SEDIMENTOLOGY AND STRATIGRAPHY OF ALBIAN TO TURONIAN SUCCESSIONS AROUND THE NORTHERN KEANA ANTICLINE, MIDDLE BENUE TROUGH, NIGERIA

BY

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Declaration

I declare that the work in this thesis entitled **SEDIMENTOLOGY AND STRATIGRAPHY OF ALBIAN TO TURONIAN SUCCESSIONS AROUND THE NORTHERN KEANA ANTICLINE, MIDDLE BENUE TROUGH, NIGERIA,** has been carried out by me in the Department of Geology. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other Institution.

'Tunji Adeoluwa, FAJULUGBE	……	……..
Name of Student	Signature	Date

Certification

This thesis entitled **SEDIMENTOLOGY AND STRATIGRAPHY OF ALBIAN TO TURONIAN SUCCESSIONS AROUND THE NORTHERN KEANA ANTICLINE, MIDDLE BENUE TROUGH, NIGERIA**by **'Tunji Adeoluwa FAJULUGBE** meets the regulations governing the award of the degree of Master of Science (M.Sc.) of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

……...	……..	…….
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Prof. K. Bala. Dean, School of Postgraduate Studies	Signature	Date

Dedication

To

God – who indeed is God; who was; who is and will forever be.

Jacob A. Fajulugbe – who did not only teach me to live right but lived and let me watch him do it.

Comfort A. Fajulugbe – through whose deeds I know that men are what their mothers made them.

Eniola Fajulugbe Duker – who taught me that life, more vast than I had imagined, is a wondrous process of discovery.

Abimbola O. Fajulugbe – who stood by me and guard even if the angels sleep.

Olalekan O. Fajulugbe – a brother in arms; not in words only but in deeds and in truth.

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Abstract

The study area isunderlain by the Uomba Formation, Awe Formation and the Keana Sandstone which all shows variations in constituent rock units to others elsewhere in the Middle Benue Trough. The Uomba Formation is made up of alternating sequence of fissile shales, mudstones and micaceous siltstones; the Awe Formation consisting of alternating sequence of arkosic fine grained sandstones, siltstones and mudstone series while the Keana Sandstone consists of massive, indurated, cross-bedded, medium to very coarse sometimes conglomeratic, gritty, sub-arkosic sandstones.

Petrographic analysis shows that the sediments of the Awe Formation are moderately well sorted, chemically immature arkoses, quartz-arenites and feldspathic greywackeswith the presence of glauconite indicating a marine origin for the sediments while Keana Sandstone sediments are mainly sub-arkose and are also chemically immature. Sieve analysisshows that sediments of Keana Sandstone are generally medium to coarse grained, poorly sorted and are mainly river sands deposited in a fluvial setting in a moderate to high energy depositional environment which is closer to the source.

Sedimentary structures such as faults, joints, quartz veins and mineralized hydrothermal veins were also observed in the study area and are believed to have resulted from the tectonic activities that affected parts of the Middle Benue Trough, in particular the study area.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

All geologic studies are aimed in one way or another at developing a better understanding of Earth's history. Studying rocks, especially sedimentary rocks and its distribution helps in a better understanding of the Earth's history because they are unique with regard to the information they provide. The scientific study of the classification, origin and interpretation of sediments and sedimentary rocks is known as Sedimentology. This is concerned with the physical (textures, structures, and mineralogy), chemical and biological (fossils) properties of sedimentary rocks and the processes by which these properties are generated (Boggs Jr., 2006).

Sedimentary rocks generally occur in forms of layers i.e. strata. The study of the form, arrangement, geographic distribution, chronologic succession, classification, correlation and the mutual relationship of these strata is known as Stratigraphy (Hill, 2003). This is done using the various properties of the rocks such as the lithology, fossil content, magnetic properties etc. Thus, applying the principles of sedimentology and stratigraphy on rocks - in a sedimentary environment - will help in obtaining a better understanding of the geologic history and economic potentials of such area.

1.2 STATEMENT OF RESEARCH PROBLEM

One of the most important sedimentary basins in Nigeria is the Benue Trough which is a NE – SW trending sediment - filled depression (Cratchley and Jones, 1965; Burke, Dessauvagie, and Whiteman, 1971). It has been sectorially sub-divided into three sections – the Lower, Middle

and Upper sectors. Several research works have been carried out in the lower and upper sections of this trough but this cannot be said of the Middle sector as previous research work carried out in the Middle Benue Trough are limited. The stratigraphy of the Lafia - Keana – Awe area of the Middle Benue Trough described by Offodile (1976) has been adopted by subsequent authors and used as the generalized stratigraphy of the whole Middle Benue Trough. This, however does not give a comprehensive geology of the whole Middle Benue Trough.

1.3 JUSTIFICATION/SIGNIFICANCE OF THE STUDY

This research is carried out so as to minimize assumptions and generalizations about the lithologies and stratigraphy in the study area and the Middle Benue Trough. It is believed that this research work will contribute significantly to solving problems in stratigraphic and sedimentological interpretation of the sediments.

1.4 PREVIOUS WORK

Though the geology of the Middle Benue Trough is fairly unknown in details, previous research works on various parts of the Middle Benue Trough by Cratchley and Jones (1965), Reyment (1965), Murat (1972), Offodile (1976), Offodile and Reyment (1977), Kogbe *et al.* (1978), Nwajide (1985), Sabo (1985), Ariyo (1987), Ofoegbu *et al*. (1990), Obaje *et al.* (1996) among others have presented a generalized geology of the Middle Benue Trough and established the presence of a major anticline – the Keana Anticline - which extends for about 100 km in a NE-SW direction within the Middle Benue Trough.

Benkhelil (1989), through gravity and aeromagnetic data identified the presence of sediment-filled sub-basins on either side of this anticline. Benkhelil (1989) also suggested that sinistral wrenching dominated the tectonic process and is responsible for the structural

arrangement and geometry of these sub-basins. However, very few research works have been carried out in the northeastern part of the Middle Benue Trough where the study area lies and as such few details of the sedimentology and lithostratigraphy of this part of the anticline are known.

1.5 AIM AND OBJECTIVES OF THE PRESENT WORK

The aim of this research work is to deduce the sedimentology and stratigraphy of the successions in the study area. This will be done so as to:

i. produce a detailed geological map of the area which would serve as update on the regional geological map of the Middle Benue Trough.

ii. establish lithostratigraphic successions in the study area and thus update the knowledge of the lithostratigraphy and sedimentology of sedimentary successions in the area.

ii. ascertain the occurrence and influence of structures to the stratigraphic succession.

iv. interpret the depositional history in terms of transgression/regression episodes.

v. elucidate on the geological history of the stratigraphic successions in the study area.

1.6 LOCATION AND ACCESSIBILITY

The study area is located within the Middle Benue Trough in the central part of Nigeria. It lies within Latitudes 8° 15' N and 8° 30' N and Longitudes 9° 00' E and 9° 15' E covering Akiri Sheet 232 NW on a scale of 1:50,000 (Fig. 1.1). Towns, villages and settlements within the study area include Gidan Soja, Adudu, Rufai (now Ribi), Arugagwu (now Rugagwu) and Azara. These

settlements are interconnected by secondary roads and footpaths thus making the study area fairly accessible (Fig. 1.1).

1.7 RELIEF AND DRAINAGE

The area is generally undulating lowland (plain terrains) with heights ranging from about 200 to 700 m. The drainage pattern in the area is generally dendritic with Ankwe, Rafin Paa, Tukuruwa, Bakabu and Rafin – Arugagwu being the prominent rivers (Fig. 1.1). These rivers flow almost parallel to each other and empty into River Benue to the south. The volume of the river discharge varies with seasons. It is high during the rainy season and low during the dry season.

1.8 CLIMATE AND VEGETATION

The climate of the study area is characterized by alternating dry and wet seasons. The dry season spans through November to February, while the wet season is from March to October. The primary vegetation is typically Guinea Savannah characterized by tall grasses, shrubs and scattered trees. There is the presence of forest along river and stream channels which largely has been tampered with by human activities like farming, cattle grazing and constructions. NASEEDS (2005) described the vegetation in the area to be divided into two zones which are made up of:

i. the flood plain complexes of the Savannah, which is a mixture of several vegetation types mostly found on river flood plains; and

ii. the mixed leguminous wooded Savannah characterized by mixed formation of trees, shrubs and grasses.

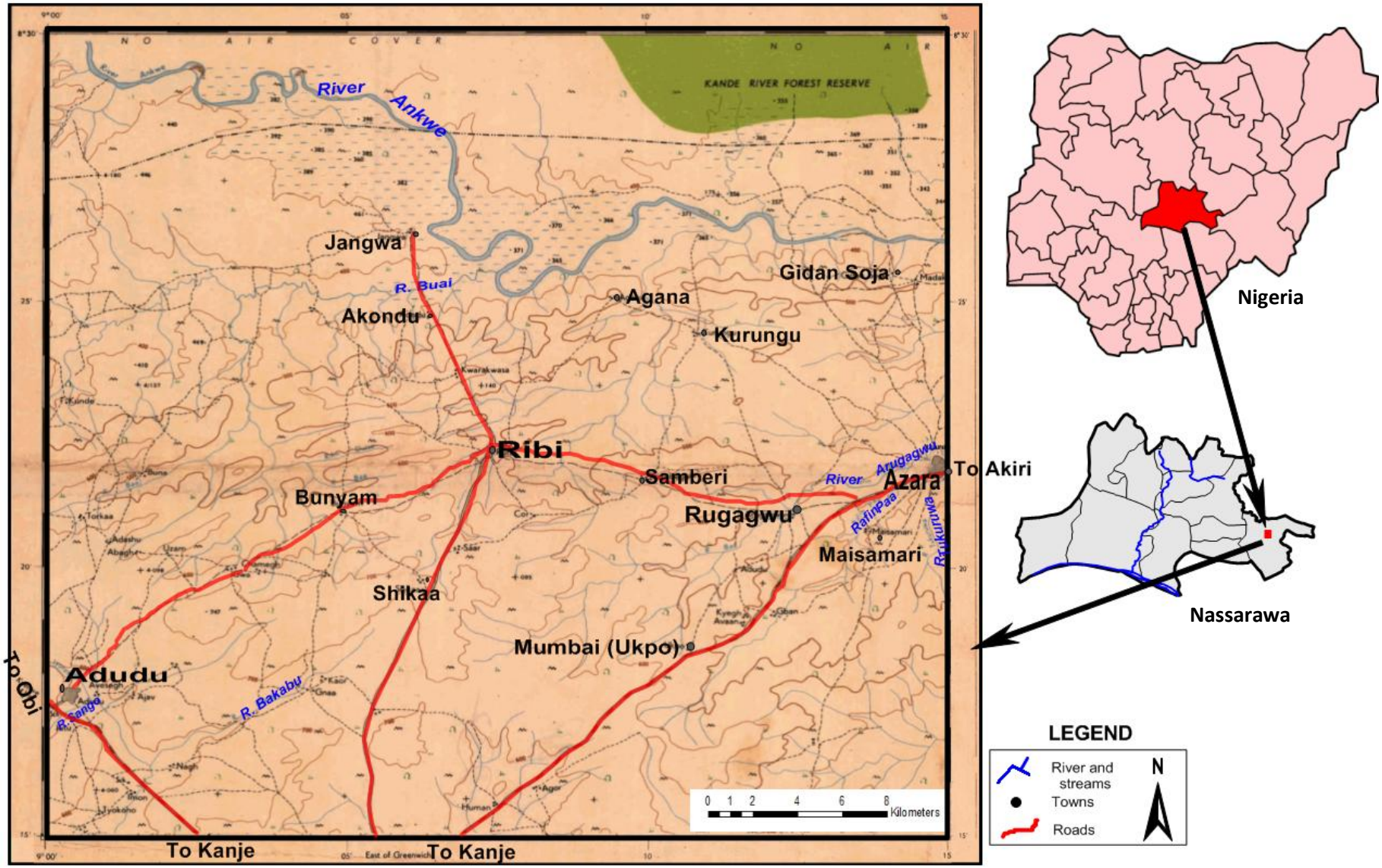


Figure 1.1. The location map of the study area.

CHAPTER TWO

LITERATURE REVIEW

2.1 GEOLOGICAL SETTING

The study area lies within the Middle part of the Benue Trough of Nigeria. The Benue Trough is one of the most important sedimentary basins in Nigeria. Reyment (1965), Avbovbo (1980), Whiteman (1982), Benkhelil (1988), Offodile (1989), Zaborski (1998) and Najime (2011) identified the Benue Trough in their various works to be a linear NE – SW trending trough with an approximate length of about 800 km opening into the Gulf of Guinea where the Cenozoic Niger Delta has built out upon the oceanic crust. It is an integral part of the "West and Central African Rift System (WCARS)" of Fairhead (1986) which is a type example of the early stage in development of continental margins.

The WCARS was formed as a resultant effect of the separation of Africa from South America on the African continent which led to the development of a closely linked rift system in the West and Central African regions. This system is divided into the West African Rift Subsystem (WARS) and the Central African Rift Subsystem (CARS). Both were developed within the Pan – African lines of lithospheric weakness (Guiraud and Maurin, 1993). These subsystems are thus intra-continental Cretaceous rift systems and are recognized based on extensive gravity data which indicated that there is a strong interaction between oceanic and intra-continental tectonics (Fairhead, 1992).

The Benue Trough has been subdivided into "Lower Benue Trough" which is equivalent of "Abakaliki Trough" of Murat (1972) and Whiteman (1982), "Middle Benue Trough" and "Upper Benue Trough" (Fig. 2.1). This subdivision of the Benue Trough with their individual

structural, sedimentary, and paleontological characteristic is based on gravity measurements of depth to the underlying basements. This measurement is based on the principle that the higher the gravity value, the closer the basement (Benkhelil, 1989).

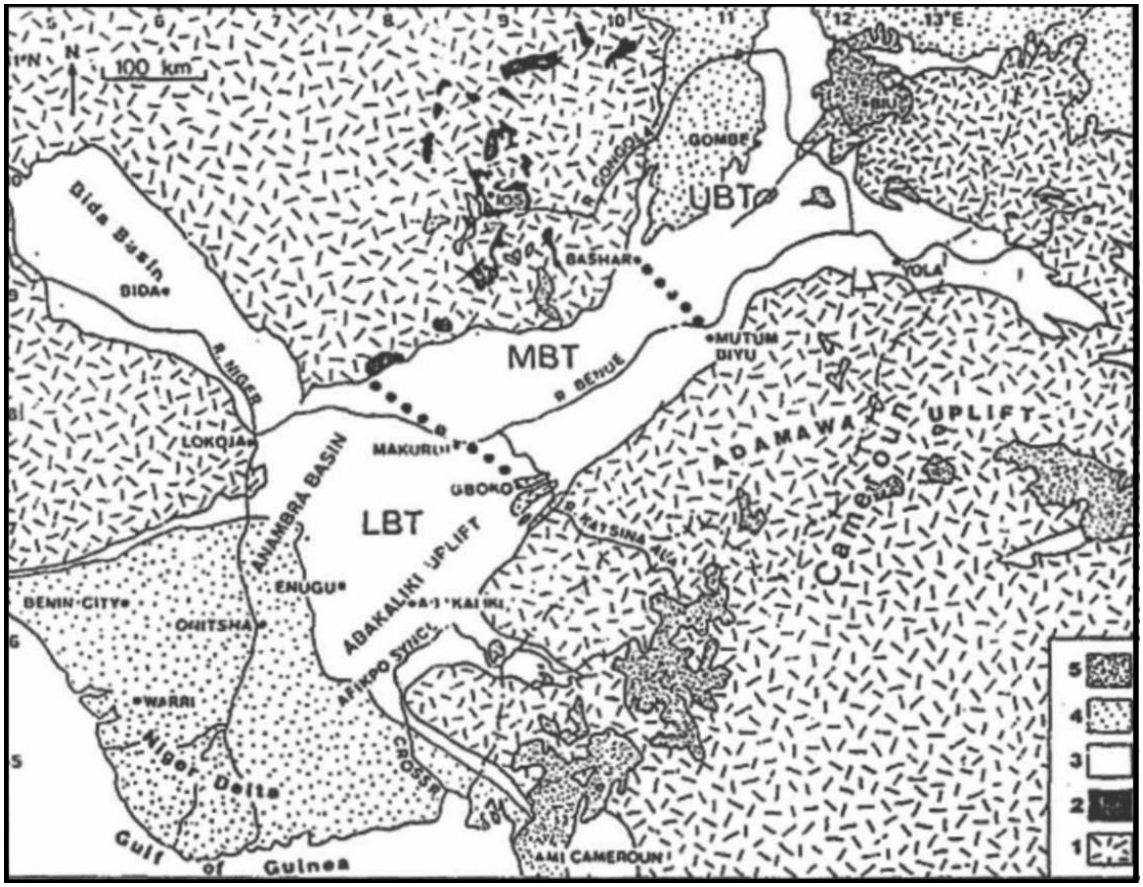


Figure 2.1: Outline geological map of the Benue Trough and adjacent areas (after Zaborski, 1998). **LBT**- Lower Benue Trough; **MBT** - Middle Benue Trough; **UBT** - Upper Benue Trough. 1. Precambrian. 2. Jurassic "Younger Granites". 3. Cretaceous. 4. Post-Cretaceous sediments. 5. Cenozoic Recent basalts (including those of Cameroon

Some areas along the trough have been found to have points characterized by gravity highs. These points were recorded over Amar, Awe, Gboko areas in the Middle and upper-lower sectors of the trough respectively and over Kaltungo area in the upper sector. Benkhelil, (1989) reported that these central gravity highs are flanked on both sides by gravity "lows" which he interpreted as areas of thickest Cretaceous sediments or depocenters. The entire Benue Trough is filled with sediments that range from Late Aptian to Paleocene in age (Allix *et al.*, 1981).

