpha* and *Skolithos*; others include *Diplocraterion, Conichnus, Arenicolites, Cylindrichnus, Lingulichnus* and *Lockeia. Ophiomorpha* and/or *Skolithos* occur dominantly as monospecific ichnofossils in moderate to high energy settings such as tidal sandwaves and shoreface deposits of the Imo Formation, crevasse splay deposits, the outer estuarine tidal sandbar deposits of the Ameki Group and the fluvio-estuarine deposits of the Ogwashi Formation. Escape structures are usually associated with the *Skolithos* ichnofacies especially in high energy environments. The *Skolithos* ichnofacies suites also occur in reduced energy setting such as intertidal, shallow subtidal, outer estuarine tidal sand bar environments of Nanka Formation of Ameki Group. Here, they occur in association with *Cruziana* ichnofacies.

Cruziana ichnofacies

The *Cruziana* ichnofacies are common in the study area; they occur chiefly in association with the *Skolithos* ichnofacies and as monospecific burrows. They are found in mudstone and sandstone facies of the Imo Formation, the Nanka Formation of the Ameki Group and the Ogwashi Formation. They are characterised by mostly horizontal to inclined burrows, vertical burrows are also present. *Cruziana* ichnofacies dominantly occur in medium to low energy settings which include subtidal and intertidal zones of tidal channels or tidal flats. Though the *Cruziana* ichnofacies are often mixed with *Skolithos* ichnofacies in the study area, the Cruziana ichnofacies are more diverse and they include *Asterosoma, Thalassinoides, Teichichnus, Planolites, Paleophycus, Chondrites, Rosselia, Rhizocorallium,* and *Protovirgularia.* This suite of trace fossils is dominantly made by organisms interpreted as deposit feeders; suspension feeders and mobile carnivores also occur (Table 7.1). Intense bioturbation is common within the *Cruziana* ichnofacies, and this may reflect abundance and accessibility of food.

***Glossifungites* ichnofacies**

The *Glossifungites* ichnofacies is a substrate controlled suite of trace fossils that develops in firm or unlithified substrates such as dewatered muds or highly compacted sands formed by subaerial exposure or burial and subsequent exhumation by erosion (MacEachern et al., 1992; Pemberton et al., 1992; 2004). The *Glossifungites* ichnofacies observed in the study is characterised by vertical and subvertical dwelling structures of suspension feeders and horizontal to inclined dwelling structures of deposit-feeders. They are associated with stratigraphic discontinuities (Pemberton et al., 2004) and occur in sequence boundaries (SB), transgressive surfaces and amalgamated sequence boundaries and marine flooding surface (FS/SB) and transgressive surface of erosion (TSE) in the study area. The *Glossifungites* suite is characterised by *Thalassinoides horizontalis* and is observed at Ugwuoba, along Oji River-Awka Expressway in the Imo Formation (Figure 4.9), where this interval is interpreted as a marine flooding surface. In the Ameki Group, *Glossifungites* ichnofacies is observed at the bases of a tidally influenced fluvial deposit at Nando: the interval is interpreted as an amalgamated sequence boundary and marine flooding surface and it exhibits *Rhizocorallium jenense, Ophiomorpha* and other unidentified burrows (Figure 7.6).

Teredolites **ichnofacies**

The *Teredolites* ichnofacies is a substrate controlled suite of borings that occur in xylic or woody substances (Pemberton et al., 1992). It is a monospecific ichnofacies characterised by ichnogenus *Teredolites*. *T. longissimus* is restricted to the estuarine embayment in the Ibeku Formation of the Ameki Group.

Figure 7.6. Outcrop section at Nando marks the discontinuity between an underlying mudstone (interpreted as shelf deposit) and overlying sandstone interpreted as tidally influenced fluvial deposit. This firmground omission suite consists of *Rhizocorallium, Ophiomorpha* and other unidentified burrows of *Glossifungites* ichnofacies.

Table 7.2 Summary of the characteristics and environmental implications of the archetypal ichnofacies found in the study area.

Ichnofacies	Characteristics	Trace fossils	Major locations in the study area	Abundance	Implications
Psilonichnus	Deep roots penetration, dominantly branching tubes (rhizoliths) most root networks have clayey infill.	Plant root penetrations.	Ezi-Umunya, Awka	High abundance	Paleosol associated with supratidal flats.
Scoyenia	Mainly meniscate feeding structures	*Beaconites,*	Umunya	Low abundance	Typical in low-energy continental environments. Occurs also in marginal marine deposits.
		Taenidium.	Ugwu-Nnadi	Low abundance	
Skolithos	Vertical, cylindrical or U-shaped burrows. Made dominantly by suspension feeders, ichnodiversity is low, though monospecific ichnofossils may be abundant.	*Arenicolites,*	Ogbunike, Ugwu-Nnadi	Low abundance	Typical in moderate to high energy conditions such as fluvio-estuarine setting, tidal sand bars, sand waves, tidal channels. Also found in low energy settings such as intertidal flats.
		Diplocraterion,	Ugwu-Akpi, Ishiagu	Low abundance	
		Conichnus,	Okauiga	Low abundance	
		Cylindrichnus,	Umunya, Ogbunike	Low to moderate abundance	
		Lingulichnus,	Ogbunike	High abundance	
		Lockeia,	Ogbunike	Low abundance	
		Ophiomorpha,	Ogbunike, Okauiga, Umunya, Ugwu-Akpi, Ebenebe	Moderate to high abundance	
		Skolithos.	Ogbunkie, Okauiga	Moderate to high abundance	
Cruziana	Dominantly horizontal to inclined burrows, vertical burrows are common. Traces are constructed by mobile organisms. Dominated by deposit feeders.	*Asterosoma,*	Umunya	Low abundance	Common in moderate to low energy depositional settings such as subtidal and intertidal zones of tidal channels or tidal flats. Also occur in fluvio-estuarine.
		Gyrolithes,	Umunya	Low abundance	
		Paleophycus,	Ogbunike, Ugwu-Nnadi, Umunya	Low abundance	
		Planolites,	Ogbunike, Umuahia, Ugwu-Akpi	Low abundance	
		Protovirgularia,	Umunya	Low abundance	
		Rosselia,	Ogbunike	Moderate abundance	
		Rhizocorallium,	Ugwu-Nnadi	Low abundance	
		Teichichnus,	Ugwu-Nnadi	Low abundance	
		Thalassinoides.	Nibo, Ugwu-Nnadi, Bende,	Low to high abundance	
Glossifungites	Substrate controlled; firm or unlithified substrates such as dewatered muds burial and subsequent exhumation by erosion	*Thalassinoides* *Rhizocorallium* *Skolithos* *Ophiomorpha*	Nando, Ugwuoba,	Low abundance	Observed at the bases of a tidally influenced fluvial deposit and at top of the tidal sandwave deposit.
Teredolites	substrate controlled; borings in xylic or woody substances	*Teredolites*	Ude-Ofeme	High abundance	Estuarine embayment

7.4 DISCUSSION

Ichnology is a useful parameter for environmental reconstruction (Gingras et al., 2011; Buatois et al., 2002; Pemberton et al., 1992; Pemberton and Wightman, 1992). The ichnological interpretation of the tidal to coastal environments in the study area is based upon the size, diversity, bioturbation intensity and distribution associated with trace fossil assemblages (Gingras et al., 2011; Heard and Pickering, 2008; Frey and Howard, 1990) in the encountered Paleogene sedimentary deposits which includes the Imo Formation, the Ameki Group and the Ogwashi Formation.

7.4.1 Depositional Implication of trace fossils in the Imo Formation

The sedimentary succession of the studied Paleocene-Eocene Imo Formation represents transgressive shallow marine deposits with minor regression. These deposits have been interpreted as tidal sandwave, offshore/ shallow marine shales, shoreface and shelf strata (see chapter 4). The high energy tidal sandwave complex is characterised by low diversity and low abundance of *Skolithos/Cruziana* ichnofacies. Sparse occurrence of horizontal to inclined burrows of *Ophiomorpha* and *Paleophycus* suggest they were opportunistic burrowers that occurred when the hydraulic energy was relatively lowered and probably at an abrupt shift in salinity level (Pemberton et al., 1992). The presence of horizontal burrows in such high energy deposits reflects periods of energy fluctuation. The top of the sandwave deposit is characterised by boxwork of *Thalassinoides horizontalis;* this probably signifies a pause in sedimentation caused by lowering of the sea level resulting in a discontinuity surface (Bottjer, 1985). This surface was then colonized by decapods crustaceans that produced the *Thalassinoides horizontalis* burrow systems. The ichnofacies of the shallow marine deposits (shoreface and shelf) are outlined in Oboh-Ikuenobe et al., (2005).

7.4.2 Recognition of trace fossils in the estuarine deposits

A low to moderately diverse ichnofossil assemblage characterises the tide-dominated estuarine deposits of the Ameki Group. Sedimentary strata of the Ameki Group represent a variety of depositional environments such as fluvial channel, tidally influenced fluvial channel, tidal channel, tidal flat, supratidal, tidal sand bar and estuarine embayment deposits. The distribution of ichnofossils in the estuarine complex varies as they are controlled mostly by salinity (Dashtgard et al., 2008); other physio-chemical parameters are food availability, substrate, high sedimentation rates, highly turbid conditions, hydrodynamic energy and depleted oxygen in bottom and interstitial water (Hubbard et al., 2004).

The fluvial channel deposits are generally unbioturbated or with low diversity *Skolithos* ichnofossils, as observed in the crevasse splays deposit of the fluvial deposit (Nsugbe Formation of Ameki Group). This is common in fluvial setting probably due to low organism tolerance of fresh water (Dashtgard et al., 2008); low diversity *Skolithos* and *Scoyenia* ichnofacies have been recorded in fluvial settings (Buatois and Mángano, 2002; 2004; D'Alessandro and Bromley, 1987). The estuarine deposits *sensu stricto* exhibit typical brackish-water ichnofaunal assemblages which consist of both *Skolithos* and impoverished *Cruziana* ichnofacies (Pemberton and Wightman, 1992; Buatois and Mángano, 2002; 2004; MacEachern and Pemberton, 1994). These trace fossils suites are characterised by (1) low diversity of ichnofossils (2) the presence of impoverished marine assemblages (3) the occurrence of vertical and horizontal trace fossils from *Skolithos* and *Cruziana* ichnofacies (4) the presence of monospecific suites (5) abundance of some ichnospecies (6) simple structures produced by trophic generalists (Pemberton and Wightman, 1992; Pemberton et al., 1982).

The transgressive estuarine succession, which begins with tidally influenced fluvial channels is separated from the fluvial deposit by a bayline surface. The tidally influenced fluvial channel deposits (Nanka Formation) are characterised by dense bioturbation with a bioturbation index of 2-5 (*sensu* Taylor and Goldring, 1993). It exhibits *Skolithos* and impoverished *Cruziana* ichnofossils which signify an abrupt increase in marine influence. Most encountered ichnofossils such *Skolithos, Arenicolites, Thalassinoides, Paleophycus, Teichichnus, Planolites* are small in size. Hakes (1985) related the occurrence of small-sized trace fossils in Upper Pennsylvanian clastic units to reduced salinity. This has been supported by authors such as Dashtgard et al., (2008), Gingras et al., (1999), Pemberton and Wightman (1992). Remane and Schlieper (1971) suggested that size reduction in brackish water fauna may have been due to factors such as growth rate, shorter life-span, reduced performance of certain organs, earlier sexual maturity and shortened time for feeding. *Rhizocorallium jenense* is common and Uchman et al., (2000) noted its occurrence in transgressive surfaces during a period of non-deposition, before or at the beginning of the subsequent deposition. Monospecific suites of *Ophiomorpha nodosa* also occur locally in the tidally influenced fluvial channel. *Scoyenia* ichnofacies such as *Taenidium* occur in low density; this is usually associated with *Skolithos* ichnofacies. The tidal channel deposits (Nanka Formation) consist of low diversity and abundance of *Cruziana* ichnofacies such as *Thalassinoides, Cylindrichnus, Paleophycus, Planolites* and *Skolithos* ichnofacies such as *Ophiomorpha* and *Skolithos*. Most burrows, especially *Thalassinoides, Ophiomorpha, Cylindrichnus* are robust and deep; this enables the organisms to buffer the effect of salinity fluctuation resulting from tidal exchange of marine and brackish (or fresh) water (Hubbard et al., 2004; Pemberton and Wightman, 1992). *Scoyenia* ichnofacies such as *Beaconites* also occur in low abundance.

Intertidal (tidal flat) deposits (Nanka Formation) are characterised by diverse ichnofossils (commonly horizontal burrows) representing dwelling, feeding and crawling traces which include *Ophiomorpha, Asterosoma, Planolites, Cylindrichnus, Skolithos, Paleophycus, Thalassinoides. Lingulichnus, Gyrolithes* and *Protovirgularia* occur locality. The moderate diversity of these ichnogenera reflects the presence of food resources (algae) in both the substrate and in the water column (Hubbard et al., 2008), but still in a stressed brackish condition due to the presence of *Gyrolithes* as observed in the Umunya section (Nanka Formation). The strong burrowing in this zone is interpreted as the product of low sedimentation rates and high rate of biogenic reworking (Gingras et al., 1999). The supratidal flat deposits are moderately to pervasively bioturbated by ichnofossils consisting solely of roots and rootlets. It is characterised by low diversity *Psilonichnus* ichnofacies. This is common in vegetated flats similar to those in the study area, where the binding of sediment by roots can discourage activities of burrowing organisms (Howard and Frey, 1984). Carbonaceous matter occurs locally, the paucity of carbonaceous matter in other areas may be due to tidal flushing of marshes (Howard and Frey, 1984).

The outer estuarine tidal sandbar is typically a high energy deposit characterised by low diversity depauperate *Skolithos* ichnofacies such as diminutive *Skolithos linearis, Diplocraterion parallelum, Lockeia* isp. and bivalve escape structures. These opportunistic traces suggest variable hydraulic energy in stressed salinity conditions. *Lockeia* isp. is a resting trace which probably occurs when the energy was relatively low and a sudden increase in sedimentation resulted in escape structures and the occurrence of suspension-feeders such as *Diplocraterion* and *Skolithos* ichnofossils.

The outer estuarine tidal sandbar deposits exhibit moderate to complete bioturbation with a bioturbation index of 3-6. It is characterised by a high abundance of *Skolithos* ichnofacies (especially *Ophiomorpha nodosa*). Estuarine embayment deposits are made up of dark grey shale, mudstone and parallel laminated to rippled siltstone. The mudrocks contain abundant body fossils, shark teeth and ray teeth. Bioturbation is low, diminutive *Teichichnus, Planolites* and *Teredolites* isp. were observed. Poor preservation of burrows and the diminutive nature of the burrows which may have resulted to paucity of bioturbation is probably due to reduced oxygen concentration at the sea bottom (Savrda,1992).

7.4.3 Implication of trace fossils in the tidally influenced coastal plain deposit

The Ogwashi Formation is interpreted as tidally influenced coastal plain deposit and is characterised by a high abundance of vertical shafts of *Ophiomorpha nodosa* in the basal conglomerate to coarse grained sandstone (Okaiuga section) and boxwork geometries of *Ophiomorpha nodosa* in coarse to medium grained sandstone (Ogbunike quarry section) interpreted as fluvio-estuarine deposits. Conditions favourable for the proliferation of *Ophiomorpha nodosa* ichnospecies include availability food derived from river and coastal sea, availability of sandy substrate that created protection from strong wind waves, and favourable bathymetry (shallow depth) that allows suspended food particles to be easily available for suspension-feeders (Pemberton and Wightman, 1992). The presence of vertical shafts of *Ophiomorpha* burrows, escape structures and the episodic occurrence of the trace fossils in the Okaiuga section suggests high energy conditions and high rate of sedimentation (Frey et al., 1978, 1990; Hubbard et al., 2004). The presence of the three dimensional polygonal system (boxwork) of vertical and horizontal components of the *Ophiomorpha nodosa* and depauperate *Cruziana* ichnofacies in the Ogbunike quarry section suggest lower energy environments (Frey et al., 1978) while the occurrence of *Skolithos linearis* signifies fluctuating energy conditions during sedimentation. The low to moderate occurrence of *Skolithos* and impoverished *Cruziana* ichnofacies is as a result of variation in sedimentation rates, hydraulic energy (Pearson et al., 2012) and stressed salinity conditions in the fluvio-estuarine deposits.

7.5 CONCLUSIONS

The occurrence of different trace fossils and ichnofacies in the study area reflect variations in environmental conditions during the Paleogene. The predominance of *Skolithos* and *Cruziana* ichnofacies indicates that the sedimentary successions of the Paleogene are dominantly of coastal to shallow marine environments (with occasional high energy conditions), though fluvial settings occur. The Imo Formation, interpreted as a tidally influenced shallow marine deposit, is characterised by low to moderate diversity of *Skolithos, Cruziana* and *Glossifungites* ichnofacies. The Ameki Group represents a tide-dominated estuarine system and it is characterised by a range of trace fossils assemblages including *Scoyenia*, *Psilonichnus, Skolithos, Cruziana, Glossifungites* and ?*Teredolites* ichnofacies. These ichnofacies reflect variable physicochemical stresses across the facies associations of the estuarine deposit. Major stresses are low salinity and burrow diminution in the fluvial setting resulting in no burrowing or monospecific *Skolithos* ichnofacies. The estuarine deposits (*senus stricto*) are controlled by low to fluctuating salinity levels, high sedimentation rate and fluctuating hydraulic energy. These resulted to the occurrence of low diversity of *Scoyenia* ichnofacies, low to moderate ichnodiversity of *Skolithos* ichnofacies and depauperate *Cruziana* ichnofacies. Low levels of dissolved oxygen in quiescent water-embayment resulted in low diversity of improvised *Cruziana* ichnofacies. The low diversity and high abundance of *Skolithos* ichnofacies in the tidally influenced coastal plain succession of the Ogwashi Formation is attributed to the high rate of sedimentation, high hydraulic energy conditions and availability of food. *Glossifungites* are substrate-controlled ichnofacies observed in the Imo Formation and Ameki Group, indicating a break or change in sedimentation and an abrupt change in facies.

Previous authors (Anyanwu and Arua, 1990; Nwajide and Hoque, 1979) documented only *Skolithos* and *Cruziana* ichnofacies in the Palaeogene stratigraphy, this may be probably due to their abundance in the successions. This study reveals five trace fossils assemblages namely *Scoyenia*, *Psilonichnus, Skolithos, Cruziana, Glossifungites* and *Teredolites* for the Paleogene strata in south-eastern Nigeria. The occurrence of these ichnofacies is significance as they reflect the environmental conditions during sedimentation.

CHAPTER EIGHT

PETROLOGY AND PROVENANCE INTERPRETATION OF THE PALEOGENE SEDIMENTS, SOUTH-EASTERN NIGERIA

8.1 INTRODUCTION

Provenance studies on clastic sedimentary rocks have been carried out using a number of analytical techniques such as petrographic modal analysis of arenites (Dickinson, 1970; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Zuffa, 1985, 1987; Johnsson, 1993). The composition of arenites is mainly controlled by source lithology, tectonics, climate, topography, weathering, transport and depositional environment, thus, the provenance is not easily interpreted from petrographic analysis alone (Johnsson, 1993; Critelli et al., 2007). Hence, a more integrated approach that includes heavy mineral analysis; and clay mineralogy is used to provide a more detailed paleogeographic reconstruction of source or basin systems. According to Pettijohn et al., (1987) statement, the aim of provenance studies is to deduce the characteristics of the source areas from the compositional and textural properties of sedimentary rocks, supplemented by information from other lines of evidence. Heavy mineral analysis is an effective tool for reconstruction of sediment provenance, for mapping and delineating heavy mineral provinces and it provides valuable information on parent rock lithologies (Lihou and Mange-Rajetzky, 1996; Mange and Otvos, 2005).

Petrology and heavy mineral analysis of sediments in the southern Nigeria sedimentary basins have been previously limited to the Benue - Abakaliki Trough and the Anambra Basin (Amajor, 1987; Hoque, 1977; Hoque and Ezeque, 1977, Odigi, 1986; Tijani, et al., 2010). Heavy mineral assemblages in the Albian-Turonian sediments show major contributions from plutonic and metamorphic rocks of the Oban and Adamawa massifs (Odigi, 1986), collectively called the Cameroon basement (Hoque, 1976). Amajor, (1987) suggested a major sedimentary source and a minor contribution from the Oban massif (Figure 8.1) for the Maastrichtian Ajali Formation of the Anambra Basin. This has recently been supported by Tijani et al., (2010), by integrating x-ray fluorescence (XRF) methods with grain-size analysis and petrography. Hoque (1977) considered the sandstones of the Abakaliki Basin to be first sedimentary cycle deposits (from the Cameroon basement) based on the dominance of feldspathic sandstone. Sediments of the Anambra Basin are considered to be a product of a second sedimentary cycle with contributions from both the Abakaliki folded terrain (as a sedimentary source) and the granitic complex of Cameroon basement. Figure 8.1 shows an overview of the geological map of Nigeria emphasizing the basement complex.

Petrographic and heavy mineral studies of the Paleogene strata of the outcropping Niger Delta is limited to the Nanka Formation (Hoque, 1977 and Nwajide, 1980). Nwajide, (1980) noted the high proportion of ultrastable minerals, zircon, tourmaline and rutile and also the presence of kyanite, staurolite and sillimanite which suggest a medium to high grade metamorphic provenance.

This research aims to use petrography and high resolution heavy mineral analysis (HRHMA) to provide a framework for reconstructing sediment provenance and delineating heavy mineral provinces in the outcropping Niger Delta, South-eastern Nigeria, as well as document controlling factors affecting the distribution of the heavy minerals in the study area.

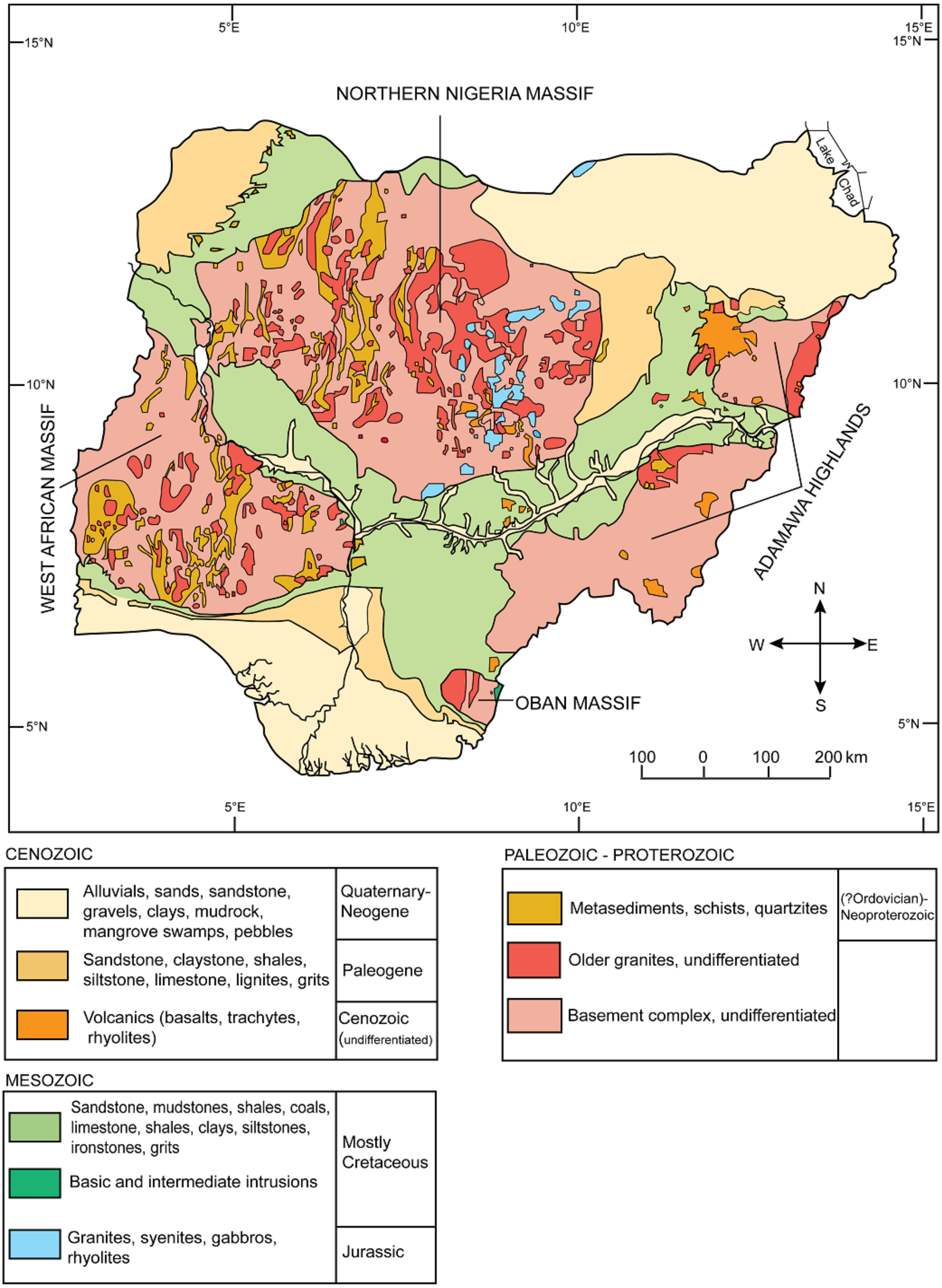


Figure 8.1. An overview of the geologic map of Nigeria showing the basement complex (Redrawn and modified after Okezie, 1974).

8.2 METHODOLOGY

Methods employed in this study are petrographic and heavy mineral analysis. These analyses on were carried out in laboratories at the Department of Earth Sciences, Royal Holloway, University of London. Appendix E8.1 shows the locations of samples analysed for petrology and heavy minerals analysis and Figure 8.2 shows the sample location map of the study area.

8.2.1 Sandstone/limestone petrography

A total of 14 unconsolidated sandstone samples were impregnated with blue epoxy resin, thin-sectioned and stained with sodium cobaltinitrate for identification of plagioclase and K-feldspar, were necessary (Houghton, 1980), while 5 limestone samples were stained with alizarin red-S for identification of carbonate grain types (Lindholm and Finkelman, 1972). About 500 points were counted for each thin section under a petrographic microscope using the Gazzi-Dickinson point-counting method (Dickinson, 1970; Zuffa, 1985 and Ingersoll et al., 1984). The objective of point-counting is to identify grain types (framework), cement, matrix and their proportion for each thin section. The results of point-counting are summarised on Table 8.1. Photomicrographs are taken from selected slides using Nikon microphoto-Fx camera mounted on an optical microscope.

The limestones have been classified based on both Dunham (1962) and Wright (1992) schemes. Limestone grains are dominated by bioclasts with few intraclasts. Interstitial components are micritc matrix and carbonate spar cement.

8.2.2 Heavy mineral analysis

A total of 27 unconsolidated sandstone samples were prepared for heavy mineral analysis. Calcareous sandstones were digested in 10% acetic acid for 3 days, to decalcify them, and then washed thoroughly with distilled water to remove traces of acid residue. Ferruginised sandstones or iron-stained sandstones were de-oxidised by using sonic bath. The sand samples were wet sieved and separated into grain size fractions using sieves of 500, 250 and 63 microns. Furthermore, to remove clays and flocculates, sodium metahexaphosphate (calgon) solution was added to the 63-250 micron sand sample and placed on an orbital shaker for 15 minutes, then decanted with distilled water and dried in a low temperature oven at 40^0C. Dried samples of 63-250 microns sand fractions were dry sieved (Von Eynatten and Gaupp, 1999) and passed through bulk magnetic separator or hand magnet to remove all magnetic grains. Heavy mineral separation of the non-magnetic grains was then carried out by gravity settling using sodium polytungstate solution (SPT) with specific gravity between 2.85 and 2.9 (Callaham, 1987, Berquist, 1990). The separated heavy mineral fractions were oven-dried and mounted on thin slides using Canada Balsam for mineral identification. About 200 (non opaque) heavy minerals were counted per slide and the proposition of each mineral was calculated as percent of the total weight of minerals counted for each sample (Morton and Hallsworth, 1994; Okay and Ergün, 2005). Opaque minerals are dominated by iron-oxide or leucoxene-coated grains and haematite but they are not discussed in this research. The following categories of mineral varieties were distinguished based on the high resolution heavy mineral analysis method proposed by Mange-Rajetzky, 1995.

Zircon: euhedral, subhedral, rounded colourless, rounded purple and grains with overgrowth.

Tourmaline: angular, prismatic, rounded prism, subrounded, rounded to well-rounded.

Apatite: prismatic, rounded prism, subrounded, rounded and spherical.

High resolution heavy mineral analysis focuses on the ultrastable heavy mineral suites such as zircon, tourmaline and apatite (Mange-Rajetzky, 1995). This method is based on the fact that numerous heavy mineral species have chemical, structural, colour, morphological and optical varieties that record signatures of crystallizing conditions in their parent rocks (Mange and Otvos, 2005). These properties make the mineral valuable indices of provenance.

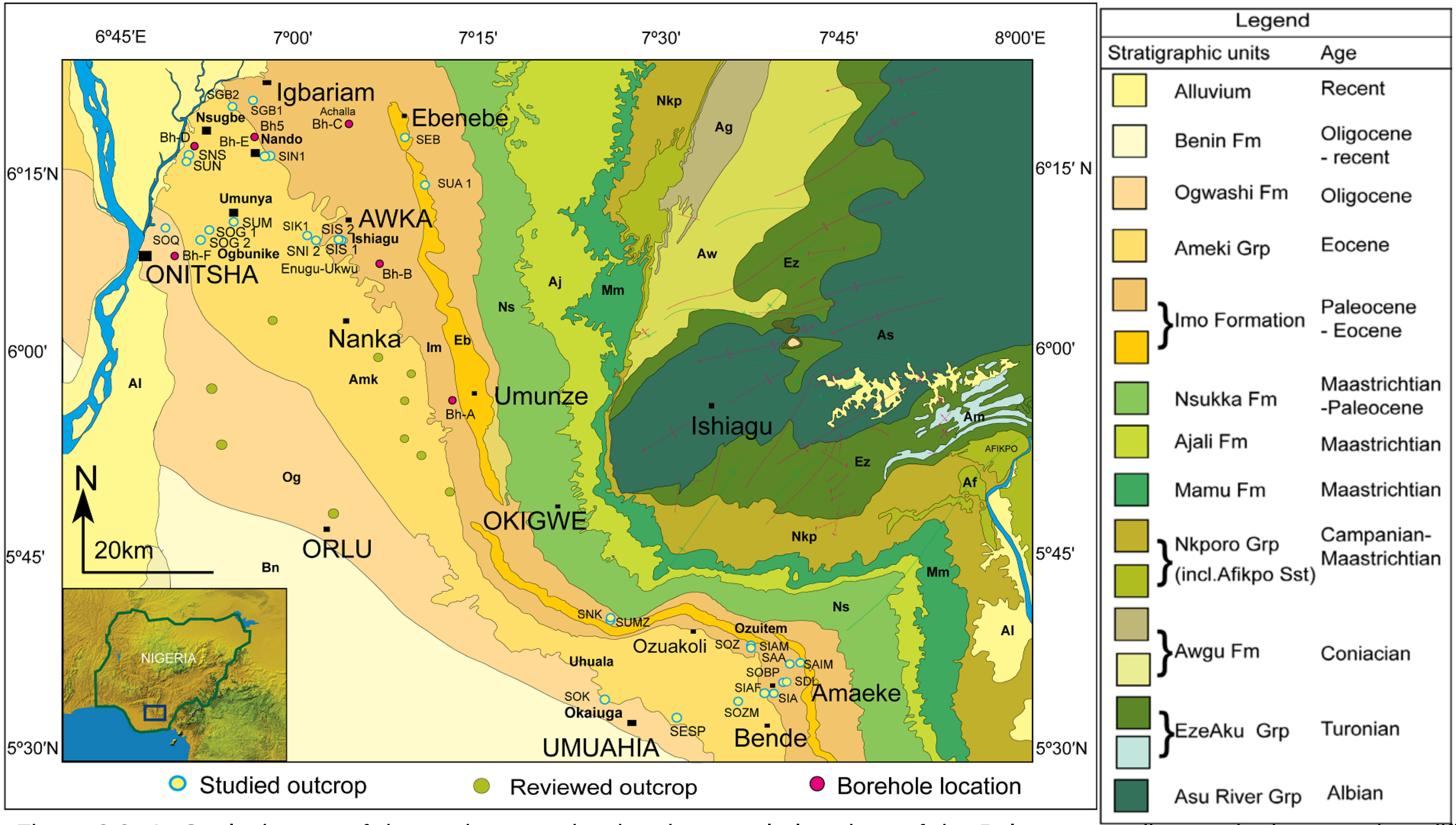


Figure 8.2. A. Geologic map of the study area, showing the sample locations of the Paleogene sediments (redrawn and modified after Nigerian Geological Survey Agency, 2009).

8.3 RESULTS

8.3.1 Petrology of the Paleogene sediments

Petrographic analysis of the Imo Formation

The Imo Formation constitute about 30% sandstone, 10% mixed sandstone and carbonate and 60% shale. The lower Sandstone Member is interpreted as offshore tidal sandwave deposits (see chapter 4) and consists of the Ebenebe Sandstone, Igbaku Sandstone and the Umuna Sandstone. The middle sandstone member is interpreted as shoreface deposit while the upper Sandstone Member (which consist of mixed sandstone and carbonate unit is interpreted as a shelf deposit. The sandstone texture varies from medium to coarse grained (moderately to poorly sorted) in the lower Sandstone Member and from medium to fine (moderately to well sorted) in the middle to upper Sandstone Member of the Imo Formation. The sandstones are mostly unconsolidated and friable.

Classification of the sandstone was determined using Pettijohn (1975) and Folk (1980) methods. Major detrital framework components of the sandstone - quartz, feldspar and lithic fragments are used to construct a QFL ternary diagram (Figure 8.3). Results of the plots on the QFL diagram show that the lower and middle Sandstone members of the Imo Formation is classified as quartz arenite (Pettijohn, 1975; Folk, 1980). The average modal composition of the quartz arenite is $Q_{97\%}$ $F_{1\%}$ $L_{2\%}$.

The upper mixed sandstone and carbonate (SIAM, SOZC-4 and SIAF) is dominated by calcareous or fossiliferous sandstone with minor thin limestone beds/layers. The sandstones in the upper mixed sandstone/carbonate unit are classified as arkosic arenite to sub-arkose (Pettijohn, 1975) or arkose (Folk, 1980).

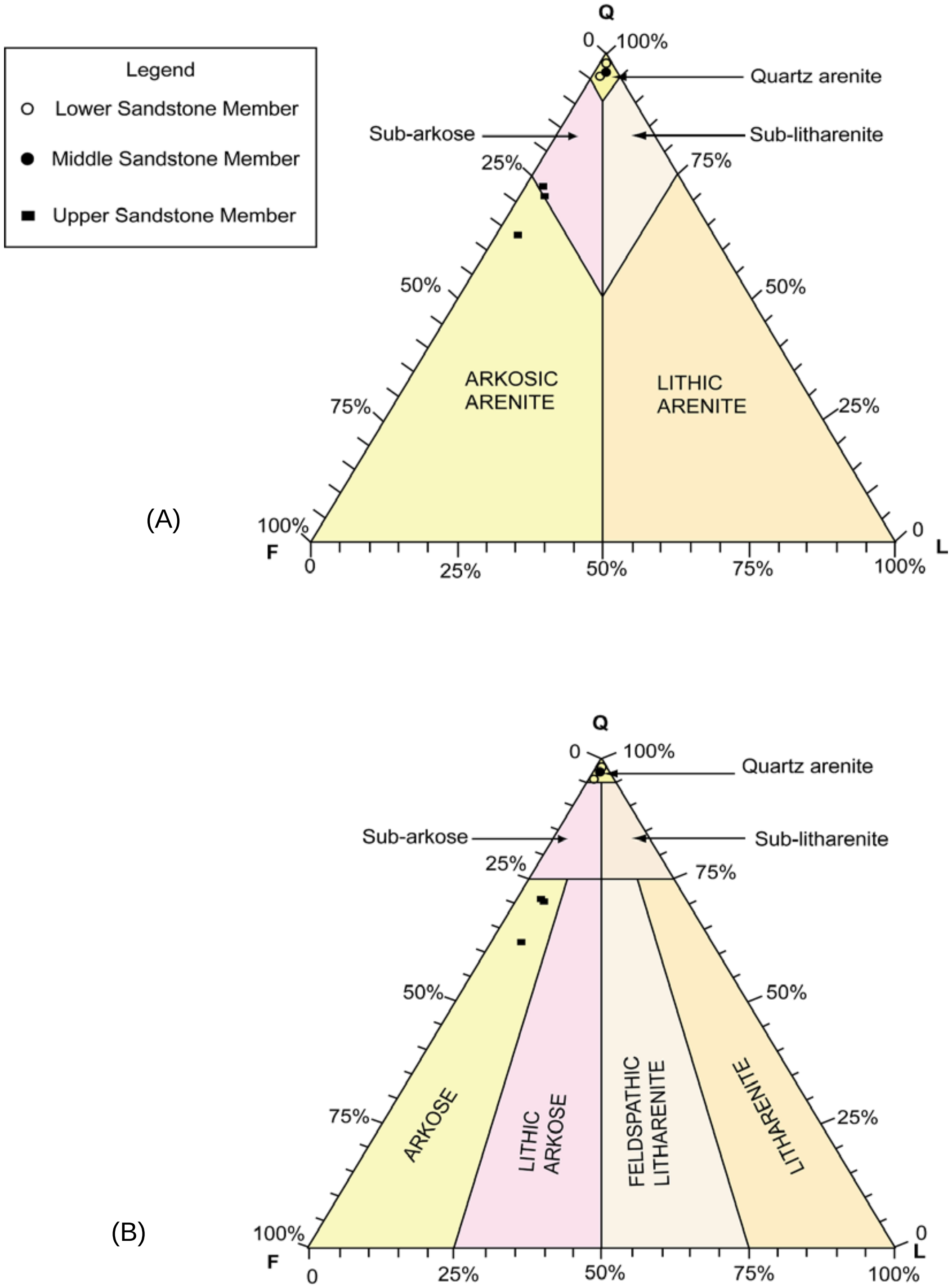


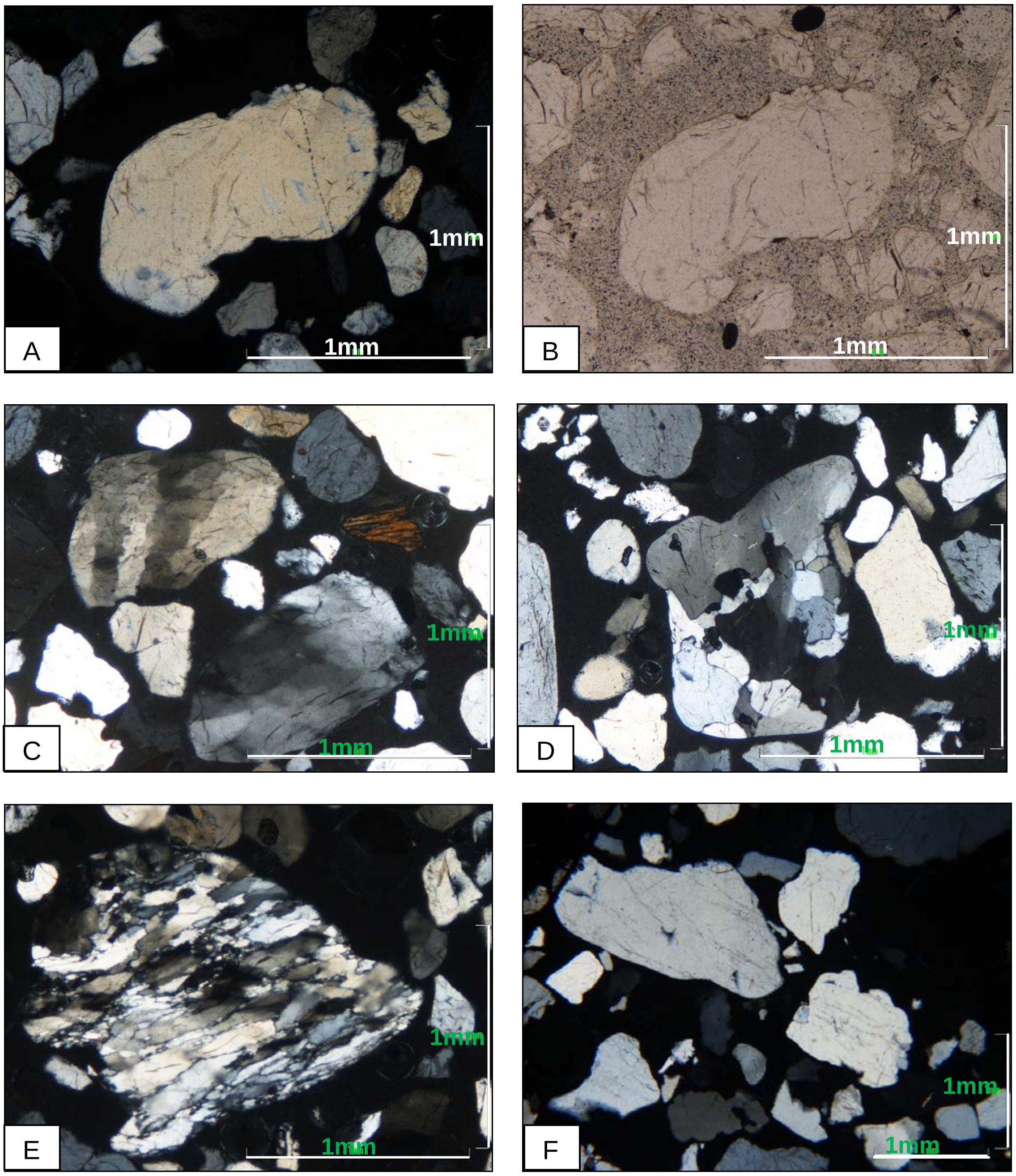
Figure 8.3. (A). Petrographic composition of the Sandstone members of the Imo Fomation plotted on a QFL (Q-quartz, F-feldspar, L-lithic fragment) diagram (after Pettijohn, 1975). (B). Petrographic composition of the Sandstone members of the Imo Formation plotted on a QFL (Q-quartz, F-feldspar, L-lithic fragment) diagram (after Folk, 1980).

Mineralogical Composition

Quartz

Quartz is the most abundant mineral, comprising between 41% and 89% in the modal composition (Table 8.1). The grain shape in the lower Sandstone Member is commonly rounded to subrounded; subangular grains are less common. The upper Sandstone Member is represented by subrounded and subangular shape grains. Angular grains are also well observed. Monocrystalline and polycrystalline quartz are present in the Imo Formation (Figure 8.4), though monocrystalline quartz prevails over the polycrystalline quartz (Table 8.1). About 53% of the monocrystalline quartz exhibits simple extinction in the lower Sandstone Member whereas 5% displays undulose extinctions and 47% of the monocrystalline quartz show partial undulose and undulose extinction depending on the orientation of the grains. In the middle Sandstone Member (SAA 5), 51% of the monocrystalline quartz shows simple extinction, 49% exhibit undulose and partial extinction. The upper Sandstone Member contains about 65% monocrystalline quartz which displays simple extinction whereas 36% shows partial undulose and undulose extinction.

Polycrystalline quartz occurs and varies from 8% to 42% of the total quartz content. Some show a coarse texture of polycrystalline quartz grains containing 2 or more crystals that have straight, equant to concave-convex boundaries. Coarse to finer texture polycrystalline quartz grains contain numerous elongate crystals that exhibit smooth, crenulated and /or sutured boundaries. Most quartz crystals contain solid inclusion such as microlites, but few vacuoles. Quartz crystals with boehm lamellae (Folk, 1980) and need-like or minute inclusions of biotite, muscovite, zircon and/or rutile are well represented.


A
1mm
1mm
B
1mm
1mm
C
1mm
1mm
D
1mm
1mm
E
1mm
1mm
F
1mm
1mm

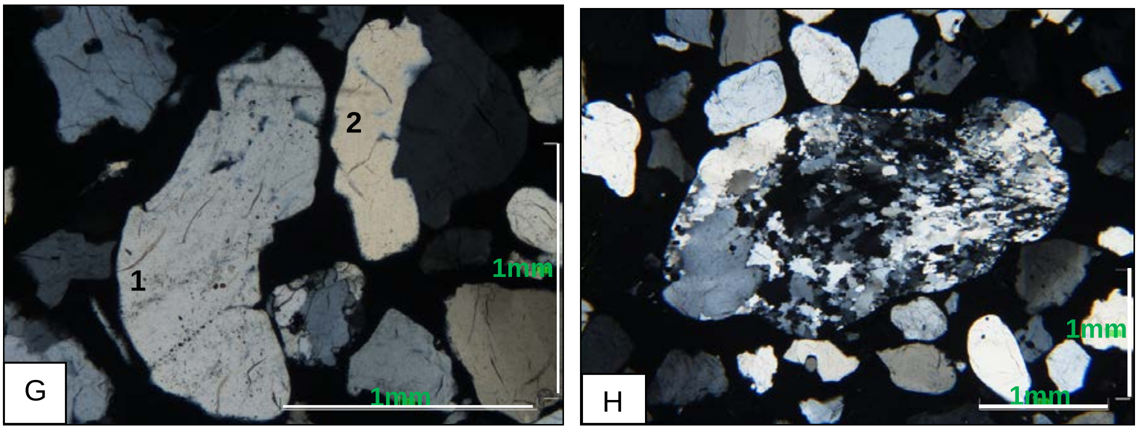
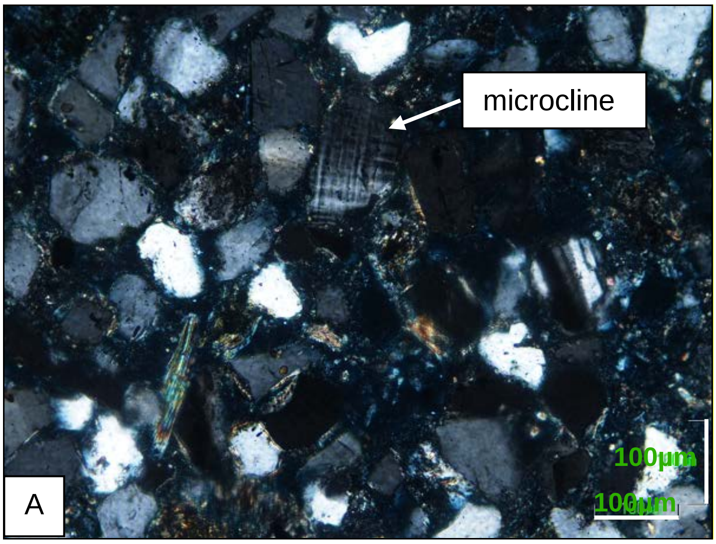
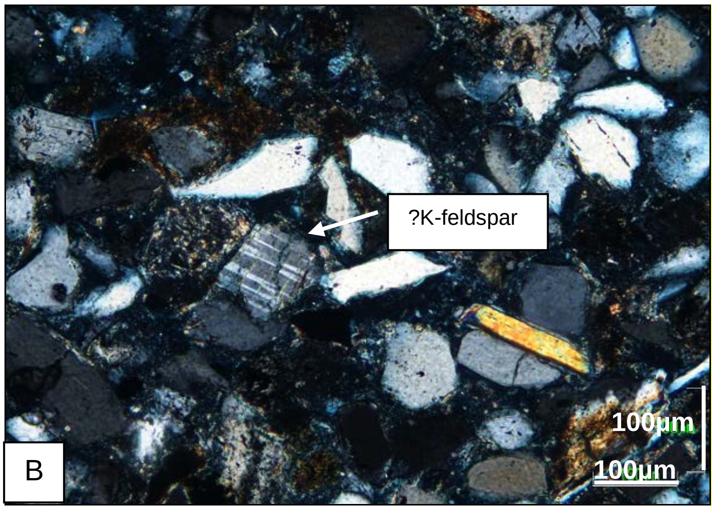


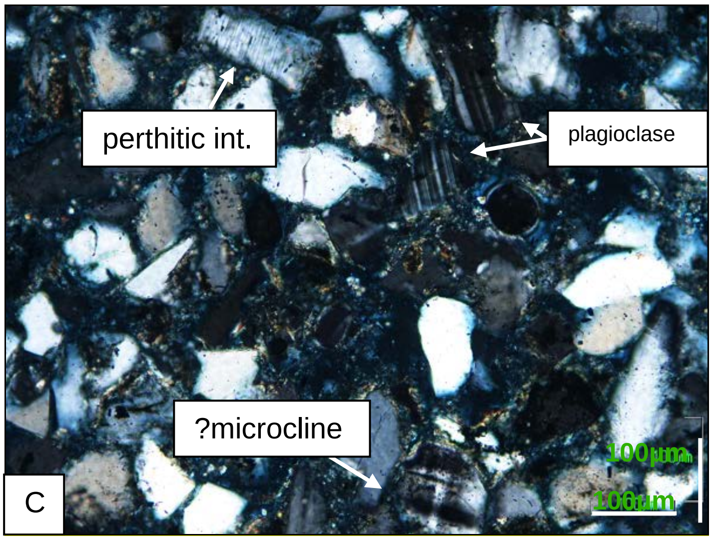
Figure 8.4. Thin section photomicrographs of detrital quartz grains from the Imo Formation (Figures A-E are of the lower Sandstone Member of the Imo Formation, while figures F-H are of middle Sandstone Member of the Imo Formation). A. Monocrystalline, fractured quartz with fluid inclusion (plutonic origin) (under cross polarized light). B. Loosely packed monocrystalline quartz is obvious under plane polarized light). C. Monocrystalline quartz showing partial undulose extinction. D. Polycrystalline coarse quartz grain with concave-convex shaped boundaries (metamorphic origin). E. Polycrystalline coarse quartz with elongate crystals that exhibit straight to concave-convex shaped boundaries (metamorphic origin). F. Monocrystalline quartz grains with boehm lamellae. G. Monocrystalline, fractured quartz with fluid inclusion (1), Polycrystalline coarse quartz with two crystals (2) which is characteristic of plutonic rocks. H. Polycrystalline quartz with fine texture, exhibiting dominantly crenulated and sutured boundaries (metamorphic origin). The subrounded to rounded quartz grains are typical of recycled sedimentary quartz.