2.2 ORIGIN OF THE BENUE TROUGH

Several theories have been proposed to explain the origin and non-uniform evolution of the Benue Trough. King (1950) proposed a rift origin based purely on geomorphology of the trough. Due to lack of marginal faults and the tremendous thickness of the sediments in the trough, Lees (1952) proposed that the trough is a geosyncline with folding involving the basement. Cratchley and Jones (1965), proposed a combination of a rift valley and a geosyncline as the origin of the trough based on the results from a regional gravity and geological survey of the entire trough. A rift whose origin is related to the separation of South America from Africa was proposed by Wright (1968).

Grant (1971) also suggested a failed arm model for the trough but considered the Niger Delta triple junction as a rift – rift - fault junction, with transform fault making up the Gulf of Guinea segment. Olade (1975) argued that the Benue Trough is a zone of an "on and off" Cretaceous hotspots based on the tectonic pattern in the trough and as such interpreted the Benue Trough as an aulacogen which he related to the intermittent mantle upwelling. Burke *et al*. (1971, 1972), Burke and Whiteman (1973) and Burke and Dewey (1974) explained that in the Gulf of Guinea where the bifurcating rift system became the site of a triple junction, two of the rifts opened into the Equatorial and South Atlantic Oceans with marginal basins underlained by half grabens (e.g. the Dahomey Embayment).

Along the third rift however, there was only limited opening – a sinistral strike-slip movement which was abandoned as a "failed arm" or juvenile aulacogen which today is the Benue Trough. Ofoegbu (1984) and Ofoegbu *et al.* (1990) proposed a model similar to that of Olade (1975), and in addition postulated that protruded dyke-like bodies within the zone of

weakness result from up-doming and have contributed to the stretching and thinning of the crust. Zaborski (2003) suggested rifting processes that are strongly modified by strike-slip faulting similar to that of Benkhelil (1989) to be the main control on the Early Cretaceous history of the upper part of the Benue Trough.

2.3 STRATIGRAPHY OF THE BENUE TROUGH

Sedimentation within the Benue Trough did not occur at once but in transgressive and regressive cycles, intermittently throughout the Cretaceous Period (Murat, 1972; Offodile, 1976; Zaborski, 2000). The 'Benue Trough proper' was terminated by a Late Santonian episode of compressional folding and subsequent sedimentation was centered on basins developed on the north – western flanks of the resultant deformed sediments (Zaborski, 1998).

Detailed stratigraphic descriptions of the sediments within the Benue Trough have been presented by Simpson (1954), Carter, Barber, Tait and Jones (1963), Reyment (1965), Cratchley and Jones (1965), Murat (1972), Offodile (1976), Adeleye and Fayose (1978), Petters and Ekweozor (1982), Popoff *et al.* (1986), Nwajide (1990), Ojoh (1990), Idowu and Ekweozor (1993), Obaje *et al.* (1996), Obaje and Abaa (1996), Zaborski *et al.* (1997), Najime (2011), Akande *et al.* (2012) and Hamidu *et al.* (2013). The generalized stratigraphic succession in the Benue Trough is as shown in Figure 2.2. However, there have been various modifications for individual portions of the Benue Trough as a result of recent research work carried out on specific parts of each region by various authors.

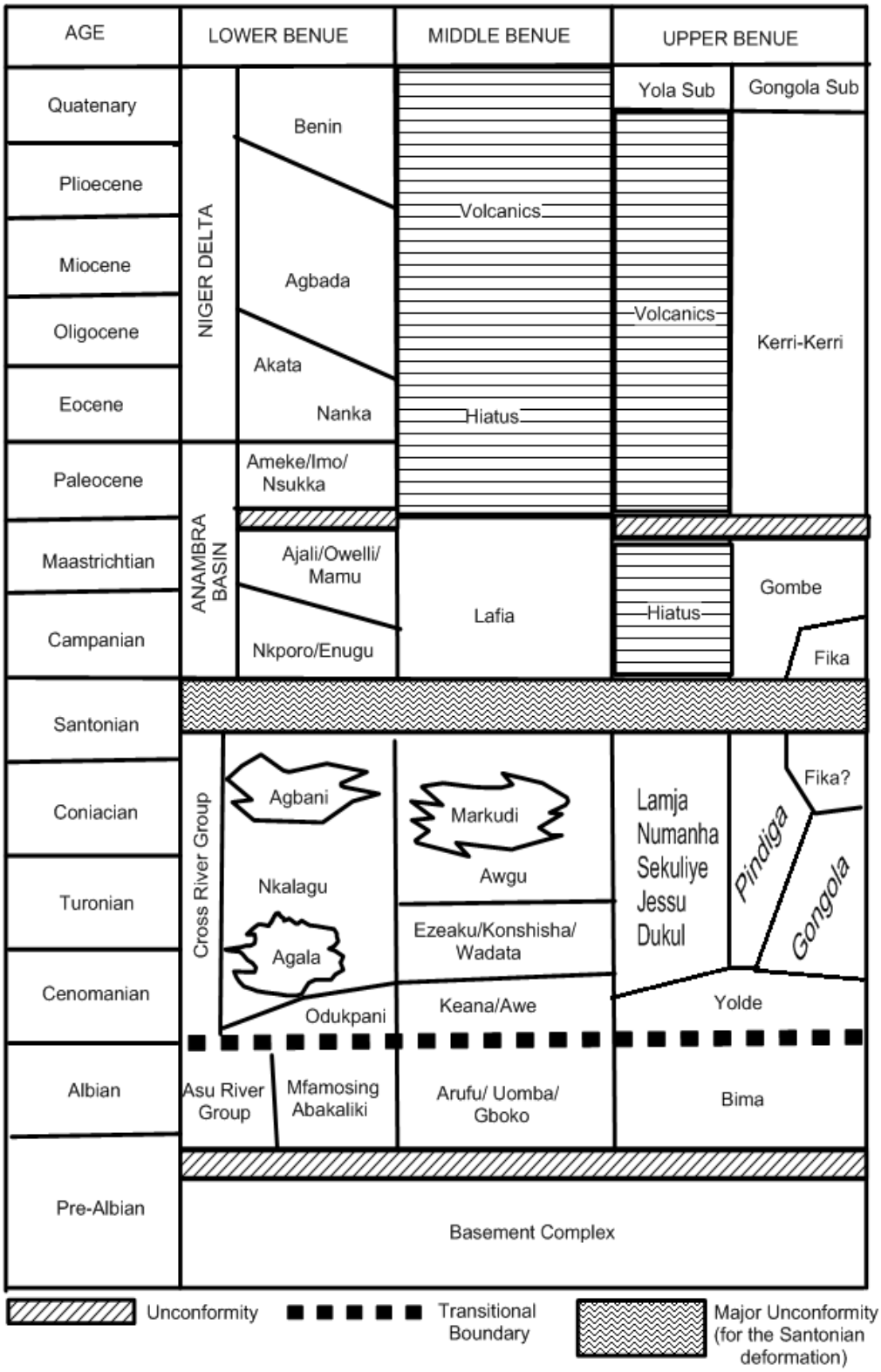


Figure 2.2: Correlation of major stratigraphic units in the Anambra Basin, Niger – Delta and the Benue Trough, Nigeria (After Obaje, 2009)

2.4 STRATIGRAPHY OF THE MIDDLE BENUE TROUGH

The Middle Benue Trough extends north-eastwards approximately as far as the line joining Bashar and Mutum Biyu (see Fig. 2.1). This boundary marks the southern limits of the Gombe and Kerri-Kerri Formations. Detailed geology and stratigraphy of the Middle Benue Trough is relatively poorly known especially in its north-eastern part. Cratchley and Jones (1965), Reyment (1965), Murat (1972), Ariyo (1987), Ofoegbu *et al.* (1990), Obaje *et al.* (1996) have, however worked in parts of the Middle Benue Trough and have described its geology and stratigraphy. The area immediately south of Bashar, the Lafia – Keana – Awe region and the area around Makurdi have also been described by Offodile (1976), Offodile and Reyment (1977), Kogbe *et al.* (1978), Sabo (1985) and Nwajide (1985).

The axial basement high of the Middle Benue Trough - the "Keana ridge" of Ajayi and Ajakaiye (1986), coincides with its main surface structural feature, the NE-SW trending Keana anticline. Either side of the basement high, sedimentary sub-basins was identified by Benkhelil (1989) based on gravity and aeromagnetic data. The sediments of the Middle Benue Trough have been assigned to six upper Cretaceous lithostratigraphic units, from the oldest to the youngest namely: Arufu, Uomba and Gboko Formations (subdivisions of the Asu River Group in the Middle Benue Trough), Awe Formation, Keana Sandstone, Eze-Aku Formation, Awgu Formation and Lafia Formation (Offodile, 1976) (Fig. 2.3). These sediments were deposited through sedimentation cycles of transgression and regression which are continuous from those identified in the Lower Benue Trough.

The sedimentation cycles are Middle Albian to Middle Cenomanian, Upper Cenomanian to Middle Turonian, Upper Turonian to Coniacian and Upper Campanian to Maastrichtian.

Differential subsidence coupled with eustatic sea level rise, however led to facies variations in the basin's sediments (Akande *et al*., 2012). A period of non-deposition during the Santonian was experienced. Reyment (1965), Burke and Whiteman (1973), Obaje (1994), and Obaje and Abaa (1996) believed this non – deposition was caused by the Santonian compression which they believed produced the main NE – SW trending fold structures found within the Middle Benue Trough such as the Keana anticline. Offodile and Reyment (1977) and Obaje and Abaa (1996) also documented a period of volcanic activity from Santonian to Campanian.

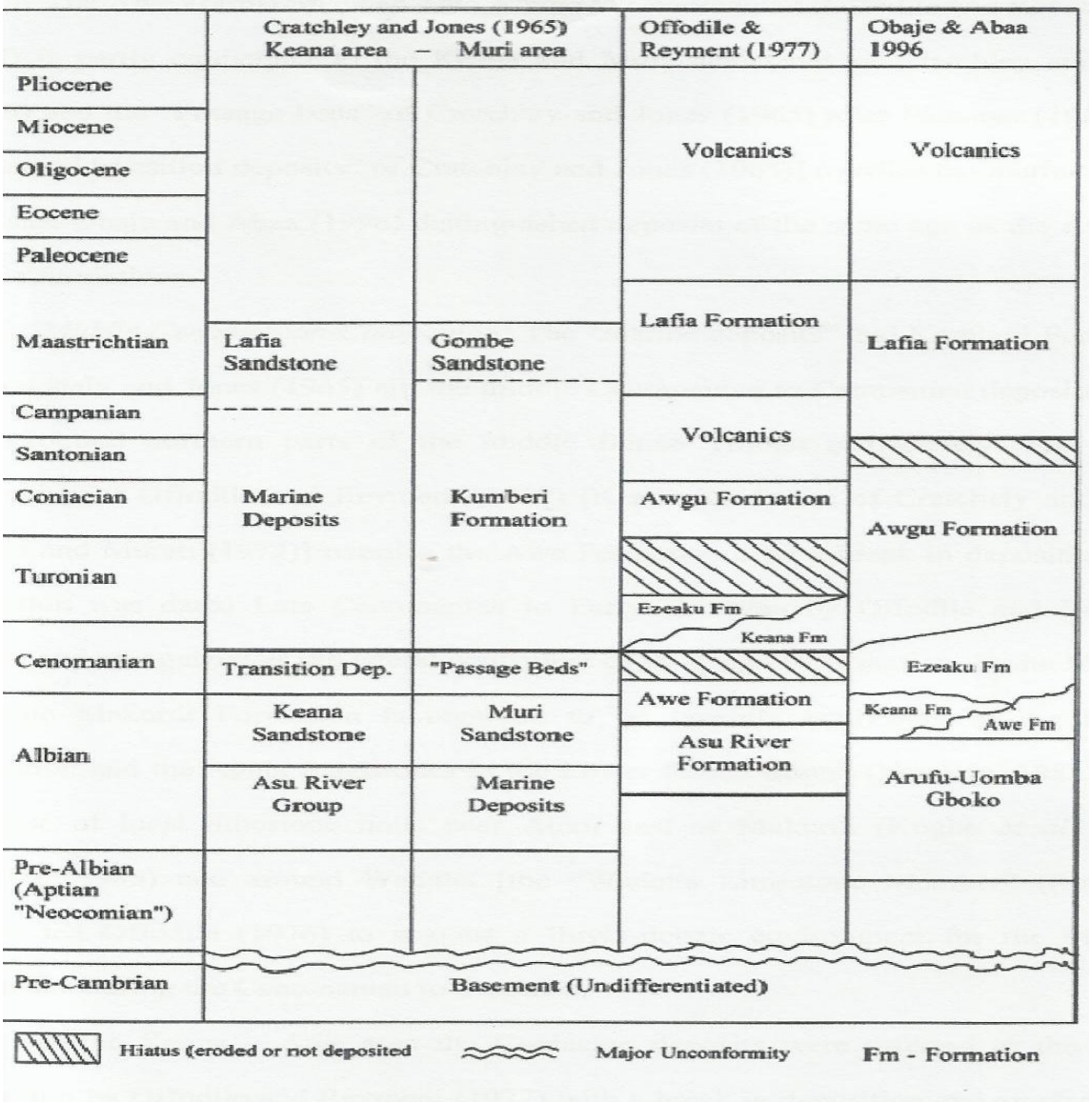


Figure 2.3: Summary of the stratigraphy of the Middle Benue Trough (After Najime, 2011).

2.4.1 Asu River Group

The Asu River Group (Cratchley and Jones, 1965) earlier referred to as "Uomba Formation" by Reyment (1964); "Asu River Formation" by Offodile (1976), and Offodile and Reyment (1977) comprises of three formations – the Arufu, Uomba and Gboko Formations which Obaje (1994) noted as lateral equivalent facies referable to anyone name of the three depending on the locality. These are the oldest known outcropping sediments in the Middle Benue Trough and are Middle Albian in age. The Uomba Formation comprises of interbedded marine shale, limestone and micaceous siltstone. The nature of any sediment underlying the Uomba Formation is speculative. In the south – eastern extremity of the Middle Benue Trough, the locally developed Arufu (Arufa) Limestone (Reyment, 1964) lies on top of the Precambrian basement and contains ammonite *Elobiceras* which is of Late Albian age (Spath, 1928; Reyment, 1965).

The Asu River Group are interpreted as having formed during the first marine transgression into the Benue valley (first depositional cycle in the Middle Benue region) and are probably the age-equivalent of the marine slumps and turbidites that make up the Ekebeligwe Formation in the Lower Benue Trough (Zaborski, 1998). The Uomba Formation [="Asu River Formation"] outcrops on the Keana anticline to the east of the town of Keana. Benkhelil, *et al.* (1988) reported shale-dominated lacustrine facies with channel fill sequences in the lower Asu River Group east of Keana town with the sediments being fossiliferous, containing Late Middle Albian ammonites *Oxytropidoceras* (Offodile and Reyment, 1977).

2.4.2 Awe Formation

The Awe Formation (Offodile, 1976) [= "passage beds" of Falconer (1911); "unnamed transition deposits" of Cratchley and Jones (1965)] is interpreted to have been formed during the Late Albian – Early Cenomanian period which saw a regressive phase that ended the first marine transgression. The formation comprises of carbonaceous shales, flaggy, medium to coarse-grained calcareous sandstones and clays. The sandstones become finer-grained and more micaceous towards the base with fine current beddings (Ariyo, 1987). Offodile (1976) estimated the thickness of the formation to be about 100 m around the town of Awe which is the type locality. Brine springs issue from the beds in some places within this locality. The Awe Formation is generally not fossiliferous although a few gastropods and pelecypods have been described by Offodile and Reyment (1977).

2.4.3 Keana Sandstone

The regression of the Albian Sea in the Middle Benue region during the Cenomanian period gave rise to the process of erosion taking place in the hinterland thereby causing a large quantity of detritus to be deposited in a restricted delta (Bima delta). The deposition of these fluviodeltaic sediments moved southwards to form the Keana Sandstone (Offodile, 1976) [= "Keana Sandstone" of Cratchley and Jones (1965) and Murat (1972), after Shell – BP]. The Keana Sandstone is thus believed to be the southern extension of the Bima delta, which apparently moved down with the retreating Albian Sea. The Keana Sandstone overlies the Awe Formation, the contact between the two formations being variously described as gradational and unconformable (Offodile and Reyment, 1977; Offodile, 1976).

The Bima Sandstone, the Keana and Makurdi Formations are possibly, part of the same lithological unit which appears to get progressively younger in age from the northeast to the southwest. Although not directly dated, the Bima Sandstone appears to be Late Albian to Cenomanian in age - but could be as old as Jurassic; the Keana Sandstone seems to be Cenomanian while the Makurdi Formation is Cenomanian to Turonian based on their stratigraphical positions of Carter *et al.,* 1963 (Offodile, 1976).

The Keana Sandstone consists mainly of massive, thickly bedded, highly indurated, current – bedded, fine to very coarse, sometimes conglomeratic, gritty, generally non-fossiliferous, arkosic sandstone of inferred fluvial or deltaic origin (Murat, 1972; Offodile, 1976). The sandstones are generally poorly sorted and according to Offodile (1976), conglomerates, bands of shales and limestones may be intercalated towards the top. The Keana Sandstone flanks both sides of the Keana anticline. Outcrops occur at various localities including Keana, Noku, Chikinye, Jangerigeri, Azara and Daudo (Offodile, 1976) with the most extensive located in the area about 500 m south of Chikinye. Offodile and Reyment (1977) described the Keana Sandstone as in places lying below beds referred to as Eze-Aku Formation and elsewhere interfingering with them.

2.4.4 Eze-Aku Formation

The Eze-Aku Formation is believed to have been deposited beginning Late Cenomanian in a shallow marine coastal environment during a period of low input of terrigenous material due to the displacement of the coastlines. Occasionally near the shores, marine and fluviatile conditions interplayed in the transitional environment between the “Keana Sandstone conditions”

and those giving rise to the Eze-Aku Formation. Further away from the coastlines, predominantly argillaceous materials were deposited including clays and shales (Offodile, 1976).

The Eze-Aku Formation consists of calcareous grey to black shales, micaceous, fine to medium-grained, friable sandstones and shaly limestones (Offodile, 1976; Offodile and Reyment, 1977). It is highly fossiliferous at certain levels containing ammonites, bivalves, ostracods and foraminifers (Offodile and Reyment, 1977). The shelly limestones found at its basal part contain bivalves *Costagyra olisiponensis* (Sharpe) while a marly horizon has yielded the late Cenomanian ammonite *Euomphaloceras septemseriatum.* Higher in the formation, a diverse 'vascoceratid'- dominated ammonite fauna occurs, containing Late Cenomanian to Early Turonian species (Zaborski, 1998).

2.4.5 Awgu Formation

The Awgu Formation is generally fossiliferous consisting predominantly of arenaceous foraminifers, some calcareous foraminifera taxa and ostracods (Offodile and Reyment, 1976). In the Keana – Awe area, which has been used to generalize for the Middle Benue Trough, the Awgu Formation overlies the Eze-Aku Formation. Comparing this formation with the Nkalagu area in the Lower Benue Trough, Offodile and Reyment (1977) was of the opinion that these formations (Eze-Aku and Awgu Formations) may be unconformable, the upper part of the Turonian being missing.

Obaje (1994) however believed that the contact is conformable and dated the Awgu Formation as Turonian to Coniacian (or Early Santonian). The Awgu Formation consists of bluish – grey, black carbonaceous shales, calcareous shales, shaly limestones, siltstones and coal seams (Obaje, 1994). The presence of coal seams suggests a rapid change in the depositional

environment between continental and shallow marine conditions with the environment of deposition of the coal-bearing sequences ranging from shallow marine through lagoonal to deltaic plain. Occasional local regression and sea level changes developed swampy environment with abundant vegetation which encouraged the development of coal measure sequences (Obaje, 1994).

2.4.6 Lafia Formation

This is the youngest known formation in the Middle Benue Trough. The Lafia Formation (Offodile, 1976) [= the "Lafia Sandstone" of Cratchley and Jones (1965); the "Sandstones of Lafia/Makurdi" of Farrington (1952); the "Upper Grits and Sandstones" of Falconer (1911)] contains the youngest sediments in the Middle Benue Trough. Its sediments were deposited during the Upper Campanian – Maastrichtian sedimentation cycle. It overlies a hiatus caused by the Santonian folding (Obaje, 1994). This formation is confined to the Kadarko sub-basin within the Middle Benue Trough (Benkhelil, 1989).

The sediments of the Lafia Formation are believed to have an origin within the south-westerly flowing fluviatile system which is discharging into the Anambra Basin (Offodile, 1976; Offodile and Reyment, 1977). The Lafia Formation consists of continental red, poorly consolidated, commonly cross bedded, frequently ferruginous sandstones, flaggy mudstones and clay. It also consists of a paleosol horizon which has been identified south of Lafia. The occurrence of identifiable fossils has not yet been found except for the presence of carbonized plants (Offodile, 1976).

CHAPTER THREE

METHODOLOGY

3.1 DESK STUDY

Extensive review of published and unpublished work on the area of study and the research subject was carried out. Landsat Images of the area were also obtained and analyzed in order to have a fore knowledge of the rock types and structural features that may be encountered in the field.

3.2 FIELD WORK

Field mapping of the area was carried out on the scale of 1:50,000. The mapping was carried out by traverses along major and minor roads, footpaths and stream channels in order to locate and make observations on exposed stratigraphic sections. Compass - clinometer was used to measure the dip and strike of various geological structures observed on outcrops and lithological sections exposed in the study area. Global Positioning System (G.P.S) receiver was used to identify precise location of the exposed sections in the area while measuring tape was used to measure the various thickness of beds and structures observed in the field. All readings taken and description of outcrops were then recorded in the field notebook.

The exposed sections were carefully logged and fresh representative rock samples were carefully collected with the aid of a geological hammer, labeled and packaged for further laboratory studies. In addition, photographs of structures, type sections and other features of interest were taken.

3.3 LABORATORY ANALYSES

Two major laboratory analyses were carried out. These are microfossil and sedimentological analyses. The microfossil analysis was carried out in order to analyse for the presence of micro and/or macrofossils especially in sedimentary rocks such as shales, limestones, mudstones and clays while the sedimentological analysis was carried out so as to describe the sedimentological properties of the various representative rock samples obtained from the field. These analyses were undertaken at the Sedimentology and Thin-Section Laboratories, Department of Geology, Ahmadu Bello University, Zaria.

3.3.1 Microfossil Analysis

Ten (10) selected representative shale, mudstone and claystone samples were subjected to microfossil analysis using the procedure of Lewis and McConchie (1994).

i. Samples were disaggregated using a porcelain mortar and pestle.

ii. About 10 – 20 g of the dry disaggregated of each sample was soaked in 100 – 200 ml of Hydrogen Peroxide (H_2O_2) separately in a beaker for 48 hours in order to allow for the complete disaggregation of the rock sample into individual grains.

iii. Each disaggregated samples was then wet sieved through a 63 µm mesh sieve under running water in order to remove the clay fraction from the sample.

iv. The residues were then put in the oven at about 50°□ to dry for about thirty (30) minutes.

v. After drying, the residue were then examined under the binocular microscope for identification of fauna present.

3.3.2 Sedimentological Analysis

Sedimentological analysis was done in order to determine the paleo-environment of sediments that formed the sedimentary rocks starting from its source through the diagenetic events that the sediments have undergone to form the sedimentary rocks. Petrographic and sieve analyses were employed to determine these. The procedures followed for these analyses are as follows:

3.3.2.1 Petrographic Analysis

This involves the identification of minerals that make up a rock using their optical properties. This was done to identify not only the constituent minerals but also the cement, matrix, average grain size, sorting, porosity, roundness, nature of contact of these minerals which gives us an idea of the diagenetic events that had taken place.

The roundness was estimated using the roundness chart of Pettijohn *et al.* (1987) (Fig. 3.1). The sorting was also estimated using visual comparators for sorting of minerals in a thin-section which is based on three-dimensional distributions of spheres that are log-normal by volume frequency (Fig. 3.2).

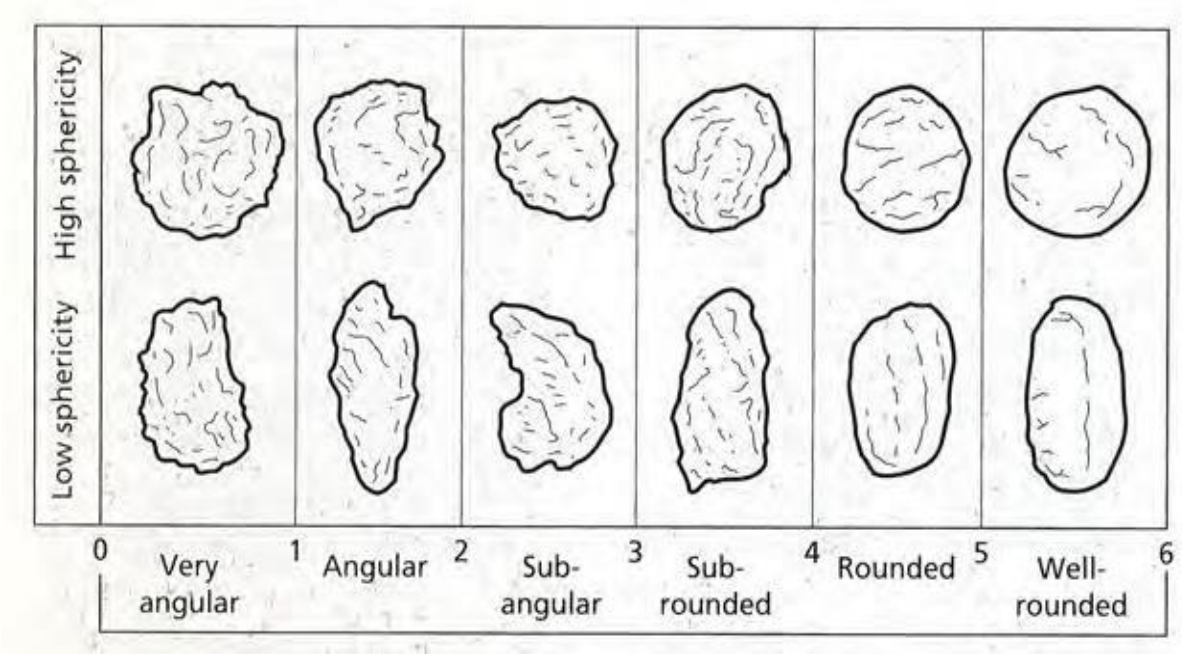


Figure 3.1.Roundness chart for sediment grains showing low and high sphericity of the grains (Pettijohn *et al.*,1987).

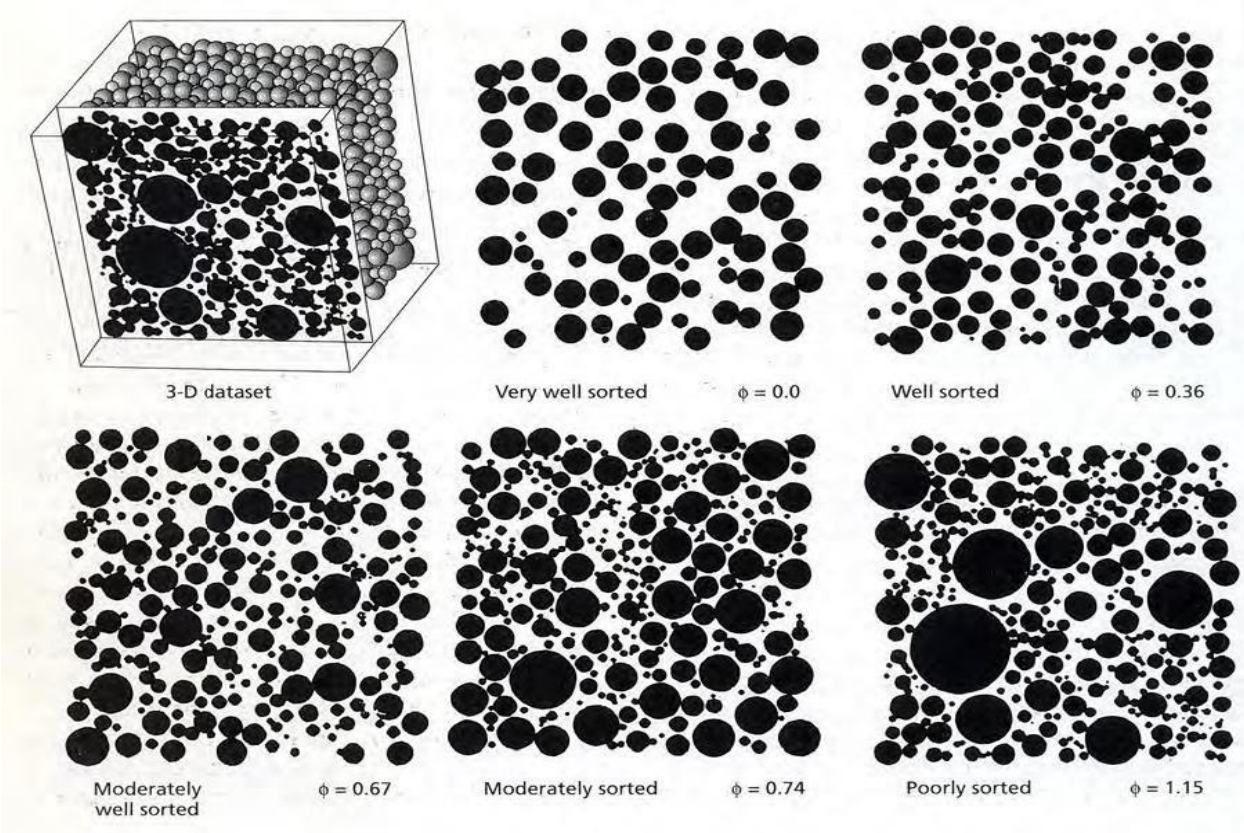


Figure 3.2.Visual comparators for the sorting of minerals in thin-sections based on distribution of spheres that is log-normal by volume frequency (Jerram, 2001).

Eight (8) representative samples of rocks collected from the field were prepared for thin-sections using standard laboratory procedures and precautions. The thin sections produced were subsequently viewed and analyzed using the petrographic microscope.

3.3.2.2 Sieve Analysis

Sieve analysis was done in order to deduce the grain size distribution of the sediments in the study area. Thirteen (13) representative samples were selected for this purpose. The sieve analysis was achieved using the following standard laboratory procedures and precautions:

i. Selected samples were first carefully disaggregated with the aid of porcelain mortar and pestle.
ii. 100 g of each disaggregated sample was weighed out using a weighing balance.
iii. Sieves with mesh sizes of 1800 µm, 600 µm, 300 µm, 150 µm, 75 µm and sieve pan were individually weighed with a weighing balance and the results recorded.
iv. The sieves were stacked together in order of decreasing mesh sizes, that is, the 1800 µm sieve at the top and the 75 µm sieve at the base directly on the sieve pan.
v. The 100 g sample was poured into the stacked sieves and placed on an electric shaker set to run for 10minutes to aid the separation of sediments according to their mesh sizes. This procedure was then repeated for each of the samples.
vi. The sample material retained in each sieve was weighed individually on a weighing balance and the result recorded in each case. To determine the weight of the grains retained in each sieve, the weight of empty sieve was subtracted from the weight of the sieve plus sample and the result recorded.