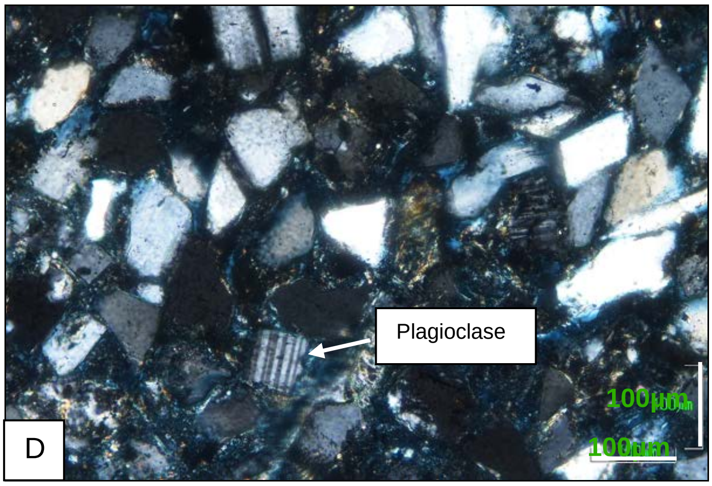
Feldspar

The occurrence of feldspar in the Sandstone members of the Imo Formation varies, with a low count of less than 2% in the lower Sandstone Member and a moderate occurrence of 14% to 23% for the middle and upper sandstone members. K-feldspar is more common with a high count of about 14% and a low count of about 5%, whereas plagioclase varies from as low as 0.6% to 9%. Microcline is the most common of the K-feldspar, comprising about 25% to 35% of the total feldspar and shows a typical cross-hatched pattern (Figure 8.5A) and subparallel twin (Figure 8.5B). Sanidine is common with a simple Carlsbad twinning. Orthoclase is also observed, but occurs as untwined crystals. Perthitic intergrowth of feldspar is well observed especially in the upper sandstone member of the Imo Formation (Figure 8.5C). Plagioclase exhibits albite (Figure 8.5C) and multiple lamellar twinning. Carlsbad twinning is usually repeated and a combination of albite-Carlsbad twinning is also present in the plagioclase feldspars (Figure 8.5D).




?K-feldspar
100µm
100µm
B


perthitic int.
plagioclase
?microcline
100µm
100µm
C


Plagioclase
100µm
100µm
D

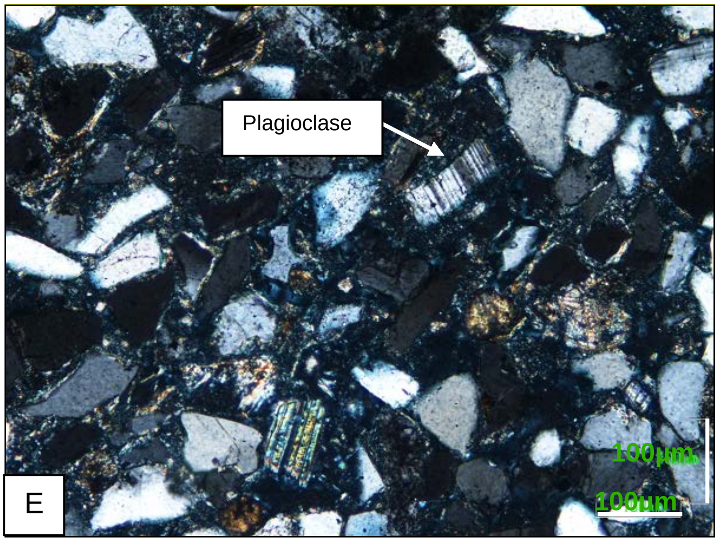


Figure 8.5. Thin section photomicrographs of feldspars obtained from upper Sandstone Member of the Imo Formation. (A) Microcline (K-feldspar) with well developed cross-hatched twinning and (B) subparallel twinning. (C). Perthitic intergrowth of sodium feldspar in K-feldspar. (C) and (D). Albite twinning in plagioclase feldspar grains. (E). Combination of albite-carlsbad twinning in plagioclase feldspars

Lithic Fragments

Lithic fragments occur as clusters of multiple grains that are represented by metamorphic, volcanic, clastic and non-clastic rock fragments. Less than 8% lithic clasts occur in the sandstone members of the Imo Formation (Table 8.1). The grains are fine to coarse grained, mostly subrounded, subangular, with few angular shapes. Sedimentary rock fragments are most common and consist of claystone, siltstone and limestone fragments. Volcanic and chert rock fragments are very rare. Metamorphic rock fragments are limited to quartzite and schist and consist of less than 3% of the lithic fragments composition. The occurrence of carbonate or non-clastic lithic fragments is limited to the upper Sandstone Member.

Accessory minerals

The accessory minerals include micas and heavy minerals. They are well represented throughout the sandstone members, especially in the upper Sandstone Member, where it varies between 19% and 23.5% (Table 8.1).

Mica content is less than 14% of the sandstone composition and it occurs also in metamorphic rock fragments. Muscovite is relatively more in abundance than biotite (Table 8.1); this probably suggests the dominance of sediments derived from metamorphic rocks (Blatt, 1982).

The heavy minerals include opaque and non-opaque minerals such as leucoxene, haematite, ilmenite, zircon, rutile, tourmaline, kyanite, and pyroxene. Few heavy minerals were easily recognised in thin section, probably because of their size. Detailed analysis of the heavy mineral distribution is discussed later in the chapter.

Limestone

Limestone beds/layers and calcareous or fossiliferous sandstone are common in the upper Imo Formation. Samples SIA-2B, SOZM-6, SOBP-1 and SDL-1 are limestone while samples SOZC-4 and SIAF are fossiliferous sandstones (Table 8.1). The limestone occurs as mixture of extrabasinal (mainly siliciclastic) with intrabasinal (mainly carbonate) grains. The extrabasinal grains which include quartz, feldspars, mica and lithic fragments are up to 20% with quartz grains counts of up to 12%. The carbonate (grains, matrix and cements) makes up about 80% of the mixed extrabasinal and intrabasinal grains.

Sample SIA-2B is sampled from Idima Abam; it is diagenetic and thus referred as microsparstone based on Wright (1992) classification. The microsparstone consists of less than 10% grains in a matrix of microsparite. The grains include very fine grained quartz, feldspar, foraminiferal tests (Figure 8.6A-E) and large bivalve fragments.

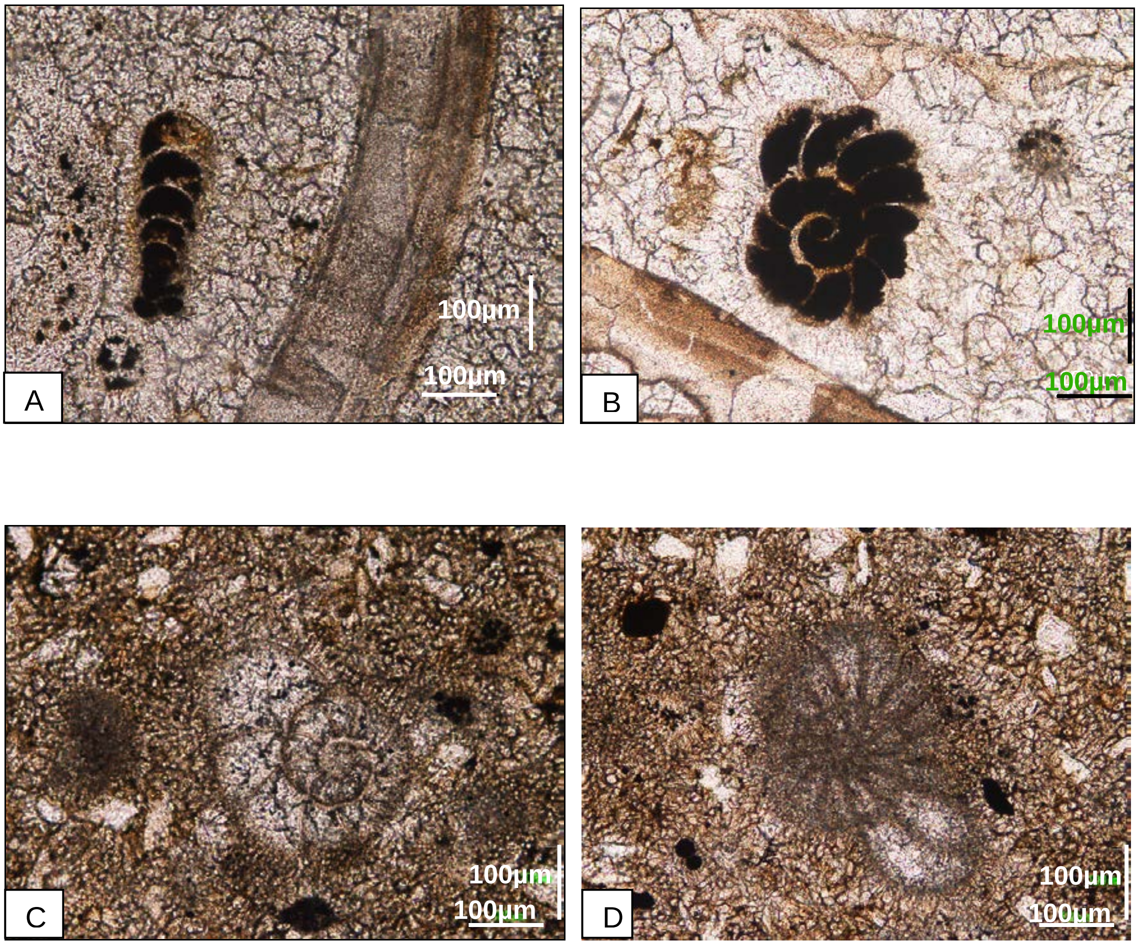
Sample SOZM-6 is obtained from Ozuitem section. It consists of 60% matrix and 40% grains, indicating that it is a wackestone. The framework comprises skeletal fragments of ostracod tests, thick bivalve shells, micritic-coated brachiopod grains, echinoid spines, and clastic grains such as quartz, feldspar and accessory minerals (Figure 8.6A-D, 8.6F-H). The ostracods are mostly well preserved, with their tests exhibiting finely prismatic microstructure, and some shells show duplicature (Figure 8.6F). The internal structure of the bivalve fragment is well preserved (Figure 8.6G).

Samples SOBP-1 and SDL-1 are obtained from Okpotong-Bende. Sample SOBP-1 has a framework comprising about 65% skeletal fragments of bivalves, gastropods, echinoid spines, green algae and foraminiferal tests. The bivalves are well preserved as fragments and articulated grains. Some of their wall structures show 2 or more layered structures, with a thick layer of coarse sparite or finely prismatic calcite microstructure and a thin layer of fibrous structure (Figure 8.6G). The former layer may have been aragonite originally indicating that the organism had a mixed aragonite/calcite skeleton (Adams et al., 1994). The limestone is classified as a packstone. Sample SDL-1 is diagenetic, with about 90% microspar and less than 10% foraminiferal tests, gastropods and ostracods.

The fossiliferous sandstone consists of 5% - 20% limestone occurring as bioclasts (which include ostracods, bivalves, gastropods and foraminiferal tests), calcite grains and cements. Although quartz grains still constitute the highest count of 40% - 45%; other grains such as lithic fragments and feldspar add up to about 20% of the modal composition.

Cement

Argillaceous and calcareous (calcite) cements are the major cement types found in the Imo Formation, each constituting less than 6% of the total rock composition. The calcareous cement is restricted to the upper sandstone member, due to the occurrence of fossiliferous sandstones. The argillaceous cement is most probably clay or silt and it forms on the rims of the grains. The calcareous cement occurs as mosaic of interlocking crystals filling pore spaces.



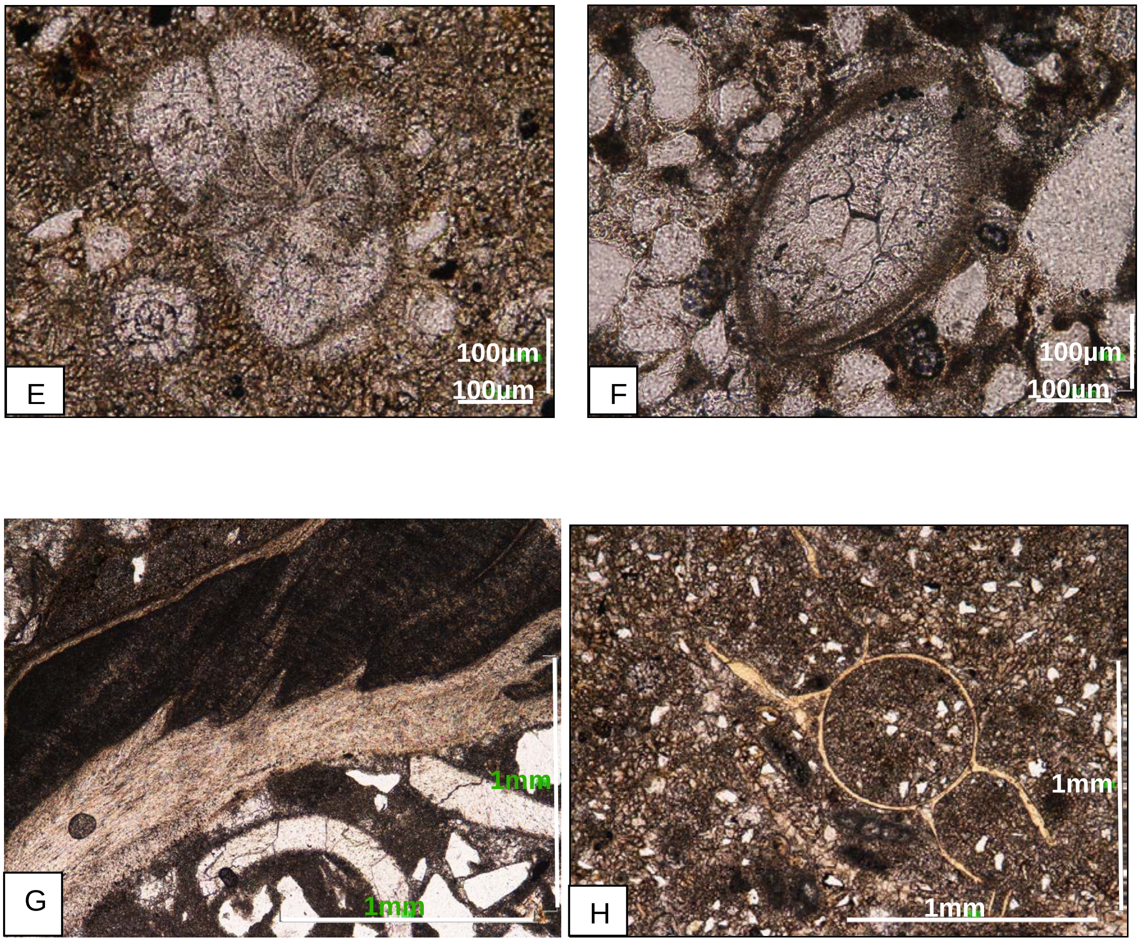
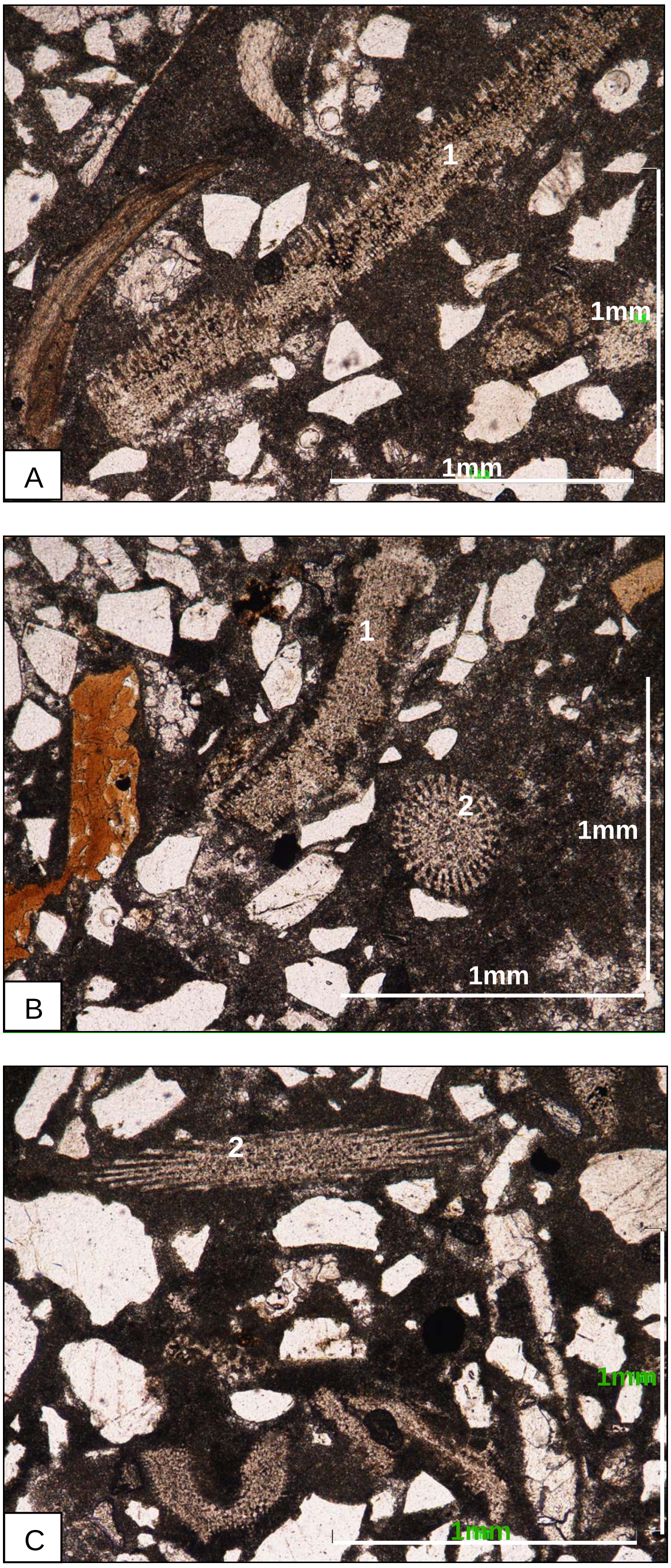


Figure 8.6. Photomicrographs of bioclasts from the limestone beds/layers at the upper Sandstone Member of the Imo Formation. (A-E). Foraminifera tests from samples in Okpotong-Bende. (F). Ostracod tests from samples in Ozuitem. Shell shows the duplicature, this excellent preservation is due to early diagenesis of test (Flügel, 2010). (G). Internal structure of a bivalve fragment showing obvious foliated inner-layer. (H). Gastropod fragment from Ozuitem limestone sample.


1
1mm
1mm
A
1
2
1mm
1mm
B
2
1mm
1mm
C

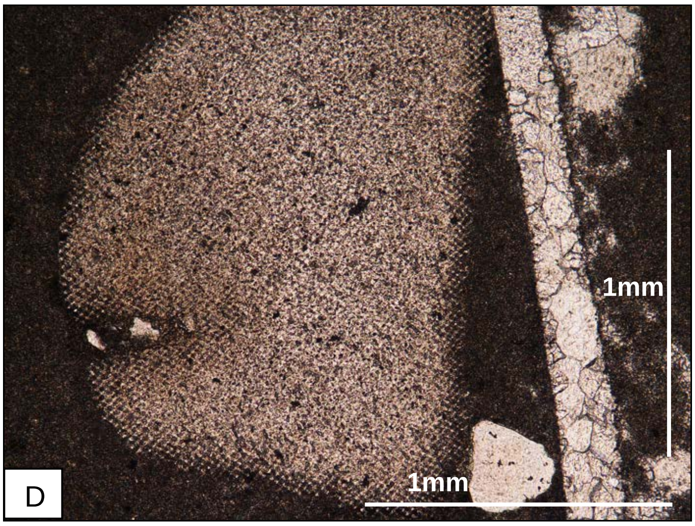


Figure 8.7. Photomicrographs of bioclasts from the limestone beds/layers at the upper Sandstone Member of the Imo Formaiton. Figures 8.7 (A-C) show micritic-coated brachiopod grains (1) and cross-section of echinoid spines (2) from samples in Ozuitem. (D). A large echinoderm fragment with honeycomb microtexture (small pores filled with micrite).

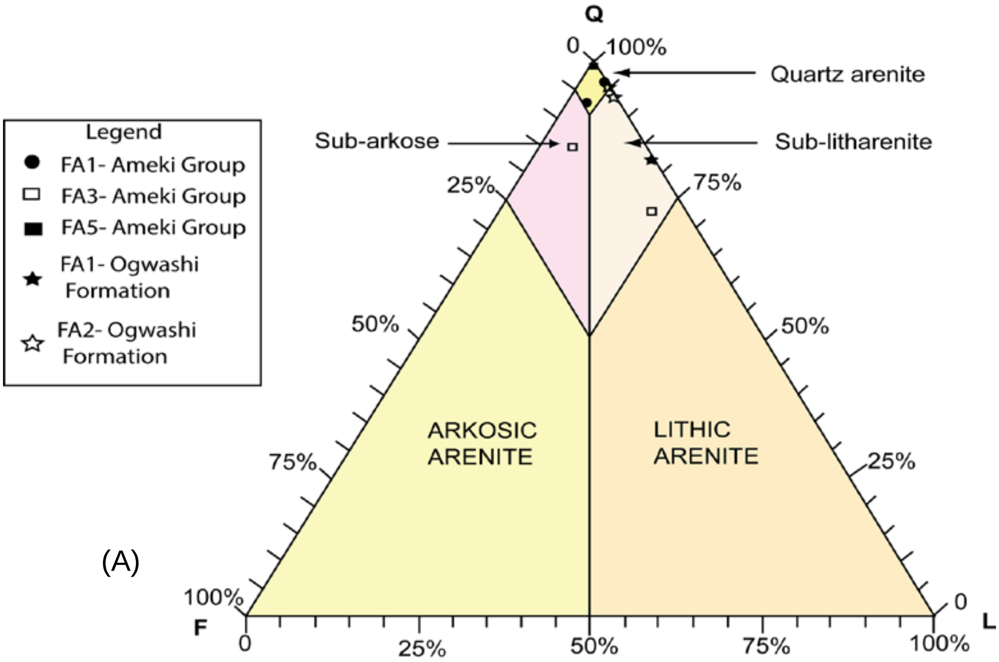
Table 8.1. Result of the modal petrographic analysis for Imo Formation

Formation/Age	IMO FORMATION (PALEOCENE-EOCENE)					
	Lower Sandstone		Middle	Upper Sandstone Member		
Sample	SEB-4	SUMZ-2	SAAP-3	SIAM	SOZC-4	SIAF
Grain size	m. - c.	m.	m. - c.	m.	f. - m.	f.
Q	86.8	83.8	89.9	46	41.4	44.4
Quartz single crystal	68.9	51.4	52.5	38.2	36.4	40.9
Quartz polycrystalline coarse texture	14	15.3	32.9	5.6	2.9	3.5
Quartz polycrystalline fine texture	3.7	17.1	4.4	2.2	2.1	0
K						
k-feldspar in single crystal	0	0	0	14.6	5.7	7.8
P						
Plagioclase in single crystal	1.2	0	0.6	9	8.6	7.8
L						
Metamorphic rock fragment	0.6	0	1.9	0	1.4	0
Volcanic rock fragment	0	0	0	0	0	2.6
Clastic lithic (clay)	0.6	0	0	0	0.7	0
Clastic lithic (siltstone)	1.8	0.9	0	3.4	0	0
Non-clastic lithic (carbonate)	0	0	0	2.2	2.9	1.7
Mica						
Muscovite	1.8	6.3	1.3	0	5	13.9
Biotite	0.6	0	0	0		0
Heavy minerals						
Heavy mineral single crystal	6.7	7.2	3.2	19.1	15	9.6
Carbonate						
Bioclast	0	0	0	0	4.3	7
calcite single grain	0	0	0	0	11.4	3.5
Non-carbonate grains						
Intraclast	0	0	0	0	0	0
Cement						
carbonate cement	0	0	0	0	3.6	1.7
Non-carbonate cement	0	1.8	3.2	5.6	0	0
Total grains in percentage	99.9	100	100	99.9	100	100

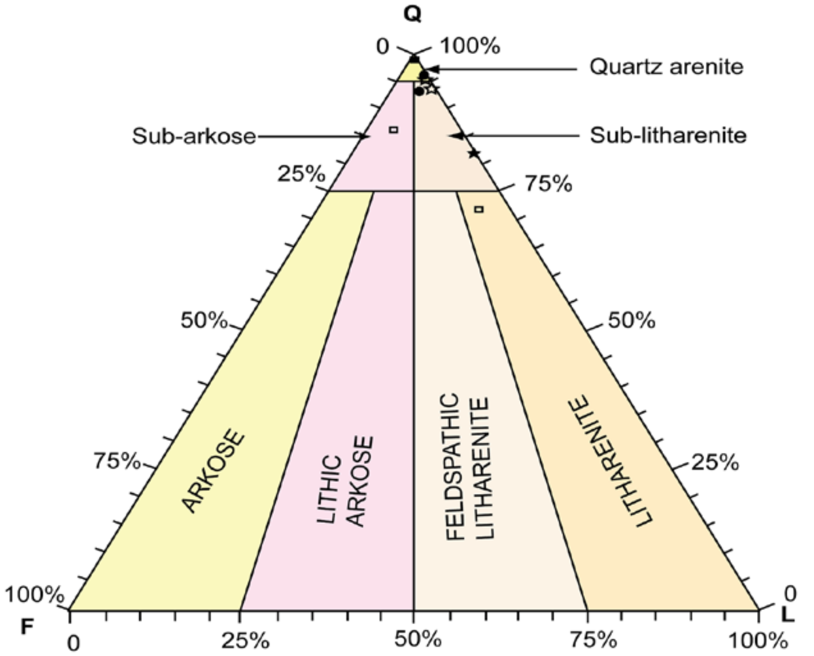
Petrographic analysis of the Ameki Group

The Ameki Group consists of about 65% sandstone and 35% mudstone/shale. Most of the sandstone (up to 85%) occurs within the Nsugbe and Nanka formations while most mudstone/shale deposits are found within the Ibeku Formation. The sandstone texture, grain size, sorting and grain morphology, is heterogeneous in the estuarine deposit. It varies from conglomeritic to fine grained sandstone in the deposits of fluvial channels, tidally influenced fluvial channels, tidal channels and tidal sand bars. Siltstone and mudstone/shale are common in floodplains, abandoned channels, tidal flats and estuarine embayment. The sorting likewise varies from very poorly sorted to well sorted depending on the sub-environment of deposition. The sandstone colour varies from white, yellowish grey, moderate pink, moderate orange, light red, moderate red to greyish red. The colour variation may be due to source material, the amount of interstitial haematite in the matrix and the type of cement (Ghazi and Mountney, 2011).

QFL ternary diagrams have been used to display the proportions of the major detrital framework components of the sandstone - quartz, feldspar and lithic fragments. Results of the plots on the QFL diagrams show that the sandstones of facies association 1 and 5 are classified as quartz arenites (Pettijohn, 1975) and sub-litharenites (Folk, 1980), while those of facies association 3 may occur as sub-arkoses and sub-litharenites (Pettijohn, 1975) or sub-arkoses and litharenites (Folk, 1980) (Figure 8.8).



(A)



(B)

Figure 8.8(A). Petrographic composition of the Sandstone members of the Ameki Group and Ogwashi Formation plotted on a QFL (Q-quartz, F-feldspar, L-lithic fragment) diagram (after Pettijohn, 1975). (B). Petrographic composition of the Sandstone members of the Ameki Group and Ogwashi Formation plotted on a QFL (Q-quartz, F-feldspar, L-lithic fragment) diagram (after Folk, 1980).

Mineralogical Composition

Quartz

Quartz is the highest occurring mineral, averaging from 57% to 84% of the total rock component (Table 8.2). Grain shape is mostly sub-rounded, with few rounded and subangular grains (Figure 8.9A). The quartz grains consist both of single or monocrystalline (45 - 58%) and polycrystalline quartz grains (40 - 55%). Approximately 46% of the monocrystalline quartz grains have straight extinction, with few slightly undulose extinction. About 30% of the polycrystalline quartz have a coarse texture while 15% of the polycrystalline quartz have a fine texture. Most polycrystalline quartz shows undulose extinction. Solid inclusions and Boehm lamellae are common in the quartz grains; fluid inclusions were rarely observed.

Feldspar

The occurrence of feldspar in the Eocene sandstone of the Ameki Group varies across the depositional facies. The facies association 3 (tidal channel deposit) has the highest proportion of feldspar grains (about 9% of the total rock components). K-feldspar is more common including microcline and grains with perthite twinning. Plagioclase feldspars are also observed in low counts (about 2%), with carlsbad, albite twinning. The low occurrence of feldspars may be due to the instable nature of the mineral, whereby feldspar easily alters to form clay minerals.

Lithic Fragments

Lithic fragments in the Eocene sediments of the Ameki Group consist of metamorphic, volcanic and sedimentary rock fragments. More lithic fragments occur in facies association 3 (<21%). The grains are medium grained, mostly subrounded, although rounded grains are also common. Sedimentary rock fragments are most common and consist of claystone/shale and siltstone fragments (Figure 8.9B, C). Metamorphic rock fragments are limited to mainly schist plus a few quartzite grains and consist of about 5% or less of the total rock composition. Volcanic rock fragments are rare.

Accessory minerals

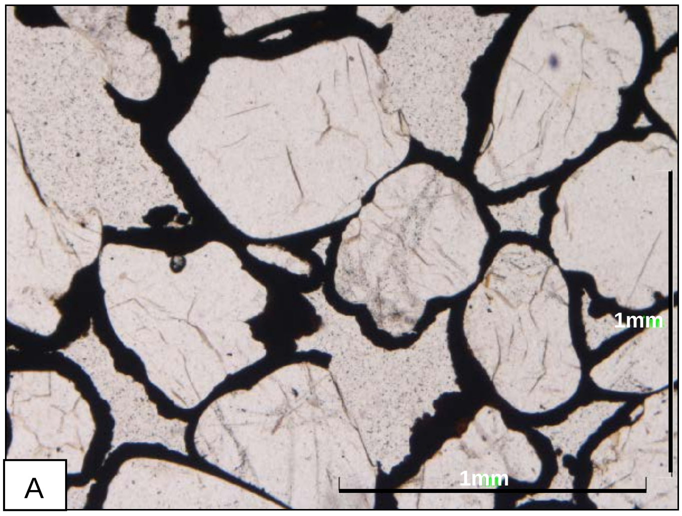
Micas were not observed in the analysed sandstone samples. However, this does not rule out the occurrence of mica in the Ameki Group, because micas have been observed in the heterolithic units in Umunya section (see Chapter 5: section 5.3.1). Heavy minerals are well represented throughout the Ameki Group and vary between 3% and 16% (Table 8.2). They include non-opaque minerals such as zircon, rutile, tourmaline, kyanite, and pyroxene. Few heavy minerals were easily recognised in thin section, probably because of their size. Detailed analysis of the heavy mineral distribution is discussed later in this chapter.

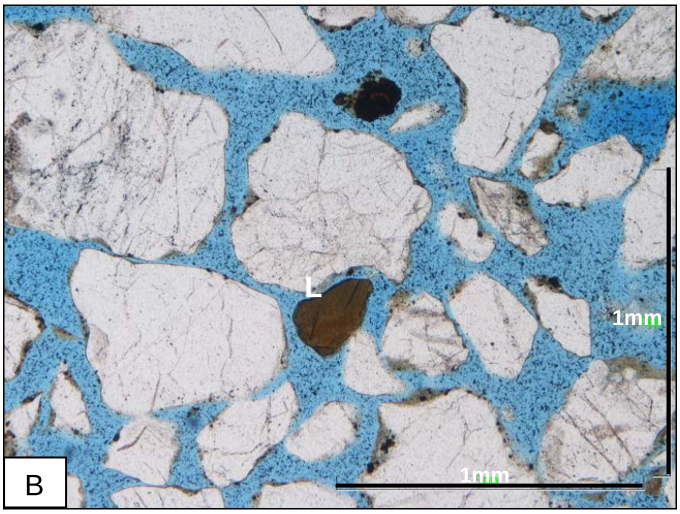
Limestone

The limestone layer (sample SESP-5) observed in the mudstone facies of the Ibeku Formation, at Ajata-Ibeku is diagenetic in origin (see Chapter 5: section 5.3.1). The limestone sample is interpreted as microsparstone based on the Wright, (1992) classification. The microsparstone consists about 35% grains in a matrix of microsparite. The grains include very fine grained quartz, feldspar, foraminiferal tests and bivalve fragments. The quartz grains (21%) are mostly monocrystalline, with few polycrystalline quartz grains (3%); the feldspar grains (4%) are dominantly plagioclase, with few k-feldspar. Foraminiferal tests and bivalve fragments are about 5%, while accessory minerals make up about 2%.

Cement

Ferruginous cement is the major cement type found in the sandstones of the Nsugbe Formation, with a high proportion about 15% of the total rock composition. Ferruginous cement is dominantly haematite and it fills pore spaces cementing the grains (Figure 8.9A).





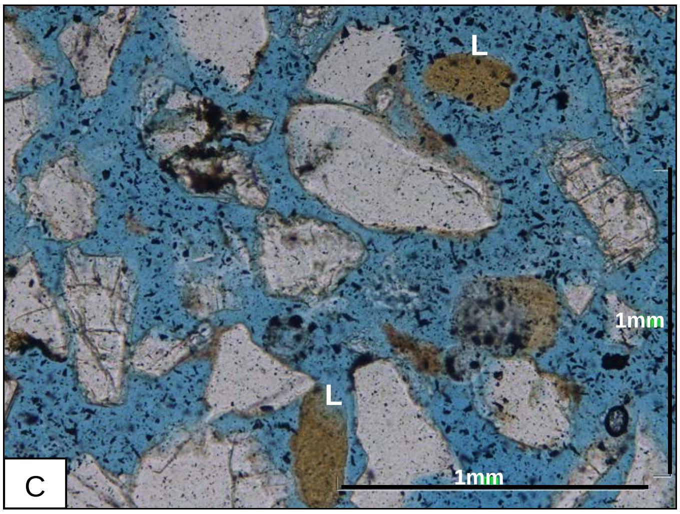


Figure 8.92. Thin section photomicrographs of detrital grains from the Ameki Group. (A).Subrounded to rounded quartz grains with ferruginous cement (sample SNS-1). (B-C). Sedimentary lithic fragments (L) from facies association 3 (samples SUMP-2 and SNIP-1 respectively).

Petrographic analysis of the Ogwashi Formation

The Ogwashi Formation consists of sandstone and claystone deposits in approximately equal amounts. The sandstone deposit is restricted to facies associations 1 and 2 while the claystone is more prominent in facies associations 3 and 4. The sandstones are poorly to moderately sorted and dominated by coarse to medium grained sandstone, with conglomerate mostly at the base of outcrop sections. Claystone, gritty claystone and fine grained sandstone are dominant in the deposits of the coastal plain channels and floodplains. The fresh sandstone shows white and light to yellowish grey colours. A light to moderate red colour present is dominantly due to presence of the interstitial haematite in the sandstone matrix.

Results of the plots in the QFL ternary diagrams also show that the sandstones of facies association 1 are classified sub-litharenites while sandstones of facies association 2 are quartz arenites and sub-litharenites (Figure 8.8).

Mineralogical Composition

Quartz

Quartz is also the highest occurring mineral in the Ogwashi sandstone samples. It consists of about 66% - 85% of the total rock composition (Table 8.2). The quartz grains are commonly subrounded and subangular in shape. Both monocrystalline and polycrystalline quartz grains were observed, with monocrystalline quartz consisting of 31 - 84% of the total quartz content. The monocrystalline quartz shows both straight and partially undulose extinction. The polycrystalline quartz has both coarse texture (11% - 58%) and fine texture (4% - 11%). Solid inclusions and Boehm lamellae are dominant in the quartz grains and fluid inclusions were also observed. The quartz grains with inclusions may contain zircon, tourmaline or microlites. Some grains are fractured and cloudy in appearance.

Feldspar

The absence of feldspars may suggest that the sediments are derived from a re-cycled source. Feldspars are unstable and can easily alter to form clay minerals during weathering, abrasion and prolonged transportation.

Lithic Fragments

Lithic fragments are mainly sedimentary rock fragments, with few metamorphic rock fragments. The grains are coarse to medium grained and are mostly rounded with some subrounded grains. Sedimentary rock fragments consist of claystone/shale and siltstone fragments; they occur more in the facies association 1 (>14%). Metamorphic rock fragments may be derived from quartzite or schist and constitute less than 2% of the total rock composition.

Accessory minerals

Micas form a minor detrital grain component (<4%); this is limited to facies association 1. The occurrence of only muscovite, is probably due to its stability or low susceptibility to dissolution during transportation (McBride, 1985). Heavy minerals are well represented in the Ogwashi Formation and vary between 5% and 13%. They include both opaque and non-opaque minerals. Detailed analysis of the heavy mineral distribution is discussed later in the chapter.

Cement

Argillaceous and ferruginous cements are the major cement types found in the Ogwashi Formation; they form less than 4% of the total rock composition. Ferruginous cement is dominantly haematite and it forms on the rims of the grains. The argillaceous cements are also found at the rims of the grains, cementing grains together.

Table 8.2. Result of the modal petrographic analysis for Ameki Group and Ogwashi Formation.

Formation/Age	AMEKI GROUP (EOCENE)					OGWASHI FORMATION (OLIGOCENE)		
Facies Association	FA 1		FA 3		FA 5	FA 1	FA2	
Sample	SNS-1	SNS-3	SNIP-1	SUMP-2	SIS-2	SOK1.1	SOK1.5	SOK1-8
Grain size	m. - c.	m. - c.	m. - c.	m.	c.	v.c.	c.	m. - c.
Q	57.3	84	80.5	62.7	84.4	66.2	85.4	84.4
Quartz single crystal	31.7	38	40.2	47	48.9	55.8	41.8	26.7
Quartz polycrystalline coarse texture	18.3	38	33.3	11.7	26.6	7.8	34.5	48.9
Quartz polycrystalline fine texture	9.8	8	7	4	8.9	2.6	9.1	8.9
K								
k-feldspar in single crystal	0	0	9.2	2	0	0	0	0
P								
Plagioclase in single crystal	0	2	0	2	0	0	0	0
L								
Metamorphic rock fragment	0	4	1.1	0	0	0	1.8	0
Volcanic rock fragment	0	0	1.1	0	0	0	0	0
Clastic lithic (clay)	0	0	0	9.8	0	13	1.8	4.4
Clastic lithic (siltstone)	2.4	0	2.3	9.8	0	1.3	1.8	0
Non-clastic lithic (carbonate)	0	0	0	0	0	0	0	0
Mica								
Muscovite	0	0	0	0	0	3.9	0	0
Biotite	0	0	0	0	0	0	0	0
Heavy minerals								
Heavy mineral single crystal	8.5	10	5.7	13.7	15.6	13	5.5	8.9
Carbonate								
Bioclast	0	0	0	0	0	0	0	0
calcite single grain	0	0	0	0	0	0	0	0
Non-carbonate grains								
Intraclast	0	0	0	0	0	0	0	0
Cement								
carbonate cement	0	0	0	0	0	0	0	0
Non-carbonate cement	29.3	0	0	0	0	2.6	3.6	2.2
Total grains in percentage	100	100	99.9	100	100	100	99.9	100

8.3.2 Heavy minerals of the Paleogene sediments

Provenance by heavy minerals analysis of the Sandstone Member of the Imo Formation

The analysed sediments contain diverse heavy mineral assemblages. Appendix E8.2 shows the quantitative point-counting results for heavy mineral composition in the Imo Formation. In table 8.1 the heavy mineral composition is summarized by percentage and is further grouped into various parent rocks. Table 8.3 shows the proportion of zircon, tourmaline and apatite varieties. The heavy mineral composition and varieties are shown as pie charts in Figures 8.10.

The heavy mineral suites consist of a high proportion of ultrastable minerals zircon, tourmaline and rutile which occurs throughout the succession except in sample SAA-1 which has a very low grain count. Index minerals of high-grade metamorphic (HGM) rocks which include kyanite, sillimanite and andalusite occur in varying proportion throughout the succession. A high proportion of unstable heavy mineral medium-grade metamorphic minerals (MGM) was encountered in all counts. They include minerals of the epidote group, garnet, sphene, staurolite, and hornblende.

The lower Sandstone Member of the Imo Formation includes the Ebenebe Sandstone (SEB1, 2), the Igbakwu Sandstone (SNK1, 3) and the Umuna Sandstone (SAIM 2). Sediments of the lower Sandstone Member consist of similar heavy mineral assemblages dominated by rutile (29 - 49%), with a high count of zircon (11 - 28%), kyanite (6 - 20%) and tourmaline (5 - 12%). Subordinate occurrences of epidote (3 - 10%), pyroxene (2 - 5%), staurolite (2 -8%) and sillimanite (1 - 4%) are observed. Andalusite, amphibolite and apatite counts (<2%) are very low. Monazite and garnet occur in trace amounts in a few samples. Dissolution is commonly observed in most of the unstable minerals.

Heavy Mineral Provinces and their provenance

The spatial distribution of the certain minerals such as high resolution heavy minerals (HRHM) (Mange-Rajetzky, 1995) such as zircon, apatite and tourmaline, index minerals of HGM and MGM shown on the location map in form of pie charts, allows the delineation of heavy mineral provinces (Mange and Otvos, 2005). Based on the heavy mineral trends, the provinces are discussed and grouped into a sandstone suite province and a mixed suite province (Figure 8.10). The sandstone suite province dominates the Imo Formation.

Sandstone suite province and sediment source area

Provenance from the sandstone suite province characterises the lower Sandstone, the middle and parts of the lower Sandstone members of the Imo Formation. It is characterised by medium to coarse grain heavy mineral assemblages that are dominated by rutile (Figure 8.10). Other common mineral types are zircon, kyanite and tourmaline (Table 8.3). A large number of the zircon grains are euhedral-subhedral; rounded colourless, zoned zircon and rounded purple coloured crystals are also well represented (Figure 8.11, Table 8.4). Tourmaline varieties are dominated by sub-rounded to rounded crystals, although prismatic, rounded prismatic and angular crystals are common in some samples. Apatite occurrence is very low and the varieties vary from prismatic to sub-rounded crystals. The paucity of apatite grains may have been caused by acidic leaching during burial diagenesis (Lihou and Mange-Rajetzky, 1996). In most samples from the lower sandstone province, heavy mineral suites such as kyanite, staurolite, and pyroxene show etch patterns, corrosion and hacksaw terminations, which suggest incipient dissolution processes due to contact with acidic fluid during diagenesis.

The high occurrence of euhedral-subhedral zircon crystals suggest first-cycle detritus and mostly derived from granitoid rocks (Lihou and Mange-Rajetzky, 1996). The presence of the rounded zircon crystals indicates polycyclic or recycled pre-existing sediments, whereby the grains have undergone multiple cycles of reworking during transportation. Although, Deer et al., (1982) noted that rounded zircon can also be derived as first-cycle detritus from metamorphic rocks that were formed from a sedimentary protolith. The occurrence of the rounded zircon crystals and euhedral-subhedral crystals in the lower sandstone province implies a mixed provenance. Similarly, the tourmaline varieties show high counts in the subrounded and rounded crystals as well as the angular and prismatic shape crystals also suggesting mixed provenance. The heavy mineral assemblages reflect sediment contribution mainly from a regional metamorphic terrain with considerable input from acid igneous or plutonic rocks (Table 8.3); small amounts of sediment were shed from basic igneous rocks, as well as recycled sedimentary rocks.

Mixed suite province and sediment source area

The mixed suite provenance is dominant in the upper Sandstone Member of Imo Formation, and the sedimentary units are characterised by mixed siliciclastic and carbonate material. The sudden high occurrence of coarse detrital grains of garnet (Figure 8.10 and 8.12) suggests a different source area from the sandstone suite province.

Epidote group minerals (dominated by epidote, with more zoisite and less clinozoisite crystals), kyanite and zircon are relatively abundant (Figure 8.12). A higher sphene count confirms the additional source area (Table 8.3 and 8.4). Tourmaline, pyroxene, apatite and staurolite are present and there are small amounts of actinolite present.

Zircon varieties are dominated by euhedral-subhedral crystals. Rounded polycyclic colourless zircons are common but purple colourless zircons are not common. Tourmaline varieties are also dominated by angular and prismatic crystals; though subrounded tourmaline grains are common, rounded tourmaline grains are relatively rare. Similarly, apatite varieties are more commonly prismatic and subrounded rather than rounded crystals.

The dominance of euhedral-subhedral, prismatic-angular and subrounded crystals of the ultrastable mineral suite - zircon, tourmaline and apatite, suggests first-cycle detritus from acid igneous or plutonic parent rocks. About 20% of the heavy mineral suite is derived from acid igneous or plutonic rock which may probably infer the Pan African granitoids or the Older Granites as the source area. These granites occur in the Oban Massif, the Western Nigeria basement and Adamawa highlands (Figure 8.1). The high counts of garnet, kyanite and the presence of sillimanite, sphene and staurolite suggest a high-amphibolite grade metamorphism (Ekwueme and Onyeagocha, 1985; Ekwueme et al., 1991; Rahaman, 1976; Schlüter, 2006; Obaje, 2009). This accounts for about 70% of the heavy mineral suites (Table 8.3). This suggests that the sediments were probably derived dominantly from the magmatic-gneiss complex of the Oban massif and/or the magmatic-gneiss complex and the schist belt of the south-western Nigeria basement. The schist belt in the south-western Nigeria includes high grade amphibolites facies as well as low grade greenschist facies (Rahaman, 1976; Obaje, 2009); this probably accounts for the minor occurrence of low grade minerals such as actinolite in the mixed suite province.

Table 8.3. Heavy mineral composition of representative samples of the Imo Formation

Sample Nos	Formation	Sandstone Member	Zrn	Tur	Apt	Mn	Sp	Rt	St	Sil	Kyn	Ep	Hb	Am	Grn	Act	And	Px	Others	TOTAL %
SEB-1	Imo Fm	Lower Sandstone	15.5	12.5	0	0	0	40.7	7.9	1.9	6.8	6.5	0	1.1	0	0	1.6	5.4	0	99.9
SEB-2	Imo Fm	Lower Sandstone	20.6	8.8	0	0	0	35.3	3.8	2.9	17.1	3.8	0	2.4	0	0	0.3	5	0	100
SNK-1	Imo Fm	Lower Sandstone	28.5	12.1	1.1	1.5	0	29.3	3.6	2.9	9.9	6.6	0	1.5	0	0	0.4	2.2	0.4	100
SNK-3	Imo Fm	Lower Sandstone	11.9	5.6	0.6	0	0	49.8	2.3	3	10.3	10	0	1	0.3	0	0.6	4.3	0.3	100
SAIM-2	Imo Fm	Lower Sandstone	22.3	8.9	0	0	0	31.6	2.6	3.7	20	5.9	0	2.2	0	0	0.7	2	0	99.9
SAA-1	Imo Fm	Lower Sandstone	6.8	6.8	3.8	0	0	13.7	3	9	29.5	9	1.5	3.8	0	0	1.5	8.4	3	99.8
SAA-3	Imo Fm	Middle Sandstone	15	5.1	0.7	0	0	43.2	1.7	2.7	11.6	5.8	0	0	0	0	1	12.9	0.3	100
SAA-4	Imo Fm	Middle Sandstone	21.1	4	1.1	0	1.4	52.1	1.1	0.9	11.4	1.7	0	0	0.3	0	0	4.6	0.3	100
SIAM-1	Imo Fm	Upper Sandstone	17.5	4.6	1.3	0	0	32.9	4.2	4.8	17.5	7.7	0	2.2	0.2	0	0.9	5.5	0.7	100
SIA-2	Imo Fm	Upper Sandstone	12.5	2.1	1.7	0	5.9	15.3	1.5	0.8	12.7	16.3	0	0	28.8	0.8	0.4	1.2	0	100
SOZ-3	Imo Fm	Upper Sandstone	9.1	3.4	1.2	0	7.2	14.4	1.8	1.3	10.8	19.7	0	0.5	26.9	0.2	0.4	2	1.1	100

Legend

Abbreviation: Zrn, Zircon; Tur, Tourmaline; Apt, Apatite; Mn, Monazite; Rt, Rutile; St, Staurolite; Sil, Sillimanite; kyn, Kyanite; Sp, Sphene; Ep, Epidote Group; Hb, Hornblende; Am, Amphibole; Grn, Garnet; Act, Actinolite; And, Andalusite; Px, Pyroxene; Oth, other heavy minerals.

Associated Parent Rock: Acid Igneous/Plutonic (Zrn–Sp) | Regional Metamorphism (Rt–Act) | Contact Metamorphism (And) | Basic Igneous (Px)

Table 8.4. Proportions of zircon, tourmaline and apatite varieties in the Imo Formation, south-east Nigeria.