The sieve analysis data obtained are presented in Appendix I. Cumulative weight frequency curves were also plotted for the data and presented in Appendix II. Important percentiles that were used in calculating the grain size parameters such as sorting, skewness and the mean were obtained. The grain size $M = \frac{\phi 16 + \phi 50 + \phi 84}{3}$ sing the Folk and Ward (1957) formulas as shown below:

1. Graphic Mean: $M = \frac{\phi 16 + \phi 50 + \phi 84}{3}$

2. Graphic Sorting: $D = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$

3. Graphic Skewness: $S = \frac{\phi 84 + \phi 16 - 2(\phi 50)}{2(\phi 84 - \phi 16)} + \frac{\phi 95 + \phi 5 - 2(\phi 50)}{2(\phi 95 - \phi 5)}$

The bivariate plots of these parameters were plotted and compared with the values o Friedman (1961) (Fig. 3.3a, b) to determine their depositional environment.

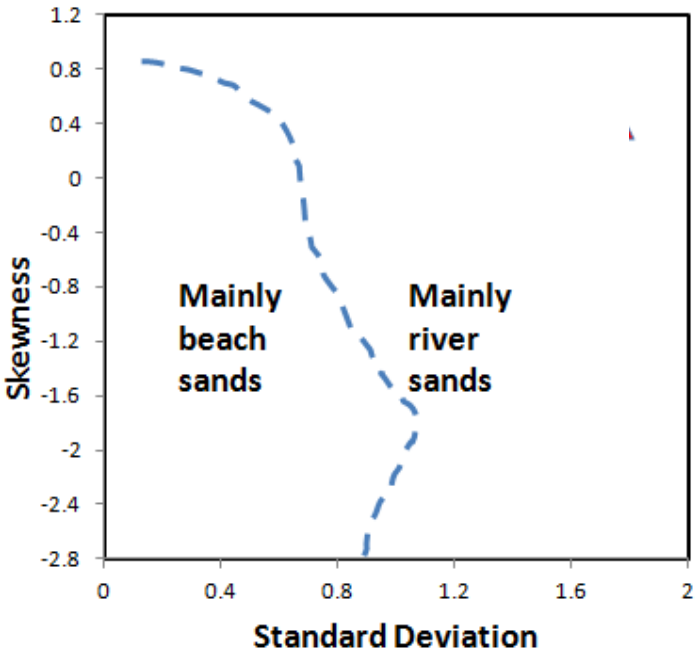


Figure 3.3a: Bivariate Plot of Skewness versus Standard deviation (after Friedman, 1961)

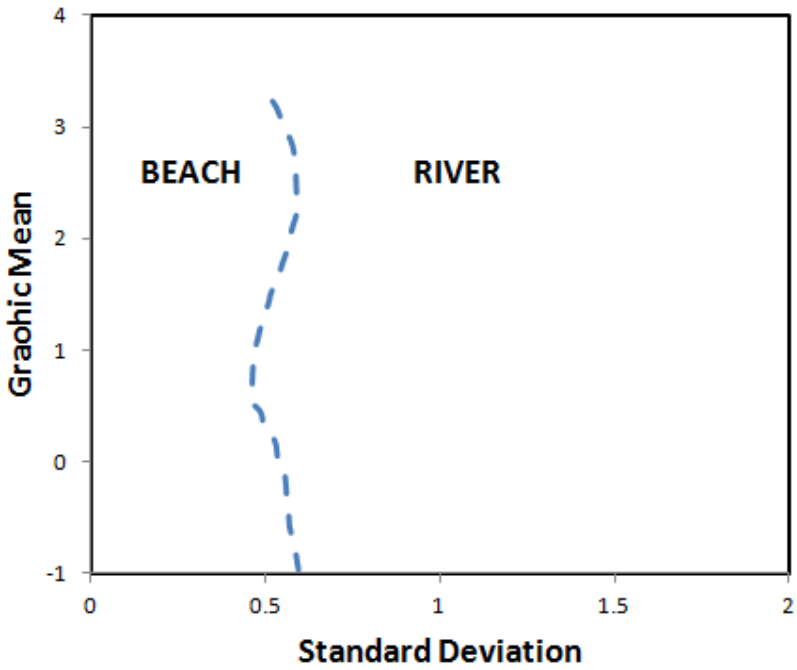


Figure 3.3b: Bivariate Plot of Graphic Mean versus Standard deviation (after Friedman, 1961)

CHAPTER FOUR

RESULTS

4.1 GEOLOGY OF THE STUDY AREA

Sedimentary rocks such as shales, mudstones, siltstones and sandstones successions are the major rock types encountered within the study area. These rocks are fairly well exposed especially along water courses (streams and rivers channels) and abandoned baryte mining pit sites from which most sections were described. Most of these streams and river channels are shallow and dry thus making traversing a bit easier. Few probable contacts were observed within baryte mining pits while the geological boundaries presented in this report are mostly inferred based on field observation and analyzed Landsat Images (Fig. 4.1).

The study area is underlained by three formations namely Uomba, Awe and Keana Formations. The Uomba Formation outcrops mainly in the southwestern part of the study area; Awe Formation outcrops along the southern half of the study area while Keana Sandstone is exposed on the northern half of the study area (Fig. 4.2). The varying dip orientation of the beds gives a valid proof of the presence of an anticline in the study area. The abundance of fractures and quartz-filled joints exposed in the study area indicates the effect of a regional tectonic activity.

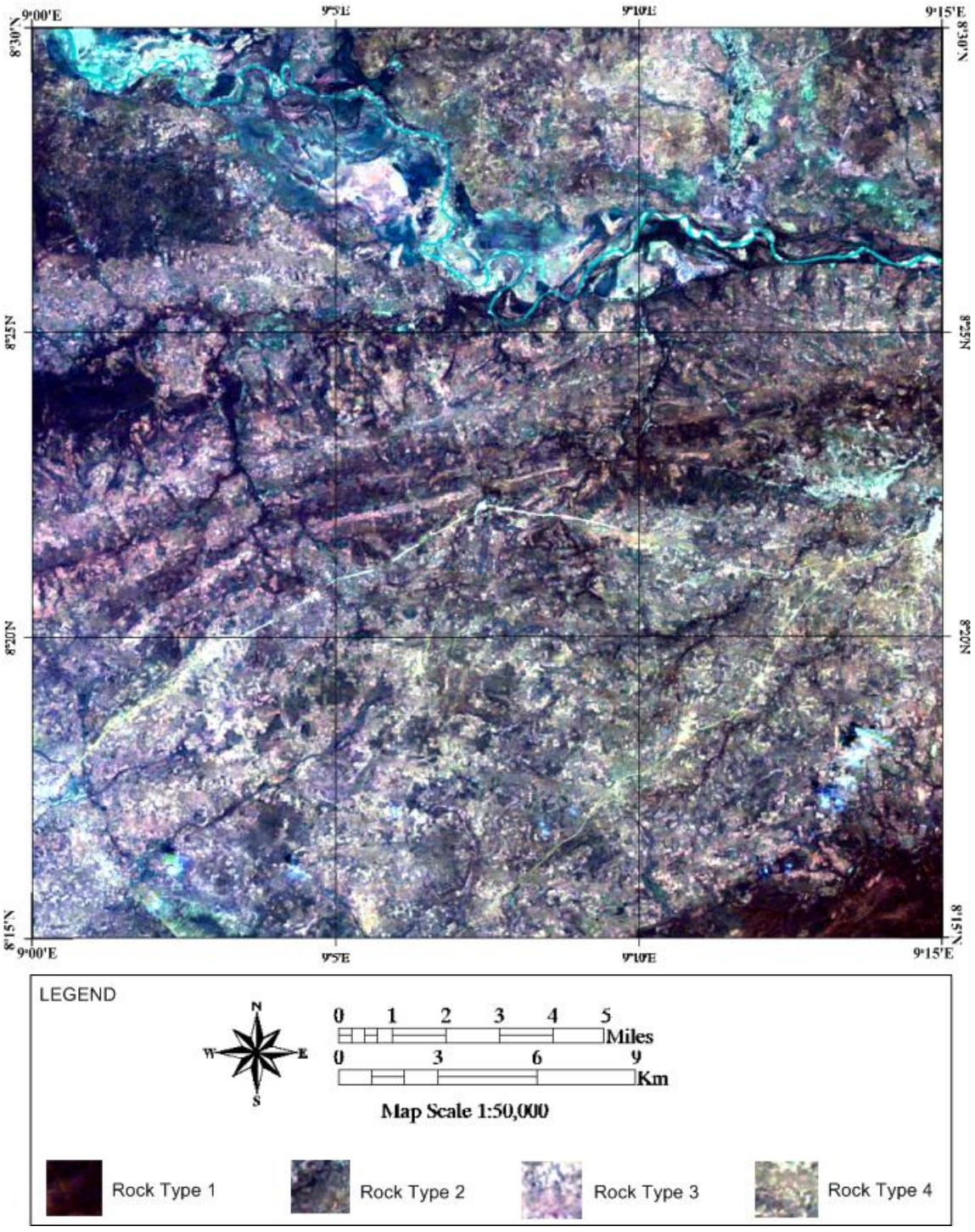


Figure 4.1: Landsat Imagery of the study area showing bands 7, 3, and 1 combined in RGB.

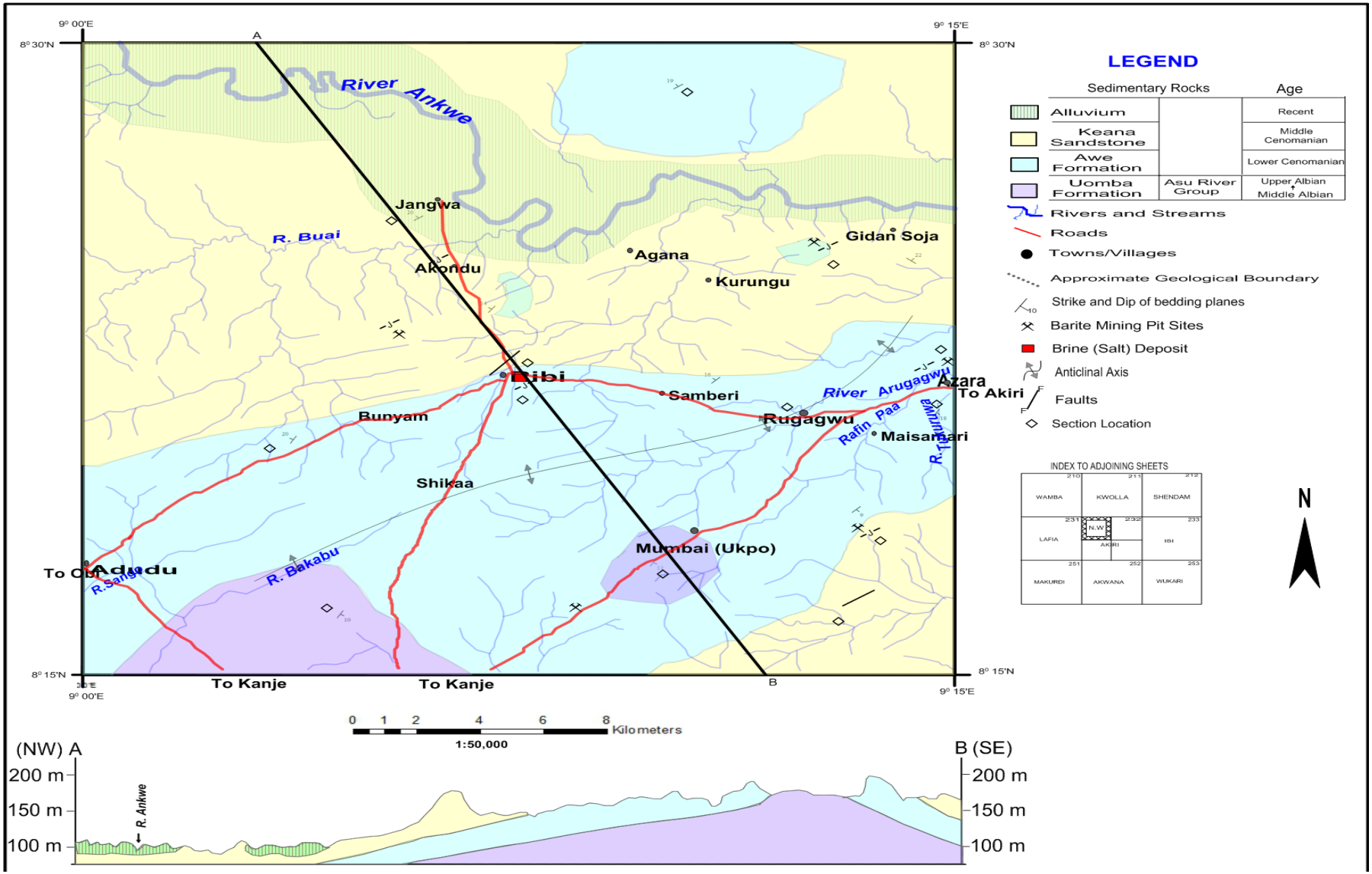


Figure 4.2. The Geological map of Ribi area, part of Akiri sheet 232 NW

4.2 LITHOSTRATIGRAPHY

Lithostratigraphy, defined as the recognition, subdivision, and correlation (establishing equivalence) of sedimentary rocks on the basis of their lithology, is one of the major aspects of stratigraphy. This involves describing the physical character of rocks such as rock type, colour, mineral composition and grain size (Boggs Jr., 2006). It is this aspect that will be used in an attempt to describe the stratigraphy of the study area. Sections encountered in the study area were logged and are presented below:

a. Exposed Section along Kanje – Azara road

The exposure is seen within a gully created by erosion. The beds dip 8° E (Fig. 4.3, Plate I). The units exposed are:

ii. B2: a lateritic overburden formed from the weathering of the overlying siltstone

i. B1: a 0.52 m thick, dark grey, fissile shale.



Plate I: Exposed Section of Uomba Formation along Kanje – Azara road **(8° 18' 34.0"N 9° 11' 20.0"E)**

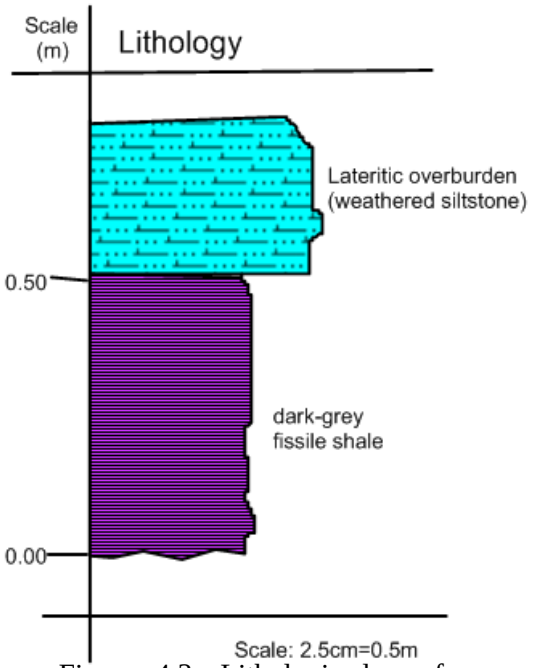


Figure 4.3: Lithologic log of exposed Section of Uomba Formation along Kanje – Azara road **(8° 18' 34.0"N 9° 11' 20.0"E).**

b. Exposed section inside Mumbai (Ukpo) town

This exposure consists of a sequence of shale – siltstone (Fig. 4.4, Plate II). The units dip 14° E.

iii. B3: a 0.23 m thick, brownish grey siltstone

ii. B2: a 0.27 m thick, dark grey carbonaceous shale.

i. B1: a 0.64 m thick, greenish grey siltstone.