Zircon varieties							
Sample No	Euhedral	Subhedral	Anhedral	Rounded colourless	Rounded purple	Zoned	Overgrowth
SEB 1	**5**	9	17	11	11	4	3
SEB 2	4	22	0	20	18	6	0
SNK 1	14	33	7	10	3	11	0
SNK 3	5	13	3	10	1	4	0
SAIM 2	17	15	2	5	12	11	0
SAA 1	1	1	0	1	0	1	0
SAA 3	3	12	5	12	3	4	5
SAA 4	4	13	5	30	14	5	3
SIAM 1	25	25	0	15	1	8	1
SIA 2	8	28	10	11	0	5	3
SOZ 3	10	28	3	6	2	2	0

Tourmaline varieties					
Sample No	Angular	Prismatic	Rounded prism	Sub-rounded	Rounded
SEB 1	2	6	10	7	18
SEB 2	1	5	1	9	14
SNK 1	7	8	1	10	2
SNK 3	3	4	0	10	0
SAIM 2	5	6	5	6	2
SAA 1	1	1	2	2	3
SAA 3	6	3	1	5	0
SAA 4	6	3	2	2	1
SIAM 1	0	14	0	7	0
SIA 2	4	3	0	5	0
SOZ 3	3	10	2	5	0

Apatite varieties					
Sample No	Prismatic	Rounded prism	Sub-rounded	Rounded	Spherical
SEB 1	5	0	0	0	0
SEB 2	0	0	0	0	0
SNK 1	1	0	2	0	0
SNK 3	1	1	1	0	0
SAIM 2	0	0	0	0	0
SAA 1	IG	IG	IG	IG	IG
SAA 3	0	1	1	0	0
SAA 4	1	2	1	0	0
SIAM 1	5	0	1	0	0
SIA 2	2	2	5	0	0
SOZ 3	1	2	3	1	0

IG: Insufficient grains

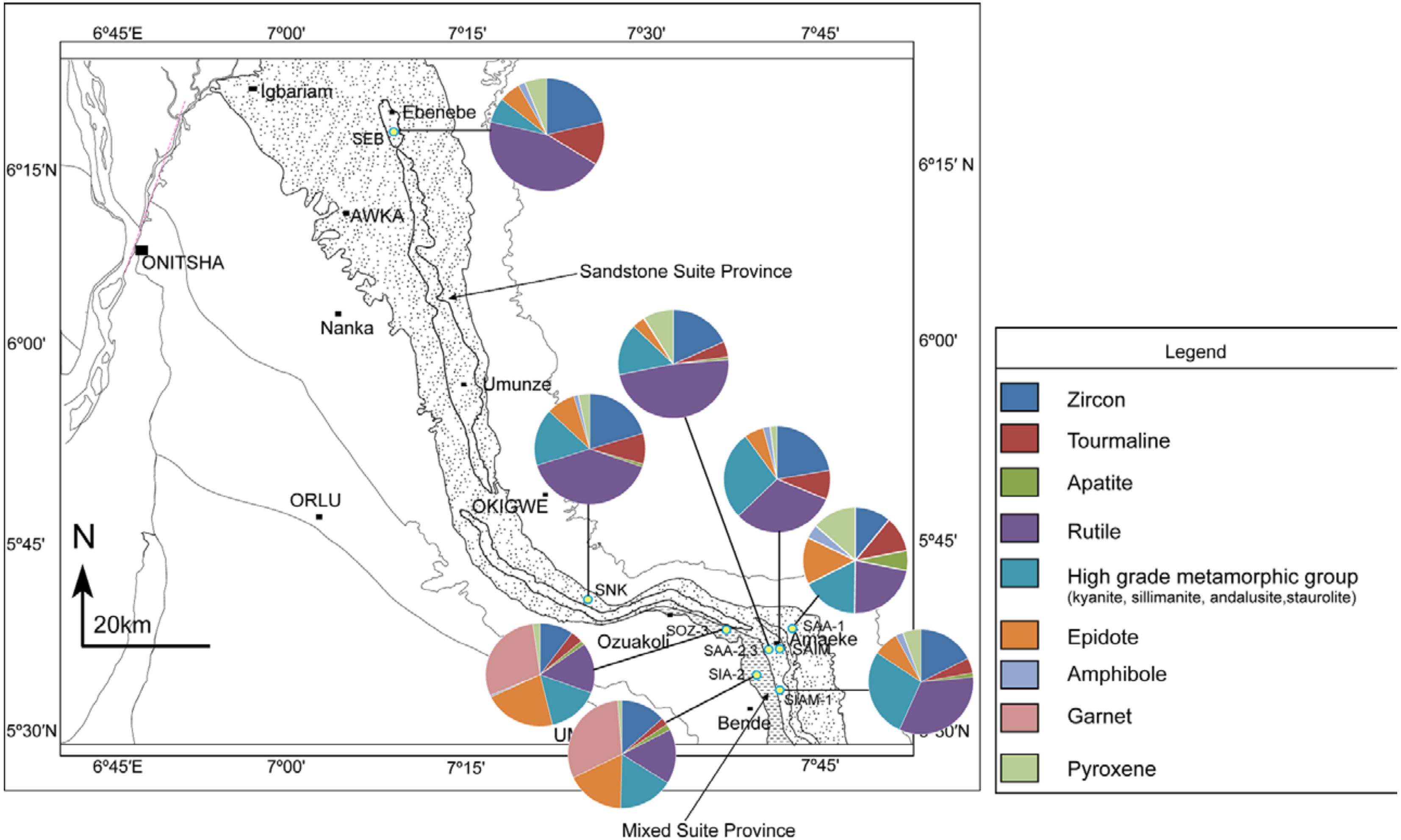


Figure 8.10. Heavy mineral composition of the Imo Formation in two heavy mineral provinces.

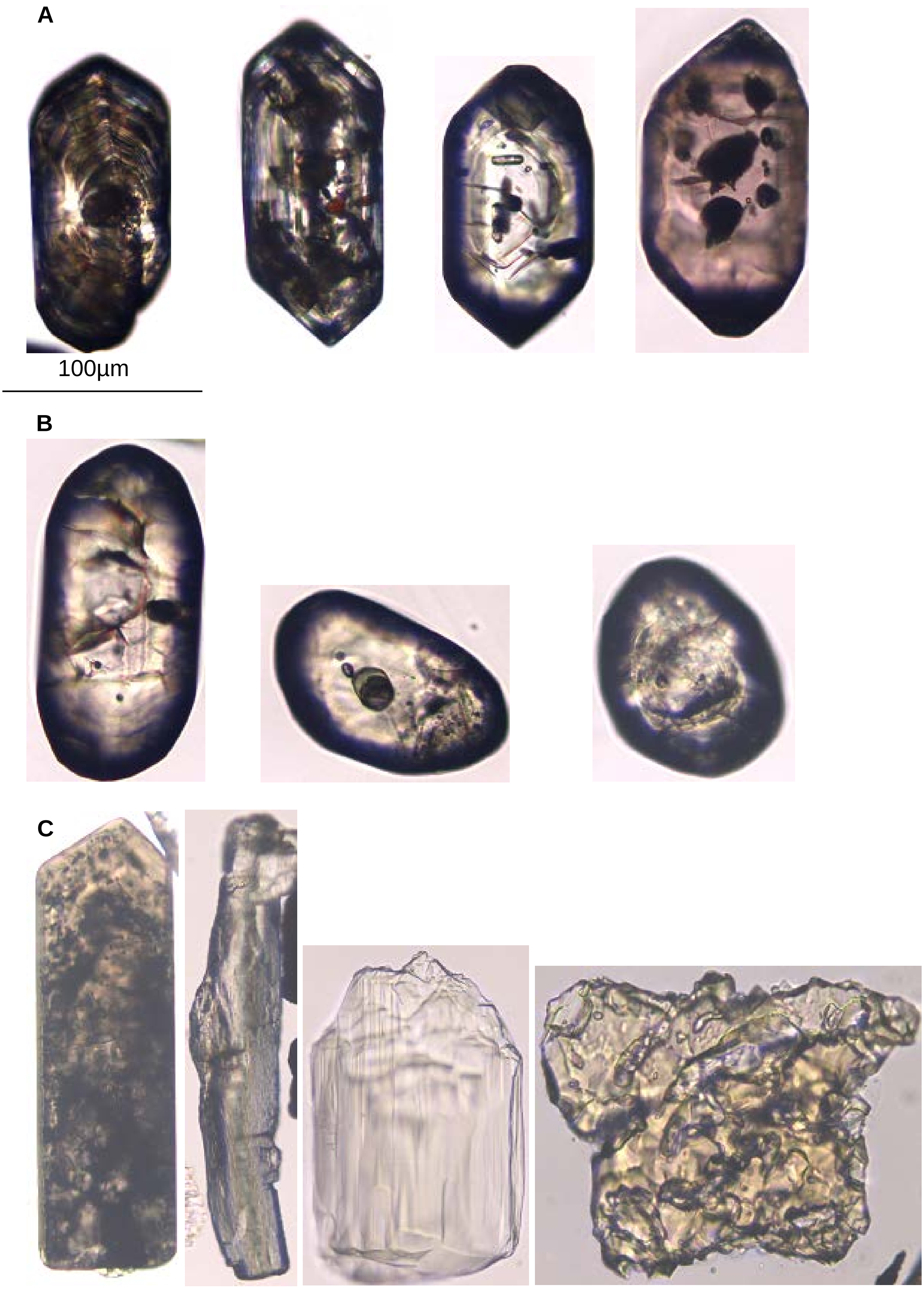
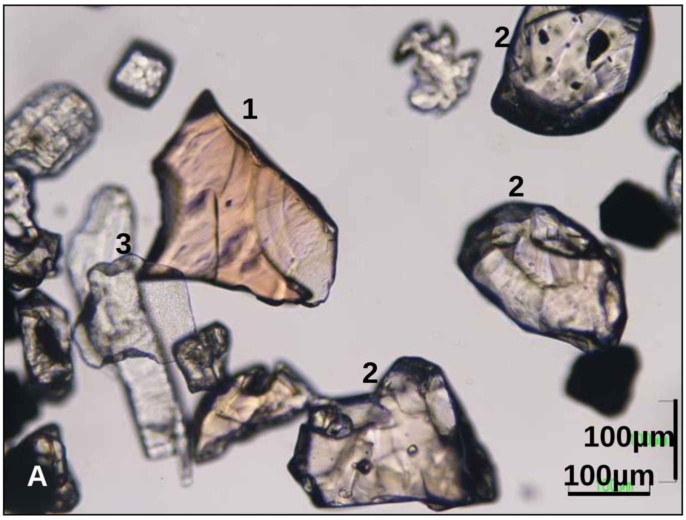
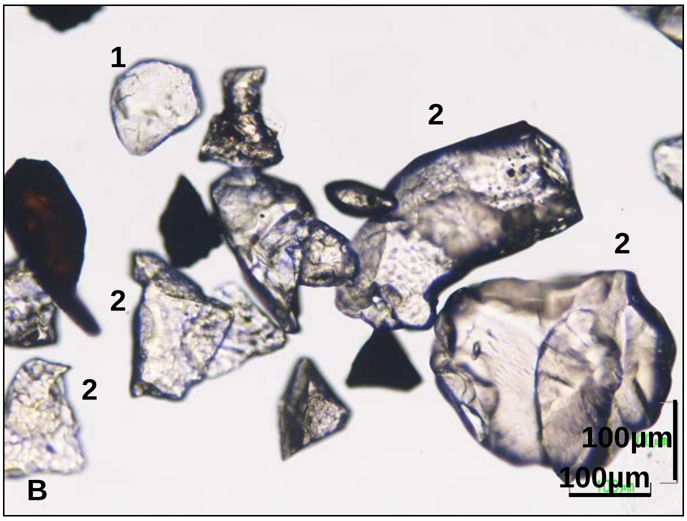

A
100µm
B
C

Figure 8.3. Images of selected heavy minerals and varieties occurring in the Sandstone Suite Province. A. Euhedral zircon crystals. B. Well rounded polycyclic zircon crystals. C. Tourmaline, pyroxene, amphibole and staurolite.





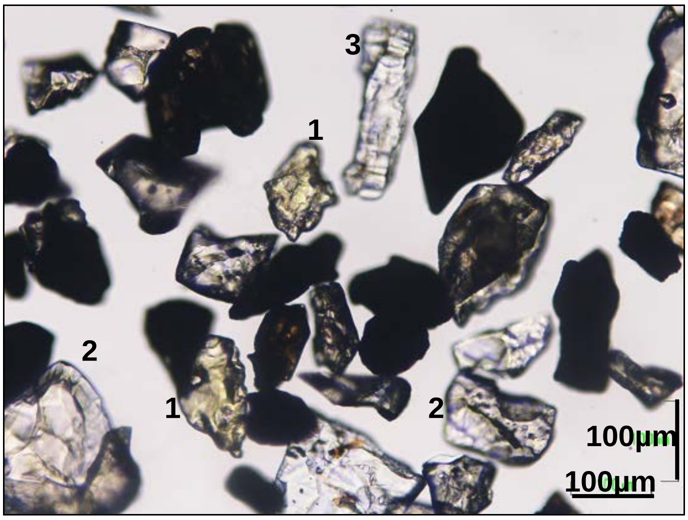


Figure 8.4. Images of selected heavy minerals occurring in the Mixed Suite Province of the upper Sandstone Member of Imo Formation. A. (1) Tourmaline crystal, (2) common garnet crystals, (3) kyanite crystal. B. (1) Apatite crystal, (2) Garnets showing mamillae facets. C. (1) Epidote crystals, (2) garnet crystals (3) kyanite crystal.

Heavy mineral of the tide-dominated estuarine Ameki Group and their provenance.

The quantitative point-counting results for the heavy mineral composition of the Ameki Group are showed in appendix E8.3. The heavy mineral compositions are further summarized into percentages and grouped into the various rocks as shown in Table 8.5.

The heavy mineral suites of ultrastable minerals zircon, tourmaline and rutile, occur in the Ameki Group (Figure 8.13). Different proportions of heavy minerals are observed throughout the succession, these include index minerals of high-grade metamorphic (HGM) rocks which are kyanite, sillimanite and andalusite; unstable heavy mineral medium grade metamorphic minerals (MGM) such as epidote group and staurolite and accessory minerals such as monazite and brookite. Facies association 6 shows a relatively lower proportion of zircon and higher proportion of rutile and kyanite, when compared to the other facies associations (Table 8.5). The distribution of the heavy mineral suite across the Ameki Group is shown as pie chart in Figure 8.14.

Ameki Group Province and sediment provenance

The Ameki Group province is characterised by predominantly ultrastable minerals, with varying amount of apatite. Kyanite is relatively abundant in facies association 3 (tidal channel deposits) and 6 (tidal sand bar deposits). The heavy mineral suites vary from fine to coarse grained crystals. Other heavy minerals such as pyroxene, staurolite and epidote group occur throughout the depositional facies, though in relatively low proportions. The spatial distribution of the heavy mineral assemblages in the Ameki Group (Figure 8.14; Table 8.5) shows no variation to allow further delineation of heavy mineral provinces. The proportion of the heavy mineral suite varies slightly probably due to hydraulic conditions which affect the grain sizes. Zircon varieties are dominated by euhedral-subhedral crystals, rounded polycyclic colourless crystals are relatively high, while zoned zircon crystals (Figure 8.13D) are common throughout the depositional facies, though in moderate to low quantity. Zircons with overgrowths are common in facies association 1 and 2. Tourmaline crystals occur in varying proportions with prismatic, rounded prisms and subrounded varieties been common. Angular and rounded tourmaline grains occur in relatively low proportions. Apatite is not abundant in the heavy mineral suite, however, the quantity of prismatic, rounded prisms and subrounded grains are high compared to the spherical and rounded crystals. The abundance of zircon, rutile and kyanite, with the common occurrence of pyroxene, tourmaline and staurolite reflect combinations of igneous and medium to high grade regional metamorphosed rocks. The high occurrence of euhedral-subhedral zircon suggests first-cycle detritus whereas the rounded colourless zircon crystals may indicate either polycylic derivation or first cycle detritus from metamorphosed sedimentary rocks or as a result of magmatization. Zircon grains with overgrowths are associated with high-grade metamorphism, contact metamorphism or granitization (Speer, 1980; Lihou and Mange-Rajetzky, 1996). A similar signature is observed in the tourmaline and apatite grains, where the prismatic crystals suggest first cycle detritus whereas the rounded prisms and subrounded to rounded grains may indicate a polycylic origin. The basement complex is one of the petrological province supplying sediments to Nigerian sedimentary basins. The Western Nigerian Massif consists of four major petro-lithological units which are the migmatite-gneiss complex, the schist belts, the older granites and the undeformed acidic and basic dykes (Obaje, 2009). The massif is probably the major source area for the sediments in the Ameki Group province; another possible source is older sedimentary rocks from older formations.

Heavy mineral of the tidally influenced coastal plain Ogwashi Formation and their provenance.

Appendix E8.3 also shows the quantitative point-counting results for the heavy mineral composition in the Ogwashi Formation. Table 8.5 shows the summarized heavy mineral composition, which is grouped into various parent rocks. The proportions of zircon, tourmaline and apatite varieties are outlined in Table 8.5. The heavy minerals composition and varieties are also shown as pie charts in Figures 8.14. Insufficient heavy mineral grains characterise sediments of the Ogwashi Formation, this may be due to the coarse and conglomeritic nature of the sediments. This is because heavy minerals different responses to hydrodynamic influences make their volumetric distribution variable (Dickinson, 1985). The heavy mineral suites have a high content of zircon; tourmaline and rutile, they are relatively low to moderate in abundance and did not occur throughout the succession. Index minerals of high-grade metamorphic (HGM) rocks such as kyanite occur throughout the depositional facies, sillimanite occurs only in facies association 1. Heavy minerals of medium-grade metamorphic (MGM) such as epidote group, staurolite, and hornblende occur in very low counts in the depositional facies.

Heavy Mineral Provinces and their provenance

The spatial distribution of minerals such as high resolution heavy minerals (HRHM) such as zircon, apatite and tourmaline, index minerals of HGM and MGM allows the delineation of heavy mineral provinces (Mange and Otvos, 2005). Based on the occurrences and trends of the heavy minerals, single province, Ogwashi province is delineated into Ogwashi 1A and 1B sub-provinces, due to slight variation observed within the province which may be as a result of hydraulic differentiation.

Ogwashi 1A Sub-province and sediment sources

The Ogwashi 1A sediments are characterised by zircon-monazite-kyanite assemblage, with subordinate staurolite, epidote and hornblende occurring in some sediments (Table 8.2). The ultrastable mineral rutile is noticeably absent in this province. Numerous zircon grains are euhedral-subhedral; rounded colourless and zoned zircon crystals are also well represented (Table 8.3). Tourmaline varieties are dominated by sub-rounded to rounded crystals, although angular crystals are observed as well. Prismatic and sub-rounded apatite morphologies occur in very low proportions. The paucity of apatite grains may have been caused by acidic leaching (Lihou and Mange-Rajetzky, 1996) or sediment reworking. The abundance of zircon, monazite and tourmaline (66-80%) in the heavy mineral suites indicate basic igneous rocks are the ultimate parentage. Less than 34% of heavy mineral suite (such as kyanite, staurolites, epidote) indicates input also from metamorphic source.

Ogwashi 1B Sub-province and provenance sources

Provenance from the Ogwashi 1B sub-province is characterised by medium grain heavy mineral assemblages that are dominated by zircon and rutile. Other common mineral types are kyanite and tourmaline (Table 8.2). Subordinate apatite, staurolite, sillimanite and epidote are observed. Many zircon grains are euhedral-subhedral; rounded colourless, and zoned zircon crystals are well represented (Table 8.3). Tourmaline is dominated by prismatic and rounded prisms morphologies; sub-rounded crystals are common in some samples. Apatite occurrence is very low and the varieties include prismatic and sub-rounded crystals. A similar mixed provenance is also proposed for the Ogwashi1B sub-province; zircon; the proportion of rutile, tourmaline, apatite and pyroxene ranges from 31-80% while the amount of rutile, staurolite, sillimanite and kyanite is equally between 30 and 88%.

The Oban Massif is differentiated into metamorphic rocks which consist of phyllites, schists, gneisses and amphibolites and intrusives which are charnockites, dolerites, granites, granodiorite, diorite, syenite, adamellite and pegmatite (Ekwueme et al., 1991). The mixed proportion of suites of minerals from metamorphic and igneous rocks suggests dominant source area to be the Oban Massif and probably Western Nigerian Massif. The occurrence of rounded and subrounded crystals of zircon and tourmaline may infer a contribution recycled sedimentary rocks. Although, the Ogwashi province is subdivided into two provinces, this may not suggest different source rocks because of insufficient grains encountered in some of the rock samples.

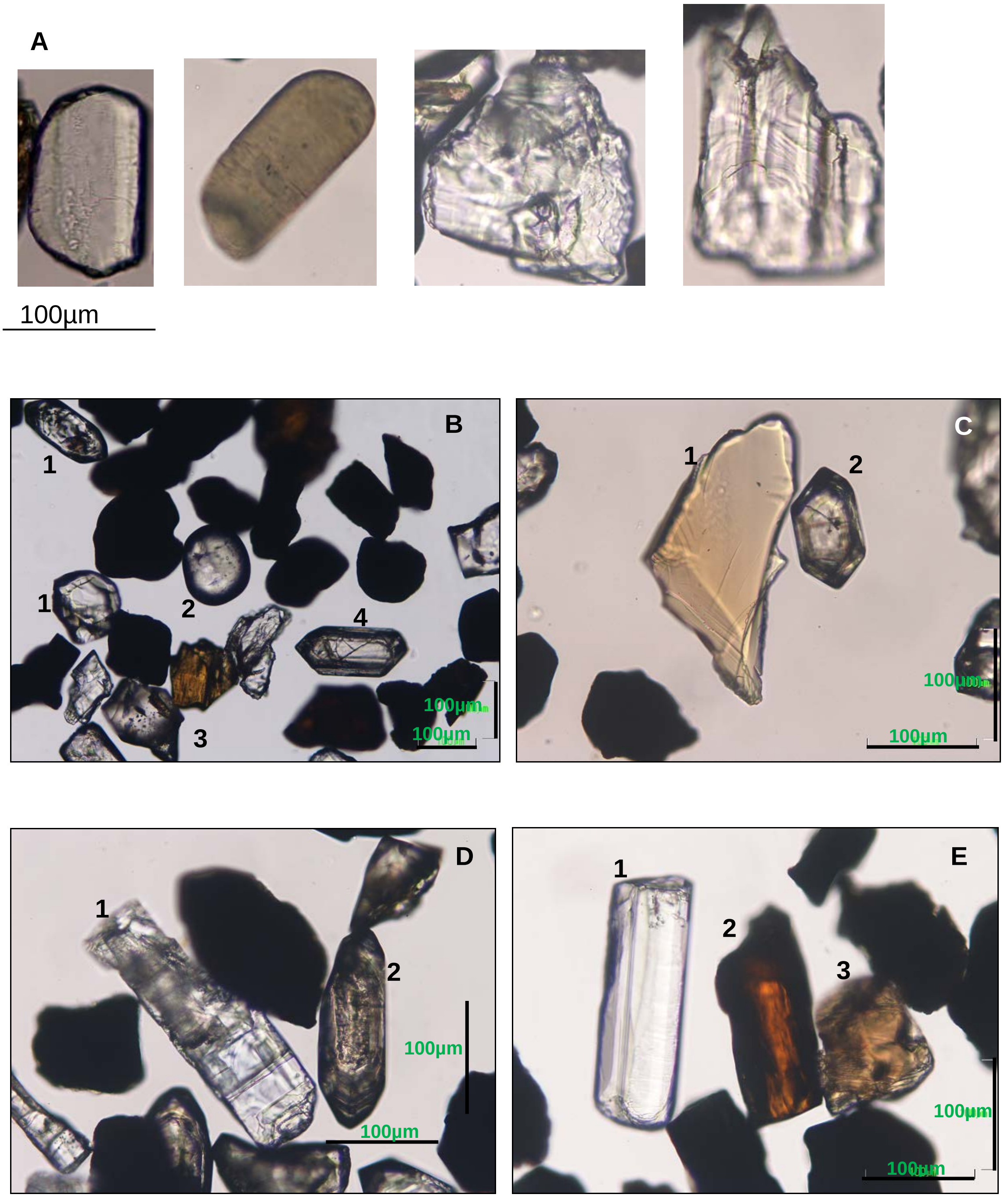


Figure 8.5. Images of selected heavy minerals and varieties occurring in the Ameki Group Province. A. Rounded prism of apatite and tourmaline crystals; clinozoisite and zoisite crystals. B. Varieties of zircon crystals: (1) subhedral, (2) rounded, (3) anhedral, (4) euhedral. C. Staurolite crystal (1), euhedral zircon crystal (2). D. Kyanite crystal (1), zoned zircon crystal (2). E. Sillimanite crystal (1), rutile crystal (2), and staurolite crystal (3).

Table 8.5. Heavy mineral composition of representative samples of the Ameki Group and Ogwashi Formation.

Sample Nos	Group	Formation	Facies Ass.	Zrn	Tur	Apt	Mn	Rt	St	Sil	Kyn	Sp	Ep	Hb	Am	Grn	Act	And	Px	Others	TOTAL %
SNS 1	Ameki	Nsugbe	FA 1	53.8	2.8	0.9	0.6	26.9	0.9	0.3	6.3	0	0.6	0	0	0	0	0.3	6.6	0.6**	100
SNS 3	Ameki	Nsugbe	FA 1	52.1	4	0.3	0.3	22.2	1.1	0.3	9.5	0	0.3	0	0	0	0	0	9.9	0.3**	100
SUN 1	Ameki	Nanka	FA 2	69.8	7.5	0	0	4.6	7.5	0	4.7	0	3.5	0	0	0	0	0.6	1.2	0.6	100
SUN3	Ameki	Nanka	FA 2	52.3	13.1	1.9	0	23.4	3.7	0	1.9	0	2.8	0	0	0	0	0	0.9	0	100
SUM 1	Ameki	Nanka	FA 3	56.3	6.1	1.2	0	19.4	0.4	0.4	9.3	0	2	0	0.4	0	0	1.2	3.2	0.8*	99.9
SUM 2	Ameki	Nanka	FA 3	44.7	4.8	1	0	28.1	1.4	1	10.7	0	4.4	0	0	0	0	0	3.9	0	100
SNI 2	Ameki	Nanka	FA 3	54.7	1.5	0	0	8.4	1	3.5	22.4	0	1.5	0	2	0	0	0	3	2	100
SUM 3	Ameki	Nanka	FA 4	39.4	7.5	0.9	0	26.5	1.8	1.8	11.9	0	4.4	0	0	0	0	0	5.8	0	100
SUM 4	Ameki	Nanka	FA 4	70.6	7.9	2.3	0	8.7	1.5	0	5.5	0	1.5	0	0	0	0	0	1.5	0.7	100.2
SIS 1	Ameki	Nanka	FA 6	20.9	2.6	0.3	0	33	2.4	2.2	26	0	0.9	0	3.4	0	0	0.9	7	0.3	99.9
SIK 1	Ameki	Nanka	FA 6	20.6	2.1	2.6	0	31.4	1.6	4.1	26.8	0	3.6	0	0	0	0	0	7.2	0	100
SOK 1A*	Ogwashi	Ogwashi	FA 1	57.1	8.6	0	14.3	0	0	0	14.3	0	0	5.7	0	0	0	0	0	0	100
SOK 1.1	Ogwashi	Ogwashi	FA 1	39.6	5.2	0.9	0	29.3	0.9	0.9	18.1	0	3.4	0	0	0	0	0	1.7	0	100
SOK 1.2	Ogwashi	Ogwashi	FA 1	12.4	5	1.7	0	33	1.6	2.1	29.3	0	2.9	0	0	0	0	0	12	0	100
SOK 1.4*	Ogwashi	Ogwashi	FA 2	80	0	0	0	13.3	0	0	6.7	0	0	0	0	0	0	0	0	0	100
SOK 2.1	Ogwashi	Ogwashi	FA 2	47.1	5.7	0	13.2	0	3.8	0	17	0	9.4	0	3.8	0	0	0	0	0	100

0.8* **Brookite**

0.6** **Oxide**

* **SOK 1A** Sample with insufficient grains.

Legend

Abbreviation: Zrn, Zircon; Tur, Tourmaline; Apt, Apatite; Mn, Monazite; Rt, Rutile; St, Staurolite; Sil, Sillimanite; kyn, Kyanite; Sp, Sphene; Ep, Epidote Group; Hb, Hornblende; Am, Amphibole; Grn, Garnet; Act, Actinolite; And, Andalusite; Px, Pyroxene; Others, other heavy minerals; Facies Ass., Facies Association.

Associated Parent Rock: Acid Igneous/Plutonic; Regional Metamorphism; Contact Metamorphism; Basic Igneous

Table 8.6. Proportions of zircon, tourmaline and apatite varieties in the Ameki Group and Ogwashi Formation, south-east Nigeria.

Zircon varieties

Sample No	Euhedral	Subhedral	Anhedral	Rounded colourless	Rounded purple	Zoned	Overgrowth
SNS 1	21	41	40	45	3	16	6
SNS 3	14	36	39	39	3	14	3
SUN 1	17	29	20	39	3	6	6
SUN 3	5	15	5	23	1	4	3
SUM 1	23	45	30	24	1	6	0
SUM 2	11	27	30	17	0	5	2
SNI 2	14	40	1	36	4	14	1
SUM 3	5	24	23	27	5	5	2
SUM 4	13	27	19	17	2	9	1
SIS 1	8	21	3	13	3	8	1
SIK 1	6	10	7	12	3	1	1
SOK 1A*	3	8	0	2	0	7	0
SOK 1.1	4	22	7	9	1	3	0
SOK 1.2	2	11	10	4	3	0	0
SOK 1.4*	1	1	2	5	0	3	0
SOK 2.1	4	14	1	4	0	2	0

Tourmaline varieties

Sample No	Angular	Prismatic	Rounded prism	Sub-rounded	Rounded
SNS 1	1	5	2	1	0
SNS 3	0	5	6	0	0
SUN 1	2	2	2	4	3
SUN 3	1	1	4	7	1
SUM 1	1	4	5	4	1
SUM 2	0	0	2	6	2
SNI 2	0	0	0	3	0
SUM 3	1	7	4	4	1
SUM 4	0	4	3	2	1
SIS 1	2	0	1	5	0
SIK 1	0	4	5	2	1
SOK 1A*	1	0	0	1	1
SOK 1.1	1	2	2	1	0
SOK 1.2	0	4	5	2	1
SOK 1.4*	IG	IG	IG	IG	IG
SOK 2.1	1	1	0	1	0

Apatite varieties

Sample No	Prismatic	Rounded prism	Sub-rounded	Rounded	Spherical
SNS 1	0	2	1	0	0
SNS 3	1	0	0	0	0
SUN 1	0	0	0	0	0
SUN 3	1	1	0	0	0
SUM 1	0	0	1	2	0
SUM 2	1	1	0	0	0
SNI 2	0	0	0	0	0
SUM 3	0	0	2	0	0
SUM 4	2	0	1	0	0
SIS 1	0	1	1	0	1
SIK 1	1	0	3	0	0
SOK 1A*	IG	IG	IG	IG	IG
SOK 1.1	1	0	0	0	0
SOK 1.2	1	0	3	0	0
SOK 1.4*	IG	IG	IG	IG	IG
SOK 2.1	IG	IG	IG	IG	IG

IG: Insufficient grains

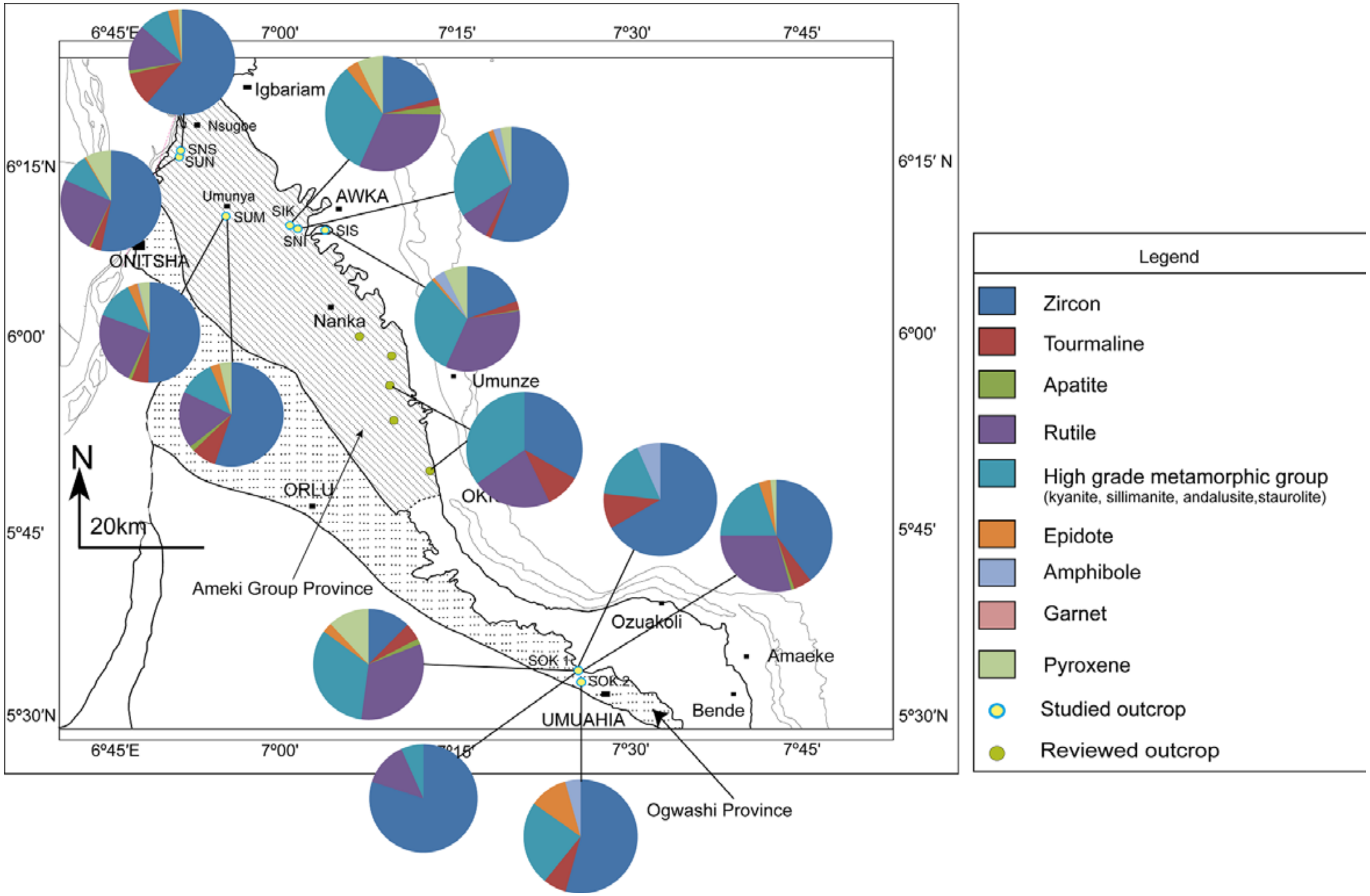


Figure 8.6. Heavy mineral composition of the Ameki Group province.

8.4 DISCUSSION

8.4.1 CONTROLLING FACTORS ON HEAVY MINERAL DISTRIBUTION PATTERN

The possible controlling factors affecting the heavy mineral distribution pattern at various geologic time during the Paleogene are probably river runoff, action of tide and wave processes, erosion of adjacent terraces and grain size which may be modified by hydraulic sorting.

The Niger Delta started to evolve in the early Paleogene when clastic river input is considered to have increased (Doust and Omatsola, 1990). This river runoff during the early Paleocene must have resulted to river input into the shelf, which led to the deposition of sandstone bodies reworked by tidal action to form tidal sandwaves. The high occurrence of euhedral –subhedral heavy mineral grains such as zircon in the tidal sandwave deposits suggests their derivation from primary sources and an incipient mechanical abrasion, whereas tourmaline crystals are dominantly rounded to subrounded forms, which suggest either a polycyclic origin or a long exposure to dynamic processes prior to deposition (Cascalho and Fradique, 2007). The upper Sandstone Member of Imo Formation interpreted as wave influenced mixed siliciclastic and carbonate shelf deposit is dominated by subangular to subrounded garnet and epidote group minerals. Zircon and Tourmaline minerals are dominated by euhedral-subhedral crystals (Table 8.4). The controlling factor affecting the heavy mineral distribution is probably wave action and erosion from adjacent terraces. The palaeoclimatic condition of semi-humid to humid climate during the Paleogene probably contributed to the weathering of a nearby source (most likely the magmatic-gneiss complex of the Oban massif); in which the weathered sediments were transported and deposited by wave process.

The middle–late Eocene Ameki Group commenced with fluvial deposit which became inundated by marine water during transgression to form an estuary. Paleocurrent readings from sediments of the fluvial deposit suggest north-easterly source (Figure 5.4A). Heavy mineral distribution within the Ameki Group suggests that the fluvial sands must have discharged into the estuary by fluvial process and the sediments were reworked by the tidal processes. The distribution of the heavy minerals river sands appears to be consistent with the heavy mineral content of the estuarine sands, although the estuarine sands show more enrichment in kyanite, which may be as a result of marine influence. The dominant input is suggested to be fluvial influx whereby the drainage basin feed the estuary through fluvial transport whereas the subordinate input is oceanic through tidal transport.

Outcrops of the Oligocene Ogwashi Formation is poorly exposed; the lithofacies of the formation are conglomerate, very coarse to medium grained sandstone, claystone, lignites beds and carbonaceous mudstone. Sediments of tidally influenced coastal plain of the Ogwashi Formation exhibit low counts or low concentration of heavy minerals in the sand-sized grains. Factors affecting the low concentration of heavy minerals in sediments include provenance, sedimentary processes and post-depositional dissolution (such as diagenetic dissolution) (Mange and Maurer, 1992; Morton and Hallsworth, 1999). Garzanti and Andò, 2007 demonstrated that heavy mineral concentration in medium to fine sand fractions is poor compared to very fine sand or coarse–silt fractions (which has strong concentration of heavy minerals) due to hydraulic sorting with respect to transport mode.

The matrix to clast–rich conglomerate and poorly to moderately sorted bioturbated sandstone of facies associations 1 and/or 2 of the Ogwashi Formation have been interpreted as fluvio-estuarine to tidal channel deposits. The absent of ultrastable mineral rutile in the Ogwashi 1A sub-province (Table 8.5) may not necessary be due to post-depositional dissolution because the Paleogene strata are poorly consolidated and have not undergone deep burial (Nwajide, 2013). Provenance and hydraulic sorting are the most probably controlling factors affecting the heavy minerals distribution in the sandstone facies of the Ogwashi Formation. Although sediments of this sub-province are enriched with euhedral-subhedral zircon, rounded to subrounded zircon, tourmaline and apatite are well represented. Similarly, sediments of Ogwashi1B sub-province show high counts of euhdedral-subhedral zircon crystals and prismatic tourmaline crystals and the rounded crystal of the aforementioned minerals are well represented (Table 8.6). These suggest that the source may probably be a close by pre-existing sedimentary terraces and probably oceanic input, as well as contributions from the basement complexes such as Oban Massif due to the occurrence of monazite, which rarely occurred in the older Paleocene-Eocene sediments. Monazite occurs as a weathering product from high-graded metasedimentary rocks or granite intrusive rocks (Horton and Zullo, 1991) such as pegmatites.

This study shows that the distribution of heavy mineral suites in the Paleogene sediments of the south-east Nigeria is controlled mainly by sedimentary processes (such as river, tide and wave actions as well as hydraulic sorting) and provenance.

8.4.2 PROVENANCE INTERPRETATION

Plots of the QtFL and the QmFLt ternary diagrams (Figure 8.15) suggest that the Paleogene sandstones may be derived mostly from mixed provenances which include cratonic interiors, transitional continental blocks as well as recycled orogen (based on the Dickinson (1985) QtFL ternary plot) and transitional continental, transitional recycled and quartzose recycled (based on the Dickinson (1985) QmFLt ternary plot). The main source for the craton/continental-derived quartzose sands are low-lying granitic and gneissic exposures. This accounts for the Western Nigerian Massif and Oban Massif as an important source for the Paleogene sediments. Orogenic recycling occurs in tectonic settings where stratified rocks are deformed, uplifted and eroded (Dickinson, 1985). This is typical of the Abakaliki anticlinorium which was formed during the Santonian (compressional phase) thermotectonic event (Figures 2.1B, 2.2), which resulted in the folding and uplifting of the Abakaliki area to form Abakaliki anticlinorium and subsequent formation of Anambra and Afikpo depocentres (Figure 2.2). The anticlinorium became the one of the sources for the Anambra and Afikpo basins. These basins later became contributors to the Niger Delta Basin, which developed from the Thanetian onwards.

Paleoclimatic conditions of the study area can be extracted from compositional maturity of the Paleogene sediments expressed in QFL using schemes proposed by Suttner and Dutta (1986) (Figure 8.16). Paleogene sandstones with average QFL ratios of 100:0:0; 97:1:2 and 82:0:17 (Table 8.7) are deposited under humid climate and exhibit higher compositional maturity than the Paleogene sandstones with QFL ratios of 79:7:14 and 69:27:4, which suggest accumulation in semi-humid conditions. Subsequently, a bivariant log/log plot (Figure 8.17) between Qp/F+R and Qm+Qp/F+R (Suttner and Dutta, 1986) is indicative of semi-humid to humid climate for the Paleogene sandstones.

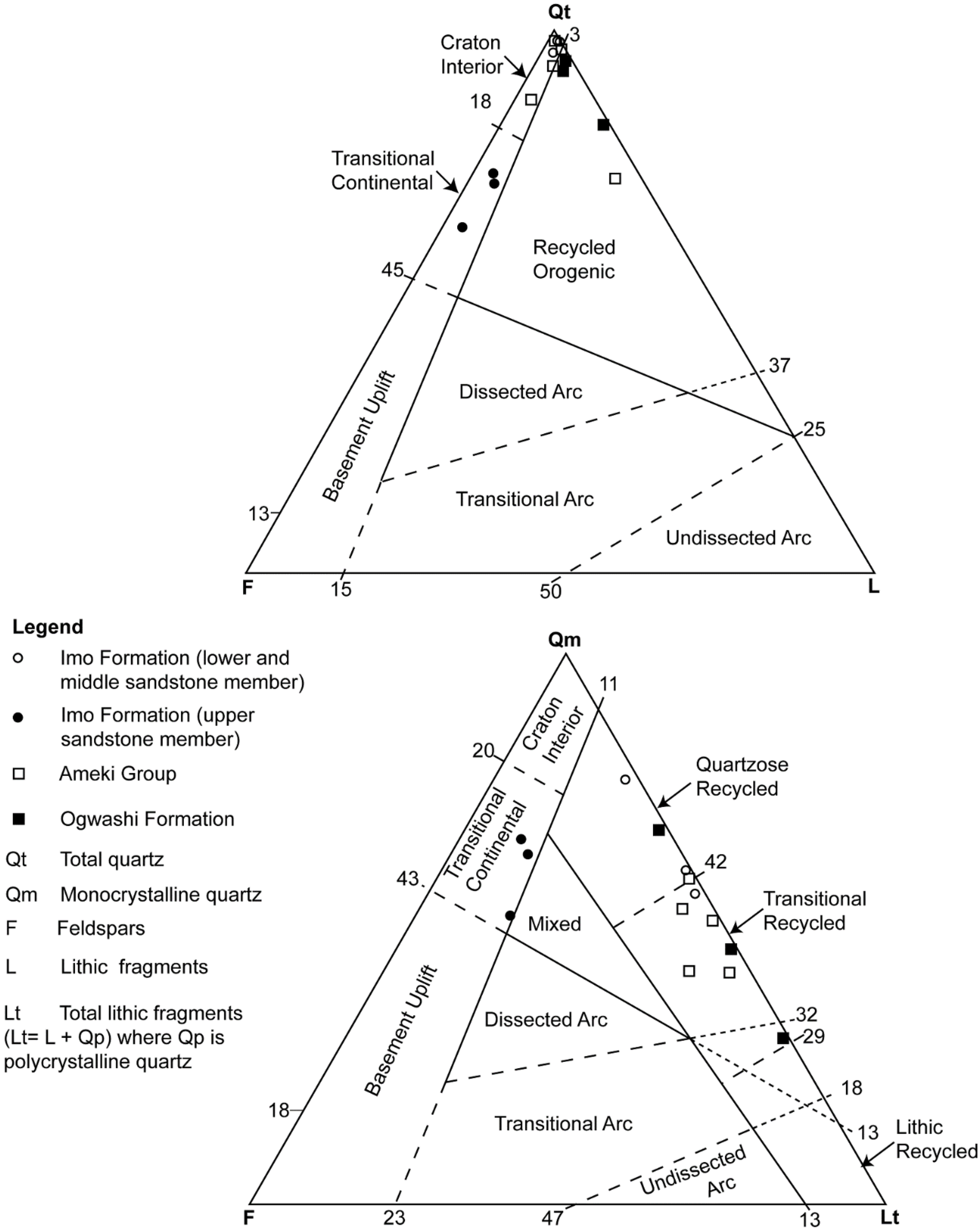


Figure 8.15 Interpretation of provenance types from the petrography of the Paleogene strata in the south-east Nigeria (after Dickinson, et al., 1983).

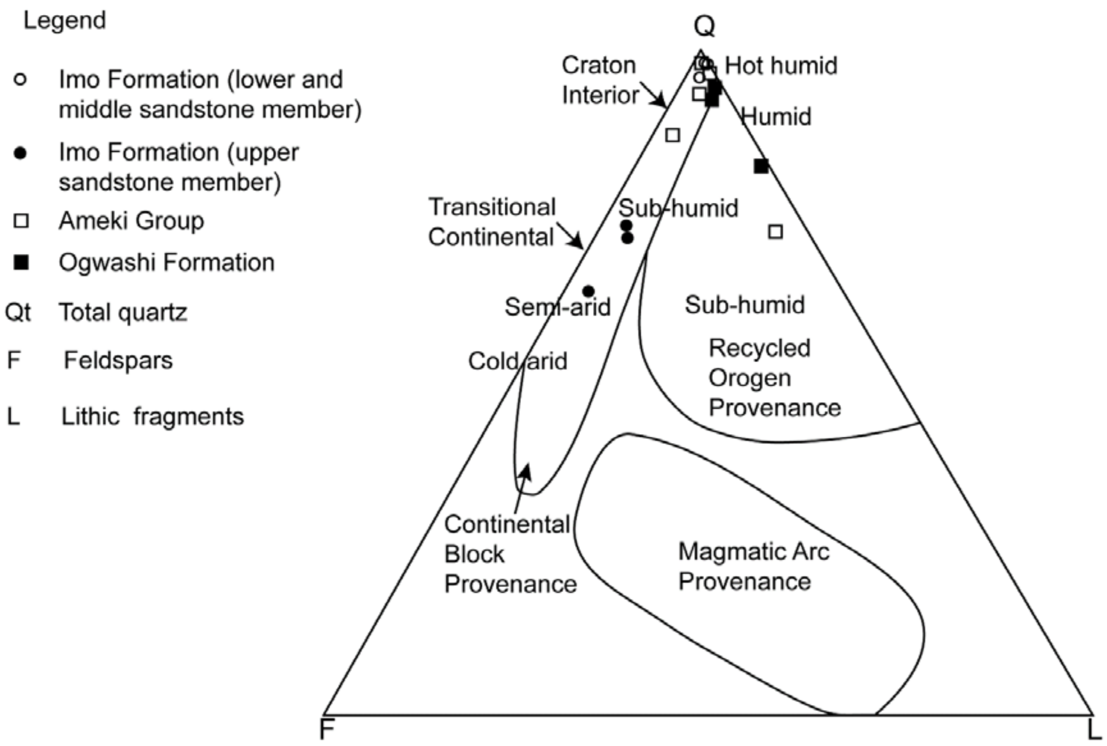


Figure 8.16. Interpretation climatic conditions from QFL ternary diagram for the Paleogene sandstones in the south-eastern Nigeria (based on Suttner and Dutta, 1986).

Table 8.7. Average detrital compositional (QFL) and (QmFLt) mode (in percentage) from the Paleogene strata in the study area.