Plate II: Exposed section of Uomba Formation inside Mumbai (Ukpo) town **(8° 18' 54.2"N 9° 10' 43.9"E).**

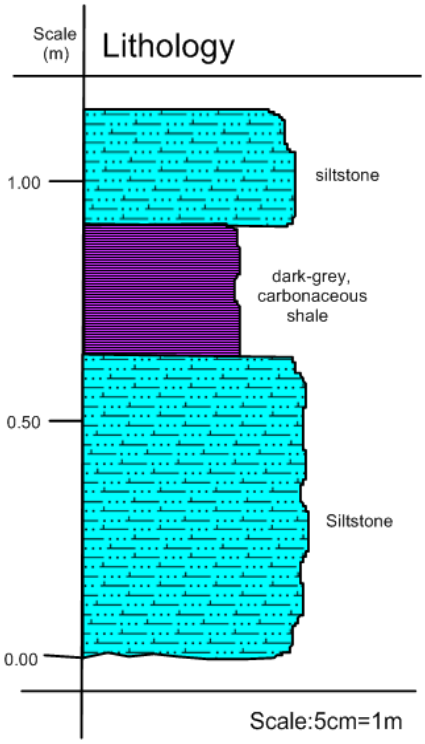


Figure 4.4: Lithologic log of exposed section of Uomba Formation inside Mumbai (Ukpo) town. **(8° 18' 54.2"N 9° 10' 43.9"E).**

c. Sections along River Bayanlabo

These sections are made up of alternating siltstone and sandstone beds which are averagely dipping 18° E. The sandstone beds are medium to coarse-grained with the composite section showing a fining upward sequence. The basal sandstone bed however shows trough cross bedding and graded bedding (Fig. 4.5, Plate III, IV).

iii. B3: a 0.81 m thick, weathered, greyish - brown fine to medium-grained sandstone

ii. B2: a 0.84 m thick, grey, fine grained and friable sandstone

i. B1: a 1.01 m thick, dark grey, highly indurated siltstone.



Plate III: Exposed section of Awe Formation along River Bayanlabo
(8° 21' 44.9"N 9° 15' 08.9" E)

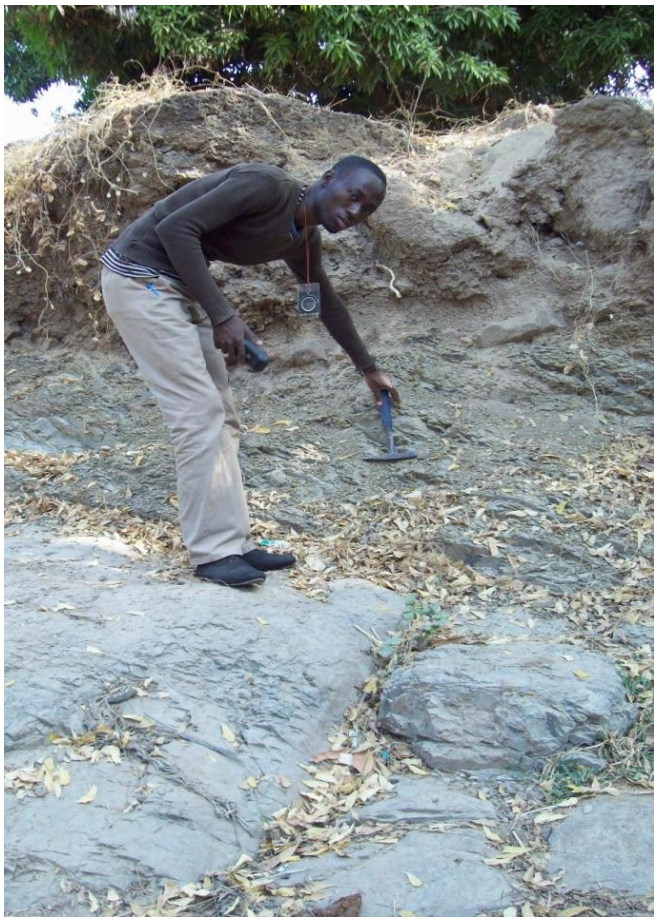


Plate IV: Exposed section of Awe Formation along the eastern part of River Bayanlabo. (**8° 21' 49.0" N 9° 15' 09.5" E)**

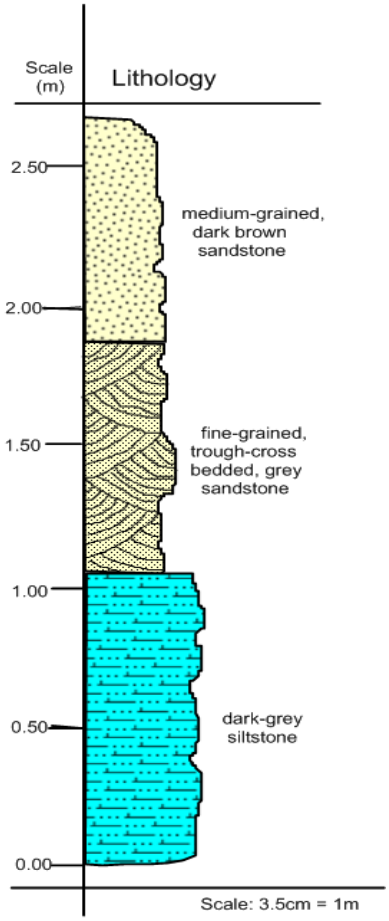


Figure 4.5: Composite lithologic log of exposed section of Awe Formation along River Bayanlabo (**8° 21' 49.0"N 9° 15' 09.5" E; 8° 21' 44.9"N 9° 15' 08.9"E)**

d. Section exposed in an abandoned Baryte mining pit at Gidan Soja

An alternating sequence of mudstone and sandstone is seen at this location and the beds dips at 22° E (Fig. 4.6, Plate V). It consists of:

vii. B7: a 0.23 m thick, yellowish brown, fine to medium-grained sandstone

vi. B6: a 0.84 m thick, fine-grained, brownish sandstone

v. B5: a 0.90 m thick, grey mudstone

iv. B4: a 0.40 m thick, fine-grained, brownish sandstone

iii. B3: a 0.59 m thick, grey mudstone

ii. B2: a 0.42 m thick, fine to medium-grained, whitish brown sandstone

i. B1: a 0.28 m thick, grey mudstone.



Plate V: Exposed section of Awe Formation in an abandoned Baryte mining pit at Gidan Soja. White broken lines showing bed planes (**8° 25' 30.8"N 9° 14' 39.3"E)**

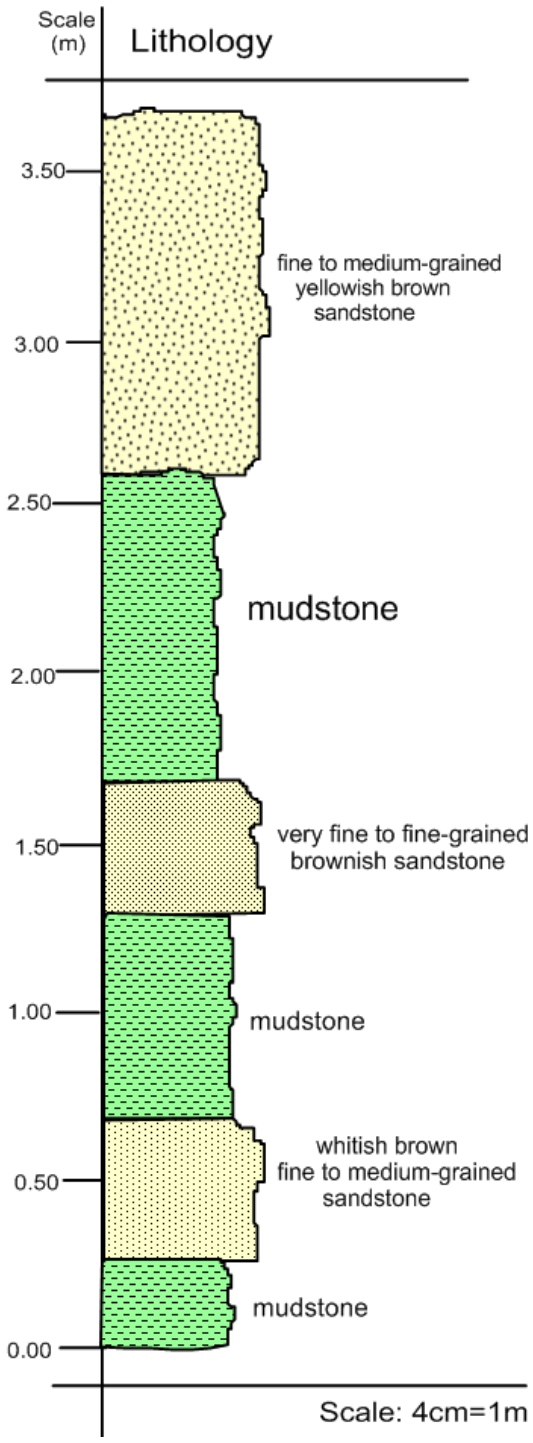


Figure 4.6: Lithologic log of exposed section of Awe Formation in an abandoned Baryte mining pit at Gidan Soja. (**8° 25' 30.8" N 9° 14' 39.3" E)**

e. Exposed section along a tributary of River Ankwe

The exposure consists of alternating sandstone and siltstone beds dipping at 18° E (Fig. 4.7, Plate VI).

iii. B3: a 0.20 m thick, fine to medium-grained, light-brown sandstone

ii. B2: a 0.23 m thick, dark grey siltstone.

i. B1: 0.36 m thick, very fine to fine-grained, brown sandstone.



Plate VI: Exposed section of Awe Formation along a tributary to River Ankwe **(8° 24' 34.3"N 9° 09' 00"E)**

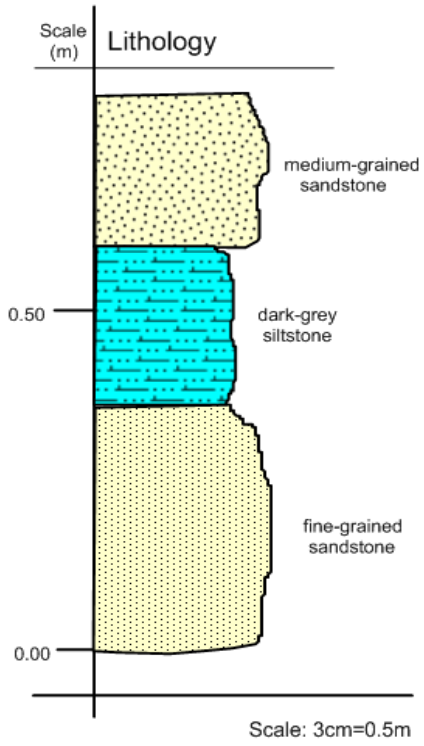


Figure 4.7: Lithologic log of the exposed section of Awe Formation along a tributary to River Ankwe **(8° 24' 34.3"N 9° 09' 00" E)**

f. Exposed section along Samberi River and Azara road

The sequence is made up of rhythmically bedded sandstone and siltstone. Each cycle seems to begin with thick medium to fine grained sandstone beds which fine upwards rapidly into siltstone (Fig. 4.8, Plate VII). The beds averagely dip at 16° E.

vii. B7: a 0.33 m thick, very fine-grained, laminated sandstone.

vi. B6: a 0.26 m thick, fine to medium-grained, friable brown sandstone.

v. B5: a 0.18 m thick, brown siltstone.

iv. B4: a 0.07 m thick, very fine-grained, brownish yellow sandstone.

iii. B3: a 0.32 m thick, medium-grained, brown sandstone

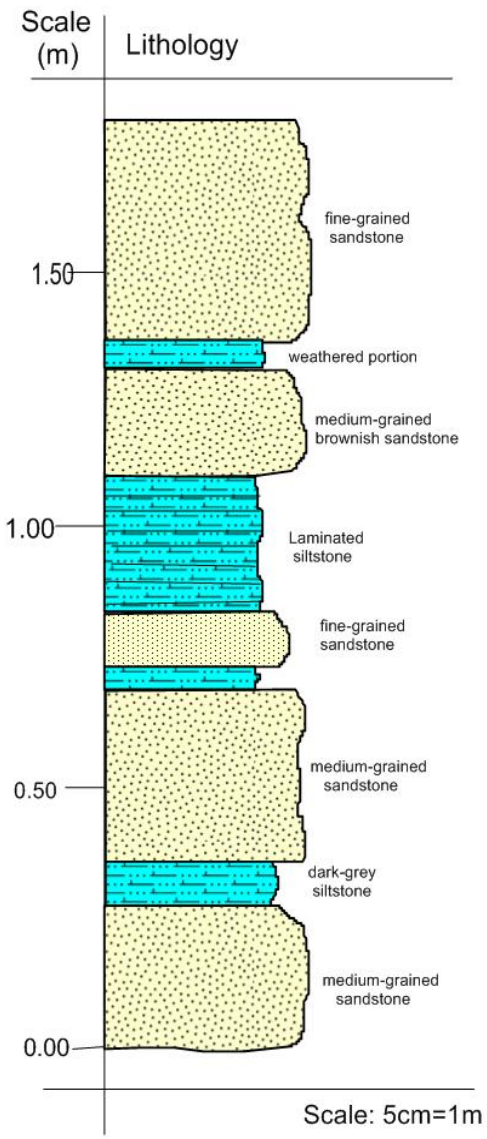
ii. B2: a 0.10 m thick, dark grey siltstone.

i. B1: a 0.20 m thick, fine to medium-grained, brownish yellow, friable sandstone.



Plate VII: Exposed section of Awe Formation along Samberi River and Azara road **(8° 21' 18.0"N 9° 10' 52.5"E).**

Figure 4.8: Lithologic log of exposed section of Awe Formation along Samberi River and Azara road **(8° 21' 18.0"N 009° 10' 52.5"E).**



g. Exposed section along Ribi – Jangwa Road

The section (Fig. 4.9, Plate VIII) consists of:

vi. B6: highly weathered mudstone unit.

v. B5: a 0.52 m thick, medium to coarse-grained, friable sandstone.

iv. B4: a 0.08 m thick, highly weathered mudstone unit.

iii. B3: a 0.28 m thick, medium-grained, light brown sandstone.

ii. B2: a 0.11 m thick, highly weathered mudstone unit.

i. B1: a 0.46 m thick, medium-grained, light brown sandstone.



Plate VIII. Exposed section of Awe Formation along Ribi – Jangwa road (**8° 22' 26.5"N 9° 07' 32.1"E).**

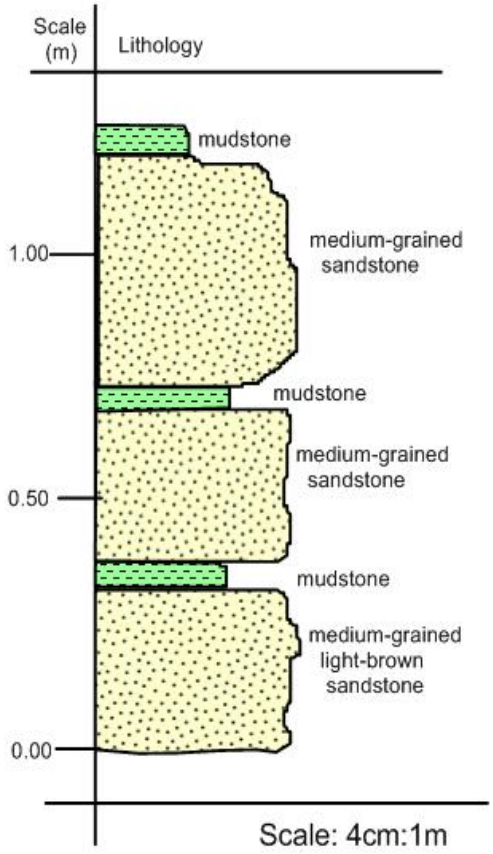


Figure 4.9 Lithologic log of exposure of Awe Formation along Ribi – Jangwa road **(8° 22' 26.5"N 9° 07' 32.1"E).**

h. A section along Ribi – Akondu road

The section consists of a sequence of mudstone, siltstone and sandstone (Fig. 4.10, Plate IX). The beds dip 23° W.

vi. B6: a 0.69 m thick, fine-grained, dark brown sandstone

v. B5: a 0.13 m thick, weathered mudstone.

iv. B4: a 2.54 m thick, reddish brown, laminated siltstone.

iii. B3: a 0.21m thick mudstone.

ii. B2: a 0.68 m thick, dark grey siltstone

i. B1: a 0.83 m thick, laminated mudstone.