	Recalculated QFL compositional modes						Bivariant logs/log plot values	
Group / Formation	Q%	F%	L%	Qm%	F%	Lt%	Qp/F+R	Qp+Qm/F+R
Lower Sandstone Member of Imo Fm	97.15	0.65	2.2	68.3	0.65	31.05	28.85/31.7 = 0.910	97.15/31.7 = 3.064
Middle Sandstone Member of Imo Fm	97.29	0.65	2	56.9	0.65	42.4	40.4/43.05 = 0.938	97.3/43.05 = 2.260
Upper Sandstone Member of Imo Fm	68.53	27.3	4.13	60.2	27.3	12.43	8.3/39.73 = 0.209	68.5/39.73 = 1.724
Ameki Group (FA1)	94.72	1.1	1.93	46.58	1.1	52.27	48.24/53.37 = 0.904	94.82/53.37 = 1.777
Ameki Group (FA3)	79	7.15	13.75	48.6	7.15	44.15	30.4/51.3 = 0.593	79/53.37 = 1.480
Ameki Group (FA6)	100	0	0	58	0	42	42/42 = 1	100/42 = 2.381
Ogwashi Formation (FA1)	82.2	0	17.8	69.3	0	30.7	12.9/30.7 = 0.420	82.2/30.7 = 2.678
Ogwashi Formation (FA2)	94.55	0	5.48	38	0	61.98	56.5/61.98 = 0.912	94.5/61.98 = 1.525

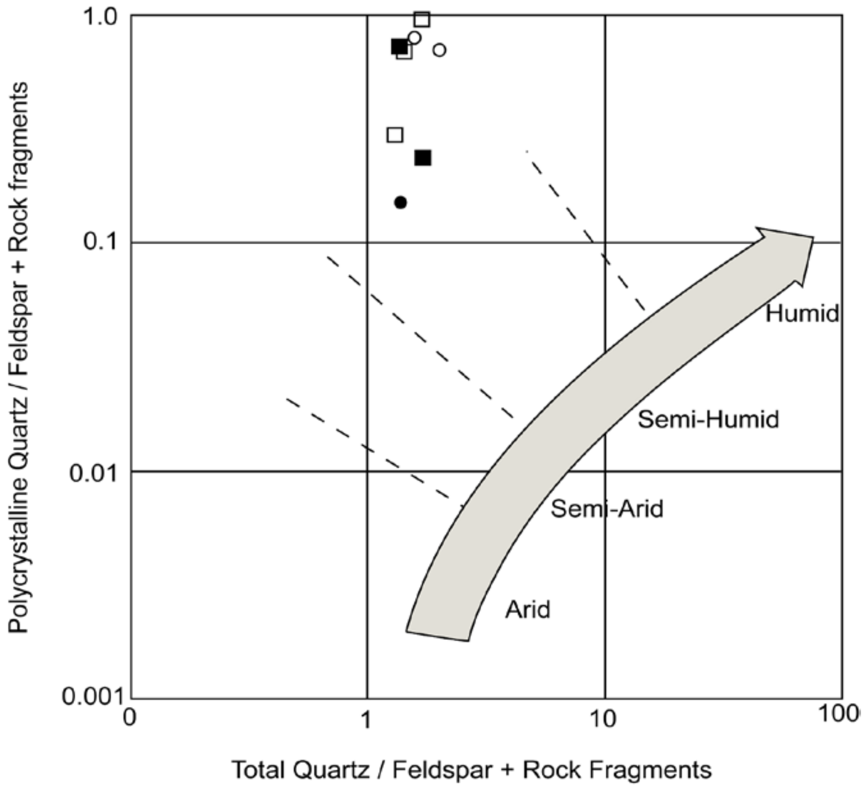
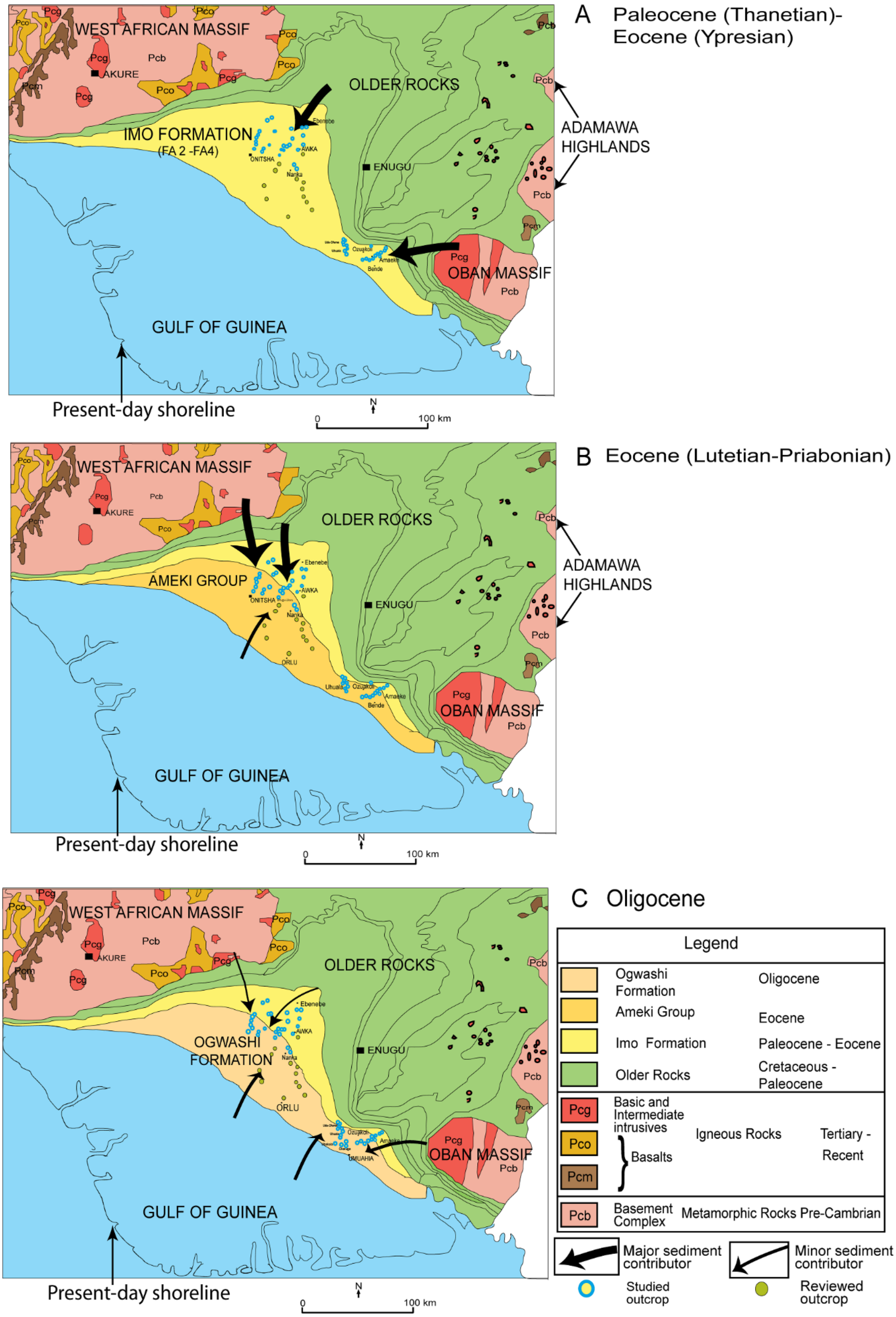


Figure 8.17. Bivariant log/log plot of the ratio of polycrystalline quartz to feldspar plus rock fragments against the ratio of total quartz to feldspar plus rock fragments in the sandstones of the Imo, Ameki and Ogwashi formations. Inferences regarding paleoclimate are indicated by the arrow (based on Suttner and Dutta, 1986).

Other petrographic and sedimentologic features are further integrated to determine the likely source areas for the Paleogene strata. The paleocurrent trends for fluvial rocks from the Nsugbe Formation of the Ameki Group show dominant south-west directions (chapter 5: section 5.3.1) which suggest source areas to north-east. The sandstone composition of the Paleogene sedimentary rocks is employed as additional information in reconstructing the source areas of the sediments. Detrital quartz grains in the Paleogene sediments were likely derived from igneous and metamorphic rocks based on the presence of plutonic rocks that are characterised by monocrystalline and polycrystalline (< 3 crystals per grain) quartz grains with healed fractures, single to slight undulose extinction, inclusions and microlites (Basu et al., 1975; Folk, 1980; Smyth et al., 2008). The occurrence of metamorphic rock is noted with the abundance of polycrystalline quartz grains (>4 crystals per grain) with elongate and stretched quartz, undulose extinction, smooth, crenulated or sutured crystal boundaries (Basu, et al., 1975; Folk, 1980; Ghazi and Mountney, 2011; Smyth, et al., 2008). Vacuoles and microlites also occur in the grains. Subrounded to rounded quartz grains in the Paleogene strata, particularly in the Nsugbe Sandstone are associated with recycled sedimentary source. Potassium feldspar (k-feldspar) is interpreted to be from mostly igneous or metamorphic rocks (gneisses) (Ghazi and Mountney, 2011; Trevena and Nash, 1981) while plagioclase feldspar is derived from igneous rocks or low-grade metamorphic rocks (Ghazi and Mountney, 2011). K-feldspar is most common in the upper Sandstone Member of the Imo Formation than other strata in the study area. The paucity of feldspar in the study area may be due to the instability of the feldspar mineral (Helmold, 1985) and/or possibly the low feldspar content from parent rock. The Cretaceous sedimentary rocks of the Anambra and Afikpo basins are the most probably recycled sedimentary source and sediments of these basins have been interpreted as quartz arenites of second sedimentary cycle (Hoque, 1977).

Heavy minerals analysis suggests that a mixed provenance probably supplied detritus to the Paleogene Niger Delta sedimentary basin. The sources are probably of regional metamorphic rocks, igneous or plutonic rocks and recycled sedimentary rocks. The high resolution heavy minerals (HRHM) such as zircon, tourmaline and apatite have high proportion of rounded and euhedral-subhedral crystals, which are indicative of recycled sedimentary rocks and igneous or plutonic rocks respectively. High-grade metamorphic minerals such as kyanite, sillimanite and andalusite and medium-grade metamorphic suites such as epidote group, garnet, sphene, staurolite, and hornblende are strong indicators of a metamorphic origin.

Integration of petrographic, sedimentology and heavy mineral analysis suggests that sediments of the lower and probably the middle Sandstone Members of the Imo Formation are derived primary from recycled sedimentary rocks with some contribution probably from the Oban massif. The sandstone grains are mostly rounded to subrounded and are classified as quartz arenites. Paleocurrent interpretation further suggested a southeast source which most probably infers recycled sedimentary rocks from Anambra and Afikpo basins and the Oban massif. The upper Sandstone Member of the Imo Formation is predominant in the southern part of the Imo Formation and it classified as (sub-)arkose to arkosic arenite. The occurrence of garnet, epidote, and kyanite points to medium-grade metamorphic rock. Quartz grains are mainly subrounded to subangular and the HRHM such as zircon, tourmaline and apatite exhibit more prismatic, euhedral and subrounded grains. These characteristics show that sediments of the upper Sandstone Member of the Imo Formation are mostly derived from the Oban massif. The fluvial deposits in the Ameki Group show a northeast (or northward) source. Estuarine deposits show paleocurrent directions in both southward and northward directions due to the influence of tides. The sandstone classification varies from quartz arenite to sub-arkose and sub-litharenite (or lithicarenite). The heavy minerals present in the Ameki Group are considered to reflect a combination of igneous and metamorphic rocks. These suggest mixed sources for sediments of the Ameki Group to include recycled sedimentary rocks and the Western Nigerian Massif, as well as oceanic input. Variation in the paleocurrent trends (north-west and south-west directions for Uhuala sandstones and north-east direction for Ogbunike quarry sandstones) of the Ogwashi sandstones (chapter 6: section 6.3.1) is due to tidal influence during sedimentation. The sandstones are classified as quartz arenite and sub-litharenite. The quartz grains are commonly subrounded to subangular in shape and the HRHM are commonly euhedral-subhedral and subrounded-rounded crystals. A mixed source of recycled sedimentary rock, Oban / Western Nigerian massifs and probably oceanic input is proposed for the Ogwashi Formation.



A Paleocene (Thanetian)-Eocene (Ypresian)
WEST AFRICAN MASSIF
AKURE
OLDER ROCKS
IMO FORMATION
(FA 2 -FA4)
ONITSHA
AWKA
ENUGU
ADAMAWA HIGHLANDS
OBAN MASSIF
GULF OF GUINEA
Present-day shoreline
0
100 km
N
B Eocene (Lutetian-Priabonian)
AMEKI GROUP
ORLU
C Oligocene
OGWASHI FORMATION
UMUAHIA
Legend
Ogwashi Formation
Oligocene
Ameki Group
Eocene
Imo Formation
Paleocene - Eocene
Older Rocks
Cretaceous - Paleocene
Pcg
Basic and Intermediate intrusives
Pco
Pcm
Basalts
Igneous Rocks
Tertiary - Recent
Pcb
Basement Complex
Metamorphic Rocks Pre-Cambrian
Major sediment contributor
Minor sediment contributor
Studied outcrop
Reviewed outcrop

Figure 8.18. Source areas for the Paleogene sediments, south-eastern Nigeria suggest mixed provenance. A. The source areas for the Imo Formation are dominantly recycled older sedimentary rocks and the Oban Massif. B. The provenances for the Ameki Group are mainly West African Massif and pre-existing sedimentary rocks. C. Mixed source areas namely the Oban Massif, recycled older sedimentary rocks and the West African Massif are likely sediment contributors to the Ogwashi Formation.

8.5 CONCLUSIONS

Petrographically, the sandstone classification of the Paleogene strata in south-eastern Nigeria varies from quartz arenite to arkosic arenite, (sub-) arkose and (sub-) litharenite. Modal sandstone composition for the Paleogene sediments consists of rounded to subangular grains, monocrystalline and polycrystalline quartz grains, potassium and plagioclase feldspars and mainly sedimentary rock fragments. The sandstone composition suggests a mixed provenance of metamorphic, plutonic and re-cycled sedimentary sources for the Paleogene strata. Likewise, the QtFL and the QmFLt ternary diagrams suggest that the Paleogene sediments may be derived from mixed provenances which are the cratonic interiors, transitional continental blocks and recycled orogen (based on the Dickinson, 1985) or transitional continental, transitional recycled and quartzose recycled (based on the Dickinson, 1985). The QFL also suggests semi-humid to humid climatic conditions for the Paleogene sediments using the model proposed by Suttner and Dutta (1986). Similarly, the bivariant log/log plot of the ratio of polycrystalline quartz to feldspar plus rock fragments against the ratio of total quartz to feldspar plus rock fragments supports the interpretation of semi-humid to humid climate for the Paleogene sandstones.

Possible factors controlling the distribution of the heavy mineral suites in the Paleogene sediments of the study area are river influx, tide and wave actions as well as hydraulic sorting. Provenance is also an important factor that affected the proportion and availability of certain heavy mineral suites in the study area (such as garnet, epidotes, sphene and monazite).

Subsequently, heavy mineral analysis confirms the possibility of mixed provenance for the Paleogene sediments. The heavy mineral distribution obtained in the Paleogene Niger Delta consists of high resolution heavy minerals (HRHM) such as zircon, tourmaline and apatite, that suggest a plutonic or igneous source; high-grade metamorphic minerals such as kyanite, sillimanite and andalusite and medium-grade metamorphic suites such as epidote group, garnet, sphene, staurolite, as well as pyroxene which indicates an igneous source. The characteristics of these heavy mineral suites suggest that sediments were derived from erosion of different source areas (Figure 8.18) such as the Oban Massif to the south-east, the Western African Massif to the west and north-west and the recycled sedimentary rocks to the north.

CHAPTER NINE

DISCUSSION

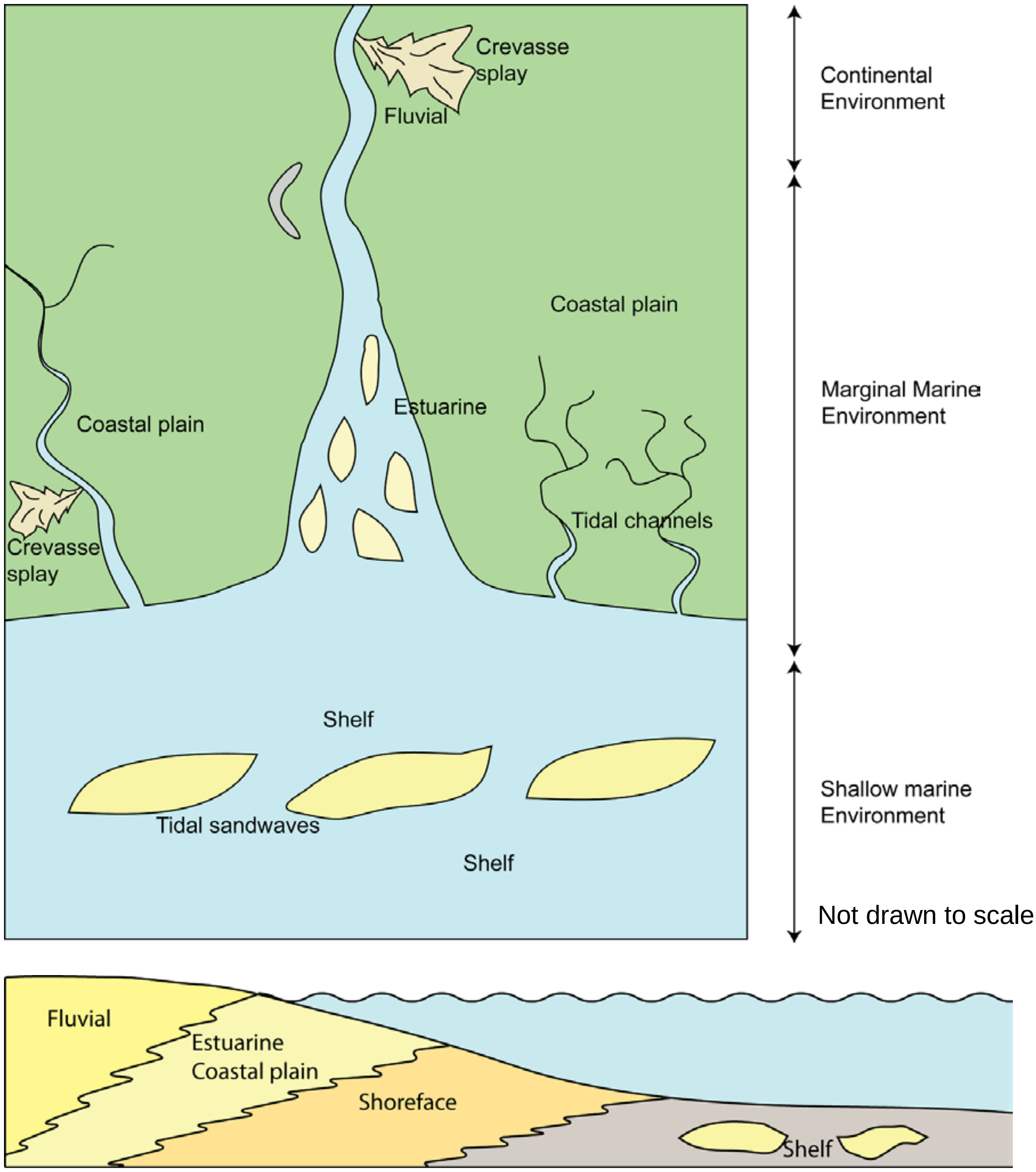
9.1 INTRODUCTION

The Paleogene sedimentary successions in the south-eastern Nigeria consist of the tidally influenced shallow marine complex of the Paleocene-Eocene Imo Formation, the tide dominated estuarine system of the Eocene Ameki Group and the tidally influenced coastal plain deposit of the Oligocene Ogwashi Formation (Figure 9.1). One of the purposes of this research is to identify the reservoir characteristics of the sand bodies in the Paleogene strata and to document the effect of clastic shorelines on depositional processes during the Paleogene. The Paleogene outcrops include sandstone units that posses good reservoir qualities and there is need to highlight these qualities as they act as analogues to the subsurface petroliferous Niger Delta. The outcome of the research also aims to reconstruct the paleogeographic evolution of the Paleogene sedimentary succession and to establish the sequence stratigraphic framework of the Paleogene strata.

9.2 RESERVOIR HETEROGENEITY OF THE PALAEOGENE STRATA

9.2.1 Introduction

The Paleogene depositional system in south-eastern Nigeria offers an opportunity to study analogue sandstone reservoirs and mudstones/shales that act as stratigraphic seals or/and traps. The stratigraphic succession which includes the Imo Formation, Ameki Group and Ogwashi Formation are referred to as outcropping Niger Delta and are the up-dip equivalent of the subsurface petroliferous Niger Delta. Field and petrographic studies on selected Paleogene reservoir analogues illustrate the complexity of the reservoir architectures and the complexities within the reservoirs. The reservoir architectural studies, lithofacies and petrology data are integrated to provide an analysis of the reservoir potential of the Paleogene sedimentary rock of the South eastern Nigeria.



Not drawn to scale

Figure 9.1. Conceptual model of the various depositional environments that dominated the Niger delta Basin (surface outcrop) during the Paleogene.

The reservoir heterogeneity of the Paleogene reservoirs is discussed based on three heterogeneity scales employed wholly or partly by Buatois et al., (1999), Galloway and Hobday (1996), Sharp et al., (2003) and Taylor and Ritts (2004); namely macroscopic, mesoscopic and microscopic heterogeneity. The macroscopic scale of heterogeneity reflects lateral and vertical variations in depositional or sedimentary facies that would affect the sandstone (reservoir) and the non-reservoir geometries. The main features in the macroscopic heterogeneity are compartmentalization, permeability distribution and stratification. The mesoscopic heterogeneity reflects lithofacies, bedding and lamina-scale variation. It includes the vertical and lateral arrangement of lithofacies units that would affect fluid flow and production efficiency in the system. The microscopic heterogeneity is expressed at the scale of individual grains and pores; this is based on petrographic and other laboratory studies such as porosity and permeability measurements.

Bioturbation is known to have an impact on reservoir quality of sedimentary rocks where it occurs. Research has shown that bioturbators in recent sediments such as earthworms, beetles, polychaetes, decapods crustaceans, bivalves, amphipods and other organisms alike, have contributed to sediment improvement and effective nutrient cycling, whereby enhancing the porosity and permeability of the sediment (Capoweiz et al., 1998; 2009; Lee and Foster, 1991; Nichols et al., 2008; Budd, 2004). Trace-fossil activity (bioturbation) in ancient sedimentary rocks has been studied and demonstrated to have either enhanced (Egbu et al., 2009; Cunningham et al., 2009; Gingras, 2004; Gingras et al., 1999; 2007; Lemiski et al., 2011; Pemberton and Gingras, 2005; Tonkin et al., 2010) or diminished (Pemberton and Gingras, 2005; Tonkin et al., 2010) reservoir quality depending on burrow type and the behaviour of the trace-maker.

9.2.2 Reservoir sand bodies of the Imo Formation

The major reservoir unit in the Imo Formation is the offshore tidal sand wave deposit, which is encased by thick offshore mudstone and shale (see chapter 4). Other reservoir units associated with the Imo Formation are shoreface deposits and the foreshore deposits. The tidal sand wave deposits are very thick continuous sand bodies with a thickness of more than 25 m and have tabular to lens-shaped geometries (Figure 4.3) with good lateral continuity and low vertical compartmentalization, representing a good quality reservoir. Petrographically, the sandstones in the Imo Formation are well to poorly sorted, with low amounts of matrix clays, texturally and compositionally mature (quartz-rich sands) and are poorly consolidated. Mesoscopic heterogeneities observed are bounding surfaces (which are limited to minor cut and fill structures) and low occurrence of mud chips, which may not necessarily act as flow baffles or reduce vertical transmissibility in the reservoir. Bioturbation is very low in the tidal sand wave deposits; it may not have any influence or affect the reservoir quality of the sandstone bodies. The tidal sand wave deposits therefore exhibit excellent reservoir potential for hydrocarbon production. The sandstone bodies are encased by offshore mudstone and shale (Chapter 4: Figure 4.3) providing an excellent seal for the reservoir.

The shoreface sand bodies possess good reservoir qualities for hydrocarbon recovery. The shoreface sandstone body is enclosed by mudstones: shelf mudstone/shale occurs below whereas lagoonal mudstone occurs above the sand body, forming a reasonable stratigraphic seal (Chapter 4: Figures 4.3; 4.11). The sandstone is fine to medium grained, well sorted, but contains mud flasers, wavy and lenticular bedding at the lower horizon and thin mud layers at the top horizon (Chapter 4: Figure 4.12). The presence of mud can affect actual vertical permeability within the sandstone reservoir as they act as baffles or barriers. Bioturbation in the shoreface sandstones is moderate to intense, burrows are mostly sand-filled (Chapter 4: Figure 4.14), although mud-filled burrows were observed. Gingras et al., (1999) demonstrated that sand-filled burrows can enhance permeability in impermeable substrate with *Glossifungites* on the surface. This suggests that the sand-filled burrows in the shoreface sandstone may enhance permeability.

9.2.3 Reservoir quality of the Ameki Group sandstone bodies.

The reservoir quality varies considerably across the depositional facies in the Ameki Group sandstone bodies. The reservoirs are divided into zones or potential flow units (Figure 9.2), each may represent varying depositional environment such as fluvial channel deposits (zone 1), tidally influenced fluvial channel deposits (zone 2), tidal channel deposits (zone 3), sandflats deposits (zone 4), inner estuarine tidal sand bar units (zone 5) and outer estuarine tidal sand bar units (zone 6). The fluvial-estuarine reservoir sand bodies are capped by the estuarine embayment mudstone/shale deposits which act as a stratigraphic seal.

Zone 1 represents the fluvial channel deposits that are characterised by multistorey channel geometry, amalgamated and cross-stratified with a fining upward profile (Chapter 5: Figures 5.2; 5.4) The sandstone bodies are poorly sorted, very coarse to fine grained sandstone, some grade upwards into very fine grained sands that represent internal heterogeneity which could affect fluid flow in an actual reservoir. Zone 1 is partitioned into three permeability zones (Figure 9.2A) based on the mesoscopic heterogeneity (lithofacies and sedimentary structures). Zone 1A coincides with the poorly sorted basal lag of conglomerate and mud clasts. Zone 1B represents the very coarse to fine grained, trough and planar cross-bedded sandstone. Zone 1C consists of fine to very fine grained rippled and parallel laminated sandstone. The sandstone bodies (at Ukwu-Nnadi quarry, Nsugbe) have good vertical and lateral connectivity, as the amalgamated channels can produces vertically continuous sandstone packages with thickness of up to 25 m. Petrologically, the grains are commonly rounded to subrounded and contain little matrix clay. The sandstone is originally poorly consolidated, but due to oxidation, consolidated ferruginised sandstones occur.

Zone 2 is the tidally influenced fluvial channel facies that is characterised by well sorted, fine to medium grained sandstone and sandy heterolithic units as observed at the Ugwu-Nnadi heterolithic section in Nsugbe (chapter 5: section 5.3.1). The basal part of the point bar is strongly bioturbated, with both vertical and horizontal burrows. Some vertical burrows are mud-filled and some inclined to horizontal such as *Rhizocorallium* and *Taenidium* have spreiten or back-filled meniscate. Mud breccia lags as well as mud flasers and discontinuous mud laminae occur. The upper part of the point bar is heterolithic, it consist of rippled, mud, sand and silt laminae. The channels are truncated laterally by thick mud plugs of abandoned channels (Figure 9.2B) which results in poor lateral continuity, connectivity and high lateral compartmentalization.

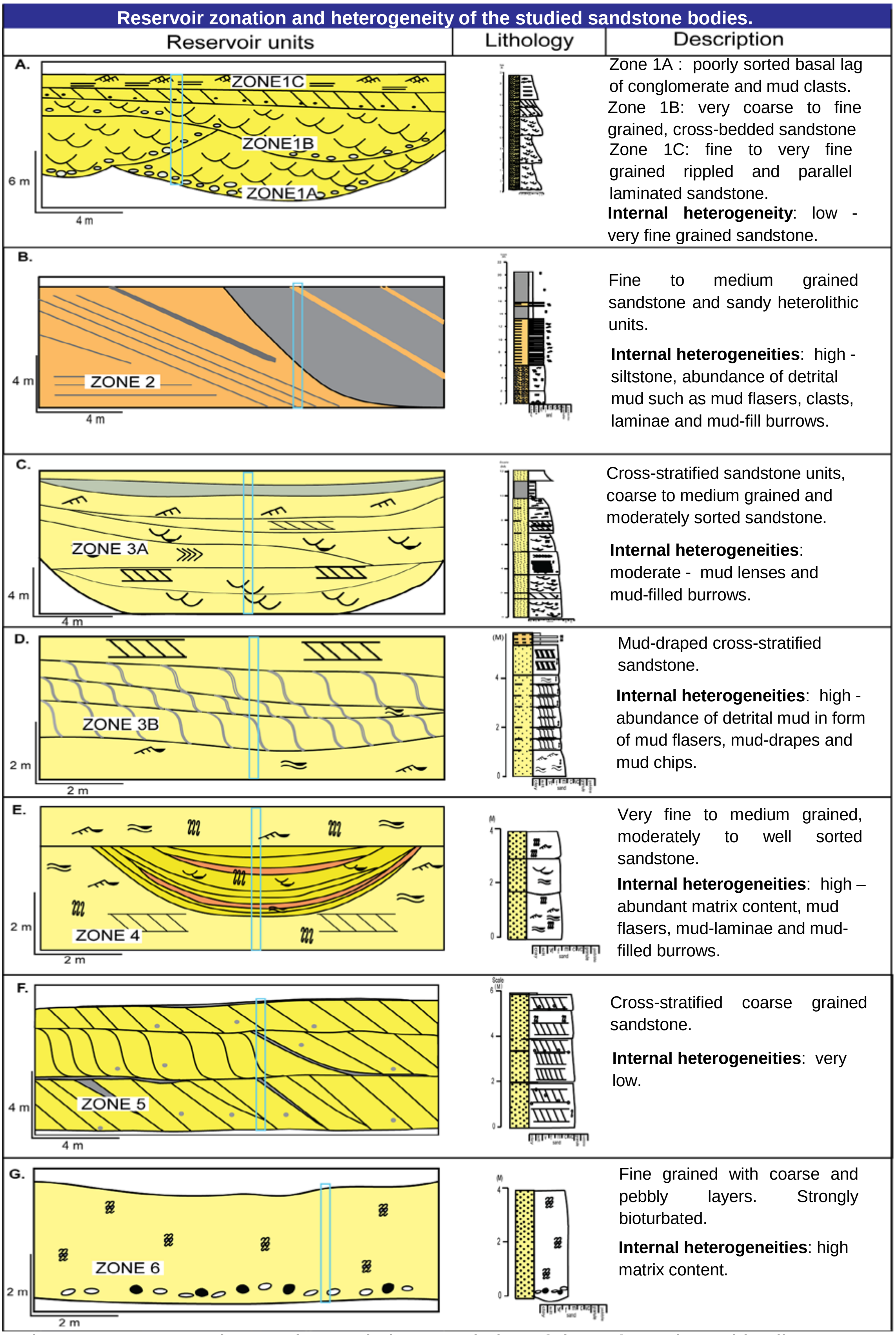


Figure 9.2. Reservoir zonation and characteristics of the selected sand bodies.

The abundance of detrital mud in form of flasers, clasts, laminae mud-fill burrows and the fine grained sandstone to siltstone will reduce the porosity and create permeability barriers within the reservoir. Activities of deposit-feeders that back-fill their burrows disperse clay sediment throughout the matrix can reduce porosity and permeability (Buatois et al., 1999).

Zone 3 represents the deposits of the subtidal zone of tidal channels. A typical example is the deposit of the Nibo section (Chapter 5: section 5.3.1). The sandstone is moderately to well sorted and varies from coarse to fine grained. This unit may be low to moderately burrowed with both horizontal and vertical burrows. Burrows may be mud-filled or with back-fill meniscate often created by deposit feeders such as *Planolites, Beaconites*, *Thalassinoides* or open structures produced by suspension-feeders and passive carnivores such as *Ophiomorpha nodosa*. Although, the deposit feeders that backfill their burrows may damage pore connectivity (Buatois et al., 1999; Gingras et al., 1999; 2004; Pemberton and Gingras, 2005), Lemiski et al., (2011) demonstrated that the open-structure burrows produced by suspension-feeders or sand-fill burrows can enhance reservoir permeability and vertical transmissivity as they act as conduits for fluid migration. Some of the tidal channels (Nibo and Awka sections) are capped by lens- or lenticular- shaped mud flat deposits that act as seals.

The tidal channels deposits can be zoned into two permeability zones based on the mesoscopic heterogeneity (lithofacies and sedimentary structures). Zone A comprises cross-stratified sandstone units with mud lenses, horizontal and vertical burrows and with little or no mud drapes. The sands are dominantly coarse to medium grained and moderately sorted (Nibo section: chapter 5, section 5.3.1). The mud lenses and mud-filled burrows act as baffles that can restrict fluid flow. However the presence of sand-filled burrows can enhance vertical connectivity in unit. The subtidal unit is channel or sheet-like shaped and with fairly good lateral continuity, moderate vertical compartmentalization and high continuity with other sandstone-rich lithofacies. The channel deposits can be overlain by lens- or lenticular shaped muddy mud flat deposits that acts as seal.

Zone B consists of cross-stratified sandstone with mud-drapes, mud-draped sigmoidal cross-beds, mud-draped reactivation surfaces and mud chips. Bounding surfaces are sharp and may be mud draped. The high occurrence of mud drapes certainly will reduce permeability (mesoscopic scale of heterogeneity) as they act as local barriers to fluid migration. The porosity may also be reduced due to the high clay content in the matrix, which makes the sand clayey. Petrographically, the sandstone has high clay and shale lithic fragment. This subtidal unit is usually characterised by sheet-like or tabular geometry (as observed in Umunya section: chapter 5, section 5.3.1). The reservoir properties include good lateral continuity of the sandstone units, high vertical compartmentalization, and poor connectivity with other lithofacies.

Zone 4 represents the sand flat zone of the tidal flat environment; this is the sandy part of the tidal flat (Umunya section: chapter 5, section 5.3.1). The sandstone is very fine to medium grained, moderately to well sorted, rippled, with discontinuous mud laminae, mud flasers and high matrix content. Scour and fill channels, interpreted as tidal creeks occur cross the sand flat. The sand flat deposits are moderately to strongly burrowed, with dominantly horizontal to inclined burrows such as *Ophiomorpha, Protovirgularia, Planolites*; vertical spreiten burrows such as *Teichichnus rectus* occur. The burrows are mostly mud lined and/or mud filled (Chapter 7: Figure 7.4I). These mud filled burrows as well as the mud flasers, lamina can act as baffles and can reduce permeability in the sand body (Buatois et al., 1999; Tonkin et al., 2010).

Zone 5 comprises the outer estuarine tidal sand bar units which are typified by 25 m thick cross-stratified coarse grained sandstone with sheet-like geometry (Ishiagu and Awka cross-stone sections: chapter 5, section 5.3.1). Individual bars of 50cm to 3m stack up laterally and vertical to form amalgamated sandstone bodies. The sandstone is moderately sorted and poorly consolidated. The presence of sand-filled low-diversity *Skolithos* ichnofacies indicates good connectivity across the sand units. The tidal bar deposits consist of nearly 100% sand with little or no mud drapes; the sands are devoid of depositional matrix because strong tidal traction process winnowed the fines (Shanmugam et al., 2000). Vertical compartmentalization is low and lateral continuity is variable. The reservoir characteristics of the tidal sand bars in the study area are similar to the tidal sand bars in the tide dominated estuary of the Hollin and Napo formations, Oriente Basin, Ecuador, which Shanmugam et al., (2000) considered as having excellent reservoir properties.

Zone 6 is the strongly bioturbated inner estuarine tidal sand bar. The sandstone is fine grained with coarse and pebbly layers that are interpreted as transgressive lag deposits. The sandstone has a high matrix content and it is homogenous due to intense bioturbation, typical of tidal bars (Wood, 2004). Permeability may be enhanced in the bioturbated sandstone due to connectivity of dominantly *Ophiomorpha* burrows and the open-structure and sand-filled burrows observed in the sandstone unit. Such biogenically enhanced permeability is classified by Pemberton and Gingras (2005) as nonconstrained textural heterogeneities, whereby sediment-filled burrows are encased in low-permeability substrate and are common in estuarine and shelf environments.

9.2.4 Reservoir quality of the sand bodies of the Ogwashi Formation.

The sandstone units of Ogwashi Formation in the study area are limited to the fluvio-estuarine and tidal channel deposits (chapter 6: section 6.3.1). The sandstone bodies of the fluvio-estuarine deposits at the Enugwu-Ukwu, Okaiuga at Umuahia occur as isolated channel and multistorey channels. The sandstone consists of matrix supported conglomerate and very coarse to medium grained sandstone. The sandstones are bioturbated, poorly sorted and contain mud clasts, thick mud lens and carbonaceous matter. Petrographically, the sandstones (Okaiuga Section) are classified as sub-litharenites (chapter 8; section 8.3.1). Bioturbation varies from low to intense, with open-structure vertical *Ophiomorpha nodosa* dominating, horizontal tunnels and cross-cutting structures are conspicuous and there are other mud-filled burrows such as *Planolites*. The high proportion of mud-baffles would restrict flow in the reservoir.

Deposits of the fluvio-estuarine and tidal flat environments observed at Ogbunike Quarry are subdivided into reservoir potential flow or permeable units namely - zones A, B and C (Figure 9.3). Zone A includes medium to coarse grained, well to moderately sorted sandstone units. Low occurrence of mud drapes foresets was observed. Bioturbation is low to moderate, dominated by vertical sand-fill burrows such as *Skolithos* isp (Chapter 7: Figure 7.4A). Other associated burrows in very low density are *Lockeia, Rosselia, Ophiomorpha, Paleophycus* and *Planolites.*

Zone B comprises strongly bioturbated sandstone units characterised by dominantly open-structure boxwork of *Ophiomorpha nodosa*, other associated trace-fossils suites are *Skolithos, Cylindrichnus, Rosselia, Conichnus, Arenicolites, Paleophycus and Planolites*. The burrows are mainly sand-fill burrows and open-structures were observed in the *Ophiomorpha nodosa* (Chapter 7: Figures 7.4D and E).

Zone C is a sandy heterolithic deposit that consists of rippled mud laminae. It is moderately burrowed and dominant burrows are *Lingulichnus* isp. (Chapter 7: Figure 7.3). Other commonly occurring burrows include *Paleophycus, Skolithos* and *Thalassinoides*.

The fluvio-estuarine deposit consists of stronger marine influence with the presence of *Skolithos* to *Cruziana* ichnofossils. The deposit represents mouth-bar sands in a coastal plain environment. The burrows found in zones A and B can enhance reservoir permeability as they act as conduits for fluid migration (Buatois et al., 1999; Gingras et al., 1999). Zones A and B also have less clay matrix that can cause mesoscopic heterogeneity making the zones good reservoirs compared to zone C (Figure 9.3). The coastal plain mud-filled channels and floodplains of the Ogwashi Formation could act as seals.

Tidal channel deposits at Okaiuga section, consist of a unidirectional cross-stratified pebbly to medium grained sandstone. The sand bodies show channelized to sheet-like geometry. Mud lens, mud band and mud drapes on foresets occur. Bioturbation is generally sparse, but abundant at the upper horizon of the sheet-like geometry sand body. Although the tidal channel-fill contains good quality reservoir sands, however, the presence of mud lens and mud bands concentrated at or towards the bounding surface, may result to moderate or high reservoir compartmentalization, while the mud drapes on foresets may act as local barriers for fluid migration.

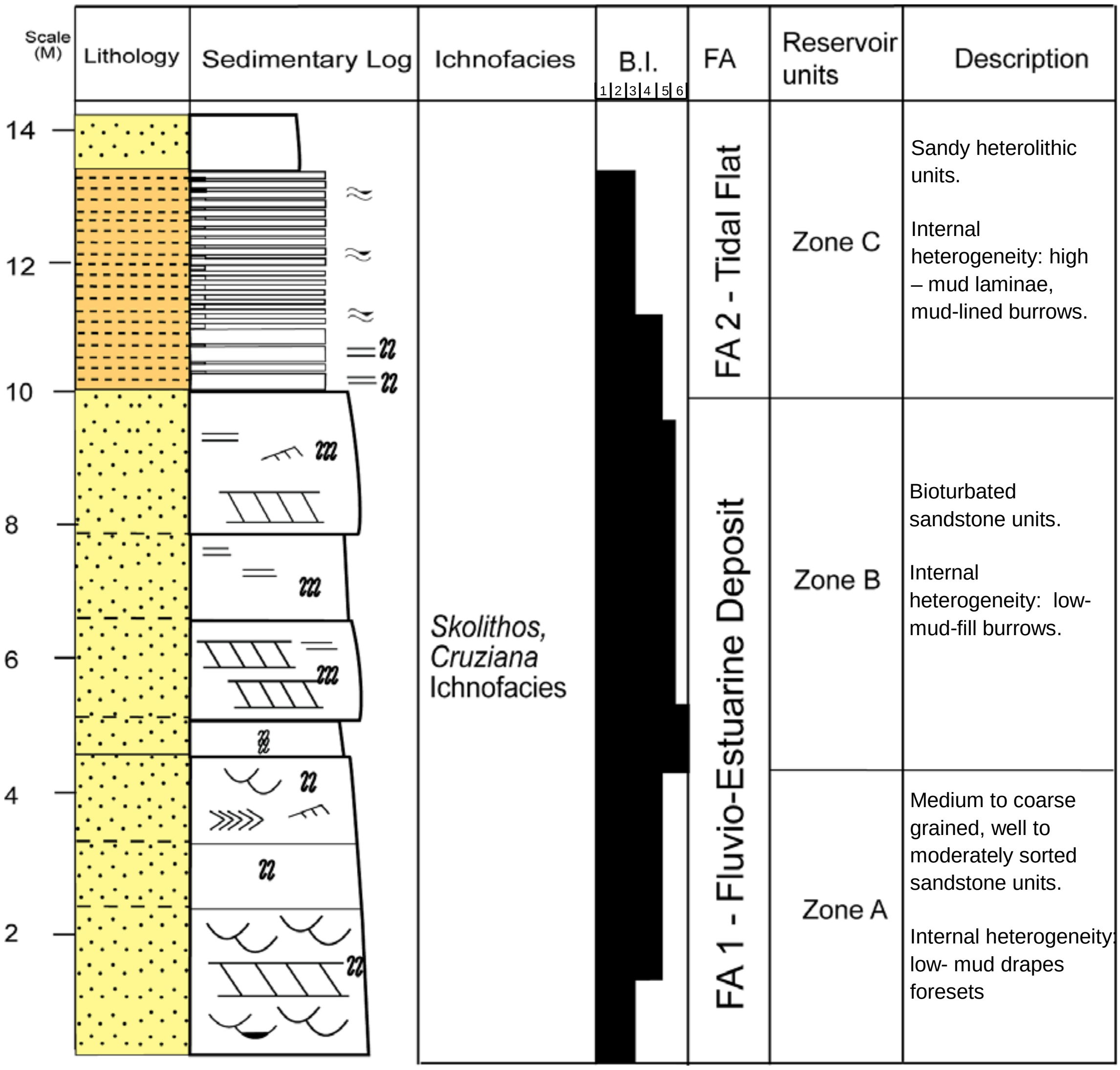


Figure 9.3. Reservoir zonation and characteristics of the sand bodies interpreted as fluvio-estuarine (zones A and B) and tidal flat (zone C) deposits (Ogbunike Quarry Section). Based on Sharp et al, 2003.

9.3 EFFECT OF CLASTIC SHORELINES ON DEPOSITIONAL PROCESSES DURING THE PALEOGENE

9.3.1 Introduction

Interpretation of the lithofacies and facies assemblages of the Paleogene strata in the south-eastern Nigeria have shown that the depositional environments of these strata are dominated or influenced by tide processes (chapters 4, 5 and 6). Another approach – a process-based classification scheme developed by Ainsworth et al., (2008, 2011) for the prediction of coastal or shoreline processes is utilised in this research. This approach have not been documented in any published article for the Paleogene strata in south-eastern Nigeria. The scheme allows for semiquantitative classification of clastic depositional systems and provides models for predicting the effect of coastal morphology, accommodation, sediment supply and shelf width on depositional processes through time and space (Ainsworth et al., 2011). Studies (Howell et al., 2008, Ainsworth et al., 2011) have shown that depositional processes operating along a shoreline control the geometry, reservoir properties and architecture of sand bodies and heterogeneities. This means that the classification scheme provides framework that will enhance prediction of depositional environments, geometries as well as reservoir properties and thus, reduce their uncertainties (Ainsworth, et al., 2011).

9.3.2 Coastal Process Classification for the Paleogene strata, SE Nigeria.

Introduction

Models employed by Ainsworth et al., (2011) is used in the study area to predict the probable dominant and subordinate processes acting at the shoreline during the Paleogene. These models use the process classification which analyses the combination of the depositional processes – fluvial, tide and wave (Figure 9.4A). This classification separates marginal marine systems into fifteen process categories (W, Wt, Wf, Wtf, Wft, T, Tw, Tf, Twf, Tfw, F, Fw, Ft, Fwt, Ftw), where ‘w’, ‘t’, and ‘f’ stand for ‘wave’, ‘tide’ and ‘fluvial’, respectively (Figure 9.4B).

Interpretation

Sedimentary structures generated from the sedimentary succession of the Imo Formation is estimated to be 69% for tide-dominated elements, 29% for wave-dominated elements and 2% for river-dominated elements (Chapter 4; Figure 4.3). On the classification scheme in Figure 9.4B, the succession is plotted and classified as a tide-dominated, wave-influenced, fluvial-affected system (Tw*f*). Sedimentary structures for the Ameki Group depositional system is estimated to be 85% for tide-dominated elements, 12% for river-dominated elements, and 3% for wave-dominated elements (Chapter 5; Figure 5.2). This is plotted on the ternary plot and classified as a tide-dominated, fluvial-influenced, wave-affected systems (Tf*w*) (Figure 9.4B). Likewise, the representative sedimentary structures from the depositional system of the Ogwashi Formation is calculated as 68% for tide-dominated elements, 30% for river-dominated elements, 2% for wave-dominated elements (Chapter 6; Figure 6.16) and thus, classified as a tide-dominated, fluvial-influenced, wave-affected systems (Tf*w*) (Figure 9.4B). This predictive classification suggests the dominance of tidal process for the Paleogene Niger Delta sedimentary succession, while the wave and fluvial processes are subordinate.

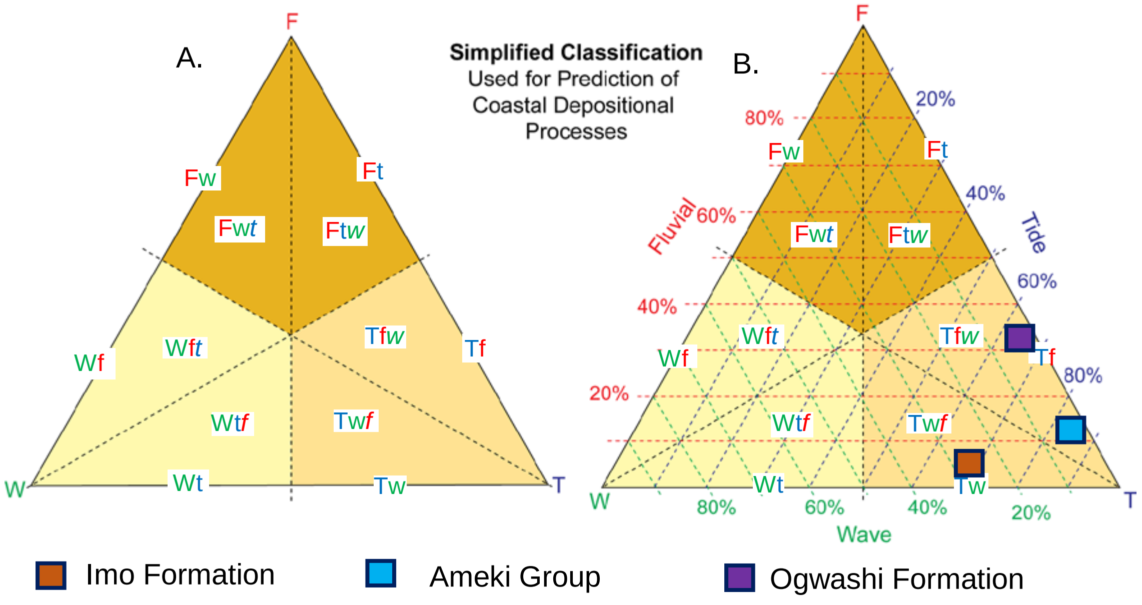


Figure 9.4. Coastal process classification ternary plots (redrawn and modified from Ainsworth et al., 2011). Depositional environments of the Imo Formation is classified as tide-dominated, wave-influenced, fluvial-affected system, whereas those of Ameki Group and Ogwashi Formation are classified as tide-dominated, fluvial-influenced, wave-affected systems. The bottom side of the triangles represents classification of non-fluvial shorelines. All other portions of the plots represent some degree of fluvial influence. F = fluvial-dominated; W = wave-dominated; T = tide-dominated; Fw = fluvial-dominated, wave-influenced; Ft = fluvial-dominated, tide-influenced; Tf = tide-dominated, fluvial-influenced; Tw = tide-dominated, wave-influenced; Wt = wave-dominated, tide-influenced; Wf = wave-dominated, fluvial-influenced; Fwt = fluvial-dominated, wave-influenced, tide-affected; Ftw = fluvial-dominated, tide-influenced, wave-affected; Tfw = tide-dominated, fluvial-influenced, wave-affected; Twf = tide-dominated, wave-influenced, fluvial-affected; Wtf = wave-dominated, tide-influenced, fluvial-affected; Wft = wave-dominated, fluvial-influenced, tide-affected.

9.3.3 Effect of Coastal Morphology on Depositional Processes

Coastal morphology or the shape of the shoreline is known to affect depositional processes acting at the shoreline (Ainsworth et al., 2008; 2011). Highly embayed or funnel-shaped coastal morphologies amplify tidal currents by constriction of the tidal waves, whereas straight to lobate shorelines are open to wave processes (Ainsworth et al., 2011; Longhitano et al., 2012). Modern and ancient tide-dominated estuaries are known to exhibit funnel-shaped shorelines (Dalrymple et al., 1991, 1992; Fenies and Tastet, 1998; Hori et al., 2001; Dalrymple and Choi, 2007; Tessier et al., 2011). The coastline morphology can be used as proxy for tidal influence. Increasing coastal rugosity may infer to increasing tidal influence at the shoreline (Ainsworth et al., 2011).

Evamy et al, 1978 highlighted the growth of the Niger Delta which is depicted by series of maps (Figure 9.5) showing the major deopocenters for selected palynological units between the Paleocene to Pliocene. These palynological zonal boundaries corresponds to isopach patterns which could be tied to the coastal morphology at the various time.

Figure 9.6 shows the coastal morphology of the Niger Delta from the Paleocene to the Oligocene. The concave-shaped shoreline during the Paleocene (Figure 9.6) is similar in shape to the isopach pattern (P200) of the Cenozoic Niger Delta (Figure 9.5A). By Miocene, the delta began to prograde (Evamy et al, 1978), exhibiting a more or less convex-shaped shoreline and this progradation continued till recent, resulting in the present day lobate-shaped morphology of the Niger Delta.

Moderately to highly embayed morphologies characterised the shorelines of the study area from the Paleocene to the Oligocene (Figure 9.6). This probably accounts for the significant influence of tidal processes during sedimentation in the study area.

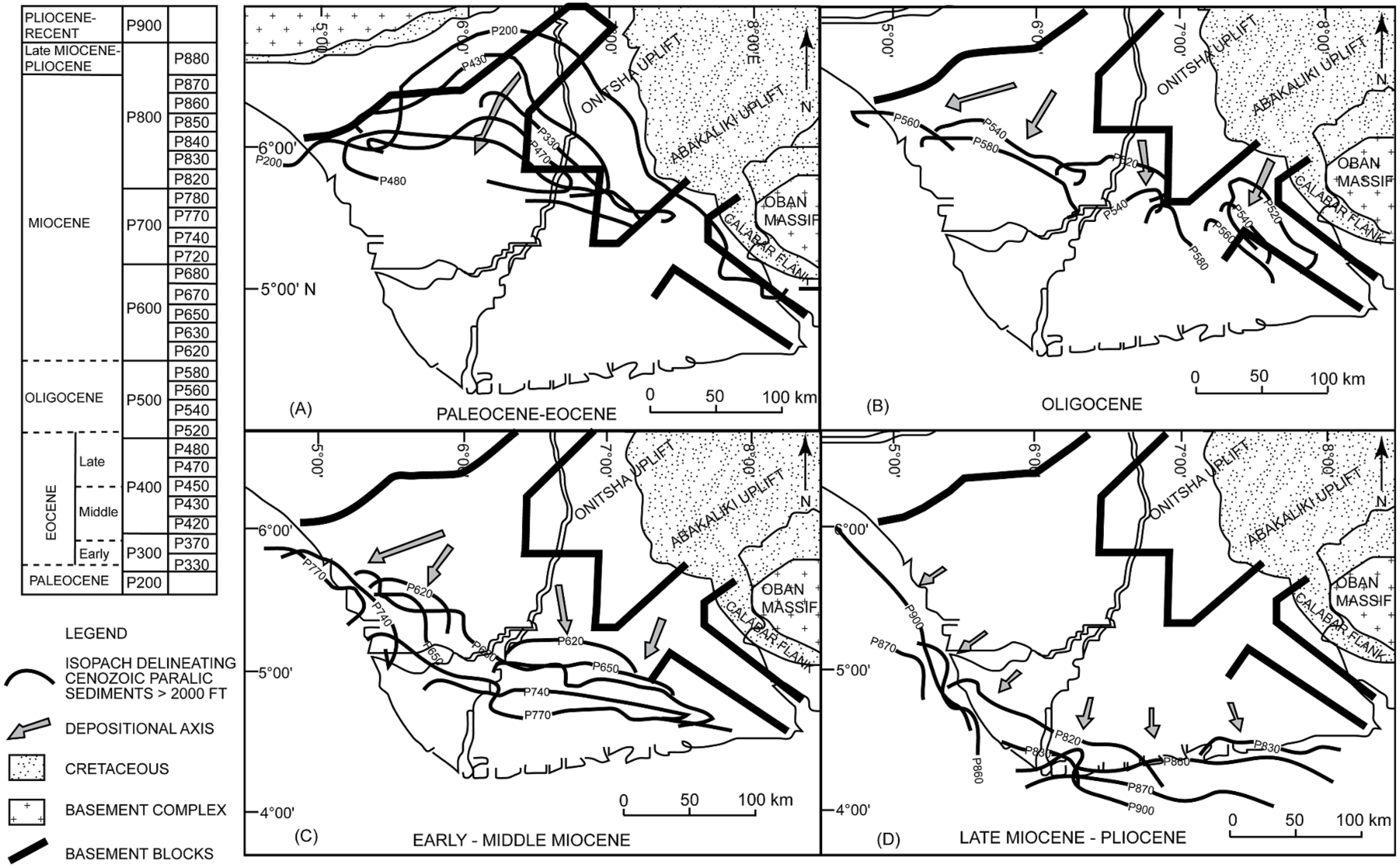
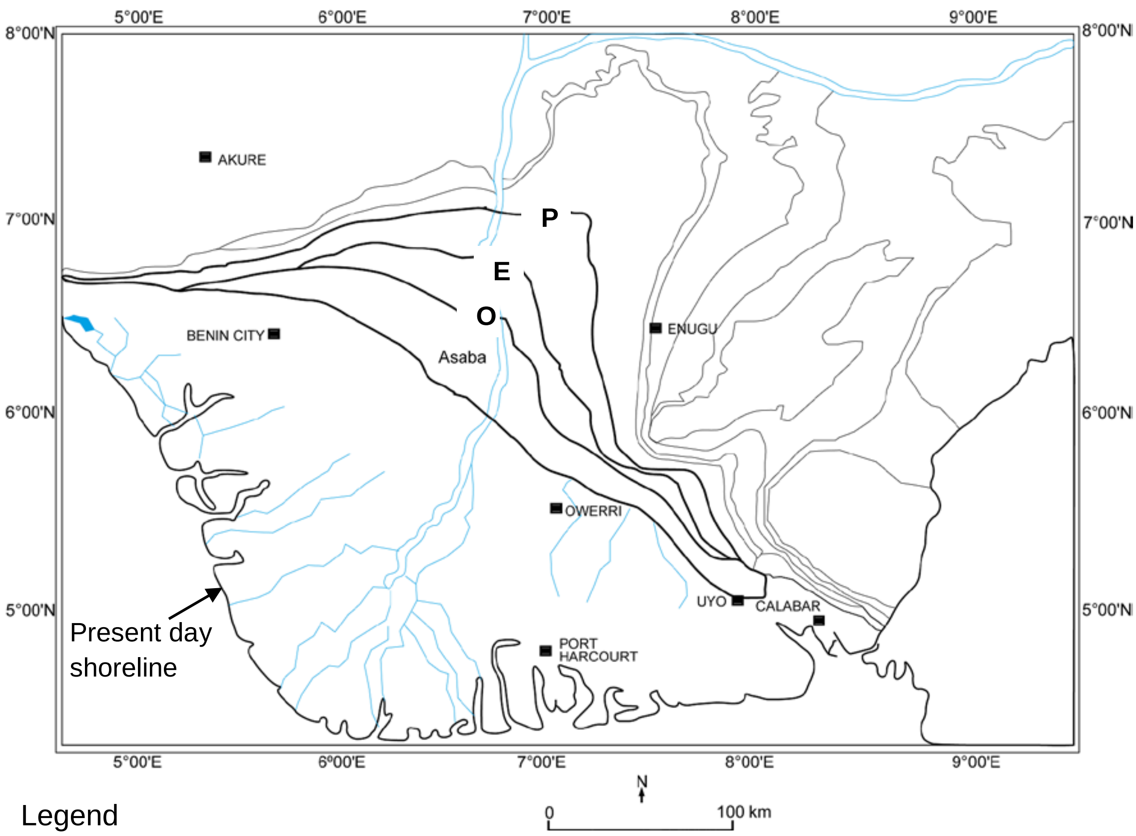


Figure 9.5. Stratigraphic evolution of the Cenozoic Niger Delta (redrawn and modified from Evamy et al., 1978).



Legend

P – Paleocene

E – Eocene

O = Oligocene

Figure 9.6. Shoreline morphology of the Niger Delta from Paleocene to Oligocene.

9.4 PALEOGEOGRAPHIC EVOLUTION OF THE PALEOGENE STRATA

9.4.1 Introduction

The paleogeography of the south-eastern Nigeria is linked to the Cretaceous sedimentation that ended with the Maastrichtian-Paleocene Nsukka Formation, also referred as the upper Coal Measures. Sedimentation ended in the Anambra Basin with the Nsukka Formation (Nwajide, 2005) and this is marked by the Paleocene unconformity. The controlling factors on sedimentation in the study area include relative sea level changes, sediment supply, availability of accommodation, topography and depositional processes. Three major stages are employed for the paleogeographic reconstruction based on the stratigraphic distribution of Paleogene sediments, the effect of the controlling factors on sedimentation pattern and the regional scale discontinuity.

9.4.2 Stage 1: Paleocene - Early Eocene

During the Paleocene, marine conditions were created due to a major relative sea-level rise (Nwajide, 2005; Oboh-Ikuenobe et al., 2005; Whiteman, 1982), which resulted in increased accommodation, but the low supply of siliciclastic sediments led to the deposition of the offshore shales of the Imo Formation (Figure 9.7A) that is considered to be the oldest strata in the Niger Delta sedimentary Basin (Petters, 1991). Evamy et al., (1978) noted the deposition of marine shales in most of the southern Nigerian basin during the Paleocene to early Eocene (P200) times. The Paleocene transgression is further supported by the presence of nontronite in the offshore shales; the clay mineral signifies low sedimentation and sea level rise (Thiry and Jacquin, 1993). Furthermore, the presence of dinoflagellates, acritarchs and foraminiferal test linings in the offshore shales are good indicators of shallow marine conditions. Terrestrial input is indicated by the occurrence of sporomorphs and freshwater algal cysts. Subsequently, the predominance of tidal process and the increase in sediment supply during the Paleocene is indicated by the deposition of thick tidal sand wave deposits (Figure 9.7B). The tidal currents were strong enough to rework fluvio-deltaic sediments of the Nsukka Formation which formed the sand wave deposits (Chapter 4: section 4.4.1). The large scale cross bed foresets (10 - 20 m thick) trend dominantly in a northwest direction, reflecting sand wave migration related to the dominant tidal current. The sandwave deposits are classified as quartz arenite, with the dominance of rounded to subrounded quartz grains (Chapter 8: section 8.3.1). The Cretaceous sedimentary rocks of the Anambra and Afikpo basins are considered to be a major recycled sedimentary source (Chapter 8: section 8.4). Results from heavy mineral analysis (chapter 8: table 8.3, 8.4) indicate the presence of heavy minerals such as zircon, tourmaline and apatite and medium to high grade metamorphic minerals, which suggest contribution from igneous and metamorphic source as well (Figure 9.7B).

Kreisa et al., (1986) interpreted similar giant–scale (3 - 12 m) cross-bed sets as tidal sandwaves deposit of Rancho Rojo Sandstone in Arizona which they further suggested to be a tide-dominated transgressive shallow marine environment.

Cessation of the incoming clastic sediments is indicated by the presence of intense bioturbation of the topmost unit of the tidal sand wave deposit. The presence of monospecific *Thalassinoides horizontalis* (Chapter 4: figure 4.9) suggests a stressed shallow marine condition. These events may have occurred as a result of a pause in sedimentation and probably lowering of the sea level which ended the deposition of the sand waves. Similar relationships are recorded by Bottjer (1985), where the lowering of the sea level with a pause in sedimentation during the Cretaceous resulted to monospecific *Thalassinoides* burrow system at the contact between Marlbook Formation and Saratoga Formation in South western Arkansas. A subsequent rise in relative sea level and reduced clastic supply initiated deposition of the offshore shale of the Imo Formation (Chapter 4: section 4.3.1) which encased the tidal sandwave deposits. The interplay between sediment supply, relative sea level changes and hydrodynamic processes affected the stratigraphic succession of the Imo Formation. The deposition of a coarsening upward succession of well sorted rippled laminated sandstone suggests a predominance of wave action and influx of siliciclastics. Heavy mineral assemblages (Chapter 8: table 8.5, 8.6) suggest a mixed provenance, and sediments probably originate from pre-existing sedimentary and metamorphic rocks, most probably from the Oban massif (Figure 9.7B) and input may also be derived from the West African massif.

A lagoonal deposit capped the first depositional sequence of the Imo Formation. The second sequence commenced with coarse grained sandstone which is overlain by shale, marl and thin limestone layer. This suggests a period of regression and a subsequent transgressive period, which may have occurred during the early Eocene. At the onset of the transgression, the Niger Delta basin became a shelf in which a marine succession (marl facies (Fc), fossiliferous shale facies (Fl2); and structureless calcareous sandstone (Sm1) with subordinate structureless non-calcareous sandstone (Sm2), bioturbated sandstone (Sb) and non-fossiliferous dark grey shale facies (Fl1), (Chapter 4: section 4.3.1) were deposited; the deposition of these sediments suggested a pause in sedimentation due to relative rise in sea level. Results of clay mineral analysis (Chapter 4: table 4.1) indicate the presence of nontronite, illite and kaolinite. Nontronite and illite are common in marine environments, while kaolinite indicates terrestrial input during transgression. The relatively moderate occurrence of palygorskite suggests a Mg-rich water condition which resulted to the deposition of marl, limestone and fossiliferous sandstone. Palygorskite occurs in wide range of environments (Weaver, 1989); it is common in alkaline lakes and perimarine environments under arid to semi-arid conditions. It is also documented in deep ocean sediments, brackish-water conditions and marine sediments.

Shallow marine conditions prevailed with the deposition of fossiliferous sandstone with fossiliferous limestone layers in the upper Sandstone Member of the Imo Formation indicates availability of clastic sediments during a gradual relative sea level rise which created accommodation for clastic accumulation. The occurrence of marl and the fossiliferous nature of the clastic sediments are restricted to the southern part of the study area (Umuahia-Bende region) which indicates variability in sediment supply. Results of the heavy mineral analysis indicate that the most probable source area would be the Oban massif. The high occurrence of coarse grained garnets is associated with a schistose lithologic unit of the Oban massif that includes quartz-mica schist, garnet-mica schist, garnet-sillimanite schist and kyanite-sillimanite schist (Ekwueme et al., 1991).

A strongly bioturbated fine grained sandstone capped the Imo Formation in the Umuhia-Bende region, the burrows are dominated by monospecific *Thalassinoides paradoxicus* (chapter 7; Figure 7.5a). This suggests a gradual fall in relative sea level and a pause in clastic input that enabled the unit to be colonized by burrowing decapod crustaceans. The top of the horizon forms a major discontinuity surface (Bottjer, 1985; Pemberton et al., 2004) that demarcated the Imo Formation from the Ameki Group.

9.4.3 Stage 2: Middle Eocene – Late Eocene

During the middle Eocene, a relative sea level fall resulted to incision, obvious in the north eastern part of the study area, and subsequent infill led to deposition of multistorey channels (Ugwu-Nnadi quarry, Nsugbe; chapter 5: section 5.3.1). The conglomeratic to coarse-fine grained sandstone of Nsugbe Formation may have originated from the Western Nigerian massif and pre-existing sedimentary rock: as indicated by the high proportion of euhedral and prismatic ultrastable heavy mineral suites such as zircon, tourmaline and apatite (as indicated in Chapter 8: table 8.6) associated with the Nsugbe Formation which suggests a close-by acid igneous or plutonic source and a basic igneous source (Figure 9.7C). However, the presence of rounded and rounded-prismatic minerals indicates multiple cycles of reworking which is common with pre-existing sediments. The trough and planar cross-stratified sandstone units have a general trend of south-west palaeoflow direction, indicating a northward direction for the source. A subsequent rise in relative sea-level and a strong influence of tidal process created estuarine (brackish-water) conditions (Figure 9.7C) characterised by tidally influenced fluvial channels, tidal channels, tidal flats, supratidal and tidal sand bars in the Ameki Group (Chapter 5: section 5.3.1). Palynological studies record terrestrial and marine influences in the estuarine deposits. Results from chapter 5 show that the palynology from the Nanka Formation is nearly barren, with only a terrestrial influence. However, results from Ibeku Formation shows mixed terrestrial and shallow marine input.

A similar incised valley succession is recorded in the Aspelintoppen Formation, Eocene Central Basin of Spitsbergen, where fluvial deposits pass upwards into macrotidal tide-dominated estuarine deposits (Plink-Björklund, 2005). Eriksson et al., (2006) also observed fluvial-tidally influenced estuarine sedimentation in high-relief zones of tectonic origin, in the Mesoarchean Moodies Group, South Africa and they related the succession to absolute sea level fluctuations. Modern macrotidal estuaries with similar depositional facies are recorded in Seine estuary and Mont-Saint-Michel Bay, English Channel, NW France (Tessier et al., 2011); Minas Basin (Yeo and Risk, 1980) and Cobequid Bay, Bay of Fundy (Dalrymple et al., 1990).

In the study area, the Nsugbe Formation is interpreted as fluvial channel deposit and marine inundation which occurred over the fluvial deposits resulted in the deposition of tidally influenced point bar deposits (Nanka Formation). The inclined heterolithic strata of this point bar deposit (Nanka Formation) trend in a eastward direction (with low dip angle of 7°-10°). The eastward direction signifies a dominance of flood tidal current, whereas a minor westward trending inclined heterolithic strata shows a subordinate ebb tidal current. The dominance of flood tidal current over the ebb current supports the interpretation as a tide-dominated estuarine system (Hovikoski et al., 2008).

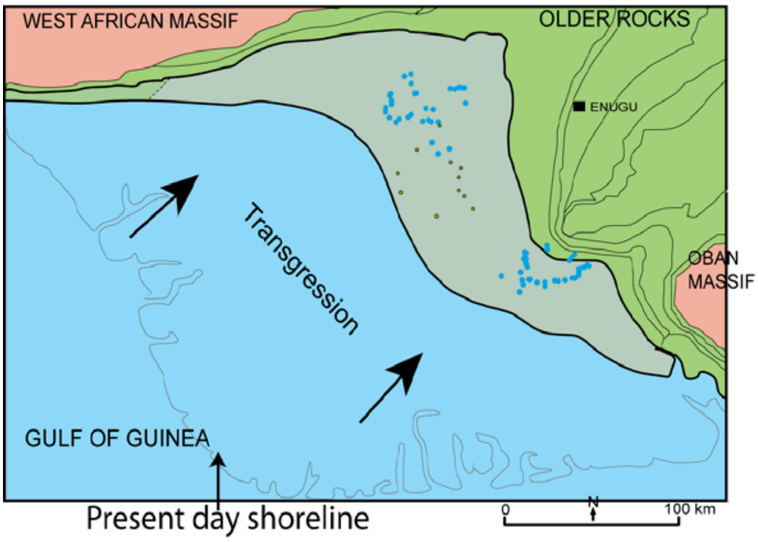
Heavy mineral analysis suggests that more than 66-77% of the clastics are of acid igneous or plutonic origin whereas 20-32% of the clastics suggest a metamorphic origin (Chapter 8: table 8.7). This may imply that more sediment is shed from the granitic lithologic unit of the Western Nigeria massif or that the ultrastable heavy minerals are more resistant to weathering and alteration. Tidal channels exhibit paleocurrent trends in south-east and north-west directions. The sandstones are quartz-arenites to lithic-arenites. Heavy minerals from the tidal channel sandstones also show higher clastic input from the acid igneous bodies. Tidal sand bar units are dominated by southwest trending paleocurrent directions. The sands are dominantly quartz arenites and heavy mineral interpretation suggest more clastic input from the metamorphic source (65-70%) than the acid igneous source (25-30%). Variation in the proportion of the heavy mineral suite may also be due to grain size and hydraulic condition (heavy minerals occur more in finer grain-size fractions), as well as differential weathering from the source areas.

The changes observed in the clay minerals in the tide dominated estuarine complex (Chapter 5: section 5.3.3) probably suggest interaction of terrigenous source and marine source clay minerals. Clay minerals from Nanka Formation consist of mainly kaolinite and mixed layer illite. Insignificant palygorskite and very limited occurrence of montmorillonite (only observed in one sample) are present. The dominance of kaolinite and mixed layer illite suggest a greater influence of terrigenous input. The presence of montmorillonite as well as chlorite in minor amount signifies a marine influence due to rise in sea level (Thiry and Jacquin, 1992; Weaver, 1989). The composition and distribution of these clay minerals is similar to those of the estuaries along the east coast of the United States though the abundances of the clay minerals differ (Weaver, 1989).

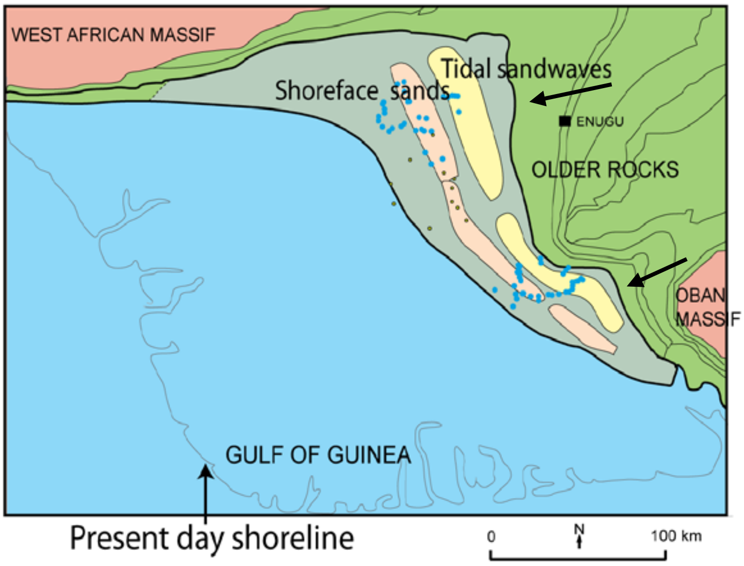
9.4.4 Stage 3: Oligocene

During the late Eocene, the estuary was filled up with the Ameki Group sediments, leaving a low topography and a low relief landscape. Probably, the activation of the paleo-Niger River or a relative sea level fall may have resulted in the fluvial incisions on the low topography coastal plain environment during the Oligocene. The tidally influenced coastal plain is considered to be controlled by relative sea level changes based on the vertical variation in the facies and facies associations from marine to non-marine conditions. The clay mineral suites in the Ogwashi Formation are dominated by kaolinite and mixed layer illite which signifies continental input. A similar composition, but with varying amount of kaolinite and illite, occurs in the Early to Middle Cenomanian sediments of the Iberian strait (Northern Spain) interpreted as fluviatile and littoral deposits (Floquet, 1991). Results from heavy mineral interpretation indicate mixed proportions of suites of minerals from metamorphic and igneous rocks which suggests the dominant source area to be the Oban Massif, which comprises basement rock (metamorphic rock) and granite (igneous rock) with contributions probably from the Western Nigeria basement, as well as recycled sedimentary rocks based on the occurrence of rounded and subrounded crystals.

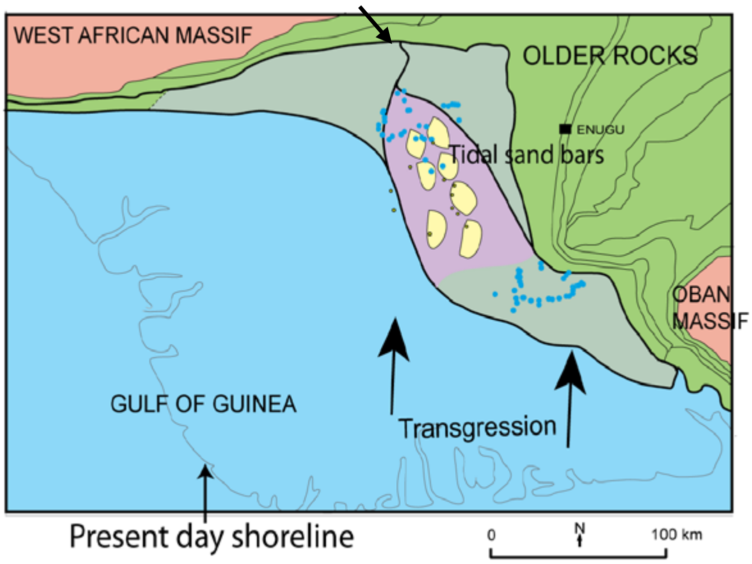
Oboh-Ikuenobe et al., (2005) demonstrated from palynlogical studies that the Ogwashi Formation contains 20-60% unstructured phytoclasts, 14-21% structured phytoclasts, <10% amorphous organic matter (AOM) and 5% fungal remains, but contains no marine palynomorphs. The high occurrence of unstructured phytoclasts and the presence of AOM may be due to the influence of nearshore marine water. Oboh-Ikuenobe et al., (2005) further suggested that the Oligocene Ogwashi Formation is a non-marine succession, but disregard the presence of low diversity, but high abundance of *Skolithos* ichnofacies found in the basal conglomerate and coarse grained sandstone of the Ogwashi Formation. MacEachern and Hobbs (2004) indicated that the presence of bioturbation in coarse grained strata is indicative of marine influence. Thus, the regressive Ogwashi Formation (Figure 9.7D) had minor marine inundation that resulted in the high level of bioturbation found in the basal units.



A Paleocene (Thanetian)



B Paleocene (Thanetian)-Eocene (Ypresian)



C Eocene (Lutetian-Priabonian)

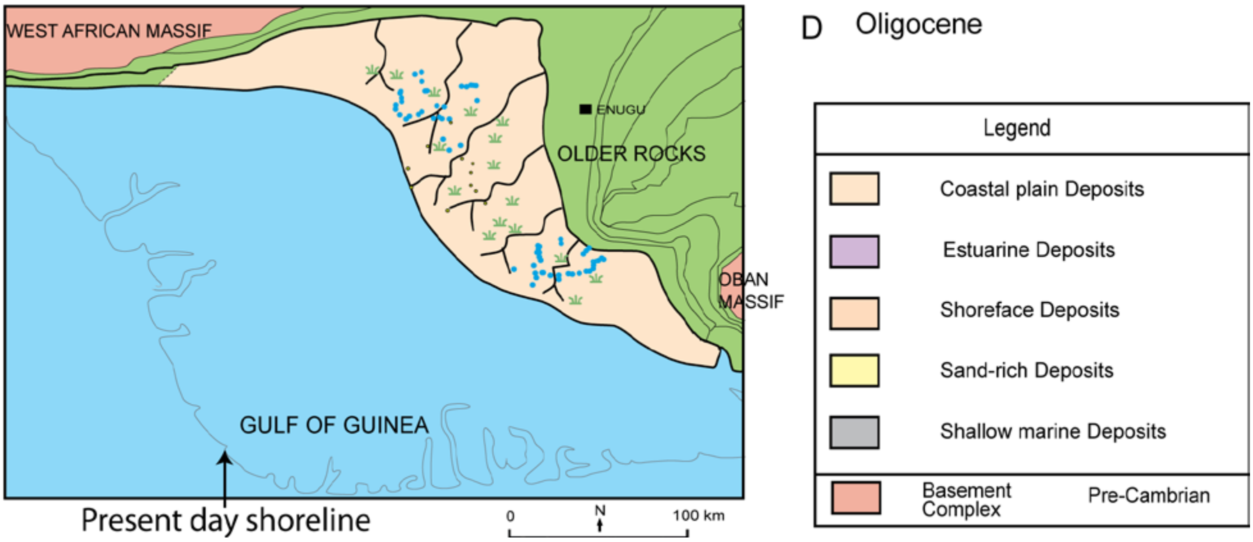


Figure 9.7. Paleogeographic evolution of the Paleogene strata, south-eastern Nigeria from Paleocene to Oligocene. (A) Paleocene transgression resulted in a shallow marine condition that led to the deposition of bluish to dark grey shale facies interpreted as offshore shale (FA1). (B) Sediment influx from most probably pre-existing sedimentary rocks and Oban massif may have resulted deposition of tidal sandwaves, shoreface/foreshore sandstone and fluvial channel in the Imo Formation. (C) Eocene sediments of the Ameki Group are dominantly derived from West African massif and recycled sedimentary rocks. A sea-level rise created an estuarine condition during the Eocene. (D) The Oligocene period witness a minor regression that resulted in coastal plain deposits with a minor transgression that led to the deposition of fluvio-estuarine sediments.

9.5 PALEOGENE SEQUENCE STRATIGRAPHIC FRAMEWORK FOR THE SOUTH-EASTERN NIGERIA

9.5.1 Introduction

Four depositional sequences are recorded for the Paleogene fluvial, estuarine, coastal plain and shallow marine depositional environments (Figure 9.1). The stratigraphic distribution and the facies characteristics of the four depositional sequences are controlled by relative sea-level changes, as well as other controlling factors such as sediment supply, tidal processes and basin bathymetry. The cycle chart of the sea-level fluctuations is based mainly on study of stratigraphic succession of outcrops (Figure 9.5) and also contributions from other research works (Avbovbo and Ayoola, 1981; Oboh-Ikuenobe et al., 2005; Nwajide, 2005; Short and Stäuble, 1967).

The stratigraphic sequences are bounded by unconformities (type-1 sequence boundaries) as a result of relative sea level changes. These sea level changes can be correlated to other parts of the world (Figure 9.9). This is not an easy task though, due to inadequate high resolution chronological data for the study area. Despite this, the timing of the Paleogene sea–level movements around southern Africa (Siesser and Dingle, 1981) is observed to be approximately close to the timing established for sea-level changes in the south-eastern Nigeria (Reyment, 1980a and b; Reijers et al., 1997; Petters, 1995). Attempts have been made by Oboh-Ikuenobe et al., (2005) and Odunze and Obi (2011) to analyse the sequence stratigraphy in terms of the global sea level curve of south-eastern Nigeria, but there is still inconstancies in the location of sequence boundaries, the interpretation of depositional facies and systems tracts.

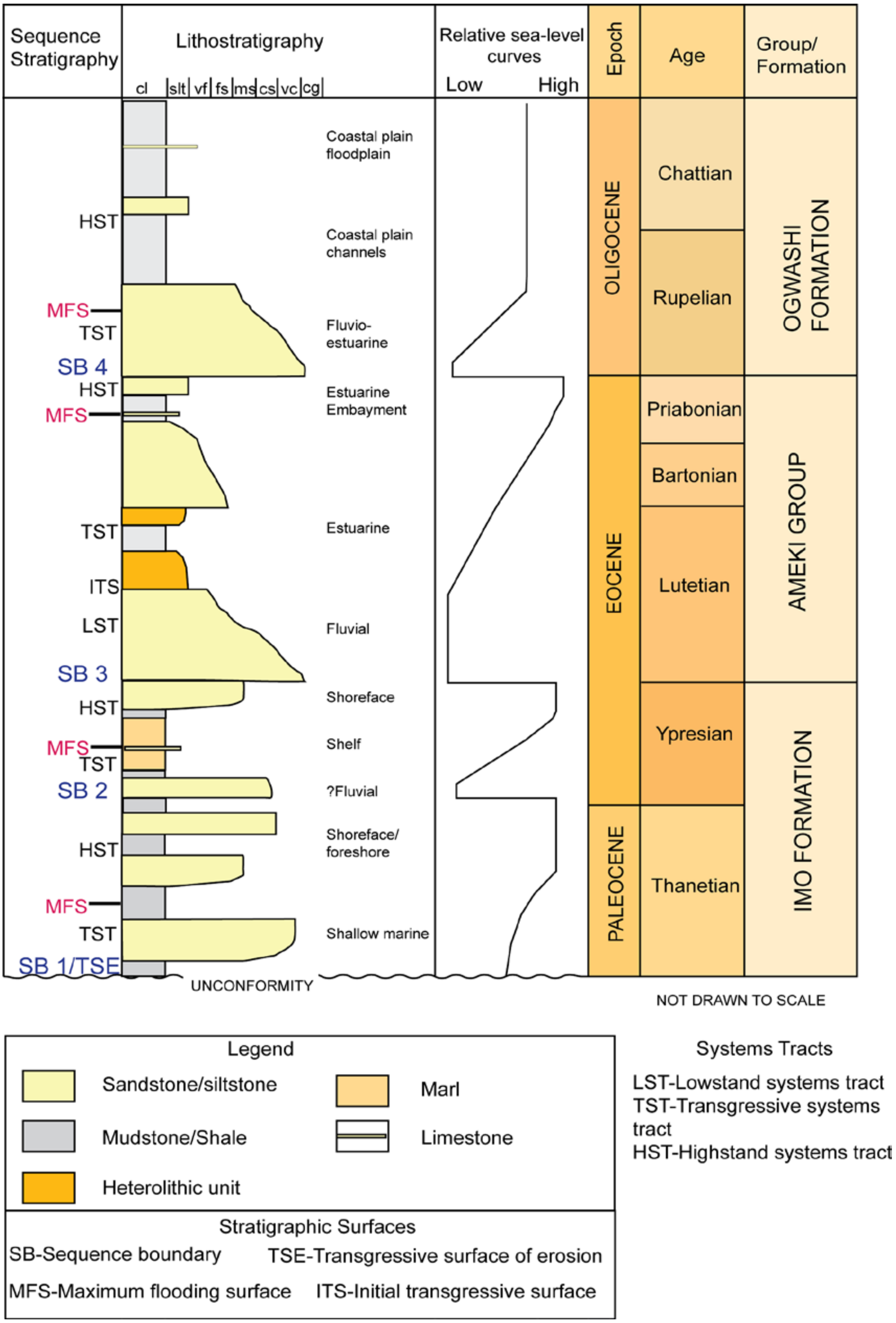


Figure 9.8. Sequence stratigraphic interpretation and relative sea-level changes of the Paleogene strata in the south-eastern Nigeria.

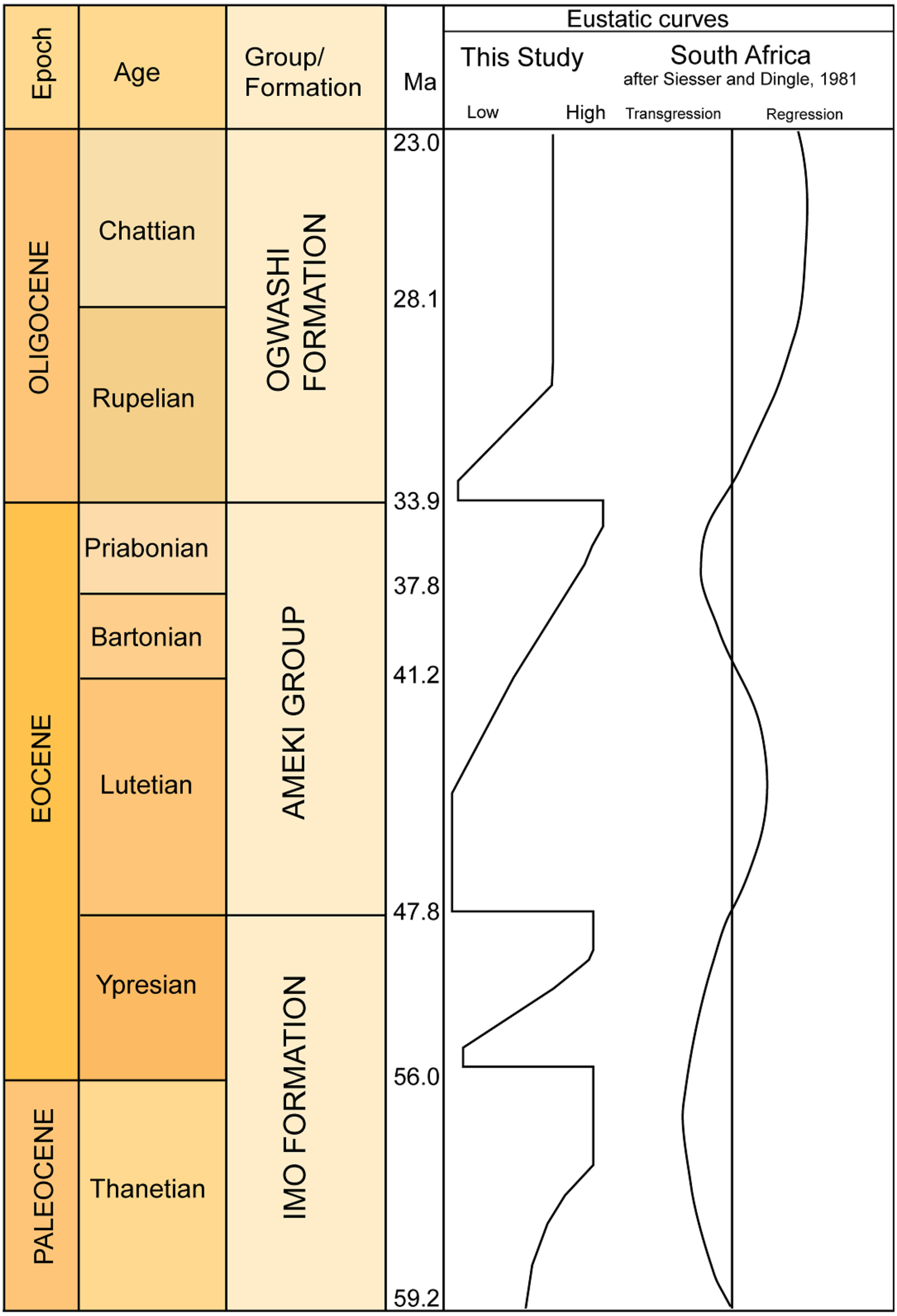


Figure 9.9. Comparison of south-eastern Nigerian and South African (Siesser and Dingle, 1981).

9.5.2 Paleocene-Early Eocene sequences

The first sequence boundary (SB1) occurs as an unconformity between the Nsukka Formation and the overlying Imo Formation (Avbovbo and Ayoola, 1981). The unconformity coincides with transgressive surface of erosion which heralded the onset of relatively rapid sea level rise during the Paleocene. This Paleocene transgression initiated with the deposition of the offshore/shelf shale/mudstone of Imo Formation. The transgressive surface of erosion (TSE) coincides with the first sequence boundary (SB1) (Figure 9.8). The lowstand deposit is absent in the first depositional sequence. The offshore/shelf shale/mudstone and tidal sandwave deposits signifies the transgressive systems tract while, the highstand systems tract is represented by shoreface-foreshore and lagoonal deposits. The Paleocene transgression in the study area is correlated to other regions of the world such as north-western and western Africa (Reyment, 1980a), Argentina (Bertels,1969), Brazil (Ponte and Asmus, 1978), South Africa (Siesser and Dingle, 1981) as well as in the northern and southern area of eastern Europe and West Siberia as evidence from the Peri-Tethys (Radionova et al., 2003). The Paleocene transgressions in southern Nigeria and South Africa are suggested to be as a result of tectono-eustacy or relative sea level changes (Reyment, 1980b; Reyment and Mörner, 1977; Siesser and Dingle, 1981; Oboh-Ikuenobe et al., 2005). The Imo Formation succession suggests that the Paleocene transgression continued into probably early Eocene times, with a minor regression pulse that resulted to in the second sequence boundary (SB2). This long-term sea level rise is related to the global sea level fluctuations (Figure 9.9) as observed in the South African sea level curve illustrated by Siesser and Dingle (1981). The regression resulted to a thin bedded, coarse to medium grained sandstone (that represents fluvial deposits) which reflects a lowstand systems tract. An increase in relative sea level resulted in the deposition of a thick succession of shale, marl with limestone layers (that represents shelf deposits) which represents the transgressive systems tract. The highstand systems tract is typified by a coarsening upward fossiliferous sandstone (that represents shoreface deposits).

9.5.3 Middle-Upper Eocene sequence

Siesser and Dingle (1981) recorded a series of transgressions and regressions during the Paleogene in South Africa and these events correlate approximately to the relative sea-level changes in south-eastern Nigeria (Figure 9.9). During middle Eocene times (Kogbe, 1976; Oloto, 1984), the Ameki Group was deposited and this corresponds to a regressive pulse which occurred during the middle Eocene in Southern Africa (Siesser and Dingle, 1981). The Ameki Group commenced with an initial regressive fluvial deposit of the Nsugbe Formation which forms the third sequence and the sequence boundary occurs at the base of the fluvial channel (SB3) or tidally influenced fluvial deposit in areas (such as Nando) where the tidal deposits rest directly on the Imo Formation deposit. The regression was followed subsequently by transgression that resulted in the estuarine condition and deposition of the Nanka Formation and the Ibeku Formation. The marine incursion marks the marine flooding surface and landward movement of the bayline which separates the regressive fluvial deposit from the transgressive estuarine deposits. The transgressive systems tract (TST) consists of thick successions interpreted as tidally influenced fluvial channels, tidal channels, tidal flats and tidal sand bars. This implies availability of accommodation and sediments supply, which may be due to regional subsidence and eustasy. Major global transgression in the Eocene is recorded by Flemming and Roberts (1973) and Siesser and Dingle (1981). This Eocene transgression may have affected sediments of the surface outcrop in the Niger Delta Basin, resulting in the estuarine conditions of the Ameki Group. The highstand systems tract is more pronounced in the Umuahia-Bende region. It is characterised by marine influence as the sea level gradually increases, which forms a inner tidal sand bar in the Enugwu-Ukwu region and estuarine embayment deposits in the Umuahia-Bende area. Siesser and Dingle, (1981), likewise suggested a regressive pulse during the middle Eocene in Southern Africa, which is represented by intense erosion that led to the absence and scarcity of middle Eocene rocks and subsequent transgression in late Eocene times.

9.5.4 Oligocene sequence

The Oligocene strata in south-eastern Nigeria are characterised by tidally influenced coastal plain deposits which suggest a period of regression. The fourth sequence boundary (SB4) is marked by an unconformity, typified by basal erosive channels that are filled with fluvio-estuarine deposits. The fluvio-estuarine deposit constitutes the transgressive systems tract while the tidal channel and coastal plain deposits *sensu stricto* which include mud-filled channels and floodplain/mire form the highstand systems tract. Likewise, Siesser and Dingle (1981), recorded regression throughout the Oligocene time; marine influence was also noted in the Oligocene strata (Flores, 1973). This sequence is similar to the Oligocene Ogwashi deposit in southern Nigeria that commenced with regressive sequence of thick conglomerate, which was later reworked by shallow marine infaunal organisms that indicate marine influence.

9.6 CONCLUSIONS

The Paleogene succession in the south-eastern Nigeria includes the Paleocene-Eocene Imo Formation, the Eocene Ameki Group and the Oligocene Ogwashi Formation. Sediments of these units were deposited in a shallow marine environment, a continental-marginal marine setting and a coastal plain environment respectively.

The Imo Formation includes sandstone bodies that are excellent reservoir analogues with minimum heterogeneity that can affect the quality of the reservoir. The tidal sand wave deposits are very good reservoirs. The sand bodies have excellent lateral continuity and they possess tabular to lobe-shaped geometry. The sands are quartz arenites with low clay matrix and clay chips. The sandstone bodies are encased by shale which acts as excellent seal for the reservoir. Similarly, the shoreface sandbodies have characteristics of good reservoirs. The fluvial channel sandbodies and the inner tidal sand bars possess features of better reservoirs in the Ameki Group. Sandbodies of the bioturbated outer estuarine tidal sand bar has high matrix content that have mesoscopic heterogeneity, but permeability can be enhanced by the sand-filled and open-structure burrows. The fluvio-estuarine and the tidal channel sandbodies are the major reservoirs in the Ogwashi Formation.

The predictive classification scheme indicated the dominance of tidal process and subordinate occurrence of wave and fluvial processes during sedimentation in the Paleogene Niger Delta Basin. The moderately to highly embayed shoreline during the Paleogene period signified tidal dominance at the coastline.

Heavy mineral analysis, sedimentology (paleocurrent trends) and petrographic studies suggest a mixed provenance of the Paleogene sediments in the south-eastern Nigeria. The possible source areas are the West African Massif, Oban Massif and pre-existing sedimentary rocks mainly from the Cretaceous Anambra and Afikpo basins. The four depositional sequences documented for the Paleogene strata in the south-eastern Nigeria are controlled primarily by relative sea level changes, sediment supply, tidal processes and basin bathymetry. Sediments of the lowstand systems tract (LST) and transgressive systems tracts (TST) have good reservoir qualities and well developed sandstone bodies. The occurrence of thick sequence of sandstone bodies in the TST is probably due to subsidence and high sediments influx during the Paleogene sedimentation.

CHAPTER TEN

SUMMARY AND CONCLUSIONS

10.1 SUMMARY AND CONCLUSIONS

The scientific aim of this research includes the study of the depositional facies, facies architecture, sedimentary environments and paleogeographic reconstruction of the Paleogene sedimentary rocks in the south-eastern Nigeria. This was achieved by organising the research work into detailed field study; laboratory analyses which includes clay mineralogy, heavy mineral analysis, petrology and palynology; interpretation of results and synthesis. Based on these studies and interpretation of results, new depositional environments, depositional models and novel framework for further studies have been established.

The research is summarised and concluded below as follows:

1. The Imo Formation is divided into lower, middle and upper sandstone members. The lower Sandstone Member has been re-interpreted based on the depositional facies succession as tidal sandwave deposits in a tide dominated transgressive shelf setting. The monospecific *Thalassinoides horizontalis* at the top of the tidal sand waves is interpreted as *Glossifungites* ichnofacies which indicates depositional hiatus, when sediment input was greatly reduced due to lowering in sea level.

2. Clay mineralogy was integrated into the interpretation of the light bluish grey to dark grey shales and mudstone in the lower Sandstone Member of the Imo Formation as offshore or shallow shelf deposits based the high occurrence of illite and nontronite. The influence of terrestrial input into the marine setting is indicated with the presence of common kaolinite.

3. The Ameki Group is re-classified into the Nsugbe Formation, Nanka Formation and Ibeku Formation (formerly Ameki Formation). The Ameki Group is re-interpreted as a tide-dominated macrotidal estuarine system. Subsequently, the Nsugbe Formation consists of the mainly fluvial deposits and tidally influenced fluvial channels, whereas the Nanka Formation includes the deposits of tidally influenced fluvial channels, tidal channels, tidal flats, supratidal and tidal sand bars. The Ibeku Formation comprises the estuarine embayment deposit. The estuarine deposits were recognised by their distinctive tidalites structures and brackish-water ichnofaunal assemblages.

4. Based on the grain textures, sedimentary structures, geometry, palaeocurrents, and lateral and vertical arrangement of lithofacies, reservoir architectures were developed for the Paleogene strata. The architectural elements are quite simple for the Imo Formation; the tidal sandwave sandbodies show sheet-like geometry encased in shale and mudstone while the shoreface sandbodies exhibit lobe to lenticular geometry. However, the Ameki Group has more complex architectural elements which include channel deposits, lateral accretion deposits, gravel bars, sandy cross-stratified and heterolithic deposits. The architectural elements of the Ogwashi Formation are simply grouped into channelized deposits (isolated channels and multistorey channels) and floodplain deposits.

5. The Oligocene Ogwashi Formation has been re-interpreted as tidally influenced coastal plain deposit. The depositional facies indicate that the regressive succession was marine influenced which resulted to the occurrence of low

diversity, but high abundance *Skolithos* ichnofacies. The dominance of vertical *Ophiomorpha nodosa*, *Skolithos linearis* and escape burrows implies high energy conditions and rapid sedimentation in the fluvio-estuarine deposits of the tidally influenced coastal plain system. The mouth-bar deposits of the fluvio-estuarine system consist of more marine ichnofossils such as *Rosselia, Ophiomorpha nodosa* boxwork as well as *Skolithos* and *Cruziana* ichnofacies.

6. Based on petrological studies, the tidal sandwave and shoreface sandstone deposits of the Imo Formation are classified as quartz arenites whereas the fossiliferous sandstone deposited in the shelf setting is considered to be arkosic arenite. Provenance studies, show that sediments of the lower and middle Sandstone Members of the Imo Formation originate from mixed sources of pre-existing sedimentary rocks and a metamorphic source (mainly the Oban massif), whereas the sandstones of the upper Sandstone Member were derived from mainly igneous and a metamorphic sources (mainly the Oban massif). Petrographically, sandstone classification for sediments of the Ameki Group varies from quartz arenite to sub-arkose and sub-litharenite (or lithicarenite). No distinct variation of heavy mineral assemblage is observed in the Ameki Group. The heavy mineral suites suggest mixed provenance, probably recycled sedimentary rocks and material derived from the West African massif. Sandstones of Ogwashi Formation are classified as quartz arenite and sub-litharenite. A mixed source of pre-existing sedimentary rocks and materials from the Oban massif are also suggested for the Ogwashi Formation.

7. Twenty-one ichnogenus and twenty-eight ichnospecies were observed in the Paleogene strata of the south-eastern Nigeria. They were further grouped into five ichnofacies which include *Scoyenia*, *Psilonichnus, Skolithos, Cruziana, Glossifungites* and *Teredolites.* *Skolithos, Cruziana and Glossifungites* ichnofacies are the most commonly occurring ichnofacies in the study area. Low to moderate diversity and moderate to high abundance of *Skolithos* and impoverished *Cruziana* ichnofacies dominate the Nando Formation of the Ameki Group and the fluvio-estuarine deposits of the Ogwashi Formation. The *Glossifungites* ichnofacies are limited to stratigraphic surfaces (such as sequence boundaries and transgressive surfaces) and discontinuities representing a pause in sedimentation.

8. The reservoir heterogeneity of the sandstone bodies in the study area is greatly influenced by environment of deposition. The sand-rich tidal sand waves and shoreface deposits of the Imo Formation possess good reservoir qualities. The reservoir heterogeneity is minimized due to low clay matrix in the sand bodies, fairly good sorting of the grains, and good lateral continuity of the sand bodies. Reservoir qualities of the fluvial-estuarine Ameki Group sand bodies vary across the depositional facies. The fluvial and outer estuarine tidal sand bar deposits have good vertical and lateral connectivity and low vertical compartmentalization. The tidally influenced fluvial channel, tidal channel and tidal sandflat deposits are dominated by high reservoir heterogeneity and moderate to high vertical compartmentalization. The presence of bioturbation in the inner estuarine sandbar deposits of Nanka Formation of Ameki Group could enhance porosity and permeability because most of the burrows are

dominantly sand filled. Meanwhile bioturbation in the fluvio-estuarine deposit of the Ogwashi Formation may not significantly enhance porosity or permeability for strata with burrows that are lined with mud or sandy mud and filled with either mud or sandy mud. However strata with sand-filled and open-structure burrows can possess higher permeability.

9. The predictive coastal process classification utilized in the study area indicates a dominant tidal process and subordinate wave and fluvial processes for the Paleogene strata in SE Nigeria. Furthermore, the significant effect of the tidal processes on these strata may be linked to the moderately to highly embayed morphology of the shorelines during the Paleogene.

10. The sequence stratigraphic framework for the Paleogene strata, south-eastern Nigeria reveals four depositional sequences bounded by type-1 sequence boundaries. These unconformities are either overlain by lowstand systems tracts or transgressive systems tracts. These genetic sequences are controlled mainly by relative sea level changes; other controlling factors include sediment supply, tidal processes and basin bathymetry.

Additional views on this research work are as follows:

1. Sedimentation commenced in the Niger Delta sedimentary basin during the Paleocene with the deposition of the Imo Formation which is the updip equivalent of subsurface Akata Formation (Short and Stauble, 1965).

2. The characteristics of the Paleogene sedimentary succession suggests deposition in tidally influenced shallow marine to tidally influenced coastal environments. The coastal environments consists of a tide dominated estuarine system and a tidally influenced coastal plain.

3. The overall paleogeography records major transgressive to regressive events related to relative sea level changes which greatly influenced the patterns of sediment accumulation.

4. The transgressive systems tracts are suggested to host the best analogue reservoirs in the study area due to the occurrence of thick and laterally extensive sandstone bodies such as tidal sandwaves, tidal sand bars and fluvio-estuarine deposits.

10.2 FURTHER RESEARCH

Further research is necessary to improve our understanding about the provenance and reservoir characterization of the sedimentary rocks found in the study area:

1. Integration of outcrop studies with subsurface data is essential to understand the relationship and differences in the sedimentary facies between the outcropping Paleogene strata and the subsurface Niger Delta Akata, Agbada and Benin formations.

2. Further porosity and permeability analyses (such as magnetic resonance imaging, (MRI), computer-aided tomography (CT) and probe permeametry which is used to obtain spot permeability data) are important for quantitative

results of reservoirs especially the bioturbated sandstones, in order to obtain proper insight into the effect of burrowing on reservoir characteristics.

3. Further palynological analysis which will involve palynofacies analysis is necessary for surface outcrops and borehole samples of the Paleogene strata especially in the Onitsha-Awka region. More palynology studies are also needed for sediments the Oligocene Ogwashi Formation outcropping in the Umuahia region: the data obtained would be very useful for dating and environmental interpretation.

4. The reservoir heterogeneity of the studied strata is valuable for the understanding of reservoir characterisation in both large and small scales. This research work has considered macroscopic, mesoscopic and microscopic heterogeneity. For continuity, it will be interesting if very large scale of heterogeneity (gigascopic and megascopic scales) is analyzed for regional reservoir and aquifer studies in order to establish factors controlling region flow system.

REFERENCES

REFERENCES

Adams, A.E., MacKenzie, W.S., Guildford, C., 1994. Atlas of sedimentary rocks under the microscope. Wiley, New York, 104 pp.

Adedosu, T.A., Adedosu, H.O., Adebiyi, F.M., 2007. Geochemical and mineralogical significance of trace metals in Benue Trough coals, Nigeria. Journal of Applied Sciences 7 (20), 3101-3105.