Plate IX: An outcrop section of Awe Formation along the road from Ribi to Akondu **(8° 22' 42.8"N 9° 07' 22.9"E).**

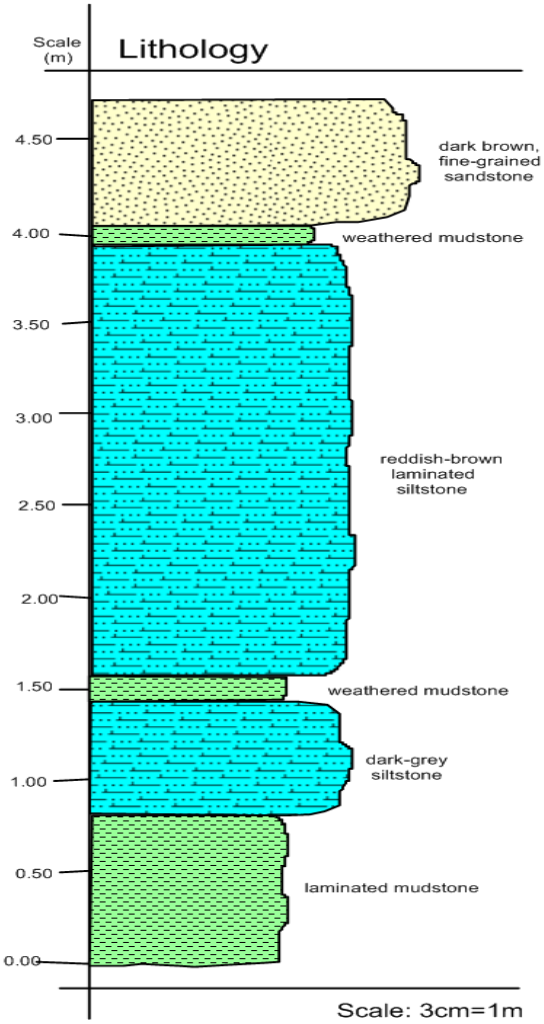


Figure 4.10: Lithologic log of an outcrop section of Awe Formation along the road from Ribi to Akondu **(8° 22' 42.8"N 9° 07' 22.9"E).**

i. An exposed section along a stream channel along Ribi – Shika road. N 08° 21' 26.9" E 009° 07' 06.5".

The outcrop shows an alternating siltstone – sandstone series (Fig. 4.11, Plate X). The beds dip 28° W.

iii. B3: a 0.49 m thick, fine-grained brown sandstone

ii. B2: a 0.14 m thick, reddish brown, laminated siltstone

i. B1: a 0.24 m thick, fine to medium-grained, purple brown sandstone.



Plate X: An exposed section of Awe Formation along a stream channel along Ribi – Shika road **(8° 21' 26.9" N 9° 07' 06.5"E).**

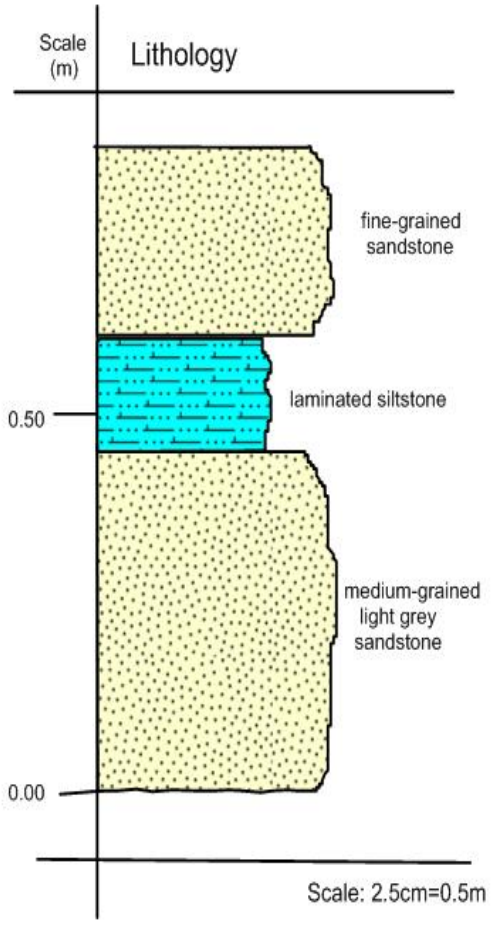


Figure 4.11: Lithologic log of exposed section of Awe Formation along a stream channel along Ribi – Shika road **(8° 21' 26.9"N 9° 07' 06.5"E).**

j. An exposed section along a river channel on Ribi to Shika road

The section (Fig. 4.12, Plate XI) consists of:

ii. B2: a 1.0 m thick, coarse-grained, brown sandstone.

i. B1: a 0.29 m thick, massive whitish claystone.



Plate XI: An exposed section of Awe Formation along a river channel on Ribi to Shika road **(8° 20' 06.21"N 9° 06' 38.6"E)**

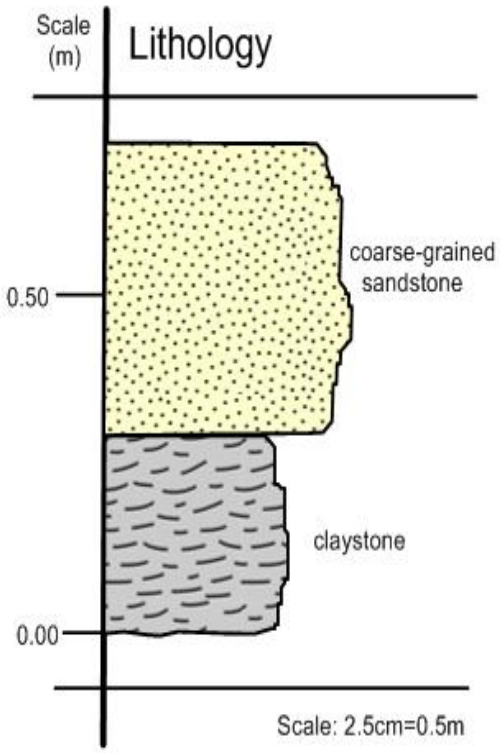


Figure 4.12: Lithologic log of exposed section of Awe Formation along a river channel on Ribi to Shika road **(8° 20' 06.21"N 9° 06' 38.6"E)**

k. An exposed section at a local Baryte mining site

This section shows alternating sandstone – claystone beds. The sandstones beds are highly fractured and quartz veined (Fig. 4.13, Plate XII). The beds dip 24° E. The section consists of:

vi. B4: a 1.70 m thick, coarse-grained sandstone

iii. B3: a 0.26 m thick, whitish claystone

ii. B2: a 0.48 m thick, coarse-grained, brown sandstone.

i. B1: a 1.67 m thick, light grey claystone.



Plate XII: An exposed section of Awe Formation overlying Keana Sandstone at a local Baryte mining site **(08° 17' 47.3"N 9° 12' 53.3"E).**

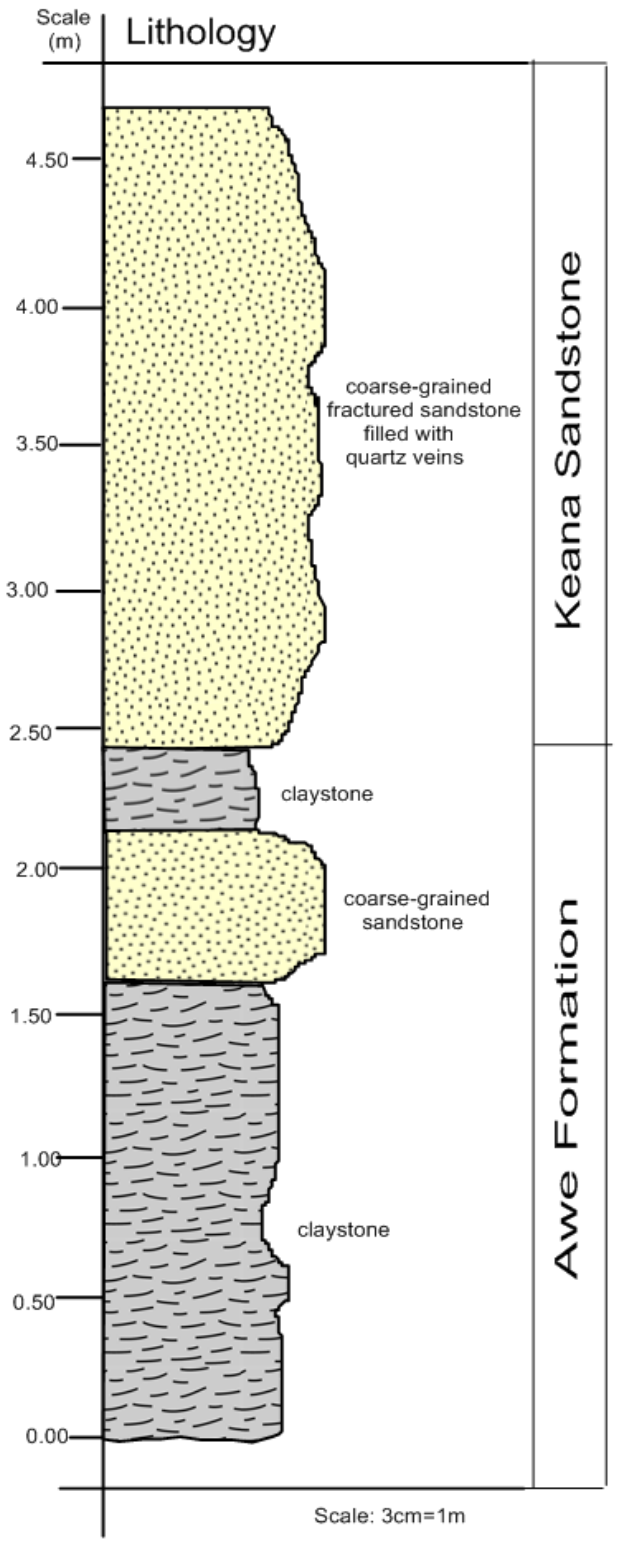


Figure 4.13: Lithologic log of exposed contact between Awe Formation and Keana Sandstone at a local Baryte mining site **(08° 17' 47.3"N 9° 12' 53.3"E).**

l. A section exposed near the local salt mine at Ribi

This section consists of sandstone units which grades from conglomeratic and pebbly lower parts into medium grained grits at the top. The sandstones are highly indurated and fractured, which in turn are in-filled with quartz veins (Fig. 4.14, Plate XIIIa, b, c.). The units encountered are:

iii. B3: a flat lying, extensive, conglomeratic, light brown sandstone

ii. B2: a 0.32 m thick, coarse-grained, dark brown sandstone

i. B1: a 0.27 m thick medium-grained, dirty brown, ferruginized sandstone.

a. 

Plate XIII: (a) Section of Keana Sandstone exposed near the local salt mine at Ribi (**8° 22' 18.5" N 9° 07' 35.4"E).**

b.  c. 

Plate XIII: (b and c) Quartz veins seen on the sandstone unit.

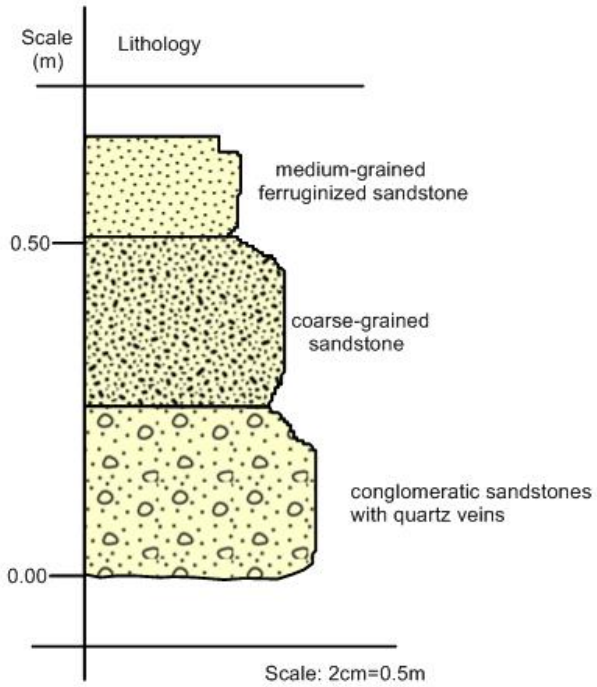


Figure 4.14: Lithologic log of Keana Sandstone exposed near the local salt mine at Ribi (**8° 22' 18.5"N 009° 07' 35.4 "E).**

4.3 PETROGRAPHY

This analysis was done to describe the petrography of each rock type and to determine the diagenetic event that had taken place during sedimentation. Eight (8) representative samples were prepared for thin – section. The thin sections were then observed under Plane Polarized Light (PPL) and Cross Polarized Light (XPL) with petrographic microscope.

4.3.1. AWE FORMATION

a. Arkosic Sandstones:

Sample I: This is a light brown, medium to coarse grained sandstone (Plate XIV). It is composed of quartz, feldspars and clay minerals. Some of the feldspar crystals have been altered thus give it the brownish coloration. Under the petrographic microscope, the sandstone is coarse grained, moderately sorted, angular to sub angular, mineralogically and texturally immature arkose with the feldspars altered to sericite and in some parts to kaolinite. The presence of glauconite serves as an indication of its marine origin.

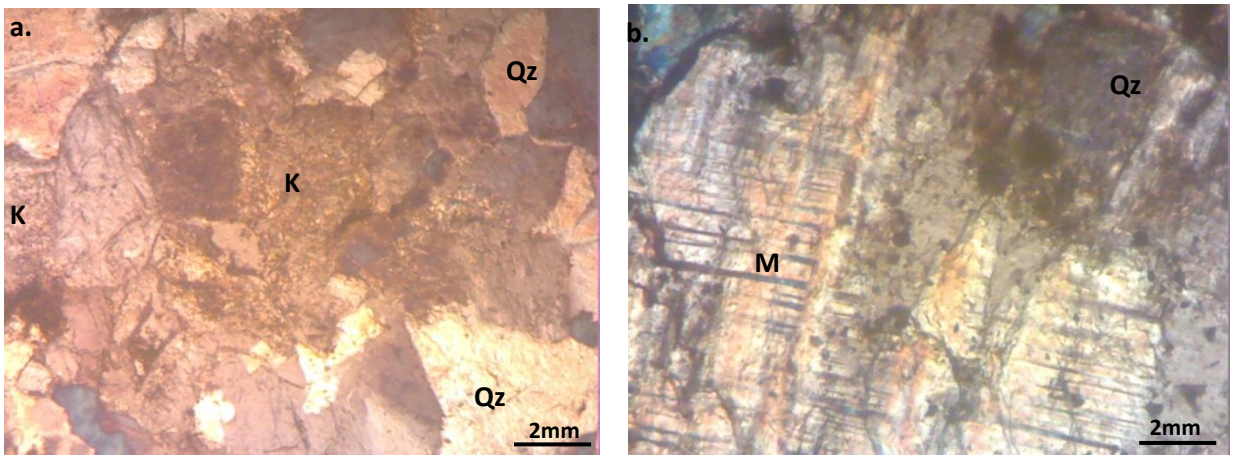


Plate XIV: Photomicrographs of arkosic sandstone of Awe Formation (a) under PPL and (b) under XPL (Mag x40). K: Kaolinite, M: Microcline; Qz: Quartz.

Sample II: This is a massive, brownish – grey sandstone with an abundance of quarts and feldspar (Plate XV). It is fine-grained, moderately well-sorted, sub-rounded arkosic sandstone composed of over 25% of the feldspar altered to sericite. Also, some of the feldspars have been partially lost in solution thereby creating a secondary porosity within the rock which shows that the rock is mineralogically and texturally immature. There is the presence of muscovite and glauconite which suggests a shallow marine deposition.