Adegoke, O.S., 1969. Eocene stratigraphy of Southern Nigeria. Colloque sur l' Eocene, 3, Bueau de Recherché Geologiques et Minieres Memoir 69, 23-48.

Adegoke, O.S., Arua, I., Oyegoke, O., 1980. Two new nautiloids from Imo Shale (Paleocene) and Ameki Formation (Middle Eocene), Anambra State, Nigeria. Journal of Mining and Geology 17, 85 – 89.

Adighije, C.I., 1981. A gravity interpretation of the Benue trough, Nigeria. Tectonophysics 79, 109–128.

Agagu, O.K., Fayose, E.A., Fetters, S.W., 1985. Stratigraphy and sedimentation in the Senonian Anambra Basin of Eastern Nigeria. Journal Mining Geology 22, 25–36.

Agumanu, A.E., Enu, E.I., 1990. Late Cretaceous clay distribution in the Lower Benue Trough: its palaeoenvironmental and tectonic implication. Journal of African Earth Sciences (and the Middle East) 10 (3), 465-470.

Ainsworth, R.B., Flint, S. S., Howell, J. A., 2008. Predicting coastal depositional style: Influence of basin morphology and accommodation to sediment supply ratio within a sequence-stratigraphic framework. In: Hampson, G. J., Steel, R. J., Burgess, P. M., Dalrymple, R. W. (Eds.), Recent advances in models of shallow-marine stratigraphy: SEPM Special Publication 90, 237–263.

Ainsworth, R.B., Vakarelov, B.K., Nanson, R.A., 2011. Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: Toward improved subsurface uncertainty reduction and management. AAPG Bulletin 95 (2), 267-297.

Akpoborie, I.A., Oteri, A.U., Idundun, S., 2005. Groundwater resources of the Asaba Capital Territory. Project Report, Delta State Ministry of Water Resources Development, Asaba, 35 pp.

Akpoborie, I.A., Nfor, B., Etobro, A.A.I., Odagwe, S., 2011. Aspects of the geology and groundwater conditions of Asaba, Nigeria. Archives of Applied Science Research 3 (2), 537-550.

Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde Estuary, France. Journal of Sedimentary Petrology 63, 378-391.

Allen, J.R.L., 1965. Late Quaternary Niger Delta and adjacent areas: sedimentary environments and lithofacies. American Association of Petroleum Geologists Bulletin 49, 547– 600.

Allen, J.R.L., 1980. Sand waves: a model of origin and internal structure. Sedimentary Geology 26 (4), 281-328.

Allen, J.R.L., 1982. Sedimentary Structures, their character and physical basis. Development in sedimentology 30B. Volume II, Amsterdam, Elsevier Scientific Publishing Company, 663 pp.

Allen, P.A., Homewood, P.P., 1984. Evolution and mechanics of a Miocene tidal sandwave. Sedimentology 31, 63-81.

Alpert, S.P., 1974. Systematic review of the genus *Skolithos*. Journal of Paleontology 48, 661-669.

Amajor, L.C., 1987. Paleocurrent, petrography and provenance analyses of the Ajali Sandstone (Upper Cretaceous), South-eastern Benue Trough, Nigeria. Sedimentary Geology 54, 47–60.

Anyanwu, N.P.C., Arua, I., 1990. Ichnofossils from the Imo Formation and their palaeoenvironmental significance. Journal of Mining and Geology 26, 1–4.

Aoki, S., Kohyama, N., 1991. The vertical change in clay mineral composition and chemical characteristics of smectite in sediment cores from the southern part of the Central Pacific Basin. Marine Geology 98, 41-49.

Archer, A.W., 1995. Modeling of cyclic tidal rhythmites based on a range of diurnal to semidiurnal tidal-station data. Marine Geology 123 (1), 1-10.

Arua, I., 1980. Palaeocene Macrofossils from the Imo Shale in Anambra State, Nigeria. Journal of Mining and Geology 17, 81–84.

Arua, I., 1986. Paleoenvironment of Eocene deposits in the Afikpo syncline, southern Nigeria. Journal of African Earth Sciences 5, 279–284.

Arua, I., 1988. Episodic sedimentation: an example from the Nkporo Shale (Campano-Maastrichtian), Nigeria. Journal of African Earth Sciences 7, 726–759.

Arua, I., 1990. Morphology and origin of calcium carbonate concretions in Eocene shale, southeastern Nigeria. Journal of African Earth Sciences 11 (3-4), 317-320.

Arua, I., 1991. The trace fossil *Teredolites longissimus* in calcareous concretions from the Eocene Ameki Formation, southeastern Nigeria. Journal of African Earth Sciences 12 (4), 605-608.

Arua, I., Rao, V. R., 1987. New stratigraphic data on the Eocene Ameki Formation, southeastern Nigeria. Journal of African Earth Sciences 6 (4), 391-397.

Avbovbo, A.A., 1978. Tertiary lithostratigraphy of the Niger Delta. American Association of Petroleum Geologists Bulletin 62, 295–306.

Avbovbo, A.A., Ayoola, E.O., 1981. Petroleum prospects of southern Nigeria's Anambra Basin. Oil and Gas Journal 79, 334 – 347.

Baas, J.H., 1999. An empirical model for the development and equilibrium morphology of current ripples in fine sand. Sedimentology 46, 123–138.

Backert, N., Ford, M., Malartre, F., 2010. Architecture and sedimentology of the Kerinitis Gilbert-type fan delta, Corinth Rift, Greece. Sedimentology 57 (2), 543-586.

Basan, P.B., Scott, R.W., 1979. Morphology of *Rhizocorallium* and associated traces from the Lower Cretaceous Purgatoire Formation, Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology 28, 5–23.

Basu, A., 1985. Influence of climate and relief on compositions of sands released at source areas. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Dordrecht, Holland, D. Reidel Publishing Company, pp.1-18.

Basu, A., Young, S.W., Lee, J., Sutter, W., Calvin, J., Mack, G.H., 1975. Re-evalution of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. Journal of Sedimentary Petrology 45, 873-882.

Batten, D. J., 1996. Palynofacies and paleoenvironmental interpretation. In: Jansonius, J., McGregor, D. C. (Eds.), Palynology: Principles and Application. American Association of Stratigraphic Palynologists Foundation 3, 1011-1064.

Beaumont, E. A., 1984. Retrogradational shelf sedimentation: Lower Cretaceous Viking Formation, Central Alberta. In: Tillman, R. W., Siemers, C. T. (Eds.), Siliciclastic shelf sediments. Society of Economic Paleontologists and Minerialogists, Special Publication 34, 163-177.

Benkhelil, J., 1982. Benue trough and Benue chain. Geological Magazine 119, 155-168.

Benkhelil, J., 1986. Structure et evolution geodynamique du basin intracontinental de la Benoue (Nigeria). Unpublished Thesis, Nice et Elf Nigeria SNEA (P), 2: 231pp. not seen, cited in Umeji, O.P. 2013. The south and central Benue Trough: Stratigraphic revisions, p. 145-181. Proceedings of University of Jos, PTDF Chair Endowment Fund Seminar.

Benkhelil, J., 1989. The origin and evolution of the Cretaceous Benue Trough (Nigeria). Journal of African Earth Sciences 8, 251-282.

Berggren, W.A., 1960. Paleocene biostratigraphy and planktonic foraminifera of Nigeria (W. Africa). Proceedings 21st International Geologic Congress, Copenhagen, p. 41 – 55.

Bermúdez-Rochas, D. D., 2009. New hybodont shark assemblage from the Early Cretaceous of the Basque-Cantabrian Basin. Geobios 42, 675-686.

Berquist, C. R., 1990. Heavy-mineral studies—Virginia Inner Continental Shelf. Virginia Division of Mineral Resources 103, 124 pp.

Bertels, A., 1969. Micropaleontologia y estratigrafia del limite Cretacico-Terciario en Huantrai-Co (Provincia de Neuquen). Ameghiniana, 6, 253-280 not seen, cited in Reyment, R.A. 1980. Paleo-oceanology and paleobiogeography of the Cretaceous South Atlantic ocean. Oceanologica Acta 3 (1), 127-133.

Bhattacharya, B., Bhattacharya, H.N., 2007. Implications of trace fossil assemblages from Late Paleozoic Glaciomarine Talchir Formation, Raniganj Basin, India. Gondwana Research 12 (4), 509-524.

Bhattacharya, J.P., 1993. The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation, Alberta foreland basin, Canada. Sequence Stratigraphy and Facies Associations, pp. 125-160.

Billings, E., 1862. On some new species of fossils from the Quebec Group: containing descriptions and figures of new or little known species of organic remains from the Silurian rocks. Geological Survey of Canada Palaeozoic Fossils 1, 96-168.

Binks, R. M., Fairhead, J. D., 1992. A plate tectonic setting for Mesozoic rifts of West and Central Africa. In: Ziegler, P.A. (Ed.), Geodynamics of Rifting. Volume II. Case History Studies on Rifts: North and South America and Africa. Tectonophysics 213, 141-151.

Blatt, H., 1982. Sedimentary petrology. San Francisco, W.H. Freeman and Company, 564 pp.

Boggs, S. Jr. 2009. Petrology of sedimentary rocks. 2nd Ed. Cambridge University Press, 597 pp.

Bottjer, D.J., 1985. Trace fossils and paleoenvironments of two Arkansas Upper Cretaceous discontinuity surfaces. Journal of Paleontology 59, 282-298.

Bridge, J. S., Droser, M. L., 1985. Unusual marginal-marine lithofacies from the Upper Devonian Catskill clastic wedge. In: Woodrow, D,. L., Sevon, W.D. (Eds.), The Catskill Delta. Geological Society of America, Special Paper 201, 143-161.

Brindley, G.W., Brown, G., 1980. Crystal Structures of Clay Minerals and Their X-ray Identification. Mineralogical Society Monograph 5, 495 pp.

Bromley, R.G., 1990. Trace Fossils: Biology and taphonomy., London, UK, Academic Division of Unwin Hyman Limited, 280 pp.

Bromley, R.G., Pemberton, S.G., Rahmani, R.A., 1984. A Cretaceous woodground: the *Teredolites* ichnofacies. Journal of Paleontology 58, 488-498.

Bruck, P.M., Forbes, W.H., Nance, D., Pickerill, R.K., 1985. *Beaconites antarcticus* in the (? Middle) Late Devonian McAras Brook Formation, Cape George, Nova Scotia. Atlantic Geology 21 (1), 87-96.

Buatois, L.A., Gingras, M.K., Mángano, M.G., Zonneveld, J.P., Pemberton, S.G., Netto, R.G., Martin, A., 2005. Colonization of brackish-water systems through time: evidence from the trace-fossil record. Palaios 20, 321-347.

Buatois, L.A., Mángano, M.G., 1993. Ecospace utilization, paleoenvironmental trends, and the evolution of early nonmarine biotas. Geology 21 (7), 595-598.

Buatois, L.A., Mángano, M.G., 2002. Trace fossils from Carboniferous floodplain deposits in western Argentina: implications for ichnofacies models of continental environments. Palaeogeography, Palaeoclimatology, Palaeoecology 183 (1–2), 71-86.

Buatois, L.A., Mángano, M.G., 2004. Animal-substrate interactions in freshwater environments: applications of ichnology in facies and sequence stratigraphic analysis of fluvio-lacustrine successions. Geological Society, London, Special Publications 228 (1), 311-333.

Buatois, L.A., Mángano, M.G., Alissa, A., Carr, T.R., 2002. Sequence stratigraphic and sedimentologic significance of biogenic structures from a late Paleozoic marginal- to open-marine reservoir, Morrow Sandstone, subsurface of southwest Kansas, USA. Sedimentary Geology 152, 99–132.

Buatois, L.A., Mángano, M.G., Carr, T.R, 1999. Sedimentology and ichnology of Paleozoic estuarine and shoreface reservoirs, Morrow Sandstone, Lower Pennsylvanian of southwest Kansas, USA. Current Research in Earth Sciences, Kansas Geological Survey Bulletin 243, part 1, 1.1 MB.

<http://www.kgs.ku.edu/Current/1999/buatois /buatois1.html> [checked 1–17–05].

Budd, G.C., 2004. Burrowing amphipods and *Eurydice pulchra* in well-drained clean sand shores, in Marine life information network: biology and sensitivity key information subprogramme (online): Plymouth, Marine Biological Association of the United Kingdom: http://www.marlin.ac.uk.

Burke, K.C., Dessauvagie, T. F. J., Whiteman, A. J., 1971. Opening of the Gulf of Guinea and geological history of the Benue Depression and Niger Delta. Nature Physical Sciences 233, 51-55.

Callaham, J., 1987. A nontoxic heavy liquid and inexpensive filters for separation of mineral grains. Journal of Sedimentary Petrology 57, 765-766.

Capowiez, Y., Cadoux, S., Bouchand, P., Roger-Estrade, J., Richard, G., Boizard, H., 2009. Experimental evidence for the role of earthworms in compacted soil regeneration based on field observations and results from a semi-field experiment. Soil Biology and Biochemistry 41 (4), 711-717.

Capowiez, Y., Pierret, A., Daniel, O., Monestiez, P., Kretzschmar, A., 1998. 3D skeleton reconstructions of natural earthworn burrow systems using CAT scan images of soil cores. Biology and Fertility of Soils 27, 51-59.

Carmona, N.B., Buatois, L.A., Ponce, J.J., Mángano, M.G., 2009. Ichnology and sedimentology of a tide-influenced delta, Lower Miocene Chenque Formation, Patagonia, Argentina: trace-fossil distribution and response to environmental stresses. Palaeogeography, Palaeoclimatology, Palaeoecology 273 (1-2), 75-86.

Cascalho, J., Fradique, C., 2007. The Sources and Hydraulic Sorting of Heavy Minerals on the Northern Portuguese Continental Margin. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Mineral in Use. Developments in Sedimentology 58, 75-110.

Cattaneo, A., Steel, R.J., 2003. Transgressive deposits: a review of their variability. Earth-Science Reviews 62 (3–4), 187-228.

Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. Journal of African Earth Sciences 35 (1), 1-43.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling M.R., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews 92 (1–2), 1-33.

Chakraborty, C., Kumar, S., Chakraborty, G.A.T., 2003. Depositional Record of Tidal-Flat Sedimentation in the Permian Coal Measures of Central India: Barakar Formation, Mohpani Coalfield, Satpura Gondwana Basin. Gondwana Research 6 (4), 817-827.

Chamberlain, C. K., Baer, J. L., 1973. *Ophiomorpha* and a new Thalassinid burrow from the Permian of Utah. Brigham Young University Geology Studies 20, 79-94.

Collinson, J., Mountney, N., Thompson, D., 2006. Sedimentary Structures. Hertfordshore, England, Terra Publishing, 292 pp.

Corbett, M.J., Fielding, C.R., Birgenheier, L.P., 2011. Stratigraphy of a Cretaceous coastal-plain fluvial succession: the Campanian Masuk Formation, Henry Mountains Syncline, Utah, USA. Journal of Sedimentary Research 81 (2), 80-96.

Cornish, F. G., 1986. The trace-fossil *Diplocraterion*: Evidence of animal-sediment interactions in Cambrian tidal deposits. Palaios 1, 478-491.

Cratchley, C.R., Jones, G.P., 1965. An interpretation of the geology and gravity anomalies of the Benue valley, Nigeria. Overseas Geological Surveys, Geophysical Paper 1, 26 pp.

Crimes, P.T., 1977. Trace fossils of an Eocene deep-sea fan, northern Spain. In: Crimes, P.T., Harper, J.C. (Eds.), Trace Fossils 2. Geologic Journal, Special Issue 9, 71–90.

Critelli, S., Lepera, E., Galluzzo, F., Milli, S., Moscatelli, M., Perrotta, S., Santantonio, M., 2007. Interpreting siliciclastic-carbonate detritals modes in foreland basin systems: an example from Upper Miocene arenites of the central Apennines, Italy. In: Arribas, J., Critelli S. Johnsson, M. J., (Eds.), Sedimentary provenance and petrogenesis: perspectives from petrography and geochemistry. Geological Society of America Special paper 420, 107-133.

Cunningham, K. J., Sukop, M. C., Alvarez, H., Huang, P. F., Curran, H. A., Renken, R. A., Dixon, J. F., 2009. Prominence of ichnologically influenced macroporosity in the karst Biscayne Aquifer: Stratiform “super-K” zones. Geological Society of America Bulletin 121, 164–180.

D’Alessandro, A., Bromley, R.G., 1987. Meniscate trace fossils and the *Muensteria-Taenidium* problem. Palaeontology 30, 743-763.

Dahmer, G., 1937. Lebensspuren aus dem Taunusquarzit und den Siegener Schichten (Unterdevon). Preussiche Geologische Landesanstalt zu Berlin, Jahrbuch 1936, 57:523-539 not seen, cited in Nara, M., 1995. *Rosselia socialis*: a dwelling structure of a probable terebellid polychaete. Lethaia 28 (2), 171-178.

Dalrymple, R. W., 1984. Morphology and internal structure of sandwaves in the Bay of Fundy. Sedimentology 31,365-382.

Dalrymple, R.W., 1992, Tidal Depositional Systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models: response to sea level changes. Geological Association of Canada, pp. 195-218.

Dalrymple, R.W., Choi, K., 2007. Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth-Science Reviews 81, 135–174.

Dalrymple, R.W., Knight, R.J., Zaitlin, B.A., Middleton, G.V., 1990. Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay – Salmon River Estuary (Bay of Fundy). Sedimentology 37, 577–612.

Dam, G., 1990. Palaeoenvironmental significance of trace fossils from the shallow marine Lower Jurassic Neill Klinter Formation, East Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology 79, 221-248.

Dashtgard, S.E., Gingras, M.K., 2005. Facies architecture and ichnology of recent Salt-Marsh deposits: Waterside Marsh, New Brunswick Canada. Journal of Sedimentary Research 75, 596-607.

Dashtgard, S.E., Gingras, M.K., Pemberton, S.G., 2008. Grain-size controls on the occurrence of bioturbation. Palaeogeography, Palaeoclimatology, Palaeoecology, 257 (1), 224-243.

Davies, J.L., 1964. A morphogenic approach to world shorelines. Zeitschrift fur Geomorphologie 8, 127–142.

Deer, W.A., Howie, R.A., Zussman, J., 1982. Rock-Forming Minerals, 1A. Orthosilicates. Longman Group Limited, London, 2nd ed., 919 pp.

Deer, W.A., Howie, R. and Zussman, J. 1992. An introduction to the rock forming minerals. Prentice-Hall Publishers, 712 pp.

Dessauvagie, T.F.G., 1975. Explanatory note on the 1:1,000,000 geological map of Nigeria. Journal of Mining and Geology, 9, 1-28.

Dickinson, W.R., 1970. Interpreting detrital modes of graywacke and arkose. Journal of Sedimentary Petrology 40, 695-707.

Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstone. In: Zuffa, G.G., (Ed.), Provenance of Arenites. Dordrecht, Holland, D. Reidel Publishing Company, pp.333-361.

Dickinson, W.R., Bead, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Linberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geologic Society of American Bulletin 94, 222-235.

Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstones composition. American Association of Petroleum Geologists Bulletin 63, 2164-2182.

Dill, H.G., Scheel, M., Köthe, A., Botz, R., Henjes-Kunst, F., 1997. An integrated environment analysis lithofacies, chemofacies, biofacies of the Oligocene calcareous-siliciclastic shelf deposits in northern Germany. Palaeogeography, Palaeoclimatology, Palaeoecology 31, 145-174.

Doust, H., Omatsola, E., 1990. Niger Delta. In: Edwards, J.D., Santogrossi, P.A. (Eds.), Divergent/Passive Margin Basins. American Association of Petroleum Geologists Memoir 48, 201–238.

Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed.), Classification of carbonate rocks. A symposium. American Association of Petroleum Geologists Memoir, 1, 108-171.

Egbu, O.C., Obi, G.C., Okogbue, C.O., Mode, A.W., 2009. Ichnofacies and Reservoir Properties of Shoreline Deposit in the Coastal Swamp Depobelt of the Niger Delta. American Association of Petroleum Geologists Search and Discovery Article #40412.

Ehrenberg, K., 1944. Ergianzende Bemerkungen zu den seinerzeit aus dem Miozan von Burgschleintz beschriebenen Gangkeren und Bauten dekapoder Krebse: Palaeontologische Zietschrift, Berlin 23, 354-359 not seen, cited in Myrow, P. M., 1995. *Thalassinoides* and the enigma of early Paleozoic open-framework burrow systems. Palaios 10 (1), 58-74.

Ehrmann, W., Setti, M., Marinoni, L., 2005. Clay minerals in Cenozoic sediments off Cape Roberts (McMurdo Sound, Antarctica) reveal palaeoclimatic history. Palaeogeography, Palaeoclimatology, Palaeoecology 229 (3), 187-211.

Ehrmann, W.U., 1998. Implications of late Eocene to early Miocene clay mineral assemblages in McMurdo Sound (Ross Sea, Antarctica) on paleoclimate and ice dynamics. Palaeogeography, Palaeoclimatology, Palaeoecology 139, 213-231.

Ehrmann, W.U., Melles, M., Kuhn, G., Grobe, H., 1992. Significance of clay mineral assemblages in the Antarctic Ocean, Marine Geology 107, 249-273.

Ekdale, A.A., 1992. Muckraking and mudslinging: the joys of deposit feeding. In: Maples, C.G., West, R.R. (Eds.), Trace Fossils. Paleontological Society Short Course 5, 145-171.

Ekdale, A.A., Bromley, R.G., 2001, A day and a night in the life of a cleft-foot clam: *Protovirgularia-Lockeia-Lophoctenium*. Lethaia 34 (2), 119-124.

Ekdale, A.A., Bromley, R.G., Pemberton, S.G., 1984. Ichnology: trace fossils in sedimentology and stratigraphy. Society of Economic Paleontologists and Mineralogists, Short Course Notes, 15, 317pp.

Ekdale, A.A., Lamond, R.E. 2003. Behavioral cladistics of trace fossils: evolution of derived trace-making skills. Palaeogeography, Palaeoclimatology, Palaeoecology 192 (1), 335-343.

Ekdale, A.A., Lewis, D.W., 1991. Trace fossils and paleoenvironmental control of ichnofacies in a late Quaternary gravel and loess fan delta complex, New Zealand. Palaeogeography, Palaeoclimatology, Palaeoecology 81, (3–4), 253-279.

Ekwueme, B.N., Caen-Vachette, M., Onyeagocha, A.C., 1991. Isotopic ages from the Oban Massif and southeast Lokoja: implications for the evolution of the Basement Complex of Nigeria. Journal of African Earth Sciences 12 (3), 489-503.

Ekwueme, B.N., Onyeagocha, A.C., 1985. Metamorphic isograds of Uwet area, southeastern Nigeria. Journal of African Earth Sciences 3, 443-454.

Eriksson, K.A., Simpson, E.L., Mueller, W., 2006. An unusual fluvial to tidal transition in the mesoarchean Moodies Group, South Africa: a response to high tidal range and active tectonics. Sedimentary Geology 190, 13–24.

Evamy, B.D., Haremboure, J., Kamerling, P., Knaap, W.A., Molloy, F.A., Rowlands, P.H., 1978. Hydrocarbon habitat of Tertiary Niger delta. American Association of Petroleum Geologists Bulletin 62, 1–39.

Fairhead, J.D., Okereke, C.S., 1987. A regional gravity study of the West African rift system in Nigeria and Cameroon and its tectonic interpretation. Tectonophysics 143, 141–159.

Falcon-Lang, H.J., 2006. Latest Mid-Pennsylvanian tree-fern forests in retrograding coastal plain deposits, Sydney Mines Formation, Nova Scotia, Canada. Journal of the Geological Society, London 163, 81–93.

Fan, D., Li, C., 2002. Rhythmic deposition on mudflats in the mesotidal Changjiang Estuary, China. Journal of Sedimentary Research 72 (4), 543–551.

Fenies, H., Faugeres, J., 1998. Facies and geometry of tidal channel-fill deposits (Arcachon Lagoon, SW France). Marine Geology 150, 131-148.

Fenies, H., Tastet, J., 1998. Facies and architecture of an estuarine tidal bar (the Trompeloup bar, Gironde Estuary, SW France). Marine Geology 150, 149-169.

Finzel, E.S., Ridgway, K.D., Reifenstuhl, R.R., Blodgett, R.B., White, J.M., Decker, P. L., 2009. Stratigraphic framework and estuarine depositional environments of the Miocene Bear Lake Formation, Bristol Bay Basin, Alaska: onshore equivalents to potential reservoir strata in a frontier gas-rich basin. North 3 (3), 379-405.

Fitton, J.G., 1980. The Benue Trough and Cameroon Line a migrating rift system in West Africa. Earth and Planetary Science Letters 51 (1), 132-138.

Flemming, B.W., 1980. Sand transport and bedform patterns on the continental shelf between Durban and Port-Elizabeth (South-East Africa continental margin). Sedimentary Geology 26, 179-205.

Flemming, N.C., Roberts, D.G., 1973. Tectono-eustatic changes in sea level and sea-floor spreading. Nature 243, 19-22.

Floquet, M., 1991. La plate-forme nord-castillane au Crétacé supérieur (Espagne): arrière-pays ibérique de la marge passive basco-cantabrique. Sédimentation et vie Centre des Sciences de la Terre, 14, 925pp not seen, cited in Thiry, M., Jacquin, T., 1993. Clay mineral distribution related to rift activity, sea-level changes and paleoceanography in the Cretaceous of the Atlantic Ocean. Clay Minerals 28, 61-84.

Flores, G., 1973. The Cretaceous and Tertiary sedimentary basins of Mozambique and Zululand. In: Bland, G., (Ed.), Sedimentary Basins of the African Coasts. Association of Africa Geological Surveys, pp. 81-111.

Flügel, E., 2010. Microfacies of carbonate rocks: analysis, interpretation and application. (2nd ed.), Springer Heidelberg, 984pp.

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill, Austin, Texas, 170 pp.

Frankl, E.J., Cordry, E.A., 1967. The Niger Delta oil province: recent developments onshore and offshore. 7th World Petroleum Congress, Mexico City Proceedings 2, 195-209.

Freeth, S.J., 1990. The origin of the Benue Trough. In: Ofoegbu, C.O., (Ed.), The Benue Trough structure and evolution. Vieweg and Sohn, Braunschweig, pp. 217-227.

Frey, R.W., Howard, J.D., 1990. Trace fossils and depositional sequences in a clastic shelf setting, Upper Cretaceous of Utah. Journal of Paleontology 64 (5), 803-820.

Frey, R.W., Howard, J.D., Pryor, W.A., 1978. *Ophiomorpha*: its morphologic, taxonomic, and environmental significance. Palaeogeography, Palaeoclimatology, Palaeoecology 23, 199-229.

Frey, R.W., Pemberton, S.G., 1987. The *Psilonichnus* ichnocoenose, and its relationship to adjacent marine and nonmarine ichnocoenoses along the Georgia coast. Bulletin of Canadian Petroleum Geology 35 (3), 333-357.

Frey, R.W., Pemberton, S.G., Fagerstrom, J.A., 1984. Morphological, ethological, and environmental significance of the ichnogenera *Scoyenia* and *Ancorichnus*. Journal of Paleontology 58, 511-528.

Frey, R.W., Pemberton, S.G., Saunders, T.D.A., 1990. Ichnofacies and bathymetry: a passive relationship. Journal of Paleontology 64, 155-158.

Friend, P. F., 1983. Towards the field classification of alluvial architecture or sequence. In: Collinson, J.D., Lewin, J., (Eds.), Modern and Ancient Fluvial Systems. International Association of Sedimentologists, Special Publication 6, 345-354.

Friend, P.F., Slater, M.J., Williams, R.C., 1979. Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain. Journal of Geological Society of London, 146, 39-46.

Fürsich, F.T., 1974a. On *Diplocraterion* Torell 1870 and the significance of morphological features in vertical, spreiten-bearing, U-shaped trace fossils. Journal of Paleontology 48, 952-962.

Fürsich, F.T., 1974b. Ichnogenus *Rhizocorallium*, Paläontologische Zeitschrift 48 (1), 16-28.

Galloway, W.E., Hobday, D.K., 1996. Terrigenous Clastic Depositional Systems. 2nd ed., Springer Verlag, Berlin, 489 pp.

Gani, M.R., Bhattacharya, J.P., 2007. Basic building blocks and process variability of a Cretaceous delta: internal facies architecture reveals a more dynamic interaction of river, wave, and tidal processes than is indicated by external shape. Journal of Sedimentary Research 77 (4), 284-302.

Garzanti, E., Andò, S., 2007. Heavy Mineral Concentration in Modern Sands: Implications for provenance interpretation. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Mineral in Use. Developments in Sedimentology 58, 517-545.

Genik, G. J., 1993. Petroleum geology of Cretaceous-Tertiary rift basins in Niger, Chad and Central African Republic. AAPG Bulletin, 77, 1405-1434.

Gernant, R.E., 1972. The paleoenvironmental significance of *Gyrolithes* (Lebensspur). Journal of Paleontology 46, 735-741.

Gérard, J.R., Bromley, R.G., 2008. Ichnofabrics in clastic sediments: applications to sedimentological core studies: a practical guide. Association des sédimentologistes français, 100 pp.

Ghazi, S., Mountney, N.P., 2009. Facies and architectural element analysis of a meandering fluvial succession: the Permian Warchha Sandstone, Salt Range, Pakistan. Sedimentary Geology 221, 99-126.

Ghazi, S., Mountney, N.P., 2011. Petrography and provenance of the Early Permian Fluvial Warchha Sandstone, Salt Range, Pakistan. Sedimentary Geology 233, 88-110.

Ghent, E.D., Henderson, R.A. 1966. Petrology, sedimentation and paleontology of Middle Miocene graded sandstone and mudstone, Kaiti Beach, Gisborne. Transactions of the Royal Society of New Zealand, Geology 4, 147–169.

Gibert, J. M. de., Martinell, J., 1995. Sedimentary substrate and trace fossil assemblages in marine Pliocene deposits in Northeast Spain. Geobios, Memoir Special, 18. 197-206.

Gibling, M. R., 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research 76, 731-770.

Gibling, M.R., Nanson, G.G., Maroulis, J.C., 1998. Anastomosing river sedimentation in the Channel Country of central Australia. Sedimentology 45, 595-619.

Gibson, J.W., Hickin, E.J., 1997. Inter- and supratidal sedimentology of a fjord-head estuary, south-western British Columbia. Sedimentology 44 (6), 1031-1051.

Gingras, M.K., MacEachern, J.A., Dashtgard, S.E., 2011. Process ichnology and the elucidation of physico-chemical stress. Sedimentary Geology 237 (3–4), 115-134.

Gingras, M.K., Mendoza, C.A., Pemberton, S.G., 2004. Fossilized worm burrows influence the resource quality of porous media. American Association Petroleum Geologists Bulletin 88 (7), 875-883.

Gingras, M.K., Pemberton, S., Henk, F., MacEachern, J.A., Mendoza, C., Rostron, B., O'Hare, R., Spila, M., Konhauser, K., 2007. Applications of ichnology to fluid and gas production in hydrocarbon reservoirs. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G., (Eds.), Applied Ichnology. SEPM (Society for Sedimentary Geology), Short Course Notes 52, 129–143.

Gingras, M.K., Pemberton, S., Saunders, T., 1999. The Ichnology of Modern and Pleistocene brackish-water deposits at Willapa Bay, Washington: variability in estuarine settings. Palaios 14, 352-374.

Gingras, M.K., Räsänen, M.E., Pemberton, S.G., Romero, L.P., 2002a. Ichnology and sedimentology reveal depositional characteristics of bay-margin parasequences in the Miocene Amazonian foreland basin. Journal of Sedimentary Research 72 (6), 871-883.

Gingras, M.K., Räsänen, M.E., Ranzi, A., 2002b. The significance of bioturbated inclined heterolithic stratification in the southern part of the Miocene Solimoes Formation, Rio Acre, Amazonia Brazil. Palaios 17 (6), 591-601.

Goldring, R., 1995. Organisms and the substrate: response and effect. Geological Society London, Special Publications 83, 151-180.

Goldring, R., 1996. The sedimentological significance of concentrically laminated burrows from Lower Cretaceous Ca-bentonites, Oxfordshire. Journal of the Geological Society, London 153, 255-263.

Graham, J. R. and J. E. Pollard, 1982, Occurrence of the trace fossil *Beaconites antarcticus* in the lower carboniferous fluviatile rocks of county Mayo, Ireland, Palaeogeography, Palaeoclimatology, Palaeoecology 38 (3), 257-268.

Grant, N., 1971. South Atlantic, Benue Trough, and Gulf of Guinea Cretaceous Triple Junction, Geological Society of America Bulletin 82, 2295-2298.

Hakes, W.G., 1976. Trace fossils and depositional environment of four clastic units, Upper Pennsylvanian megacyclothems, northeast Kansas. University of Kansas Paleontological Contributions, Article 63, 46 pp.

Hakes, W.G., 1985. Trace fossils from brackish-marine shales, Upper Pennsylvanian of Kansas, U.S.A. In: Curran, H.E. (Ed.), Biogenic Structures: their use in interpreting depositional environments. Society of Economic Paleontologists and Mineralogists, Special Publication 35, 21– 35.

Haldeman, S.S., 1840. Supplement to Number One of "A monograph of the *Limniades*, or fresh-water univalve shells of North America," containing descriptions of apparently new animals in different classes, and the names and characters of the subgenera in *Paludina* and *Anculosa.* J. Dobson, Philadelphia not seen, cited in Alpert, S.P., 1974. Systematic review of the genus *Skolithos*. Journal of Paleontology 48, 661-669.

Hall, J., 1843. Geology of New York. Part IV. Survey of the Fourth Geological District. Carroll and Cook, Albany. 683 pp. not seen, cited in Alpert, S.P., 1974. Systematic review of the genus *Skolithos*. Journal of Paleontology 48, 661-669.

Hall, J., 1847. Palaeontology of New York. Vol. 1, C. Van Benthuysen, Albany, 338 pp., not seen, cited in Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma., Journal of Paleontology 56 (4), 843-881.

Heard, T.G., Pickering, K.T., 2008. Trace fossils as diagnostic indicators of deep-marine environments, Middle Eocene Ainsa-Jaca basin, Spanish Pyrenees. Sedimentology 55 (4), 809-844.

Heer, O., 1877. Flora fossilis Helvetiae. Die vorweltliche Flora der Schweiz. J, Würster and Company, 182 pp. not seen, cited in Keighley, D., Pickerill, R., 1994. The ichnogenus *Beaconites* and its distinction from *Ancorichnus* and *Taenidium*. Palaeontology 37 (2), 305-338.

Helmold, K. P., 1985. Provenance of feldspathic sandstones - The effect of diagenesis on provenance interpretations: A review. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Dordrecht, Holland, D. Reidel Publishing Company, pp. 139-163.

Hillier, S., 1995. Erosion, sedimentation and sedimentary origin of clays. In: Velde, B. (Ed.), Origin and mineralogy of clays. Springer Berlin Heidelberg, pp. 162-219.

Hopkins, J.C., 1985. Channel-fill deposits formed by aggradation in deeply scoured, superimposed distributaries of the lower Kootenai Formation (Cretaceous). Journal of Sedimentary Petrology 55 (1), 42-52.

Hoque, M., 1977. Petrographic differentiation of tectonically controlled Cretaceous Sedimentary cycles, South-eastern Nigeria. Sedimentary Geology 17, 235–245.

Hoque, M., 1984. Pyroclastics from the lower Benue Trough of Nigeria and their tectonic implications. Journal of African Earth Sciences 2, 351 – 358.

Hoque, M., Ezepue, M.C., 1977. Petrology and paleogeography of the Ajali Sandstone. Journal of Mining and Geology 14, 16 - 22.

Hoque, M., Nwajide, C.S., 1984. Tectono-sedimentological evolution of an elongate Intracratonic basin (Aulacogen): the case of the Benue Trough of Nigeria. Nigerian Journal of Mining and Geology 21, 19-26.

Hori, K., Saito, Y., Zhao, Q., Cheng, X., Wang, P., Sato, Y., Li, C., 2001. Sedimentary facies of the tide-dominated paleo-Changjiang (Yangtze) estuary during the last transgression. Marine Geology 177, 331-351.

Horton, J.W., Zullo, V.A., 1991. The geology of the Carolinas. Carolina Geological Society. Fiftieth anniversary volume, 384 pp.

Houghton, H. F., 1980. Refined techniques for staining plagioclase and alkali feldspars in thin section. Journal of Sedimentary Petrology 50, 629-631.

Hovikoski, J., Rasanen, M., Gingras, M., Ranzi, A., Melo, J., 2008. Tidal and seasonal controls in the formation of Late Miocene inclined heterolithic stratification deposits, western Amazonian foreland basin. Sedimentology 55, 499-530.

Howard, J.D., Frey, R.W., 1984. Characteristic trace fossils in nearshore to offshore sequences, Upper Cretaceous of east-central Utah. Canadian Journal of Earth Sciences 21, 200-219.

Howard, J.D., 1966. Characteristic trace fossils in Upper Cretaceous sandstones of the Book Cliffs and Wasatch Plateau, Utah. Geological and Mineralogical Survey Bulletin 80, 35-53.

Howard, J.D., Reineck, H.E., 1979. Sedimentary structures of a “high energy” beach to offshore sequence Ventura Port Hueneme area, California, U.S.A. (abstr.). American Association of Petroleum Geologists Bulletin 63, 468–469.

Howell, J.A., Skorstad, A., MacDonald, A., Fordham, A., Flint, S., Fjellvoll, B., and Manzocchi, T., 2008. Sedimentological parameterization of shallow-marine reservoirs. Petroleum Geoscience 14, 17–34.

Hubbard, S.M., Gingras, M.K., Pemberton, S.G., 2004. Paleoenvironmental implications of trace fossils in estuarine deposits of the Cretaceous Bluesky Formation, Cadotte region, Alberta, Canada. Fossils and Strata 51, 68-87.

Humphreys, B., Morton, A.C., Hallsworth, C.R., Gatliff, R.W., Riding, J.B., 1991. An integrated approach to provenance studies: a case example from the Upper Jurassic of the Central Graben, North Sea. In: Morton, A.C., Todd, S.P., Houghton, P.D.W. (Eds.), Developments in Sedimentary Provenance Studies. Geological Society Special Publication 57, 251-262.

Ibrahim, M.I.A., 2002. Late Albian-Middle Cenomanian palynofacies and palynostratigraphy, Abu Gharadig-5 well, Western Desert, Egypt. Cretaceous Research 23, 775-788.

Igbozurike, M. U., 1975. Vegetation types. In: Ofomata, G.E.K. (Ed.), Nigeria in Maps: Eastern States. Midwest Mass Communication Corporation, Benin City, Nigeria., Ethiope Publishing, 146 pp.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sares, S.W., 1984. The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. Journal of Sedimentary Petrology 54, 212-220.

Ingersoll, R.V., Suczek, C.A., 1979. Petrology and provenance of Neogene sands from Nicobar and Bengala fans, DSDP Sites 211 and 218. Journal of Sedimentary Petrology 49, 1217-1228.

Inyang, P.E.B., 1975. Climatic Regions. In: Ofomata, G.E.K. (Ed.), Nigeria in Maps: Eastern States. Midwest Mass Communication Corporation, Benin City, Nigeria., Ethiope Publishing, 146 pp.

James, U.P., 1879. Description of new species of fossils and remarks on some others, from the Lower and Upper Silurian rocks of Ohio. The Paleontologist 3: 17–24, not seen, cited in Seilacher, A., Seilacher, E., 1994. Bivalvian trace fossils: a lesson from actuopaleontology. Courier Forschungsinstitut Senckenberg 169, 5-15.

Jan du Chêne, R., Onyike, M.S., Sowumi, M.A., 1978. Some new Eocene pollen of the Ogwashi-Asaba Formation, Southeastern Nigeria. Revista de Espanol Micropaleontologie 10, 285–322.

Jeans, C.V., 1978. The origin of the Triassic Clay assemblages of Europe with special reference to the Keuper Marl and Rhaetic of parts of England. Philosophical Transactions of the Royal Society of London A289, 549-639.

Johansson, M., Braakenburg, N. E., Stow, D. A., Faugères, J. C., 1998. Deep-water massive sands: facies, processes and channel geometry in the Numidian Flysch, Sicily. Sedimentary geology, 115 (1), 233-265.

Johnson, H.D., Baldwin, C.T., 1996. Shallow clastic seas. In: Reading, H. G., (Ed.), Sedimentary environments: processes, facies and stratigraphy. Blackwell Science, United Kingdom, pp. 232-280.

Johnsson, M. J., 1993. The system controlling the composition of clastic sediments. In: Johnsson, M.J., Basu, A. (Eds.), Processes controlling the composition of clastic sediments. Geological Society of America Special paper 284, 1-19.

Jones, J.A., Hartley, A.J., 1993. Reservoir characteristics of a braid-plain depositional system: the Upper Carboniferous Pennant Sandstone of South Wales. Geological Society, London, Special Publications 73 (1), 143-156.

Keighley, D., Pickerill, R., 1994. The ichnogenus *Beaconites* and its distinction from *Ancorichnus* and *Taenidium.* Palaeontology 37 (2), p. 305-338.

Kelly, S.R.A., Bromley, R.G., 1984. Ichnological nomenclature of clavate borings. Palaeontology 27 (4), 793-807.

King, L.C., 1950. Outline and description of Gondwanaland. Geological Magazine 87, 353-359.

Kitazawa, T., 2007. Pleistocene macrotidal tide-dominated estuary–delta succession, along the Dong Nai River, southern Vietnam. Sedimentary Geology 194 (1–2), 115-140.

Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology 27 (6), 613-629.

Knaust, D., 1998. Trace fossils and ichnofabrics on the Lower Muschelkalk carbonate ramp (Triassic) of Germany: tool for high-resolution sequence stratigraphy. Geologische Rundschau 87, 21–31.

Knox, G.J., Omatsola, E.M., 1989. Development of the Cenozoic Niger Delta in terms of the ‘‘Escalator Regression model’’ and impact on hydrocarbon distribution. In: Van der Linden, W.J.M., Cloetingh, S.A.P., Kaasschieter, J.P.K., Van der Graaf, W.J.E., Vandenberghe, J., Van der Gun, J.A.M. (Eds.), Coastal Lowlands, Geology and Geotechnology. Royal Geological and Mining Society of the Netherlands (K.N.G.M.G.) Symposium, Dordrecht, Kluwer Academic Publishers, pp. 181–202.

Kogbe, C.A., 1976. The Cretaceous and Paleogene sediments of Southern Nigeria. In: Kogbe, C. A., (Ed.), Geology of Nigeria. Elizabethan Publishing Company, Lagos, pp. 273-282.

Kohsiek, L.H.M., Terwindt, J.H.J., 1981. Characteristics of foreset and topset bedding in megaripples related to hydrodynamic conditions on an intertidal shoal. In: Nio, S.D., Schuttenhelm, R.T.E., van Weering, Tj.C.E. (Eds.), Holocene marine sedimentation in the North Sea Basin. Special Publication 5, International Association of Sedimentologist: Boston, Blackwell Scientific Publication, pp. 27-37.

Komatsubara, J., 2004. Fluvial architecture and sequence stratigraphy of the Eocene to Oligocene Iwaki Formation, northeast Japan: channel-fills related to the sea-level change. Sedimentary Geology, 168 (1), 109-123.

Kraus, M.J., Bown, T.M., 1993. Short-term sediment accumulation rates determined from Eocene alluvial paleosols. Geology 21, 743–746.

Kraus, M.J., Davies-Vollum K.S., 2004. Mudrock-dominated fills formed in avulsion splay channels: examples from the Willwood Formation, Wyoming. Sedimentology 51, 1127–1144.

Kraus, M.J., Hasiotis, S.T., 2006. Significance of different modes of rhizolith preservation to interpreting paleoenvironmental and paleohydrologic settings: examples from Paleogene paleosols, Bighorn Basin, Wyoming, U.S.A. Journal of Sedimentary Research 76, 633-646.

Kreisa, R.D., Moiola, R.J., 1986. Sigmoidal tidal bundles and other tide-generated sedimentary structures of the Curtis Formation. Geological Society of America Bulletin 97, 381-387.

Kvale, E. P., 2006. The origin of neap–spring tidal cycles. Marine Geology 235 (1-4), 5-18.

Kvale, E.P., Cutright, J., Bilodeau, D., Archer, A., Johnson, H.R., Pickett, B., 1995. Analysis of modern tides and implications for ancient tidalites. Continental Shelf Research 15, 1921-1943.

Ladipo, O.K., 1988. Paleogeography, sedimentation and tectonics of the Upper Cretaceous Anambra Basin, South-eastern Nigeria. Journal of African Earth Sciences 7, 865-871.

Ladipo, O.K., 1986. Tidal shelf depositional model for the Ajali Sandstone, Anambra Basin, southern Nigeria. Journal of African Earth Sciences 5, 177–185.

Lee, K.E., Foster, R.C., 1991. Soil fauna and soil structure. Australian Journal of Soil Research 29, 745– 775.

Leithold, E.L., Bourgeois, J., 1984. Characteristics of coarse-grained sequences deposited in nearshore, wave-dominated environments ?examples from the Miocene of south-west Oregon. Sedimentology 31 (6), 749-775.

Lemiski, R.T., Hovikoski, J., Pemberton, S.G., Gingras, M., 2011. Sedimentological, ichnological and reservoir characteristics of the low-permeability, gas-charged Alderson Member (Hatton gas field, southwest Saskatchewan): implications for resource development. Bulletin of Canadian Petroleum Geology 59 (1), 27-53.

Leymerie, M.A., 1842. Suite de mémoire sur le terrain Crétacé du département de l'Aube. Mémoires de la Société Géologique de France 5, 1-34. In: Kelly, S.R., Bromley, R.G., 1984. Ichnological nomenclature of clavate borings. Palaeontology 27 (4), 793-807.

Lihou, J.C., Mange-Rajetzky, M.A., 1996. Provenance of the Sardona Flysch, eastern Swiss Alps: example of high-resolution heavy mineral analysis applied to an ultrastable assemblage. Sedimentary Geology 105, 141-157.

Lindholm, R.C., Finkelman, R.B., 1972. Calcite staining; semiquantitative determination of ferrous iron. Journal of Sedimentary Research 42 (1), 239-242.

Longhitano, S., 2008. Sedimentary facies and sequence stratigraphy of coarse-grained Gilbert-type deltas within the Pliocene thrust-top Potenza Basin (Southern Apennines, Italy). Sedimentary Geology 210, 87-110.

Longhitano, S.G., Mellere, D., Steel, R.J., Ainsworth, R.B., 2012. Tidal depositional systems in the rock record: A review and new insights. Sedimentary Geology 279, 2-22.

Lubeseder, S., Redfern, J., Boutib, L., 2009. Mixed siliciclastic-carbonate shelf sedimentation—Lower Devonian sequences of the SW Anti-Atlas, Morocco. Sedimentary Geology 215, 13-32.

Lundgren, SAB 1891. Studier öfver fossilförande Iosa block. Gcohgiska Foreningens i Stockholm Forhandlingar 13, 111-121, not seen cited in Frey, R.W., Howard, J.D., Pryor, W. A., 1978. *Ophiomorpha:* Its morphologic, taxonomic, and environmental significance., Palaeogeography, Palaeoclimatology, Palaeoecology 23, 199-229.

MacEachern, J.A., Burton, J.A., 2000. Firmground *Zoophycos* in the Lower Cretaceous Viking Formation, Alberta: a distal expression of the *Glossifungites* ichnofacies. Palaios 15, 387-389.

MacEachern, J.A., Gingras, M.K., Bann, K.L., Pemberton, S.G., 2007. The ichnofacies paradigm: high-resolution palaeoenvironmental interpretation of the rock record. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. Society of Economic Paleontologists and Minerialogists Short Course Notes 52, 27-64.

MacEachern, J.A., Hobbs, T.W., 2004. The ichnological expression of marine and marginal marine conglomerates and conglomeratic intervals, Cretaceous Western Interior Seaway, Alberta and northeastern British Columbia. Bulletin of Canadian Petroleum Geology 52 (1), 77-104.

MacEachern, J.A., Pemberton, S.G., 1994. Ichnological aspects of incised valley fill systems from the Viking Formation of the Western Canada Sedimentary Basin, Alberta, Canada. Special Publication-Society of Economic Paleontologists and Mineralogists 51, 129-129.

MacEachern, J.A., Raychaudhuri, I., Pemberton, S.G., 1992. Stratigraphic application of the Glossifungites ichnofacies: Delineating discontinuities in the rock record. In: Pemberton, S.G. (Ed.), Applications of ichnology to petroleum exploration. Society of Economic Paleontologists and Mineralogists, Core Workshop 17, 169-198.

Mángano, M.G., Buatois, L.A., West, R.R., Maples, C.G., 1998. Contrasting behavioral and feeding strategies recorded by tidal-flat bivalve trace fossils from the Upper Carboniferous of eastern Kansas, Palaios 13 (4), 335-351.

Mange, M.A., Maurer, H.F.W., 1992. Heavy Minerals in Colour. Chapman and Hall, London.

Mange, M.A., Otvos, E.G., 2005. Gulf coastal plain evolution in West Louisiana: heavy mineral provenance and Pleistocene alluvial chronology. Sedimentary Geology 182, 29-57.

Mange-Rajetzky, M.A., 1995. Subdivision and correlation of monotonous sandstone sequences using high resolution heavy mineral analysis, a case study: the Triassic of the Central Graben. In: Dunay, R.E., Hailwood, E.A. (Eds.), Non-Biostratigraphical methods of dating and correlation, Special Publication Geological Society of London 89, 23–30.

Martinius, A.W., Van den Berg, J.H., 2011. Atlas of sedimentary structures in estuarine and tidally-influenced river deposits of the Rhine-Meuse-Scheldt system: their application to the interpretation of analogous outcrop and subsurface depositional systems. EAGE Publications, Netherlands, 298 pp.

Maurin, J.C., Benkhelil, J., Robineau, B., 1986. Fault rocks of the Kaltungo lineament, NE Nigeria and their relationship with Benue Trough tectonics. Journal of the Geological Society, London 143, 587-599.

McBride, E.F., 1985. Diagenetic processes that affect provenance determinations in sandstone. In: Zuffa, G.G., (Ed.), Provenance of Arenites. Dordrecht, Holland, D.Reidel Publishing Company, pp. 95-113.

McCoy, F., 1850. On some genera and species of Silurian Radiata in the collection of the University of Cambridge. Annales and Magazine of Natural History, Series 2 (6), 270–290 not seen, cited in Ekdale, A.A., Bromley, R.G., 2001. A day and a night in the life of a cleft-foot clam: *Protovirgularia*-*Lockeia*-*Lophoctenium*. Lethaia 34 (2), 119-124.

McCubbin D.G., 1982. Barrier-Island and strand-plain facies. In: Scholle, P.A., Spearing, D. (Ed.), Sandstone depositional environments. American Association of Petroleum Geologists Memoir 31, 247-279.

McIlroy, D., 2004. Ichnofabrics and sedimentary facies of a tide-dominated delta: Jurassic Ile Formation of Kristin Field, Haltenbanken, Offshore Mid-Norway. In: McIlroy, D. (Ed.), The Application of ichnology to paleoenvironmental and stratigraphic analysis. Geological Society London, Special Publications 228, 237-272.

Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth Science Review 22, 261-308.

Miall, A.D., 1996. The Geology of fluvial deposits. Berlin, Springer, 582 pp.

Miller, S.A., 1875. Some new species of fossils from the Cincinnati group and remarks upon some described forms. Cincinnati Quaternary Journal of Science 2 (4), 349-355 not seen, cited in Fürsich, F. T., 1974. On *Diplocraterion* Torell 1870 and the significance of morphological features in vertical, spreiten-bearing, U-shaped trace fossils. Journal of Paleontology 48, 952-962.

Mode, A.W., 1993. Ethology and paleoenvironmental significance of trace fossils from Cenomanian – Turonian sediments in the Upper Benue Trough, Nigeria. Journal of Mining and Geology 29, 111 – 124.

Mode, A.W., 2002. Hydrocarbon evaluation of Campanian-Maastrichtian strata within a sequence stratigraphic framework, southeastern Anambra basin, Nigeria. Unpublished Ph.D thesis, University of Nigeria, Nsukka, 225 pp.

Morton, A.C., Hallsworth, C., 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sedimentary Geology 90, 241-256.

Morton, A.C., Hallsworth, C.R., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. Sedimentary Geology 124, 3–29.

Murakoshi, N., Masuda, F., 1992. Estuarine, barrier-island to strand-plain sequence and related ravinement surface developed during the last interglacial in the Paleo-Tokyo Bay, Japan. Sedimentary Geology 80 (3), 167-184.

Murat, R.C., 1972. Stratigraphy and paleogeography of the Cretaceous and Lower Tertiary in southern Nigeria. In: Dessauvagie, T.F.J., Whiteman, A.J. (Eds.), African Geology. University of Ibadan Press, Nigeria, pp. 251–266.

Myannil, R.M. 1966. O vertikalnykh norkakh za-ryvaniya v Ordovikskikh izvestiyakakh Pribal-tiki (A small vertically excavated cavity in Baltic Ordovician limestone) in Organizm i sreda v gedogischoskum proshlom, pp. 200-207. Akad Nauk, not seen cited in Frey, R.W., Howard, J.D., 1981. *Conichnus* and *Schaubcylindrichnus*: redefined trace fossils from the Upper Cretaceous of the Western Interior. Journal of Paleontology 55 (4), 800-804.

Myrow, P.M., 1995. *Thalassinoides* and the enigma of early Paleozoic open-framework burrow systems. Palaios 10 (1), 58-74.

Nara, M., 1995. *Rosselia socialis*: a dwelling structure of a probable terebellid polychaete, Lethaia 28 (2), 171-178.

Nara, M., 2000. Paleoecological and paleoenvironmental studies from trace fossils. In: Nara, M., (Ed.), Dynamic Paleoecology: interaction between paleoenvironments and fossil benthic communities. Topics in Paleontology, No. 1 (in Japanese): Palaeontological Society of Japan, Tokyo, pp. 69–95.

Nara, M., 2002. Crowded *Rosselia socialis* in Pleistocene inner shelf deposits: Benthic paleoecology during rapid sea-level rise. Palaios, 17:268–276.

Neto de Carvalho, C., Rodrigues, N.P.C., 2007. Formas compuestas de *Asterosoma ludwigae* Schlirf, 2000 en el Jurásico de la Cuenca Lusitánica (Portugal): análisis icnotaxonómico. In: Meléndez, G., Herrera, Z., Delvene, G., Azanza, B. (Eds.), Los Fósiles y la Paleogeografía - XVII Jornadas de la Sociedad Española de Paleontología. Publicaciones del Seminario de Paleontología de Zaragoza (SEPAZ) 5 (2), 388-396.

Netto, R.G., Buatois, L.A., Mángano, M.G., Balistieri, P., 2007. *Gyrolithes* as a multipurpose burrow: An ethologic approach. Revista Brasileira de Paleontologia 10 (3), 157-168.

Nichols, E., Spector, S., Louzada, J., Larsen, T., Amezquita, S., Favila, M. E., 2008. Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. Biological Conservation 141 (6), 1461-1474.

Nichols, G., 1999. Sedimentology and Stratigraphy. Blackwell Publishing Oxford, United Kingdom, 355 pp.

Nichols, G., 2009. Sedimentology and Stratigraphy. 2nd Ed. Blackwell Publishing Oxford, United Kingdom, 419 pp.

Nicholson, H. A., 1873. Contributions to the Study of the Errant Annelides of the Older Palaeozoic Rocks. Proceedings of the Royal Society of London, vol. 21, no. 139-147, p. 288-290 not seen, cited in Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma. Journal of Paleontology 56 (4), 843-881.

Nigerian Geological Survey Agency, 2009. Geological Map of Nigeria. Published by the Authority of the Federal Republic of Nigeria.

Nio, S.N., Yang, C.S., 1991. Sea-level fluctuations and the geometric variability of tide-dominated sandbodies. Sedimentary Geology 70, 161-193.

Nouidar, M., Chellai, E.H., 2001. Facies and sequence stratigraphy of an estuarine incised-valley fill: Lower Aptian Bouzergoun Formation, Agadir Basin, Morocco. Cretaceous Research 22 (1), 93-104.

Nwachukwu, S.O., 1972. The tectonic evolution of the southern portion of the Benue Trough, Nigeria. Geological Magazine 109, 411-419.

Nwadinigwe, C.A., 1992. Wax and resin characteristics of Nigeria's lignites and sub-bituminous coals. Journal of Mining and Geology 28 (1), 75-80.

Nwajide, C.S., 1980. Eocene tidal sedimentation in the Anambra Basin, Southern Nigeria. Sedimentary Geology 25, 189-207.

Nwajide, C.S., 2005. Anambra Basin of Nigeria: Synoptic basin analysis as a basis for evaluating its hydrocarbon prospectivity. In: Okogbue, C.O. (Ed.) Hydrocarbon potentials of the Anambra basin: geology, geochemistry and geohistory perspectives. Proceedings of the 1st seminar organized by Petroleum Technology Development Fund Chair in Geology, University of Nigeria, Nsukka, pp.1-46.

Nwajide, C. S., 2013. Geology of Nigeria's Sedimentary Basins. CSS Bookshops Limited, Lagos. 565 pp.

Nwajide, C.S., Reijers, T.J.A., 1996. Geology of the Southern Anambra Basin. In: Reijers, T.J.A. (Ed.), Selected Chapters on Geology. Shell Petroleum Development Company, Warri, pp. 133–148.

Obaje, N.G., 2009. Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Sciences. Springer-Verlag Berlin Heidelberg, pp. 13-30.

Obi, G.C., 2000. Depositional Model for the Campanian-Maastrichtian Anambra Basin, Southern Nigeria. Unpublished Ph.D. Thesis, University of Nigeria, Nsukka, 291 pp.

Obi, G.C., Okogbue, C.O., 2004. Sedimentary response to tectonism in the Campanian-Maastrichtian succession, Anambra Basin, Southeastern Nigerian. Journal Africa Earth Sciences 38, 99–108.

Obi, G.C., Okogbue, C.O., Nwajide, C.S., 2001. Evolution of the Enugu Cuesta: a tectonically driven erosional process. Global Journal of Pure Applied Sciences 7, 321-330.

Obiora, S.C., Umeji, A.C., 2005. Petrography of some altered intrusive rocks from the lower Benue Trough, Nigeria. Journal of Mining and Geology 41, 1 – 9.

Oboh-Ikuenobe, F.E., Obi, C.G., Jaramillo C.A., 2005. Lithofacies, palynofacies and sequence stratigraphy of Paleogene strata in Southeastern Nigeria. Journal of African Earth Sciences 41, 79-102.

Odigi, M.I., 1986. Significance of heavy-mineral suites from Cretaceous sediments of part of the southern Benue Trough, Nigeria. Journal of African Earth Sciences 5 (6), 665-674.

Odunze, O.S., Obi, G.C., 2011. New perspective on the lithostratigraphy and depositional environment of the Imo Formation in the Southern Benue Trough, Journal of Geology and Mining 47.

Ofomata, G.E.K., 1975. Nigeria in Maps: Eastern States. Midwest Mass Communication Corporation, Benin City, Nigeria, Ethiope Publishing, 146 pp.

Ofomata, G.E.K., 2002. Relief, drainage and landforms. In: Ofomata, G.E.K. (Ed.), A survey of the Igbo Nation. African first publishers, Ibadan, 703 pp.

Ogala, J., Siavalas, G., Christanis, K., 2012. Coal petrography, mineralogy and geochemistry of lignite samples from the Ogwashi–Asaba Formation, Nigeria. Journal of African Earth Sciences 66–67, 35-45.

Ojoh, K. A., 1992. The southern part of the Benue Trough (Nigeria) Cretaceous stratigraphy, basin analysis, paleo-oceanography and geodynamic evolution in the Equatorial domain of the South Atlantic. Nigerian Association of Petroleum Explorationists' Bulletin 7 (2), 131-152.

Okay, N., Ergün, B., 2005. Source of the basinal sediments in the Marmara Sea investigated using heavy minerals in the modern beach sands. Marine Geology 216, 1-15.

Okezie, C.N., Onuogu, S.A., 1985. The lignites of Southeastern Nigeria. A summary of available information. Geological Survey of Nigeria Occasional Paper 10, 28 pp.

Okezie, L.N., 1974. Geological Map of Nigeria, Scale 1:2,000,000. Geological Survey of Nigeria.

Olade, M.A., 1975. Evolution of Nigeria's Benue Trough (aulacogen): a tectonic model. Geological Magazine 112 (6), 575-583.

Olóriz, F., Rodríguez-Tovar, F.J., 2000. Diplocraterion: a useful marker for sequence stratigraphy and correlation in the Kimmeridgian, Jurassic (Prebetic Zone, Betic Cordillera, southern Spain). Palaios 15 (6), 546-552.

Oloto, I. N., 1984. A Palynological Study of the Late Cretaceous and Tertiary boreholes from Southern Nigerian Sedimentary Basin, Doctoral dissertation, University of Sheffield, Department of Geology.

Oomkens, E., 1974. Lithofacies relations in the Quaternary Niger delta complex. Sedimentology 21, 195–222.

Orajaka, I.P., Onwemesi, G., Egboka, B.C.E., Nwankor, G.I., 1990. Nigerian Coal. Mining magazine 162, 446-451

Oti, M.N., Postma, G., 1995. Causes of architectural variation in Delta. In: Postma, G., (Ed.), Geology of Deltas. Rotterdam, Netherlands, A. A. Balkema, pp. 3-16.

Otto, E. von. 1854 Additamente zur Flora des Quadergebirges in Sachsen. Leipzig, Heft 2: 53 pp., not seen, cited in Carmona, N.B., Buatois, L.A., Mángano, M.G., Bromley, R.G., 2008. Ichnology of the Lower Miocene Chenque Formation, Patagonia, Argentina: animal-substrate interactions and the modern evolutionary fauna. Ameghiniana 45 (1), 93-112.

Owen, R.A., Owen, R.B., Renaut, R.W., Scott, J.J., Jones, B., Ashley, G.M., 2008. Mineralogy and origin of rhizoliths on the margins of saline, alkaline Lake Bogoria, Kenya Rift Valley. Sedimentary Geology 203 (1-2), 143-163.

Pearson, N. J., Mángano, M.G., Buatois, L.A., Casadío, S., Raising, M.R., 2012. Ichnology, sedimentology, and sequence stratigraphy of outer-estuarine and coastal-plain deposits: implications for the distinction between allogenic and autogenic expressions of the *Glossifungites* ichnofacies. Palaeogeography, Palaeoclimatology, Palaeoecology, 333, 192-217.

Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the Planolites-Paleophycus dilemma. Journal of Paleontology 56 (4), 843-881.

Pemberton, S.G., Gingras, M.K., 2005. Classification and characterizations of biogenically enhanced permeability. American Association of Petroleum Geologists Bulletin 89 (11), 1493-1517.

Pemberton, S.G., MacEachern, J.A., Frey, R.G., 1992. Trace fossil facies model: environmental and allostratigraphic significance. In: Walker, R.G., James, N.P., (Eds.), Facies Models: response to sea level change. Newfoundland, Canada, Geological Association of Canada, pp. 47-72.

Pemberton, S.G., MacEachern, J.A., Saunders, T., 2004. Stratigraphic applications of substrate-specific ichnofacies: delineating discontinuities in the rock record. In: McIlroy, D. (Ed.) The application of ichnology to palaeoenivronmental and stratigraphic analysis. Geological Society Special Publications 228, 29-62.

Pemberton, S.G., Wightman, D.M., 1992. Ichnological characteristics of brackish water deposits. In: Pemberton, S.G., (Ed.), Applications of Ichnology to Petroleum Exploration: a core workshop. Society of Economic Paleontologists and Minerialogists Core Workshop 17, 141-167.

Petters, S.W., 1978. Mid-Cretaceous paleoenvironments and biostratigraphy of the Benue Trough, Nigeria. Geological Society of America Bulletin 89, 151-154.

Petters, S.W., 1991. Regional Geology of Africa (Lecture Notes in Earth Sciences). Springer-Verlag, Berlin 40, 722 pp.

Petters, S.W. 1995. Foraminiferal biofacies in the Nigerian rift and continental margin deltas. In: Oti, M.N., Postma, G. (Eds.), Geology of Deltas. Rotterdam, Netherlands, A. A. Balkema, pp. 219-235.

Pettijohn, F.J., 1975. Sedimentary Rocks. Harper and Row, New York, (3rd ed.), 628 pp.

Pettijohn, F.J., Potter, P.E., Siever, R., 1987. Sand and sandstone. (2nd ed.), Springer-Verlag, 533 pp.

Phillips, C., McIlroy, D., Elliott, T., 2011. Ichnological characterization of Eocene/Oligocene turbidites from the Grès d'Annot Basin, French Alps, SE France. Palaeogeography, Palaeoclimatology, Palaeoecology 300 (1–4), 67-83.

Pickerill, R.K., Donovan, S.K., Dixon, H.L., 1992. The Richmond Formation of eastern Jamaica revisited-further ichnological observations. Caribbean Journal of Science 28, 89-98.

Pickerill, R.K., Donovan, S.K., Portell, R.W., 2003. *Teredolites longissimus* Kelly & Bromley from the Miocene Grand Bay Formation of Carriacou, the Grenadines, Lesser Antilles. Scripta Geologica 125, 1-9.

Plink-Björklund, P., 2005. Stacked fluvial and tide-dominated estuarine deposits in high frequency (fourth-order) sequences of the Eocene Central Basin, Spitsbergen. Sedimentology 52, 391–428.

Pollard, J.E., 1981. A comparison between the Triassic trace fossils of Cheshire and South Germany. Palaeontology 24, 555–588.

Ponte, F.C., Asmus, H.E., 1978. Geological framework of the Brazilian continental margin. Geologische Rundschau 61, 201-235.

Pontén, A., Plink-Björklund, P., 2009. Regressive to transgressive transits reflected in tidal bars, Middle Devonian Baltic Basin, Sedimentary Geology 218, (1–4), 48-60.

Posamentier, H.W., Allen, G.P., 1999. Siliciclastic sequence stratigraphy: concepts and applications. SEPM (Society for Sedimentary Geology), 210 pp.

Quattrocchio, M.E., Martínez, M.A., Pavisich, A.C., Volkheimer, W., 2006. Early Cretaceous palynostratigraphy, palynofacies and palaeoenvironments of well sections in northeastern Tierra del Fuego, Argentina. Cretaceous Research 27 (4), 584-602.

Radionova, E.P., Beniamovski, V.N., Iakovleva, A.I., Muzylöv, N.G., Oreshkina, T.V., Shcherbinina, E.A., Kozlova, G.E., 2003. Early Paleogene transgressions: stratigraphical and sedimentological evidence from the northern Peri-Tethys. In: Wing, S.L., Gingerich, P.D., Schmitz, B., Thomas, E. (Eds.), Causes and consequences of globally warm climates in the Early Paleogene. Geological Society of America, Special Papers, pp. 239-262.

Radley, J.D., Barker, M.J., Munt, M.C., 1998. Bivalve trace fossils (*Lockeia*) from the Barnes High Sandstone (Wealden Group, Lower Cretaceous) of the Wessex Sub-basin, southern England. Cretaceous Research 19 (3), 505-509.

Rahaman, M.A., 1976. Review of the basement geology of southwestern Nigeria. Geology of Nigeria, pp. 41-58.

Raymer, J.D., 2010. Cretaceous/Paleogene boundary biostratigraphy and palynofacies of the Alo-1 well, Southeastern Nigeria, Missouri University of Science and Technology, 66 pp.

Rebata, L.A., Gingras, M.K., Räsänen, M.E., Barberi, M., 2006a, Tidal-channel deposits on a delta plain from the Upper Miocene Nauta Formation, Maranon Foreland Sub-basin, Peru. Sedimentology, vol. 53, p. 971-1013.

Rebata., L.A., Räsänen, M.E., Gingras, M.K., Vieira, V.Jr., Barberi, M., Irion, G., 2006b. Sedimentology and ichnology of tide-influenced Late Miocene successions in western Amazonia: the gradational transition between the Pebas and Nauta formations, Journal of South American Earth Sciences 21 (1–2), 96-119.

Reijers, T.J.A., Petters, S.W., Nwajide, C.S., 1997. The Niger Delta basin. In: Selley, R.C. (Ed.), African Basins. Sedimentary Basins of the World 3. Elsevier Science B.V., Amsterdam, pp. 151 – 172.

Reineck, H.E., Singh, I.B. 1975. Depositional sedimenary environments. Springer-Verlag, Berlin, 439 pp.

Reineck, H. E., Singh, I. B. 1980. Depositional Sedimentary Environments. 2nd Ed. Springer-Verlag, Berlin.

Remane, A., Schlieper, C., 1971. Biology of brackish water (Volume 372). E. Schweizerbart'sche Verlagsbuchhandlung.

Retallack, G.J., 1990. Soils of the Past: An Introduction to Paleopedology. Allen&Unwin, London, 520 pp.

Retallack, G.J., 2001. Cenozoic expansion of grasslands and climatic cooling. Journal of Geology 109, 407-426.

Reyment, R.A., 1965. Aspects of the Geology of Nigeria: The stratigraphy of the Cretaceous and Cenozoic deposits, Ibadan University Press, Ibadan, 145 pp.

Reyment, R.A., 1980a. Biogeography of the Saharan Cretaceous and Paleocene epicontinental transgressions. Cretaceous Research 1 (4), 299-327.

Reyment, R.A., 1980b. Paleo-oceanology and paleobiogeography of the Cretaceous South Atlantic ocean. Oceanologica Acta 3 (1), 127-133.

Reyment, R.A., Mörner, N.A., 1977. Cretaceous transgressions and regressions exemplified by the South Atlantic. Palaeontology Society Japan, Special Papers 21, 247-261.

Rice, D.D., 1984. Widespread, shallow-marine, storm-generated sandstone units in the Upper Cretaceous Mosby Sandstone, Central Montana. In: Tillman, R.W., Siemers, C.T. (Eds), Silicilastic shelf sediments. Society of Economic Paleontologists and Minerialogists, Special Publication 34, 143-161.

Richter, R., 1937. Marken und Spuren aus allen Zeiten. I-II. Senckenbergiana 19:150-169 not seen, cited in Frey, R.W., Howard, J.D., 1990. Trace fossils and depositional sequences in a clastic shelf setting, Upper Cretaceous of Utah. Journal of Paleontology 64 (5), 803-820.

Rieth, A., 1932. Neue Funde spongeliomorpher Fucoiden aus dem Jura Scwabens: Geologische und Palaontologishe Abhandlungen, new series, v. 19, p. 257-294 not seen cited in Singh, R.K., Rodriguez-Tovar, F.J., Soibam, I., 2008. Trace fossils of the Upper Eocene–Lower Oligocene transition of the Manipur Indo-Myanmar Ranges (Northeast India). Turkish Journal of Earth Sciences 17, 821-834.

Rodríguez-Tovar, F.J., Pérez-Valera, F., 2008. Trace Fossil Rhizocorallium from the Middle Triassic of the Betic Cordillera, Southern Spain: characterization and environmental implications. Palaios 23 (2), 78-86.

Rodríguez-Tovar, F.J., Uchman, A., 2006. Ichnological analysis of the Cretaceous–Palaeogene boundary interval at the Caravaca section, SE Spain. Palaeogeography, Palaeoclimatology, Palaeoecology 242 (3), 313-325.

Rohais, S., Eschard, R., Guillocheau, F., 2008. Depositional model and stratigraphic architecture of rift climax Gilbert-type fan deltas (Gulf of Corinth, Greece). Sedimentary Geology 210 (3-4), 132-145.

Rossetti, D.F., Santos Júnior, A.E., 2004. Facies architecture in a tectonically influenced estuarine incised valley fill of Miocene age, northern Brazil. Journal of South American Earth Sciences 17 (4), 267-284.

Salter, J.W., 1857. On annelide-burrows and surface-markings from the Cambrian rocks of the Longmynd. No. 2. Geological Society London Quaternary Journal 13, 199-206 not seen cited in Pickerill, R.K., Donovan, S.K., and Dixon, H.L., 1992. The Richmond Formation of eastern Jamaica revisited-further ichnological observations. Caribbean Journal of Science 28, 89-98.

Saporta, G. de, 1872. Paleontologie francaise ou description des fossiles de la France. 2 ser. Vegetaux. Plantes Jurassiques. G. Masson, Paris 1, 506 pp, not seen cited in Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma, Journal of Paleontology 56 (4), 843-881.

Saporta, G. de, 1884. Les organismes problématiques des anciennes mers. Paris, Masson, 102 pp not seen, cited in Bromley, R.G., Frey, R.W., 1974, Redescription of the trace fossil *Gyrolithes* and taxonomic evaluation of *Thalassinoides, Ophiomorpha* and *Spongeliomorpha*. Bulletin of the Geological Society of Denmark 23, 311-335.

Sarkar, S., Bose, P., Bandhyopadhayay, S., 1991. Intertidal occurrence of mesoscale scours in the Bay of Bengal, India, and their implications. Sedimentary Geology, 75 (1-2), 29-37.

Savrda, C.E., 1991. *Teredolites*, wood substrates and sea-level dynamics. Geology 19, 905-908.

Savrda, C.E., 1992. Trace fossils and benthic oxygenation. In: Maples, C.G., West, R. (Eds.), Trace Fossils. Paleontological Society Short Course Notes 5, 172-196.

Savrda, C.E., Ozalas, K., Demko, T.H., Huchison, R.A., Scheiwe, T.D., 1993. Log-grounds and the ichnofossil Teredolites in transgressive deposits of the Clayton Formation (lower Paleocene), western Alabama, Palaios 8 (4), 311-324.

Schlüter, T., 2006. Geological Atlas of Africa with Notes on stratigraphy, tectonics, economic geology, geohazards and geosites of each country, pp.180-185.

Seilacher, A., 1955. Spurenu nd Fazies im Unterkambrium, pp. 373- 399. In: Schindewolf, O.H., Seilacher, A., Beitrige zur Kenntnis des Kambriums in der Salt Range (Pakistan). Akademie der Wissen-schaften und der Literatur zu Mainz, mathematisch-naturwissen-schaftliche Klasse, Abhandlungen 10, 1955 not seen, cited in Frey, R.W., Howard, J.D., 1990. Trace fossils and depositional sequences in a clastic shelf setting, Upper Cretaceous of Utah. Journal of Paleontology 64 (5), 803-820.

Seilacher, A., 1967. Bathymetry of trace fossils. Marine geology, 5 (5), 413-428.

Seilacher, A., Seilacher, E., 1994. Bivalvian trace fossils: a lesson from actuopaleontology., Courier Forschungsinstitut Senckenberg 169, 5-15.

Shanley, K.W., McCabe, P.J., Hettinger, R.D., 1992. Tidal influence in Cretaceous fluvial strata from Utah, USA: a key to sequence stratigraphic interpretation, Sedimentology 39 (5), 905-930.

Shanmugam, G., Poffenberger, M., Alava, J.T., 2000. Tide-dominated estuarine facies in the Hollin and Napo (" T" and" U") formations (Cretaceous), Sacha field, Oriente basin, Ecuador. American Association of Petroleum Geologists Bulletin, 84 (5), 652-682.

Sharp, J.M.Jr. Shi, M., Galloway W.E., 2003. Heterogeneity of fluvial systems-control on density-driven flow and transport. Environmental and Engineering Geoscience 9 (1), 5–17.

Shi, Z., 1991. Tidal bedding and tidal cyclicities within the intertidal sediments of a microtidal estuary, Dyfi River Estuary, west Wales, U.K. Sedimentary Geology 73 (1-2), 43-58.

Short, K.C., Stäuble, A.J., 1967. Outline of geology of Niger Delta. American Association of Petroleum Geologists Bulletin 51, 761-779.

Siesser, W.G., Dingle, R.V., 1981. Tertiary sea-level movements around southern Africa. The Journal of Geology 89 (4), 523-536.

Simpson, A., 1955. The Nigerian Coalfield. The geology of parts of Onitsha, Owerri and Benue Provinces. Geological Survey of Nigerian Bulletin 24, 85 pp.

Smyth, H.R., Hall, R., Nichols, G.J., 2008. Significant volcanic contribution to some quartz-rich sandstones, East Java, Indonesia. Journal of Sedimentary Research 78, 335-356.

Soil Survey Staff, 1999. Soil Taxonomy: a basic system of soil classification for making and interpreting soil surveys. (2nd ed.), Agricultural Handbook 436, Natural Resources Conservation Service, USDA, Washington DC, USA, 869 pp.

Speer, J.A., 1980. Zircon. In: Ribbe, P.H. (Ed.), Reviews in mineralogy. Volume 5. Orthosilicates. Mineralogical Society of America, Washington DC, pp. 67-112.

Stoneley, R., 1966. The Niger Delta region in the light of the theory of the continental drift. Geological Magazine 103, 266-385.

Stride, A.H., 1982. Offshore tidal sands: processes and deposits. New York, Chapman and Hall., 222 pp.

Stupples, P., 2002. Tidal cycles preserved in late Holocene tidal rhythmites, the Wainway Channel, Romney Marsh, southeast England. Marine Geology 182, 231-246.

Sudo, T., Shimoda, S., 1978. Clays and Clay minerals of Japan (Development in sedimentology 26). Elsevier Scientific Publishing Company, Tokyo, 326 pp.

Suttner, L. J., Dutta, P.K., 1986. Alluvial sandstone composition and paleoclimate, I. Framework mineralogy, Journal of Sedimentary Research 56, 329-345.

Tardy, Y., Roquin, C., 1992. Geochemistry and evolution of lateritic landscapes. In: Martini, I.P., Chesworth, W., (Ed.), Weathering, Soils and Paleosols. Amsterdam, Elsevier, pp. 407-444.

Tattam, C.M., 1944. A review of Nigerian stratigraphy. Report from the Geological Survey of Nigeria. pp. 27 – 46.

Taylor, A.M., Gawthorpe, R.L., 1993. Application of sequence stratigraphy and trace fossil analysis to reservoir description: examples from the Jurassic of the North Sea Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference Geological Society London 4, 317-335.

Taylor, A.M., Goldring, R., 1993. Description and analysis of bioturbation and ichnofabrics. Journal of the Geological Society London 150, 141-148.

Taylor, A.M., Goldring, R., Gowland, S., 2003. Analysis and application of ichnofabrics. Earth-Science Reviews 60 (3), 227-259.

Taylor, A.W., Ritts, B.D., 2004. Mesoscale Heterogeneity of Fluvial-lacustrine Reservoir Analogues: Examples from the Eocene Green River and Colton Formations, Uinta Basin, Utah, USA. Journal of Petroleum Geology 27 (1), 3-26.

Tessier, B, Billeaud, I., Sorrel, P., Delsinne, N., Lesueur, P., 2011. Infilling stratigraphy of macrotidal tide-dominated estuaries. Controlling mechanisms: sea-level fluctuations, bedrock morphology, sediment supply and climate changes (The examples of the seine estuary and the Mont-Saint-Michel Bay, English Channel, NW France), Sedimentary Geology, doi:10.1016/j.sedgeo.2011.02.003.

Thiry, M., 2000. Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin. Earth-Science Reviews 49, 201-221.

Thiry, M., Jacquin, T., 1993. Clay mineral distribution related to rift activity, sea-level changes and paleoceanography in the Cretaceous of the Atlantic Ocean. Clay Minerals 28, 61-84.

Thomas, R.G., Smith, D.G., Wood, J.M., Visser, J., Calverley-Range, A., Koster, E., 1987. Inclined heterolithic stratification: terminology, deposition, interpretation and significance. Sedimentary Geology 53, 123-179.

Tijani, M.N., Nton, M.E., Kitagawa, R., 2010. Textural and geochemical characteristics of the Ajali Sandstone, Anambra Basin, SE Nigeria: implication for its provenance. Comptes Rendus Geoscience, 342 (2), 136-150.

Tirsgaard, H., 1993. The architecture of Precambrian high energy tidal channel deposits: an example from the Lyell Land Group (Eleonore Bay Supergroup), northeast Greenland. Sedimentary Geology, 88 (1), 137-152.

Tonkin, N.S., McIlroy, D., Meyer, R. Moore-Turpin, A., 2010. Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d’Arc Basin, offshore Newfoundland, Canada. American Association of Petroleum Geologists Bulletin 94 (7), 1059–1078.

Torell, O., 1870. Petrificata Suecana Formationis Cambricae. Lunds. Univ. Arsskr. 6. Avdel. 2, VIII, 1-14, not seen cited in Fürsich, F.T., 1974. On Diplocraterion Torell 1870 and the significance of morphological features in vertical, spreiten-bearing, U-shaped trace fossils. Journal of Paleontology 48, 952-962.

Trevena, A.S., Nash, W.P., 1981. An electron microprobe study of detrital feldspar, Journal of Sedimentary Petrology 51, 137-150.

Tyson, R.V., 1995. Sedimentary Organic Matter: organic facies and palynofacies. Chapman and Hall, London, 615 pp.

Uba C.E., Heubeck, C., Hulka, C., 2005. Facies analysis and basin architecture of the Neogene Subandean synorogenic wedge, southern Bolivia. Sedimentary Geology 180, 91–123.

Uchman, A., 1992. Ichnogenus *Rhizocorallium* in the Paleogene flysch (outer Western Carpathians, Poland). Geologica Carpathica 43, 57–60.

Uchman, A., Bubniak, I., Bubniak, A., 2000. The *Glossifungites* ichnofacies in the area of its nomenclatural archetype, Lviv, Ukraine. Ichnos 7, 183–193.

Umeji, O.P., 2002. Mid-Tertiary (Late Eocene – Early Miocene) Lignites from Mpu Formation, Abakaliki Basin, southeastern Nigeria. J. Mining and Geol., v. 38, p.111 – 117.

Umeji, O.P., 2003. Palynological data from the road section at the Ogbunike toll gate, Onitsha, southeastern Nigeria. Journal of Mining and Geology 39, 95–102.

Umeji, O.P., 2005. Palynological study of the Okaba coal mine section in the Anambra Basin, southeastern Nigeria. Journal of Mining and Geology 41, 193 – 203.

Umeji, O.P., 2007. Late Albian to Campanian palynostratigraphy of southeastern Nigeria sedimentary basins. Unpublished PhD Thesis University of Nigeria, Nsukka, 232pp.

Umeji , O.P., Edet, J.J., 2008. Palynostratigraphy and Paleoenvironments of the Type Area of Nsukka Formation of Anambra Basin, South-eastern Nigeria. Nigerian Association of Petroleum Explorationists Bulletin 20, 72-88.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. American Association of Petroleum Geologists Methods in Exploration 7, 22–31.

Velde, B., 1985. Clay minerals: a physico-chemical explanation of their occurrence, Elsevier Publishing Company, Amsterdam, 427 pp.

Vialov, O.S., 1962. Problematica of the Beacon Sandstone at Beacon Height West, Antarctica. New Zealand Journal of Geology and Geophysica, 5, 718-732 not seen, cited in Bruck, P.M., Forbes, W.H., Nance, D., Pickerill, R.K., 1985. *Beaconites antarcticus* in the (?Middle) Late Devonian McAras Brook Formation, Cape George, Nova Scotia. Atlantic Geology, Maritime Sediments and Atlantic Geology 21 (1), 87-96.

Visser, M.J., 1980. Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits : a preliminary note. Geology 8, 543-546.

Von Eynatten, H., Gaupp, R., 1999. Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis and mineral chemistry. Sedimentary Geology 124, 81-111.

Vossler, S.M., Pemberton, G.S., 1989. Ichnology and paleoecology of offshore siliciclastic deposits in the Cardium Formation (Turonian, Alberta, Canada). Palaeogeography, Palaeoclimatology, Palaeoecology 74, 217-239.

Weaver, C.E., 1989. Clays, muds, and shales (Developments in Sedimentology 44). Elsevier Science Publishers, Netherlands, 818pp.

Weber, K.J., 1971. Sedimentological aspects of oil fields in Niger delta. Geologishe en Minjbouw 50, 559–576.

Weber, K.J., Daukoru, E.M., 1975. Petroleum geological aspects of the Niger delta. 9th World Petroleum Congress Tokyo, Proceedings 2, 209–221.

Wetzel, A., Tjallingii, R., Stattegger, K., 2010. *Gyrolithes* in Holocene estuarine incised-valley fill deposits, offshore Southern Vietnam. Palaios 25, 239–246.

White, E.I., 1926. Eocene Fishes of Nigeria. Bulletin of the Geological Survey of Nigeria 10, 78 pp.

Whiteman, A., 1982. Nigeria: its petroleum geology, resources and potential. Graham and Trotman 2, 394 pp.

Wood, L.J., 2004. Predicting tidal sand reservoir architecture using data from modern and ancient depositional systems, in integration of outcrop and modern analogs modelling. American Association of Petroleum Geologists Memoir 80, 45-66.

Woodroffe, C.D., Bardsley, K.N., Ward, P.J., Hanley, J.R., 1988. Production of mangrove litter in a macrotidal embayment, Darwin Harbour, N.T., Australia. Estuarine, Coastal and Shelf Science 26 (6), 581-598.

Woodward, S., 1830. A Synoptic Table of British Organic Remains. Longman, Rees, Orme, Brown and Green, London. 50 pp.

Worsley, D., Mørk, A., 2001. The environmental significance of the trace fossil *Rhizocorallium jenense* in the Lower Triassic of western Spitsbergen, Polar Research 20 (1), 37-48.

Wright, J.B., 1968. South Atlantic continental drift and the Benue Trough. Tectonophysics 6, 301-310.

Wright, J.B., 1981. Review of the Origin and Evolution of the Benue Trough in Nigeria. Earth Evolution Science 2, 98-103.

Wright, V.P., 1992. A revised classification of limestones. Sedimentary Geology, 76 (3), 177-185.

Yang, C.S., Nio, S.D., 1985. The estimation of palaeohydrodynamic processes from subtidal deposits using time series analysis methods. Sedimentology 32 (1), 41-57.

Yeo, R.K., Risk, M.J., 1981. The sedimentology, stratigraphy, and preservation of intertidal deposits in the Minas Basin system, Bay of Fundy. Journal of Sedimentary Petrology 51, 245-260.

Yoshida, S., 2000. Sequence and facies architecture of the Upper Blackhawk Formation and the Lower Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah, USA. Sedimentary Geology 136, 239-276.

Zaghloul, M. N., Critelli, S., Perri, F., Mongelli, G., Perrone, V., Sonnino, M., Tucker, M., Aiello M., Ventimiglia. C., 2010. Depositional systems, composition and geochemistry of Triassic rifted-continental margin redbeds of the Internal Rif Chain, Morocco. Sedimentology 57 (2), 312-350.

Zenker, J.C., 1836. Historisch-topographisches Taschenbuch von Jena und seiner Umgebung besonders in seiner naturwissenschaftlicher und medicinischer Beziehung: Wackenhoder, Jena, 338 pp, not seen cited in Rodríguez-Tovar, F.J., Pérez-Valera, F., 2008. Trace fossil *Rhizocorallium* from the Middle Triassic of the Betic Cordillera, Southern Spain: characterization and environmental implications. Palaios 23 (2), 78-86.

Zonneveld, J.P., Beatty, T.W., Pemberton, S.G., 2007. Lingulide brachiopods and the trace fossil Lingulichnus from the Triassic of Western Canada: implications for faunal recovery after the end-Permian mass extinction. Palaios 22 (1), 74-97.

Zonneveld, J.P., Gingras, M.K., Pemberton, S.G., 2001. Trace fossil assemblages in a Middle Triassic mixed siliciclastic-carbonate marginal marine depositional system, British Columbia, Palaeogeography, Palaeoclimatology, Palaeoecology 166, 249-276.

Zonneveld, J.P., Pemberton, S.G., 2003. Ichnotaxonomy and behavioral implications of lingulide-derived trace fossils from the Lower and Middle Triassic of Western Canada. Ichnos 10 (1), 25-39.

Zuffa, G.G., 1985. Optical analyses of arenites: influence of methodology on compositional results. In Zuffa, G.G., (Ed.), Provenance of Arenites. Dordrecht/Boston/Lancaster, D. Reidel Publishing Company, NATO ASI series 148, 165-189.

Zuffa, G.G., 1987. Unravelling hinterland and offshore paleogeography from deepwater arenites. In: Legggett, J.K., Zuffa, G.G. (Eds.), Marine clastic sedimentology: concepts and case studies. London, Graham and Trotman, pp. 39-61.

APPENDIX

APPENDIX A

S/NO	LOCATION NO	LOCALITY	COORDINATES		GROUP/FORMATION (FM)
			LATITUDE	LONGITUDE	
1	SGB 1	IGBARIAM/NANDO (ROAD)	06 19.106 N	06 56.656 E	IMO FORMATION
2	SGB 2	AGULERI	06 18.792 N	06 54.077 E	IMO FORMATION
3	SEB 1	EBENEBE	06 18.599 N	07 09.385 E	IMO FORMATION
4	SEB 2	EBENEBE	06 18.629 N	07 09.118 E	IMO FORMATION
5	SEB 3	EBENEBE	06 18.639 N	07 09.158 E	IMO FORMATION
6	SEB 4	EBENEBE	06 18.598 N	07 08.225 E	IMO FORMATION
7	SEB 5	EBENEBE	06 18.500 N	07 07.837 E	IMO FORMATION
8	SIN 1	NANDO	06 16.700 N	06 57.511 E	IMO FORMATION
9	SAK 1	OKPUNO-AWKA	06 14.580 N	07 03.420 E	IMO FORMATION
10	SUA 1	UGWUOBA	06 15.576 N	07 09.631 E	IMO FORMATION
11	SME 1	MKPA, UMUEZIKE	05 39.653 N	07 25.324 E	IMO FORMATION
12	SOF 1	UDE-OFEME	05 39.040 N	07 25.373 E	IMO FORMATION
13	SOF 2	UDE-OFEME	05 38.864 N	07 25.413 E	IMO FORMATION
14	SOS 1	OHUHU	05 37.125 N	07 26.281 E	IMO FORMATION
15	SAM 1	AMEKE-ABAM	05 35.584 N	07 43.248 E	IMO FORMATION
16	SAM 2	AMEKE-ABAM	05 36.050 N	07 42.633 E	IMO FORMATION
17	SAM 3	AMEKE-ABAM	05 35.883 N	07 41.859 E	IMO FORMATION
18	SAM 4	AMEKE-ABAM	05 35.723 N	07 41.205 E	IMO FORMATION
19	SAM 5	AMEKE-ABAM	05 35.344 N	07 40.204 E	IMO FORMATION
20	SAM 6	AMEKE-ABAM	05 34.954 N	07 39.662 E	IMO FORMATION
21	SED 1	IDOYI-ABAM	05 35.104 N	07 39.743 E	IMO FORMATION
22	SED 2	IDOYI-ABAM	05 34.925 N	07 39.633 E	IMO FORMATION
23	SED 3	OKPUTONG-BENDE	05 34.685 N	07 39.457 E	IMO FORMATION
24	SED 4	OKPUTONG-BENDE	05 34.188 N	07 39.020 E	IMO FORMATION
25	SID 1	IDIMA-ABAM	05 33.856 N	07 38.819 E	IMO FORMATION
26	SID 2	IDIMA-ABAM	05 33.750 N	07 39.635 E	IMO FORMATION
27	SID 3	IDIMA-ABAM	05 33.848 N	07 38.645 E	IMO FORMATION
28	SID 4	IDIMA-ABAM	05 33.602 N	07 38.311 E	IMO FORMATION
29	SID 5	IDIMA-ABAM	05 33.378 N	07 38.535 E	IMO FORMATION
30	SID 6	IDIMA-ABAM	05 33.546 N	07 38.086 E	IMO FORMATION
31	SIG 1	OKWAFIA IGBERE	05 41.000 N	07 38.000 E	IMO FORMATION
32	SIG 2	OZUITEM-IGBERE (ROAD)	05 40.700 N	07 37.780 E	IMO FORMATION
33	SIG 3	ISIEGBU OZUITEM	05 37.439 N	07 36.905 E	IMO FORMATION
34	SIH 1	IHENZU AHABA	05 42.110 N	07 33.179 E	IMO FORMATION
35	SIH 2	AKOLI IMENYI	05 40.648 N	07 33.120 E	IMO FORMATION
36	SAW 1	UMUAWULU	06 09.770 N	07 05.144 E	IMO FORMATION
37	SIG 4	BENDE-OZUITEM (ROAD)	05 32.978 N	07 36.971 E	IMO FORMATION
38	SUG 1	NSUGBE	06 16.327 N	06 49.447 E	AMEKI GROUP
39	SUG 2	NSUGBE	06 01.411 N	06 49.494 E	AMEKI GROUP
40	SUG 3	NSUGBE	06 12.618 N	06 48.501 E	AMEKI GROUP
41	SUG 4	NSUGBE	06 12.213 N	06 48.495 E	AMEKI GROUP
42	SOYR 1	OYI RIVER	06 14.591 N	06 49.375 E	AMEKI GROUP
43	SOYR 2	OYI RIVER	06 13.271 N	06 49.528 E	AMEKI GROUP
44	SUM 1	UMUNYA	06 12.332 N	06 53.909 E	AMEKI GROUP
45	SUM 2	EZI-UMUNYA	06 13.127'N	06 54.396E	AMEKI GROUP
46	SOG 1	OGBUNIKE	06 10.819 N	06 52.003 E	AMEKI GROUP
47	SOG 2	OGBUNIKE	06 09.780 N	06 51.234 E	AMEKI GROUP
48	SIS 1	AWKA (CROSS-STONE)	06 11.340 N	07 03.611 E	AMEKI GROUP
49	SIS 2	NIBO	06 11.120	07 04.003 E	AMEKI GROUP
50	SIS 3	IFITE-AWKA	06 14.441 N	07 05.273 E	AMEKI GROUP
51	SNI 1	ENUGWU-UKWU	06 11.055 N	06 59.808 E	AMEKI GROUP/OGWASHI FM
52	SNI 2	ISHIAGU	06 11.012 N	07 06.106 E	AMEKI GROUP
53	SNI 3	ENUGWU-AGIDI	06 12.332 N	07 00.155 E	AMEKI GROUP
54	SNI 4	NANKA	06 04.804 N	07 03.572 E	AMEKI GROUP
55	SNI 5	NANKA	06 02.496 N	07 04.870 E	AMEKI GROUP
56	SNI 6	NANKA	06 04.184 N	07 07.567 E	AMEKI GROUP
57	SOF 3	UDE-OFEME	05 38.254 N	07 25.529 E	AMEKI GROUP
58	SAA 1	OHUHU	05 37.125 N	07 26.281 E	AMEKI GROUP
59	SAA 2	OHUHU	05 36.463 N	07 26.586 E	AMEKI GROUP
60	SAA 3	UHUALA UMUEZEOMA	05 35.383 N	07 25.926 E	AMEKI GROUP/OGWASHI FM
61	SIA 1	IBEKU	05 32.622 N	07 34.822 E	AMEKI GROUP
62	SIA 2	IBEKU	05 32.675 N	07 34.256 E	AMEKI GROUP
63	SIA 3	AJATA- IBEKU	05 32.467 N	07 32.407 E	AMEKI GROUP
64	SIH 3	UZUAKOLI ROAD	05 33.660 N	07 28.728 E	AMEKI GROUP
65	SIH 4	OKAUIGA JUNCTION	05 33.636 N	07 28.690 E	OGWASHI FORMATION
66	SIH 5	ISIEKE IBEKU	05 32.769 N	07 31.823 E	OGWASHI FORMATION
67	SOQ 1	OGBUNIKE	06 10.894 N	06 49.898 E	OGWASHI FORMATION
68	SOK 1	OKAIUGA	05 34.598 N	07 26.954 E	OGWASHI FORMATION
69	SOK 2	OKAIUGA	05 32.827 N	07 27.463 E	OGWASHI FORMATION
70	SUB 1	UBAKALA	05 30.371 N	07 26.696 E	OGWASHI FORMATION

Appendix A1.1 Localities and coordinates of selected outcrops locations of the Paleogene strata occurring in the study area.

APPENDIX B

Appendix B4.1. Estimation of true thickness for selected outcrops in the study area.