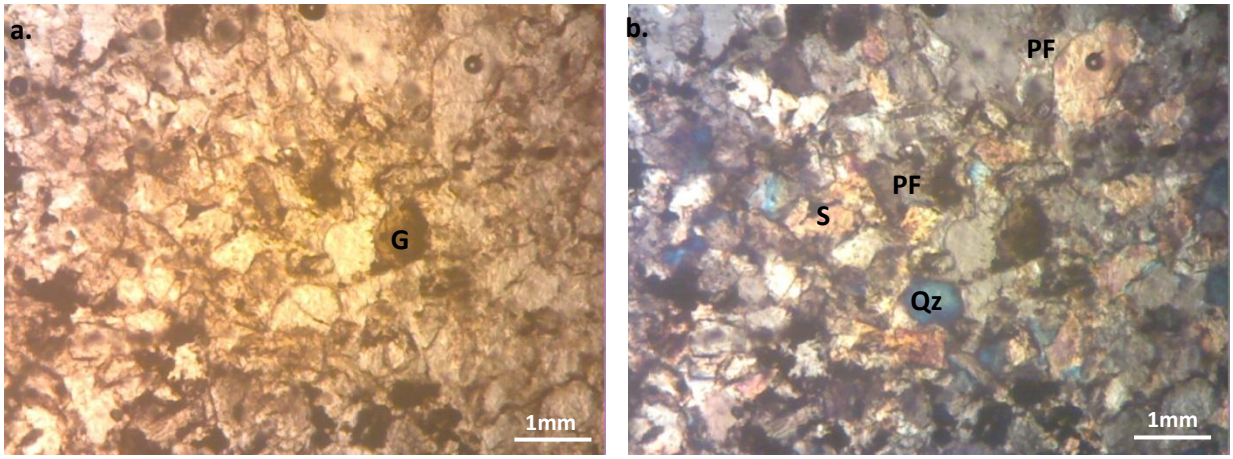


Plate XV: Photomicrographs of an arkosic sandstone of Awe Formation (a) under PPL and (b) under XPL. (Mag x40) Qz: Quartz, S: Sericite, PF: Plagioclase Feldspar, G: Glauconite.

Sample III: This is a massive, highly indurated, purplish brown sandstone composed of quartz, feldspar and micas (Plate XVI). It is poorly sorted, angular to sub-angular arkosic sandstone containing more than 25% feldspar minerals. It is very immature both texturally and mineralogically. Most plagioclase feldspar present has been altered and lost in solution thereby creating a secondary porosity. Where the dissolution is not total, there is the formation of sericite and kaolinite which then doubles as cement material in some parts of the rock.

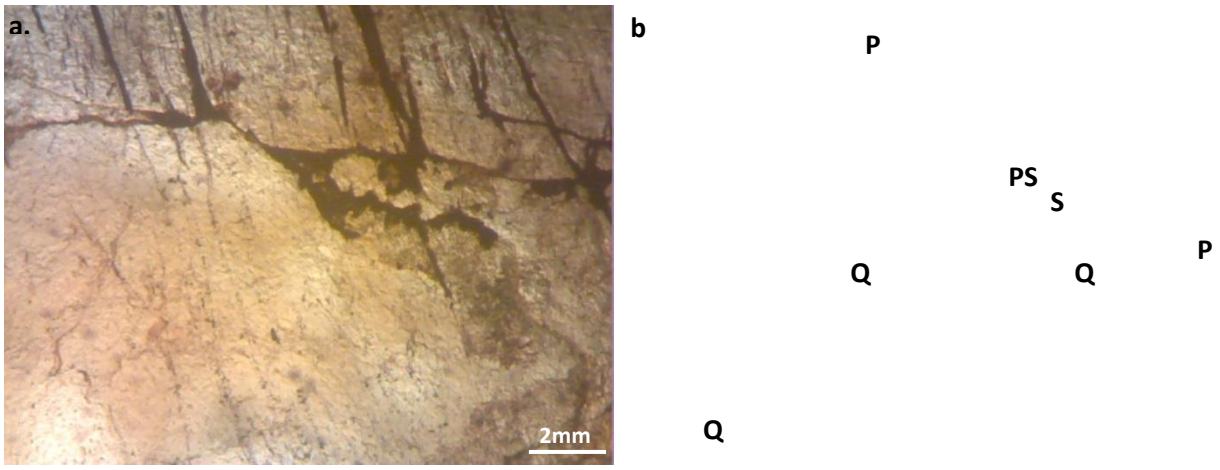


Plate XVI: Photomicrographs of an arkosic sandstone of Awe Formation (a) under PPL and (b) under XPL (Mag x40) Q: Quartz, P: Perthite, PS: Pore Space, S: Sericite.

Sample IV: This is a massive and highly indurated, greyish sandstone (Plate XVIII). It is a poorly sorted arkosic sandstone composed mainly of monocrystalline quartz, a few polycrystalline quartz, microcline and plagioclase feldspars that have been altered first to sericite and finally to kaolinite.. The constituent minerals are coarse silt to very fine grained in size while the rock is texturally and mineralogically immature.

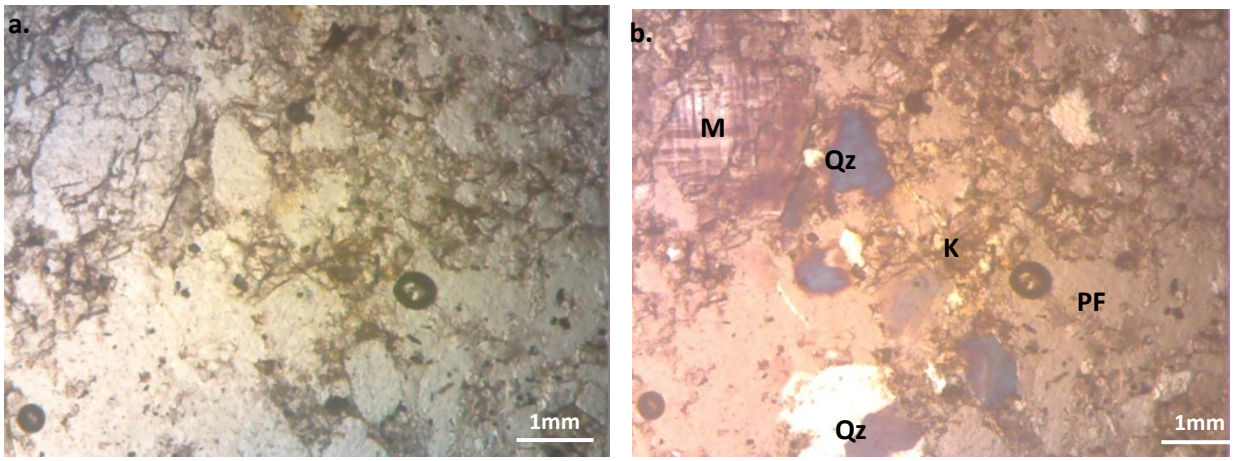


Plate XVII: Photomicrographs of an arkosic sandstone of Awe Formation (a) under PPL and (b) under XPL (Mag x40) Qz: Quartz, PF: Plagioclase Feldspar, K: Kaolinite, M: Microcline,

b. Siltstones:

Sample I: This is a dark grey, highly indurated, very fine grained siltstone (Plate XVII). Thin section analysis shows abundant and well aligned silt-sized quartz grains and thin mica flakes as the main constituent minerals of the rock. The micas include both muscovite (colourless) and biotite (yellow or brown). The rock is grain supported.

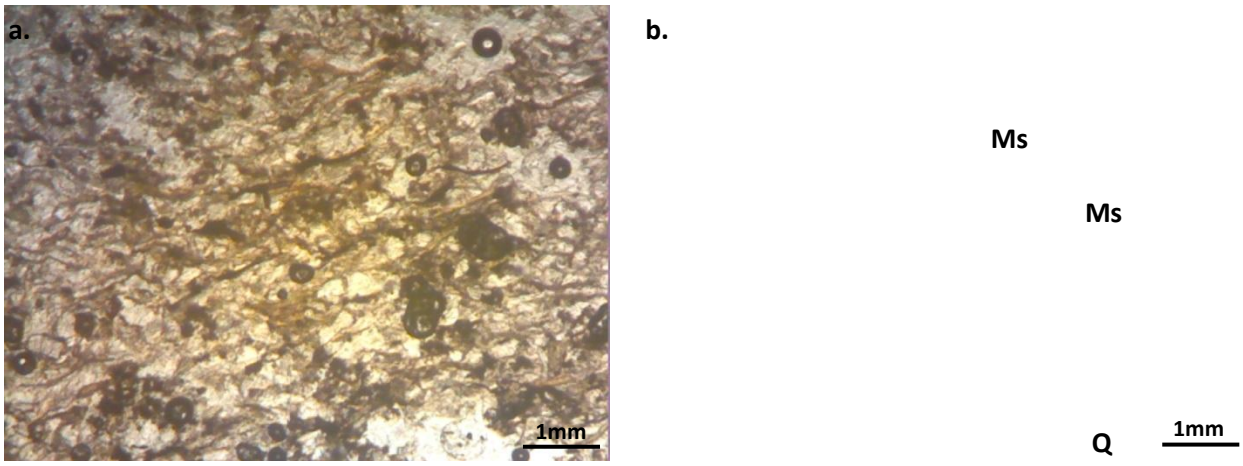


Plate XVIII: Photomicrographs of laminated siltstone of Awe Formation (a) under PPL and (b) under XPL (Mag x40). Q: Quartz, Ms: Muscovite

c. Feldspathic Greywackes:

Sample I: This is a dark - grey, massive and indurated, very fine silt grained sandstone (Plate XIX). It is a poorly sorted, sub-angular to sub-rounded greywacke with about 15% matrix and containing monocrystalline quartz and abundant feldspar grains. Feldspars include plagioclase with multiple twinning and perthitic alkali feldspar.

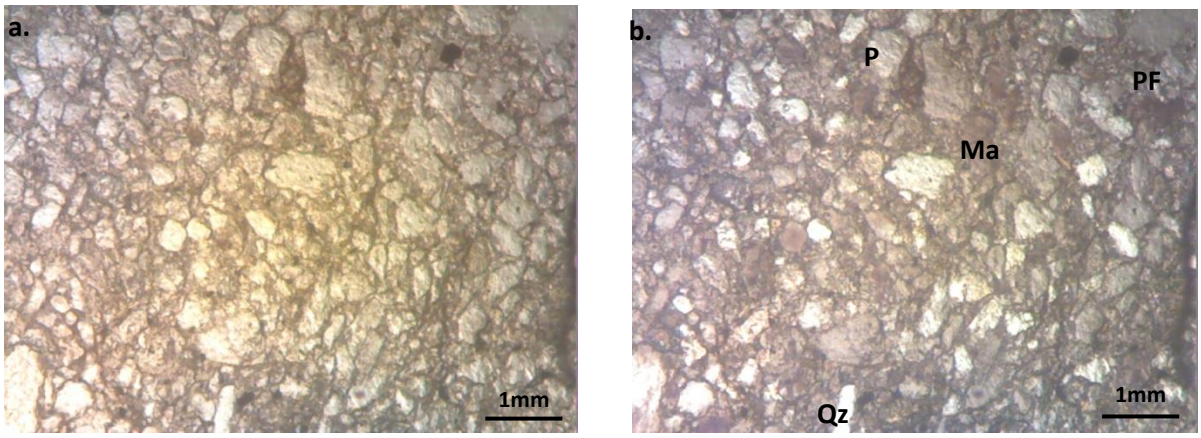


Plate XIX: Photomicrographs of a feldspathic greywacke sandstone of Awe Formation (a) under PPL and (b) under XPL (Mag x40) Qz: Quartz, Ma: Matrix, PF: Plagioclase Feldspar, P: Perthite

4.3.2 KEANA SANDSTONE

a. Sub-Arkose Sandstones:

Sample I: This is a massive indurated, fine grained sandstone (Plate XX). It is greyish in colour. Microscopic examination reveals that the rock is a moderately well sorted sub-arkose. It is both texturally and mineralogically immature. It is composed of monocrystalline quartz and plagioclase feldspars. The plagioclase feldspars shows alteration to sericite and kaolinite with both acting as a clay cement material within the contacts of the other grains in the rock.

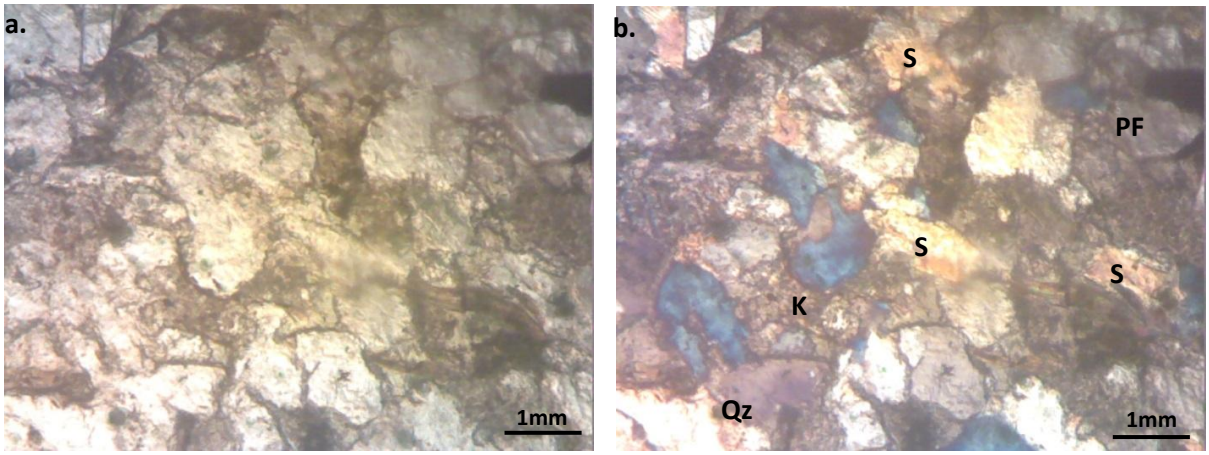


Plate XX: Photomicrographs of a sub-arkose sandstone of Keana Sandstone (a) under PPL and (b) under XPL (Mag x40) Qz: Quartz, S: Sericite, K: Kaolinite, PF: Plagioclase Feldspar.

Sample II: This is a yellowish - brown, massive and indurated sandstone (Plate XXI). Mineral constituent includes quartz, feldspars and little amount of mica. It is a fine grained, moderately sorted, texturally and mineralogically immature sub-arkose with the constituent feldspars already being altered to sericite and in some places to kaolinite. It also consists of monocrystalline quartz grains and muscovite. The kaolinite serves as the clay cement material between the grains.

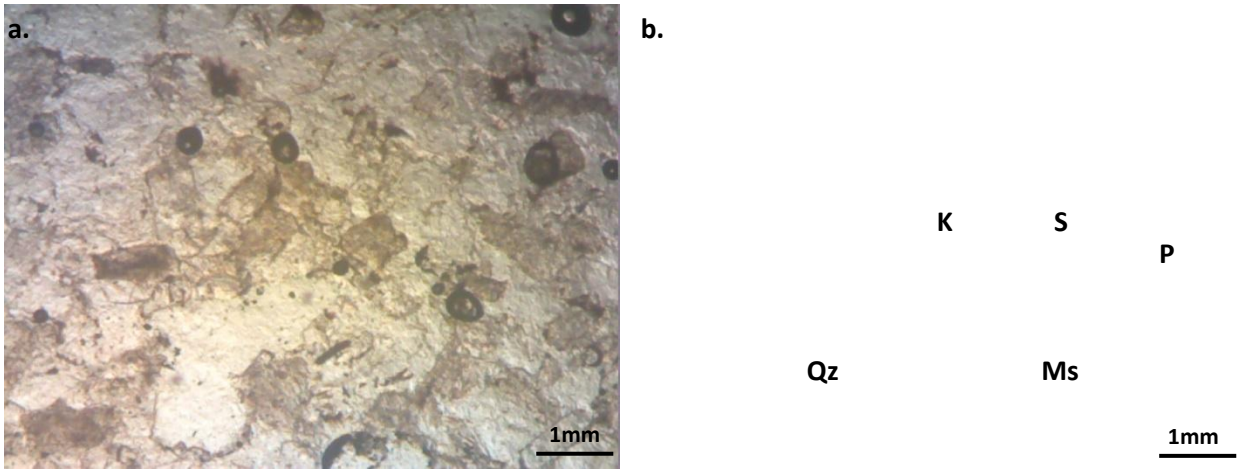


Plate XXI: Photomicrographs of a sub-arkose sandstone of Keana Sandstone (a) under PPL and (b) under XPL (Mag x40) Qz: Quartz, Ms: Muscovite, S: Sericite, P: Perthite, K: Kaolinite.

4.4 SIEVE ANALYSIS

Sieve analysis was carried out in order to determine the grain size distribution and other

parameters that will enable the depositional conditions and environment of the sediments to be established. The statistical parameters calculated for the sediments include the graphical mean, sorting, and its graphical skewness. Samples A to H represent sediments of Awe Formation while samples I to M belong to Keana Sandstone. The results of these parameters and their interpretation are presented in Appendix III based on Folk and Ward (1957).