1 SAM 1 - SAM 2
Distance from SAM 1-SAM 2= 1.16 km
Elevation difference between SAM1 and SAM 2
191 - 172 ft = 19ft ≈ 6.2 m
Dip amount = 4º

2 SAM 5 - SED 1
Distance from SAM 5-SED 1= 958 m
Elevation difference between SAM 5 and SED 1
268 - 234 ft = 34ft ≈ 9 m
Dip amount = 4º

3 SEB 1 - SEB 2
Distance from SEB 1-SEB 2= 499 m
Elevation difference between SEB 1 and SEB 2
223 - 168ft = 55ft ≈ 18 m
Dip amount = 4º

4 SEB 4 - SEB 5
Distance from SEB 4 - SEB 5= 740 m
Elevation difference between SEB 4 and SEB 5
183 - 119ft = 64ft ≈ 21 m
Dip amount = 4º

Nando Borehole (Bh-E)

	Depth(m)	Description
	0-3	Overbudern
	3-6	Reddish brown, clayey, coarse grained, moderately sorted
	6-12	Mudrock, dark grey, shows no fissilty
	12-15	Mudrock, dark grey, shows crude fissilty
15	15-18	Mudrock, dark grey, shows fissilty
	18-21	Mudrock, dark grey, shows fissilty
	21-24	Mudrock, dark grey, highly fissilty
	24-27	Mudrock, grey, shows crude fissilty, iron stains, strings of siltstone
	27-31	Mudrock, grey, shows crude fissilty, iron stains
31	31-34	Mudrock, dark grey, shows crude fissilty
	34-37	Mudrock, dark grey, shows fissilty
	37-40	Mudrock, dark grey, shows fissilty
	40-43	Mudrock, dark grey, shows slight fissilty
	43-46	Mudrock, dark grey, shows slight fissilty
46	46-49	Mudrock, dark grey, shows slight fissilty, lenses of siltstone
	49-52	Mudrock, dark grey, shows fissilty, iron stains
	52-55	Mudrock, dark grey
	55-58	Mudrock, dark grey, shows slight fissilty, lenses of siltstone
	58-61	Mudrock, dark grey, shows slight fissilty
61	61-64	Mudrock, dark grey, shows slight fissilty, white precipitate
	64-67	Mudrock, dark grey, shows slight fissilty, white precipitate
	67-70	Mudrock, dark grey, shows slight fissilty, white precipitate
	70-73	White coloured sandstone, medium grained, moderately sorted, micaceous
	73-76	White coloured sandstone, medium grained, moderately sorted, micaceous
76	76-79	White coloured sandstone, medium-coarse grained, poorly sorted, micaceous
	79-82	White coloured sandstone, medium-coarse grained, poorly sorted, micaceous
	82-85	Light brown, medium grained, moderately sorted, micaceous
	85-88	Light brown, medium - coarse grained, moderately sorted, micaceous
	88-91	Light brown, medium - coarse grained, moderately sorted, micaceous
91	91	Light brown, medium grained, moderately-poorly sorted, micaceous

Legend

Sandstone

Mudrock

Appendix B4.2. Borehole log at Nando (Bh-E)

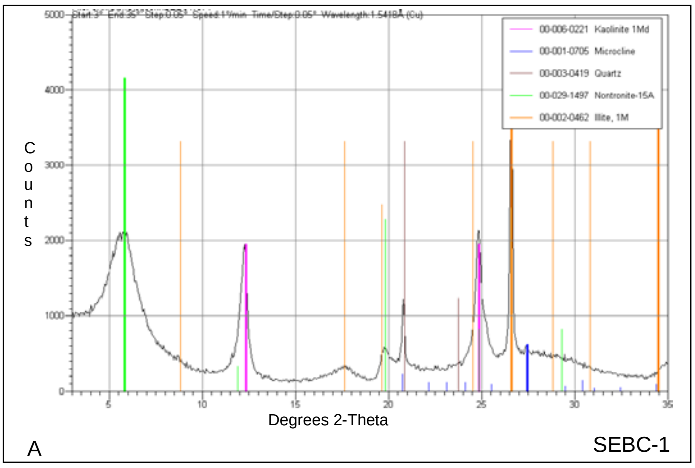
Umunze-Orumba South Borehole (Bh-A)

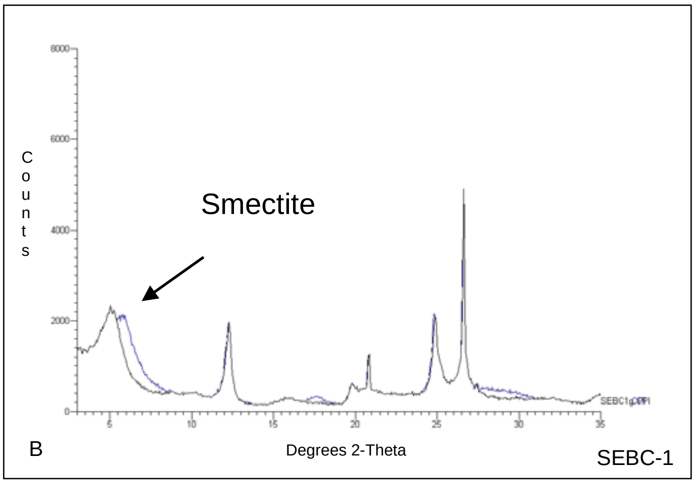
	Lithology	Depth(m)	Description
		0-12	Reddish brown, sandstone, medium grained, overbudern
15		15-18	Brown, medium grained, moderately sorted
		18-21	Light brown, medium grained, moderately - poorly sorted, clay chips
		21-24	Brown, medium grained, moderately sorted
		24-27	Brown, medium grained, moderately sorted
		27-31	Light brown, medium grained, poorly sorted, clayey,calcareous
31		31-34	Light brown, medium grained, poorly sorted, clayey,calcareous
		34-37	Light brown, coarse grained, poorly sorted, clayey,calcareous
		37-40	Brown, coarse grained, poorly sorted, clayey,calcareous
		40-43	Light brown, coarse grained, moderately sorted, clayey, calcareous
		43-46	Light brown, coarse grained, moderately sorted, clayey, calcareous
46		46-49	Light brown, medium grained, moderately sorted, calcareous
		49-52	Light brown, medium grained, moderately sorted, calcareous
		52-55	Light brown, medium grained, poorly sorted, slightly clayey, calcareous
		55-58	Brown, coarse grained, moderately sorted, clayey,calcareous
		58-61	Light brown, coarse grained, poorly sorted, clay chips, slghtly clayey,calcareous
61		61-64	Light brown, coarse grained, poorly sorted, clay chips
		64-67	Light brown, very coarse grained, poorly sorted, slghtly clayey
		67-70	Very light brown, fine grained, moderately sorted, slightly calcareous
		70-73	Very light brown, medium-fine grained, moderately sorted, calcareous
		73-76	Very light brown, medium grained, moderately sorted, calcareous
76		76-79	Very light brown, coarse grained, moderately sorted, calcareous
		79-82	Very light brown, medium grained, moderately sorted, clay chips, calcareous
		82-85	Very light brown, medium-fine grained, moderately sorted
		85-88	Very light brown, coarse grained, moderately sorted, calcareous
		88-91	Brown, medium grained, moderately sorted
91		91-94	Brown, coarse-fine grained, moderately sorted, slightly clayey
		94-97	Light brown, medium grained, moderately sorted
		97-100	Light brown, medium grained, poorly sorted
		100-103	Light brown, medium grained, moderately sorted
		103-106	Very light brown, coarse grained, moderately sorted
106		106	Very light brown, coarse grained, poorly sorted, calcareous

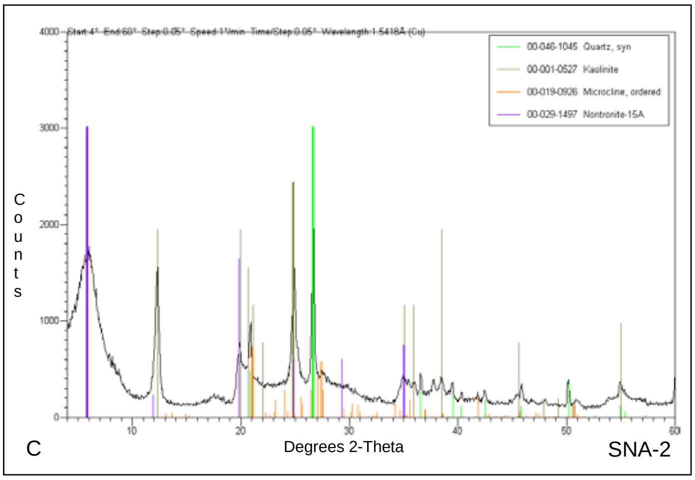
Legend

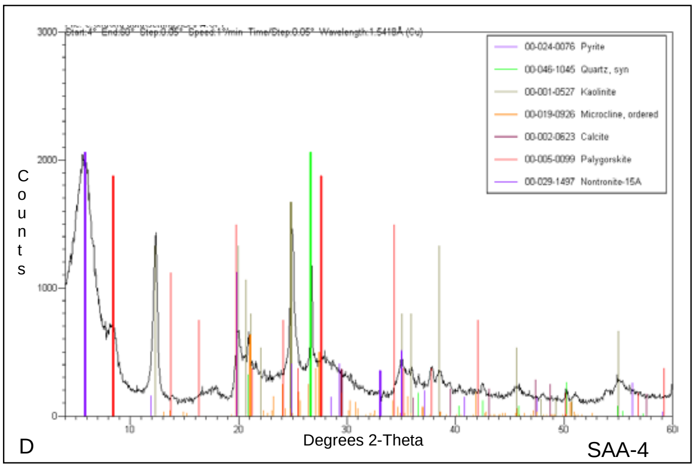
sandstone

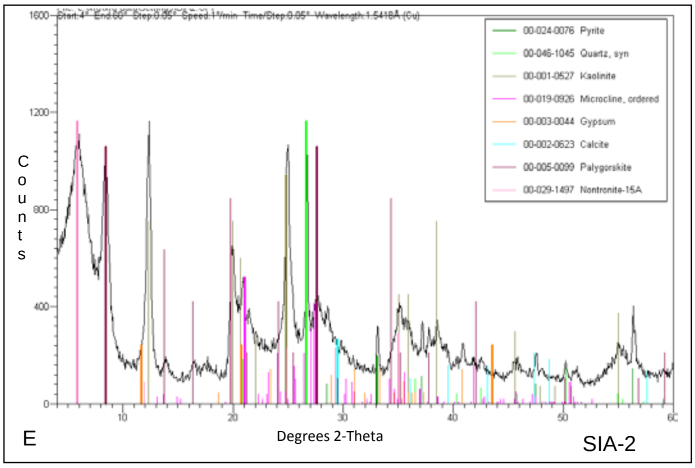
Appendix B4.3. Borehole log (Bh-A) from Umunze characterised by calcareous sandstone

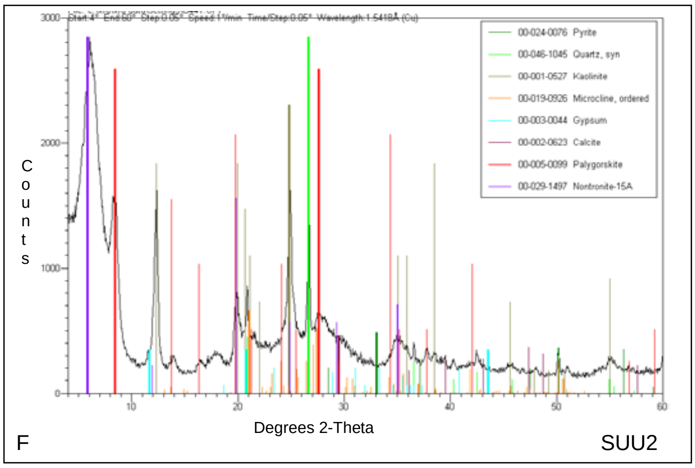

00-006-0221 Kaolinite 1Md
00-001-0705 Microcline
00-003-0419 Quartz
00-029-1497 Nontronite-15A
00-002-0462 Illite, 1M
Counts
Degrees 2-Theta
A
SEBC-1


Counts
Smectite
Degrees 2-Theta
B
SEBC-1


00-046-1045 Quartz, syn
00-001-0527 Kaolinite
00-019-0926 Microcline, ordered
00-029-1497 Nontronite-15A
Counts
Degrees 2-Theta
C
SNA-2







Appendix B4.4. Representative XRD patterns of clay samples from Imo Formation. (c) Confirmation analysis showing the presence of smectite clay in Ebenebe sample (SEBC1)

Appendix B4.5. Qualitative estimate of palynomorphs from borehole samples in the south-eastern region of Nigeria

Formation	Imo Formation (lower Sandstone Member)					Imo Formation (middle Sandstone Member)						
Sample no (ft)	**Achalla 130-160**	**Achalla 160-190**	**Achalla 190-220**	**Achalla 220-240**	**Achalla 300**	**Nando 30-70**	**Nando 70-110**	**Nando 110-150**	**Nando 150-190**	**Nando 190-220**	**Umuleri 200-230**	**Umuleri 230-260**
Identifiable Palynomorphs	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**
Fresh water algal cysts type 1	18	10	18	10	36	4	13	11	18	8	3	8
Fresh water algal cysts type 2	11	3	7	3	2	1	4	3	5	3	3	2
Fresh water algal cysts type 3	13	7	4	2	4	10	13	10	5	5	1	8
Dinoflagellate type 1	10	4	6	2	3	2	0	1	0	0	0	1
Dinoflagellate type 2	3	1	3	9	0	2	0	0	3	3	0	0
Acritarch type 1	2	0	3	2	1	0	0	1	0	0	0	0
Acritarch type 2	1	2	4	5	3	0	0	0	1	0	0	2
Acritarch type 3	0	0	0	2	5	1	0	1	0	0	0	1
Flowering plant pollen	35	12	9	11	14	39	30	38	35	56	18	31
Spore monolete	2	3	3	3	6	9	3	6	8	12	2	13
trilete	6	0	1	9	17	7	7	19	15	7	8	13
crumpled	8	3	9	1	8	3	2	4	1	5	1	9
Fungal	10	5	6	9	7	5	7	3	3	3	0	5
Foraminiferal lining	3	4	1	4	1	0	0	0	0	0	0	0
Unidentifiable Palynomorphs	8	5	2	4	3	1	0	1	2	3	0	3
Fragmentary Palynomorphs	18	8	4	3	5	0	9	5	3	9	2	2
Structured phytoclasts	12	8	14	10	13	7	15	6	5	5	3	5
Unstructured phytoclasts	6	5	4	6	6	2	1	1	2	2	5	8
Resin	4	6	4	5	5	5	3	6	5	5	3	2
AOM	low	low	low	low	low	low	low	low	low	low	low	low
Pyrite	common	common	common	common	common	low	low	low	low	low	common	common

Legend
*abund - abundant
*comm - common
Sst- Sandstone
Marine palynomorphs

Appendix B4.6. Qualitative estimate of palynomorphs from outcrop samples in the south-eastern region of Nigeria

Formation	Imo Formation (lower Sst. Member)					Imo Formation (upper)	
Sample no	**Ebenebe 1 - 2**	**Ebenebe 3 - 4**	**Ebenebe 5 - 6**	**Ebenebe 7 - 8**	**Ebenebe 10 - 11**	**SIA-1**	**SIA-2**
Identifiable Palynomorphs	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**
Fresh water algal cysts type 1	1	4	2	0	0	0	3
Fresh water algal cysts type 2	0	0	0	0	0	0	2
Fresh water algal cysts type 3	0	0	0	0	0	2	1
Dinoflagellate type 1	0	0	0	0	0	1	2
Dinoflagellate type 2	0	0	0	0	0	1	4
Acritarch type 1	0	0	0	0	0	1	0
Acritarch type 2	0	0	0	0	0	0	0
Acritarch type 3	0	0	0	0	0	0	0
Flowering plant pollen	0	0	0	0	0	3	3
Spore monolete	0	0	0	0	0	1	2
trilete	0	0	0	0	1	2	2
crumpled	0	0	0	0	0	0	4
Fungal	0	2	1	5	0	3	0
Foraminiferal lining	0	0	0	0	0	1	1
Unidentifiable Palynomorphs	0	0	0	0	0	0	0
Fragmentary Palynomorphs	0	0	0	0	0	1	2
Structured phytoclasts	4	10	1	3	0	0	0
Unstructured phytoclasts	1	3	0	2	0	3	2
Resin	0	0	0	0	0	3	3
AOM	low	low	low	low	low	abund	abund
Pyrite	low	common	common	low	low	abund	abund

Legend
*abund - abundant
*comm - common
Sst- Sandstone
[shaded box] Marine palynomorphs

APPENDIX C

Appendix C5.1. Localities and coordinates of selected outcrops in the study area.

S/NO	LOCATION NO	LOCALITY	COORDINATES		DEPOSITIONAL
			LATITUDE	LONGITUDE	ENVIRONMENT
1	SUG 1	NSUGBE	06 16.327 N	06 49.447 E	Fluvial Dominated
2	SUG 2	NSUGBE	06 01.411 N	06 49.494 E	Fluvial Dominated
3	SUG 3	NSUGBE	06 12.618 N	06 48.501 E	Fluvial Dominated
4	SUG 4	NSUGBE	06 12.213 N	06 48.495 E	Fluvial Dominated
5	SOYR 1	OYI RIVER	06 14.591 N	06 49.375 E	Estuarine System
6	SOYR 2	OYI RIVER	06 13.271 N	06 49.528 E	Estuarine System
7	SUM 1	UMUNYA	06 12.332 N	06 53.909 E	Estuarine System
8	SUM 2	EZI-UMUNYA	06 13.127'N	06 54.396E	Estuarine System
9	SOG 1	OGBUNIKE	06 10.819 N	06 52.003 E	Estuarine System
10	SOG 2	OGBUNIKE	06 09.780 N	06 51.234 E	Estuarine System
11	SIS 1	AWKA (CROSS-STONE)	06 11.340 N	07 03.611 E	Estuarine System
12	SIS 2	NIBO	06 11.120	07 04.003 E	Estuarine System
13	SIS 3	IFITE-AWKA	06 14.441 N	07 05.273 E	Estuarine System
14	SNI 1	ENUGWU-UKWU	06 11.055 N	06 59.808 E	Estuarine System
15	SNI 2	ISHIAGU	06 11.012 N	07 06.106 E	Estuarine System
16	SNI 3	ENUGWU-AGIDI	06 12.332 N	07 00.155 E	Estuarine System
17	SNI 4	NANKA	06 04.804 N	07 03.572 E	Estuarine System
18	SNI 5	NANKA	06 02.496 N	07 04.870 E	Estuarine System
19	SOF 3	UDE-OFEME	05 38.254 N	07 25.529 E	Estuarine Embayment
20	SAA 1	OHUHU	05 37.125 N	07 26.281 E	Estuarine Embayment
21	SAA 2	OHUHU	05 36.463 N	07 26.586 E	Estuarine Embayment
22	SAA 3	UHUALA UMUEZEOMA	05 35.383 N	07 25.926 E	Estuarine Embayment
23	SIA 1	IBEKU	05 32.622 N	07 34.822 E	Estuarine Embayment
24	SIA 2	IBEKU	05 32.675 N	07 34.256 E	Estuarine Embayment
25	SIA 3	AJATA- IBEKU	05 32.467 N	07 32.407 E	Estuarine Embayment
26	SIH 3	UZUAKOLI ROAD	05 33.660 N	07 28.728 E	Estuarine Embayment

Appendix C5.2. Rietveld quantification of the analysed whole rock showing the clay minerals in percentage (Ameki Group).

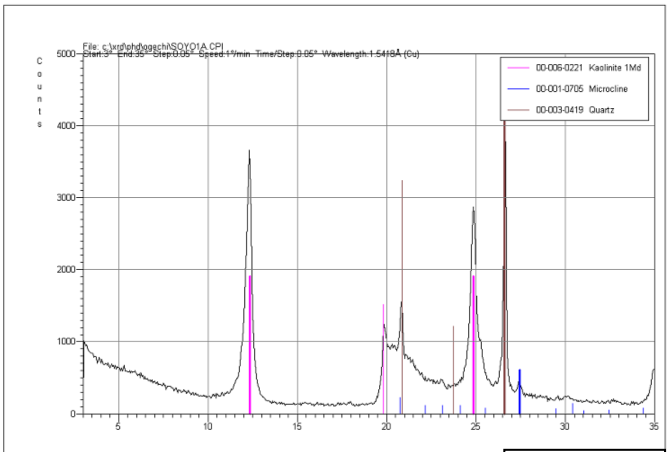
Formation	**Nsugbe Fm.**	**Nanka Formation**						**Ibeku Formation (formerly Ameki Formation)**						
Sample No/ Mineral (%)	**SUN-5**	**SOYO 1A**	**SUMY-2**	**SUMY-4**	**SOGU-1**	**SPP4**	**SNI-6**	**SESM2**	**SESM 10**	**SESM 11**	**SUF-2**	**SUF-5**	**SOU-1**	**SOU-2**
Nontronite-15 A	0	0	0	0	0	0	2.2	4	1.2	6.7	4.2	6.6	0.1	3.4
Kaolinite	50.8	78.8	70.1	66.1	73.6	71.3	49.2	56.3	42.4	53.7	47.3	56.6	36.4	45
Illite	16.5	7.9	3	6.1	3.8	5.1	28.2	5.7	9.5	11.6	7.9	5.4	1.9	0
Palygorskite	0	0	0	0	0	0.5	0	0.4	0.7	0	0	0	0	0
Goethite	0	0	1.1	0.8	0	0	0	0	0	0	0	0	0	0
Chlorite	0	0	0	0	0	0	0	0	0	0	0	1.1	0.9	1.2
Quartz 2%	32.6	9.5	23.2	25.5	17.8	18	20.1	11.4	17.3	6.5	16.5	20.2	21.6	20.6
Microcline	0	1.2	0	0.2	2.1	2.5	0	13.6	13.7	0	0	0	0	0
Orthoclase	0	0	0.5	0	0	0	0	0	0	1.2	0	1.7	17.9	11.2
Albite	0	0	0	0	0	0	0	0	0	3.6	0.7	0	9.1	8.2
Calcite 1%	0	0	0	0	0	0	0	0	0	0.4	0	0.1	0.8	0.2
Gypsum	0	0	0	0	0	0.4	0	1.2	0.5	0	12.4	1	1.2	0.9
Rutile	0	0	0	0	0	0	0.2	0	0	0	1.7	3.1	3.9	3.9
Graphite	0	0	0	0	0	0	0	0	0	0	7.6	4.1	6.3	5.4
Pyrite	0	0.1	0	0	0	2.2	0	5.2	10.6	15.9	0	0	0	0
Stilbite	0	0	0	0	0	0	0	2.1	4.2	0	0	0	0	0
Siderite	0	2.5	2.2	1.3	2.6	0	0	0	0	0.4	0	0	0	0
Anatase	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Legend

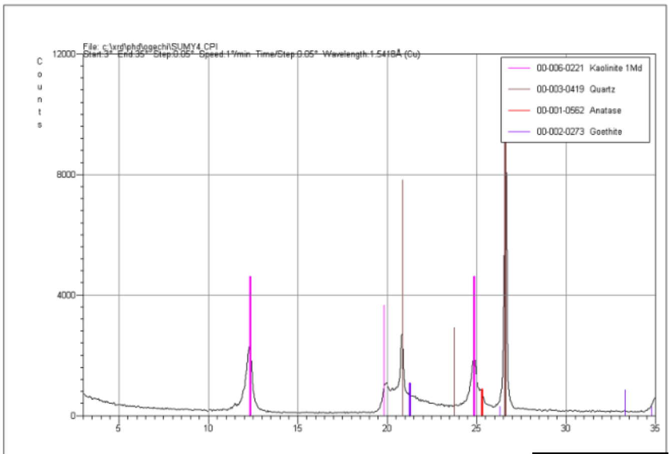
Clay minerals

Non-clay minerals

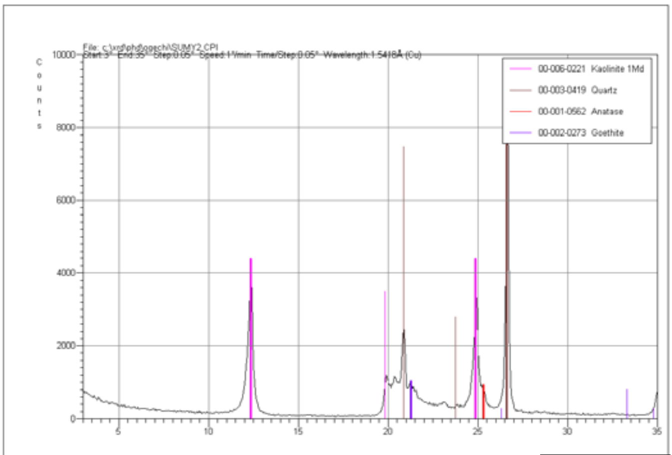
Fm. Formation



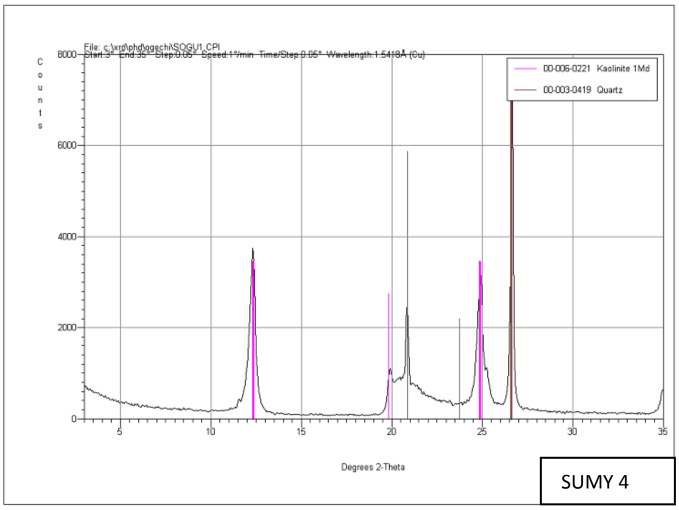
SOYO-1A

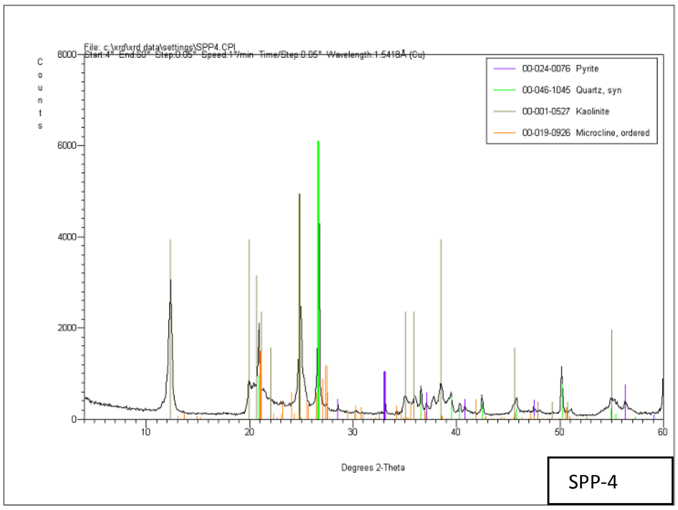


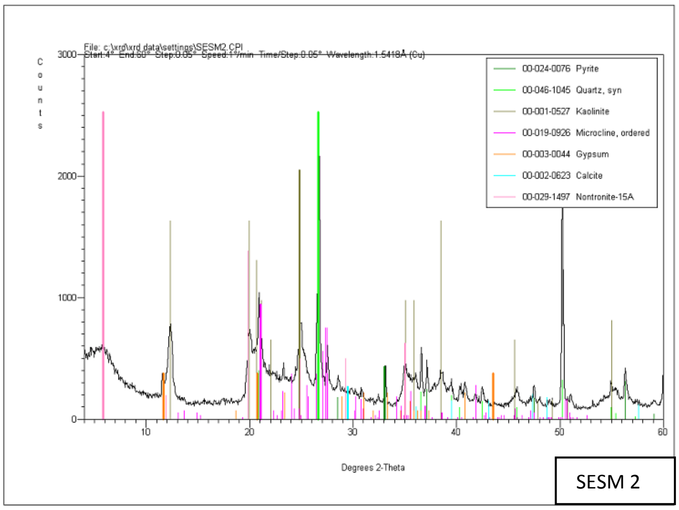
SOGU-1

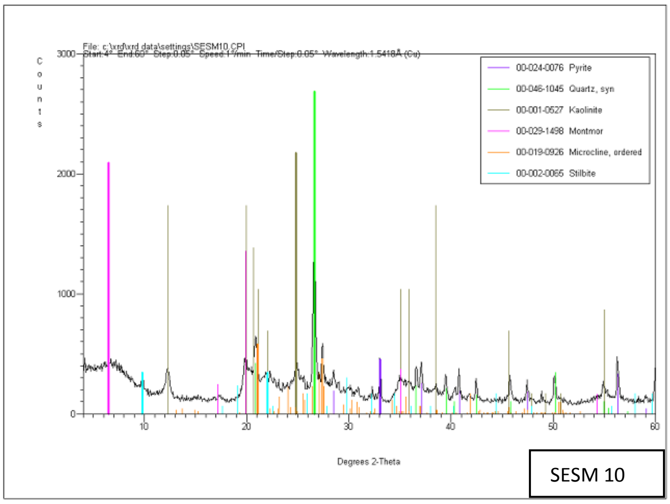


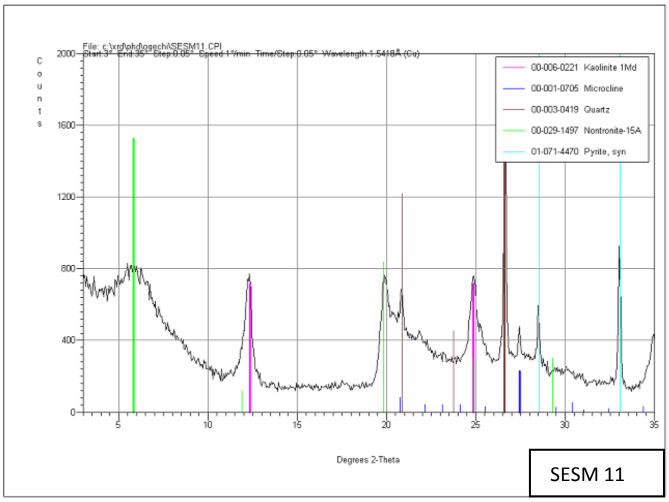
SUMY 2

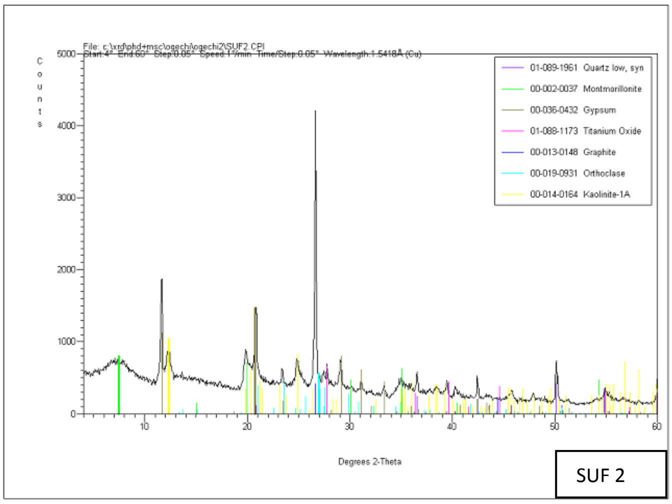

File: c:\xrd\phd\ogechi\SOGU1.CPI
Start:3° End:35° Step:0.05° Speed:1°/min Time/Step:0.05° Wavelength:1.5418Å (Cu)
Counts
8000
6000
4000
2000
0
5
10
15
20
25
30
35
Degrees 2-Theta
00-006-0221 Kaolinite 1Md
00-003-0419 Quartz
SUMY 4

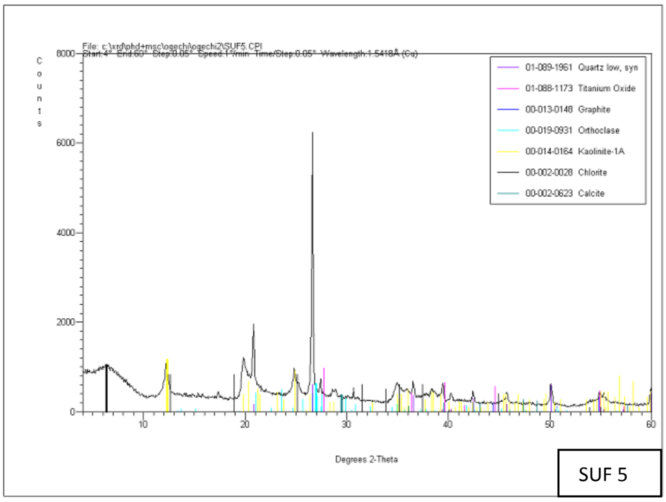

File: c:\xrd\xrd data\settings\SPP4.CPI
Start:4° End:60° Step:0.05° Speed:1°/min Time/Step:0.05° Wavelength:1.5418Å (Cu)
Counts
8000
6000
4000
2000
0
10
20
30
40
50
60
Degrees 2-Theta
00-024-0076 Pyrite
00-046-1045 Quartz, syn
00-001-0527 Kaolinite
00-019-0926 Microcline, ordered
SPP-4

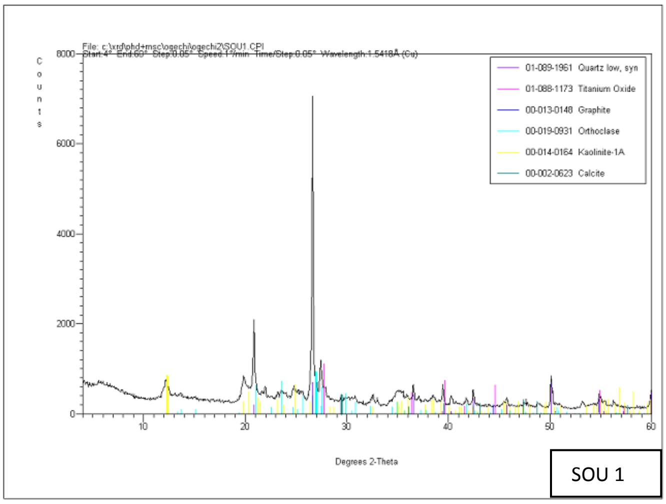

File: c:\xrd\xrd data\settings\SESM2.CPI
Start:4° End:60° Step:0.05° Speed:1°/min Time/Step:0.05° Wavelength:1.5418Å (Cu)
Counts
3000
2000
1000
0
10
20
30
40
50
60
Degrees 2-Theta
00-024-0076 Pyrite
00-046-1045 Quartz, syn
00-001-0527 Kaolinite
00-019-0926 Microcline, ordered
00-003-0044 Gypsum
00-002-0623 Calcite
00-029-1497 Nontronite-15A
SESM 2

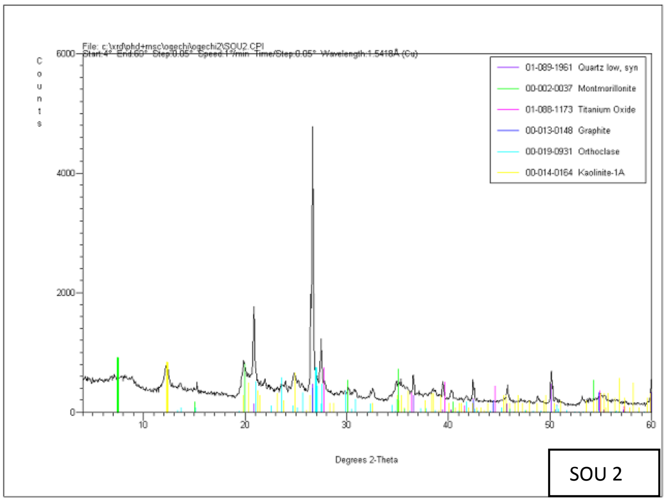

Counts
Degrees 2-Theta
00-024-0076 Pyrite
00-046-1045 Quartz, syn
00-001-0527 Kaolinite
00-029-1498 Montmor
00-019-0926 Microcline, ordered
00-002-0065 Stilbite
SESM 10


Counts
Degrees 2-Theta
00-006-0221 Kaolinite 1Md
00-001-0705 Microcline
00-003-0419 Quartz
00-029-1497 Nontronite-15A
01-071-4470 Pyrite, syn
SESM 11


Counts
Degrees 2-Theta
01-089-1961 Quartz low, syn
00-002-0037 Montmorillonite
00-036-0432 Gypsum
01-088-1173 Titanium Oxide
00-013-0148 Graphite
00-019-0931 Orthoclase
00-014-0164 Kaolinite-1A
SUF 2







Appendix C5.3. Representative XRD patterns of clay samples from sediments of the Ameki Group.

Appendix C5.4. Quantitative estimate of palynomorphs from outcrop samples in the south-eastern region of Nigeria

Formation	Ameki Group (Nsugbe Sandstone)						Ameki Group (Nanka Sandstone)												Ameki Group (Ibeku Fm)		
Sample no	**Nsugbe 1 - 2**	**Nsugbe 4 -6**	**Nsugbe 7 - 9**	**Nsugbe 11 -13**	**Nsugbe 14- 16**	**Nsugbe 17 - 20**	**UMU 1 - 2**	**UMU 3A**	**EMU 1 - 2**	**EMU 3 - 4**	**EMU 5 - 6**	**SPP-1**	**SPP-4**	**SOYO-1A**	**Oyi River**	**UGA 1 - 2**	**UGA 3 - 4**	**UGA 5**	**SESM-2**	**SESM-4**	**SESM-10**
Identifiable Palynomorphs	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**	**Counts**
Fresh water algal cysts type 1	0	0	0	1	0	0	0	0	1	1	0	1	3	1	0	0	0	0	2	1	0
Fresh water algal cysts type 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Fresh water algal cysts type 3	0	0	0	0	0	0	0	0	0	0	0	1	3	2	0	0	0	0	1	1	0
Dinoflagellate type 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Dinoflagellate type 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3
Acritarch type 1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2
Acritarch type 2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Acritarch type 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	2
Flowering plant pollen	2	0	1	0	1	0	0	0	0	0	0	7	7	13	0	0	0	0	0	1	2
Spore monolete	0	0	0	0	0	0	0	0	0	1	0	3	1	0	0	0	0	0	18	6	2
trilete	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	3	2	1
crumpled	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0
Fungal	1	1	1	0	0	1	0	0	0	1	0	5	3	8	0	0	0	0	1	0	3
Foraminiferal lining	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	4	5	2
Unidentifiable Palynomorphs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0
Fragmentary Palynomorphs	0	0	0	0	0	0	0	0	0	1	0	2	5	12	0	0	0	0	0	0	0
Structured phytoclasts	2	2	0	0	1	1	1	0	1	1	0	5	5	8	0	0	0	0	0	1	5
Unstructured phytoclasts	0	0	0	0	0	0	0	0	0	0	0	6	6	10	0	0	0	0	8	4	9
Resin	0	0	0	0	0	1	0	0	0	0	0	6	5	5	0	0	0	0	1	2	1
AOM	barren	barren	barren	low	low	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	*abund	*abund	*abund
Pyrite	low	low	barren	low	barren	barren	barren	barren	low	low	low	*comm	*comm	*comm	barren	barren	barren	barren	*abund	*abund	*abund

Sample no: Umunya- UMU Ezi-Umunya- EMU Ugwu-Akpi- UGA

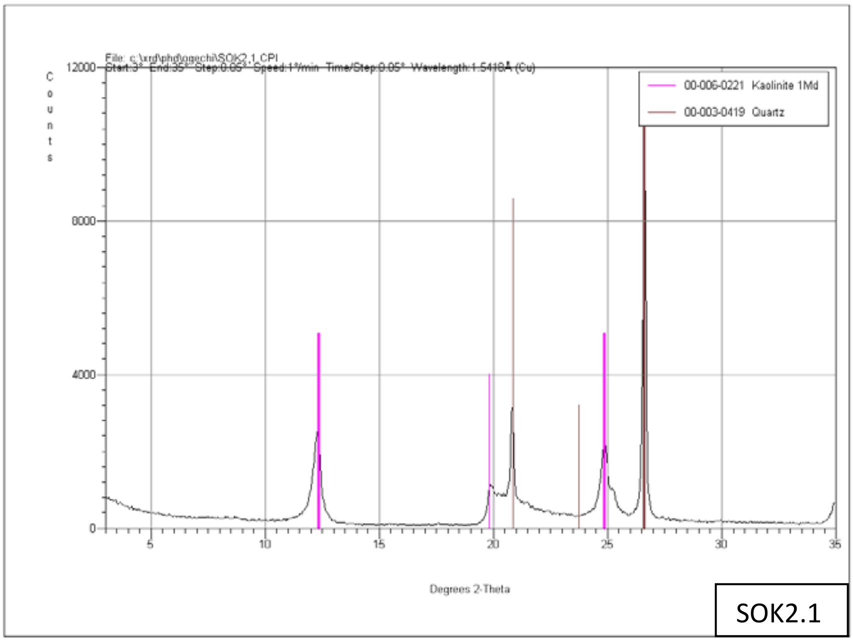
Legend

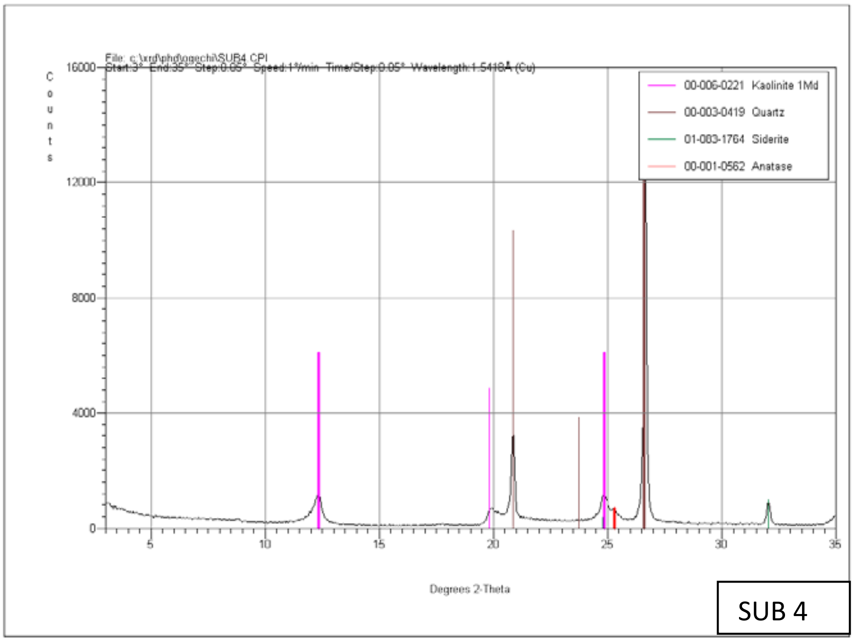
*abund - abundant

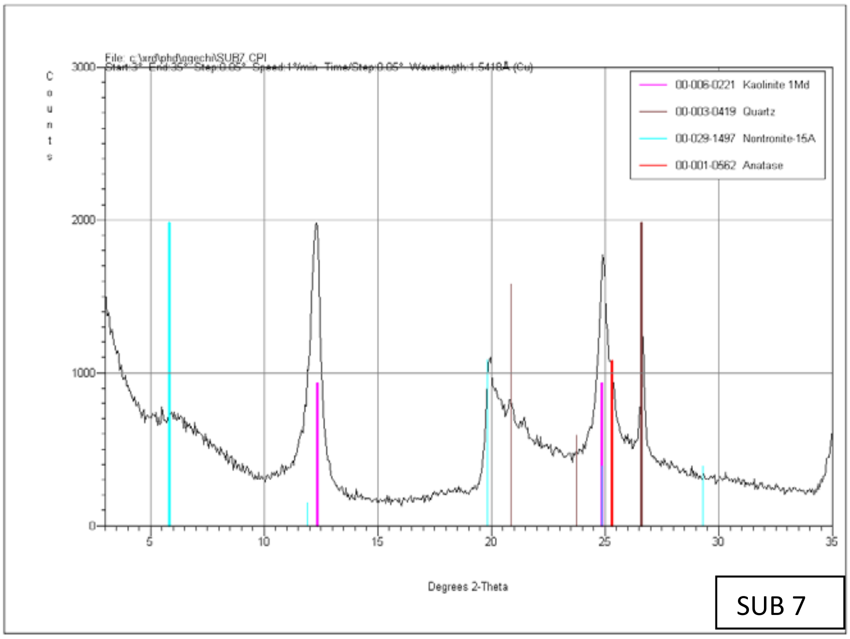
*comm - common

Marine palynomorphs

APPENDIX D


File: c:\xrd\phd\ogechi\SOK2.1.CPI
Start:3° End:35° Step:0.05° Speed:1°/min Time/Step:0.05° Wavelength:1.5418Å (Cu)
Counts
12000
8000
4000
0
5
10
15
20
25
30
35
Degrees 2-Theta
00-006-0221 Kaolinite 1Md
00-003-0419 Quartz
SOK2.1


File: c:\xrd\phd\ogechi\SUB4.CPI
Start:3° End:35° Step:0.05° Speed:1°/min Time/Step:0.05° Wavelength:1.5418Å (Cu)
Counts
16000
12000
8000
4000
0
5
10
15
20
25
30
35
Degrees 2-Theta
00-006-0221 Kaolinite 1Md
00-003-0419 Quartz
01-083-1764 Siderite
00-001-0562 Anatase
SUB 4



Appendix D6.1. Representative XRD patterns of clay samples from sediments of the Ogwashi Formation.

APPENDIX E

Appendix D8.1. Localities of samples analyzed for petrology and heavy minerals analysis.

S/No	Sample No	Lithology	Locality	Group/Formation	Member
1	SEB 1	Sandstone	Ebenebe	Imo Formation	Lower Sandstone
2	SEB 2	Sandstone	Ebenebe	Imo Formation	Lower Sandstone
3	SEB 4	Sandstone	Ebenebe	Imo Formation	Lower Sandstone
4	SNK 1	Sandstone	Mkpa, Umuezike	Imo Formation	Lower Sandstone
5	SNK 3	Sandstone	Mkpa, Umuezike	Imo Formation	Lower Sandstone
6	SUMZ 2	Sandstone	Mkpa, Umuezike	Imo Formation	Lower Sandstone
7	SAIM 2	Sandstone	Ameke-Abam	Imo Formation	Lower Sandstone
8	SAA 1	Sandstone	Ameke-Abam	Imo Formation	Lower Sandstone
9	SAA 3	Sandstone	Ameke-Abam	Imo Formation	Middle Sandstone
10	SAA 4	Sandstone	Ameke-Abam	Imo Formation	Middle Sandstone
11	SAA 5	Sandstone	Ameke-Abam	Imo Formation	Middle Sandstone
12	SIAM 1	Fossiliferous Sstone	Onyi- Bende	Imo Formation	Upper Sandstone
13	SIAF	Fossiliferous Sstone	Idima-Abam	Imo Formation	Upper Sandstone
14	SIA 2	Carbonate	Idima-Abam	Imo Formation	Upper Sandstone
15	SOZ 3	Fossiliferous Sstone	Ozuitem	Imo Formation	Upper Sandstone
16	SOZC 4	Fossiliferous Sstone	Ozuitem	Imo Formation	Upper Sandstone
17	SOZM 6	Carbonate	Ozuitem-Bende Rd	Imo Formation	Upper Sandstone
18	SOBP 1	Carbonate	Okpotong-Bende	Imo Formation	Upper Sandstone
19	SDL 1	Carbonate	Okpotong-Bende	Imo Formation	Upper Sandstone
20	SNS 1	Sandstone	Nsugbe	Ameki Group	
21	SNS 3	Sandstone	Nsugbe	Ameki Group	
22	SUN 1	Sandstone	Ugwu-Nnadi	Ameki Group	
23	SUN 3	Sandstone	Ugwu-Nnadi	Ameki Group	
24	SUMP 2	Sandstone	Umunya	Ameki Group	
25	SNIP 1	Sandstone	Nibo	Ameki Group	
26	SUM 1	Sandstone	Umunya	Ameki Group	
27	SUM 2	Sandstone	Umunya	Ameki Group	
28	SUM 3	Sandstone	Umunya	Ameki Group	
29	SUM 4	Sandstone	Umunya	Ameki Group	
30	SNI 2	Sandstone	Nibo	Ameki Group	
31	SIS 1	Sandstone	Ishiagu	Ameki Group	
32	SIS 2	Sandstone	Ishiagu	Ameki Group	
33	SIK 1	Sandstone	Awka	Ameki Group	
34	SESP-5	Carbonate	Ajata-Ibeku	Ameki Group	
35	SOK 1A	Sandstone	Okaiuga	Ogwashi Formation	
36	SOK 1.1	Sandstone	Okaiuga	Ogwashi Formation	
37	SOK 1.2	Sandstone	Okaiuga	Ogwashi Formation	
38	SOK 1.4	Sandstone	Okaiuga	Ogwashi Formation	
39	SOK 1.5	Sandstone	Okaiuga	Ogwashi Formation	
40	SOK 1.6	Sandstone	Okaiuga	Ogwashi Formation	
41	SOK 1.8	Sandstone	Okaiuga	Ogwashi Formation	
42	SOK 2.1	Sandstone	Okaiuga	Ogwashi Formation	

Appendix E8.2. Quantitative point-counting results for heavy mineral composition in the Imo Formation

Sample Nos	Formation	Sandstone Member	Zrn	Tur	Apt	Mn	Rt	St	Sil	Kyn	Sp	Ep	Hb	Am	Grn	Act	And	Px	Oth	TOTAL
SEB-1	Imo Fm	Lower Sandstone	57	46	0	0	150	29	7	25	0	24	0	4	0	0	6	20	0	368
SEB-2	Imo Fm	Lower Sandstone	70	30	0	0	120	13	10	58	0	13	0	8	0	0	1	17	0	340
SNK-1	Imo Fm	Lower Sandstone	78	33	3	4	80	10	8	27	0	18	0	4	0	0	1	6	1	273
SNK-3	Imo Fm	Lower Sandstone	36	17	2	0	150	7	9	31	0	30	0	3	1	0	2	13	1	301
SAIM-2	Imo Fm	Lower Sandstone	60	24	0	0	85	7	10	54	0	16	0	6	0	0	2	5	0	269
SAA-1	Imo Fm	Lower Sandstone	9	9	5	0	18	4	12	39	0	12	2	5	0	0	2	11	4	132
SAA-3	Imo Fm	Upper Sandstone	44	15	2	0	127	5	8	34	0	17	0	0	0	0	3	38	1	294
SAA-4	Imo Fm	Upper Sandstone	74	14	4	0	183	4	3	40	5	6	0	0	1	0	0	16	1	351
SIAM-1	Imo Fm	Upper Sandstone	80	21	6	0	150	19	22	80	0	35	0	10	1	0	4	25	3	456
SIA-2	Imo Fm	Upper Sandstone	65	11	9	0	80	8	4	66	31	85	0	0	150	4	2	6	0	521
SOZ-3	Imo Fm	Upper Sandstone	51	19	7	0	80	10	7	60	40	110	0	3	150	1	2	11	6	557

Abbreviation: Zrn, Zircon; Tur, Tourmaline; Apt, Apatite; Rt, Rutile; St, Staurolite; Sil, Sillimanite; And, Andalusite; kyn, Kyanite; Sp, Sphene; Ep, Epidote Group; Px, Pyroxene; Hb, Hornblende; Am, Amphibole; Gr, Garnet; Mn, Monzite; Act, Actinolite; Oth, other heavy minerals

Appendix E8.3. Quantitative point-counting results for heavy mineral composition in the Ameki group and Ogwashi Formation.

Sample Nos	Group	Formation	Facies Ass.	Zrn	Tur	Apt	Mn	Rt	St	Sil	Kyn	Sp	Ep	Hb	Am	Grn	Act	And	Px	Oth	TOTAL
SNS 1	Ameki	Nsugbe Formation	FA 1	172	9	3	2	86	3	1	20	0	2	0	0	0	0	1	21	2**	320
SNS 3	Ameki	Nsugbe Formation	FA 1	148	11	1	1	63	3	1	27	0	1	0	0	0	0	0	28	1**	284
SUN 1	Ameki	Nanka Formation	FA 2	120	13	0	0	8	13	0	8	0	6	0	0	0	0	1	2	1	172
SUN3	Ameki	Nanka Formation	FA 2	56	14	2	0	25	4	0	2	0	3	0	0	0	0	0	1	0	107
SUM 1	Ameki	Nanka Formation	FA 3	139	15	3	0	48	1	1	23	0	5	0	1	0	0	3	8	2*	247
SUM 2	Ameki	Nanka Formation	FA 3	92	10	2	0	58	3	2	22	0	9	0	0	0	0	0	8	0	206
SNI 2	Ameki	Nanka Formation	FA 3	110	3	0	0	17	2	7	45	0	3	0	4	0	0	0	6	4	201
SUM 3	Ameki	Nanka Formation	FA 4	89	17	2	0	60	4	4	27	0	10	0	0	0	0	0	13	0	226
SUM 4	Ameki	Nanka Formation	FA 4	89	10	3	0	11	2	0	7	0	2	0	0	0	0	0	2	1**	126
SIS 1	Ameki	Nanka Formation	FA 5	57	8	1	0	107	8	7	80	0	3	0	4	0	0	3	23	1	302
SIK 1	Ameki	Nanka Formation	FA 5	40	4	5	0	61	3	8	52	0	7	0	0	0	0	0	14	0	194
SOK1A*	Ogwashi	Ogwashi Fm	FA 1	20	3	0	5	0	0	0	5	0	0	2	0	0	0	0	0	0	35
SOK 1.1	Ogwashi	Ogwashi Fm	FA 1	46	6	1	0	34	1	1	21	0	4	0	0	0	0	0	2	0	116
SOK 1.2	Ogwashi	Ogwashi Fm	FA 1	30	12	4	0	80	4	5	71	0	7	0	0	0	0	0	29	0	242
SOK 1.4*	Ogwashi	Ogwashi Fm	FA 2	12	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	15
SOK 2.1*	Ogwashi	Ogwashi Fm	FA 2	25	3	0	0	7	2	0	9	0	5	0	2	0	0	0	0	0	53

2* **Brookite**
3** **Oxide**
SOK 1A* Samples with insufficient grains.
Fm - Formation

Abbreviation: Zrn, Zircon; Tur, Tourmaline; Apt, Apatite; Rt, Rutile; St, Staurolite; Sil, Sillimanite; And, Andalusite; kyn, Kyanite; Sp, Sphene; Ep, Epidote Group; Px, Pyroxene; Hb, Hornblende; Am, Amphibole; Gr, Garnet; Mn, Monzite; Act, Actinolite; Oth, other heavy minerals