4.4.1 GRAPHICAL MEAN

The graphical mean is the average value of the grains of the sample taking into account the grain sizes at 16^{th}, 50^{th} and 84^{th} percentiles. It tells of the average grain size of the sample. From Table 2 (Appendix III), we see that the graphical mean of analyzed sediments in the study area ranges from 0.00 (Sample K) to 1.91 (Sample B) which means the sediments' grain sizes ranges from medium grained sands to very coarse sands.

4.4.2 SORTING

This is a measure of the standard deviation. That is, the spread of the grain-size distribution. It is one of the most useful parameters because it gives an indication of the effectiveness of the depositional medium in separating grains of different classes. The sorting of a sediment are determined by several factors (Tucker, 2001);

i. **The sediment source**: if granite is providing the sediment, the grain sizes will be quite different from those sediment supplied by the reworking of sandstones.
ii. **The grain itself:** sorting is dependent on the grain size in that coarse sediments, gravels and conglomerates, and fine sediments, silts and clays generally are more poorly sorted

than sand-sized sediments, which are more easily transported and therefore sorted by wind and water.

iii. **The depositional environment:** sediments that were deposited quickly, such as storm beds, or were deposited from viscous flows, such as mudflows, are generally poorly sorted; sediments that have been reworked by the wind or water, the sandy deposits of deserts, beaches and shallow shelf seas, for example, are much better sorted. Generally, sorting improves along the sediment transport path.

From Table 2 (Appendix III), we see that sorting values of the sediments ranges from 0.21 to 1.56. This indicates that the analyzed sediments in the study area are predominantly poorly sorted except for samples A, B, H and L which are moderately sorted. These values as such suggests that these sediments are closer to the source. Sample K which is very well sorted indicates that its sediments were deposited in a fairly gentle environment far from the source.

4.4.3 SKEWNESS

This is a measure of the symmetry of the distribution and is best seen from the smoothed frequency curve. A sediment is said to be negatively skewed if the distribution has a coarse "tail" that is, excess coarse material while the skewness is regarded positive if there is a fine "tail". However if the distribution is symmetrical, then there is no skew. Skewness is also a reflection of the depositional process. For example, beach sands tend to be negatively skewed (due to finer components being carried off by persistent wave actions thereby leaving behind coarse materials); River sands are usually positively skewed (because much silt and clay is not removed by the currents but trapped between larger grains).

In general, sediments become more negatively skewed (and finer grained) along its sediment transport path whereas the source sediment becomes more positively skewed and

relatively coarse. Table 2 (Appendix III) shows that the sediments analyzed have skewness values ranging between 0.27 and 1.15. This range indicates a dominant positively skewed distribution and thus infer that the sediments are mainly river sands and are closer to the sediments' source.

4.4.4 DEPOSITIONAL ENVIRONMENTS

Bivariate plots were plotted for grain size parameters of the sediments of Keana Sandstone in order to determine their depositional environment. Comparing these bivariate plots of Skewness vs. Sorting (Fig. 4.15), Means vs. Sorting (Fig. 4.16) with similar works of Friedman (1961) (Fig. 3.3a, b), all samples plotted are indicative of fluvial environment. The dominance of medium to coarse grained particles for the sandstones in the study area probably points to a moderate to high energy depositional environment that may be likened to those of a fluvial setting.

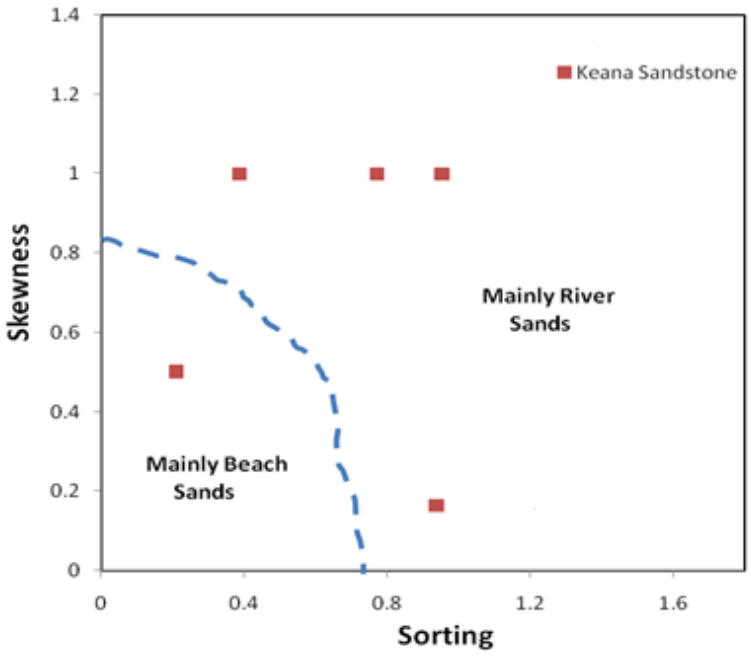


Figure 4.15: Bivariate plot of Skewness versus Sorting

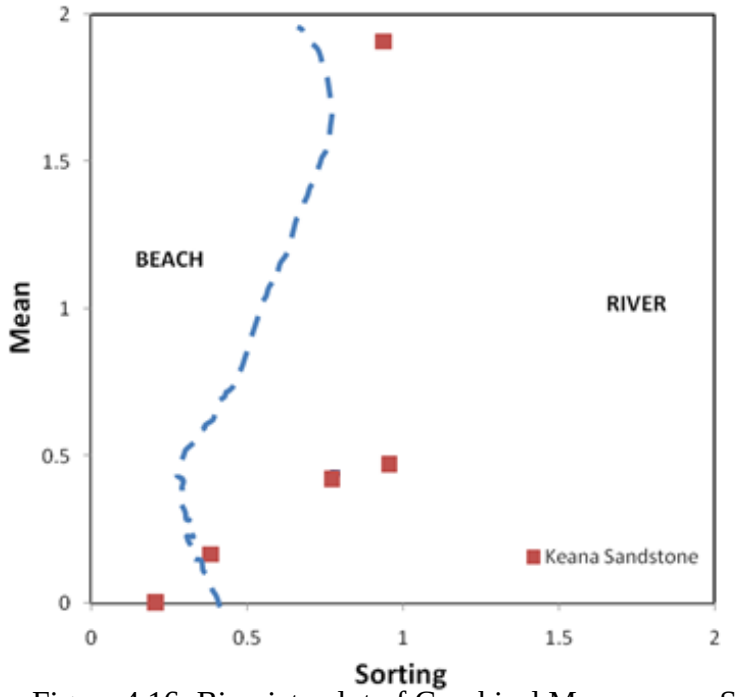


Figure 4.16: Bivariate plot of Graphical Mean versus Sorting

4.5 MICROFOSSIL ANALYSIS

Ten (10) representative samples were prepared in the laboratory for paleontological analysis; however none yielded the presence of micro fossils.

4.6 GEOLOGICAL STRUCTURES

Geological structures observed on the sedimentary rocks encountered in the study area are both syn–depositional and post depositional. Syn-depositional structures include:

Bedding Planes: These are exposed within most sections logged. Most bedding planes are parallel and even while some are discontinuous due to weathering (Plate VII).

Graded Beddings: This is seen as a normal grading within exposed Keana Sandstone (Plate XIII a) showing a vertical gradation in size from conglomerates - at the base – to medium grained sizes at the top.

Laminated Beddings: These are exposed mainly on the siltstones units of the Awe Formation in the study area (Plate VII). They are parallel to each other.

Cross Bedding: These are exposed within some sandstone units of the Keana Sandstone. The laminae are trough shaped with curved bounding surfaces (Fig. 4.17).



Figure 4.17: Cross beddings shown on an outcrop of Keana Sandstone exposed near Akondo town [8° 23' 50.8"N, 9° 06' 50.7"E].

Post – depositional structures includes:

Folds: The folds in the study area are represented by the various dip angles of the sedimentary beds encountered. The beds average dip vary from between 8° to 25° either to the East or West (Plate V and VIII). The change in dip direction at various locations in the study area gives an indication of an anticline within the study area. The variability of the strike trends reflects the sinuosity of the fold axes (Fig. 4.2) and it is oriented averagely in a 230° direction coinciding with the direction of the Benue Trough axis.

Fractures and Joints: These are well exposed on the Keana Sandstone in the study area. They strike predominantly in the NE-SW direction but some are also oriented in the NNW – SSE directions. Field measurements of some joints vary between 220° and 260°. These joints are mostly filled with quartz forming veins with some running parallel and cross-cutting one another (Plate XIII). The presence of these numerous fractures is possibly as an effect of a major fault in

the region. The orientation of the joints and fractures are given in Appendix IV and represented by the rose diagram shown in Figure 4.18.

Faults: Within the study area, faults are not well exposed while the few faults exposed in the study area are longitudinal, strike slip faults and runs in the NE – SW direction. Joints on some Awe Formation showing slicken-slides are evidences of this fault movement.

Hydrothermally mineralized baryte veins trends predominantly in the NW – SE, NNW – SSE directions and an unconformity between Awe and Keana Sandstones (Fig. 5.1) is also observed.

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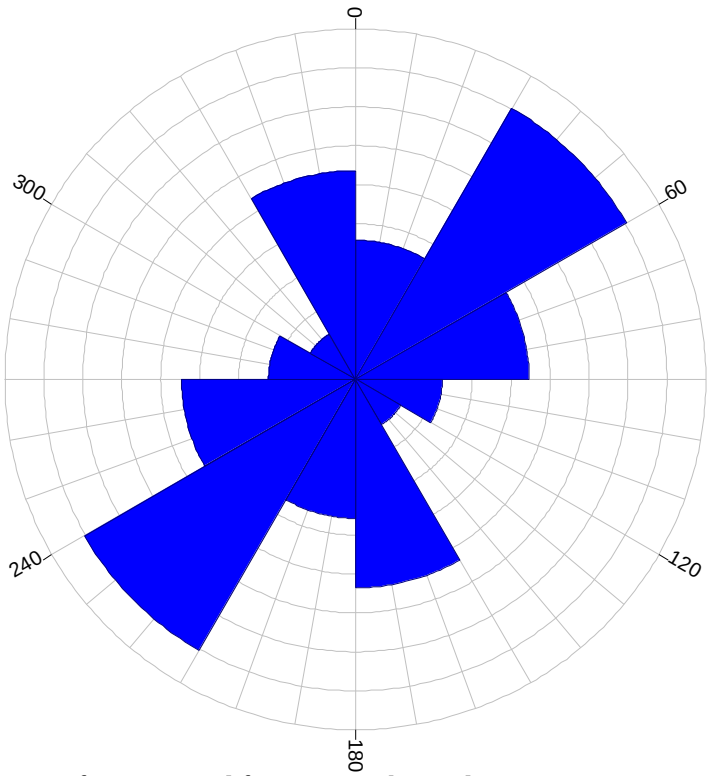


Figure 4.18: Rose diagram for joints and fractures in the study area

4.7 ECONOMIC MINERAL DEPOSITS

Within the study area, economic mineral deposits such as halite (gotten from brine) and baryte were encountered. At Ribi, where a brine spring was encountered, the indigenes believed that the discovery and local mining of the halite mineral dates back to the origin of the town and has been their traditional source of edible salt. They believe that the saline water can cure many internal and external diseases and such; spiritual importance has been attached to it.

Baryte mining pits were encountered at various places around Azara town most of which were those abandoned by the defunct Nigeria Mining Corporation. Artesanal miners now patronize these pits during the dry season. Brine spring from which the halite mineral is extracted is found in the study area issue out from the Keana Sandstone while the baryte is found in hydrothermal veins within the underlying Awe Formation.

CHAPTER FIVE

DISCUSSIONS

5.1 INTRODUCTION

The study area lies within the Middle Benue Trough of Nigeria. Cratchley and Jones (1965), Offodile (1976), Sabo (1985), Ariyo (1987), Ofoegbu *et al.* (1990), Obaje *et al.* (1996) contributed to the general knowledge of the geology of the Middle Benue Trough. Their works were done mainly in the Lafia-Keana-Awe area and this have been the point of reference and basis of generalization of the geology of the whole Middle Benue Trough. However, observations from field traverses during the mapping exercise show that this generalization does

not give in detail, the geology of the study area which is in the north-eastern part of the western half of the Middle Benue Trough.

5.2 STRATIGRAPHY, STRUCTURE AND DEPOSITIONAL HISTORY OF THE STUDY AREA

5.2.1 STRATIGRAPHY

As shown in Figure 4.2, the area is underlained by three major formations namely Uomba Formation, Awe Formation and Keana Sandstone. In addition, alluvium – formed along the banks of River Ankwe are also observed. The descriptions of these formations are presented in the order of their relative ages.

1. Uomba Formation of the Asu River Group: The Asu River Group comprises of three formations – Gboko, Arufu and Uomba Formations which Obaje (1994) noted are lateral equivalent facies and can refer to any one name of the three depending on the locality. The Uomba Formation (Reyment, 1964) comprises essentially of olive-green to dark-grey and pink micaceous siltstones, fissile shales, mudstones and subordinate clays which Offodile (1976) referred to as "Asu River Formation". The term "Uomba Formation" (Reyment, 1964) is reverted to in this study. This formation outcrops mainly in the south western part of the study area along the road from Adudu to Kanje, Azara to Kanje and Ribi to Kanje, as a lateral Awe Fm. continuation of the "Asu River Formation" observed in Kanje area by Offodile and Reyment (1976). Along River Bakabu's bank [8° 15' 51.4"N, 9° 01' 37.2"E] where there was no exposed sections, there were depositions of dark shale fragments which probably have been eroded and transported by stream from the shaly part of this formation elsewhere.

Exposures of this formation were observed along the road from Azara to Kanje [N 08° 18' 34.0", E 009° 11' 20.0"] (Fig. 4.2). The settlement of Mumbai (Ukpo) [N 08° 18' 54.2", E 009° 10' 43.9"] is sitting on this formation as various sections could be seen along the river channels. The outcrop here generally dips at angle of 9° to the east. The Uomba Formation of the Asu River Group exposed in the study area comprises of alternating sequence of fissile shales, mudstone and micaceous siltstones. No fossil was found in the analysed samples of this formation. This could be a result of less deposition of marine sediments into this area by the transgressing Atlantic Sea. In terms of age, this formation is the oldest (Reyment, 1964) in the study area and the expected underlying basement rocks were not encountered.

2. Awe Formation: Awe Formation, proposed by Offodile (1976) in the study area is made up of an alternating mudstones, siltstones and fine grained, arkosic, feldspathic sandstones, greywackes and quartz – arenitic sandstones series. This series is found underlying Azara town and extending westward to Rugagwu settlement and Ribi town; northwards toward Gidan Soja and to the south beyond Maisamari settlement (Fig. 4.2).

This series is well exposed near Gidan Soja [8° 25' 30.8"N, 9° 14' 39.3"E] where the beds dip at 24° to the west. Another exposed section at the local baryte mining site [8° 17' 47.3"N, 9° 53.3"E], shows that it underlies the Keana Sandstone (Fig. 5.1). It is observed that the direction of dip of this formation varies. In the areas close to Azara town and southwards, the beds dips between 14° and 25° towards the east while at areas close to Ribi and northwards where this formation outcrops, the dip of the beds ranges between 12° and 20° to the West. Based on the following reasons this series is believed to be the Awe Formation of Offodile (1976) in this area.

i. Its position in exposed sections (Fig. 5.1) where it is seen underlying the massive sandstones of the Keana Sandstone;

ii. Its constituent rock types – mudstones, siltstones and fine grained, arkosic, feldspathic sandstones, greywackes and quartz – arenitic sandstones - are formed from shallow marine sediments most probably in a quiet environment where the water is stagnant or not moving. This depositional environment was most likely prevalent during a period of relative slow movement of a transgressing sea when the energy is low.

This invariably corroborates with the depositional environment of the Awe Formation which was deposited in a transitional environment towards the end of the Albian marine episode when marine and fluviatile conditions prevailed as confirmed by the presence of glauconite. The regression of the Albian Sea is also accompanied by the forward and backward movement of the coastline. These oscillations resulted in the interplay of shallow marine and transitional marine conditions (Offodile, 1976).

Based on field observation, a geological boundary between Awe Formation and the older Asu River Group can be found between Azara town and Ukpo community while the unconformity between this formation and the overlying Keana Sandstone is seen as a paraconformity with little discernable evidence of erosion or prolonged non-deposition (Fig 5.1).

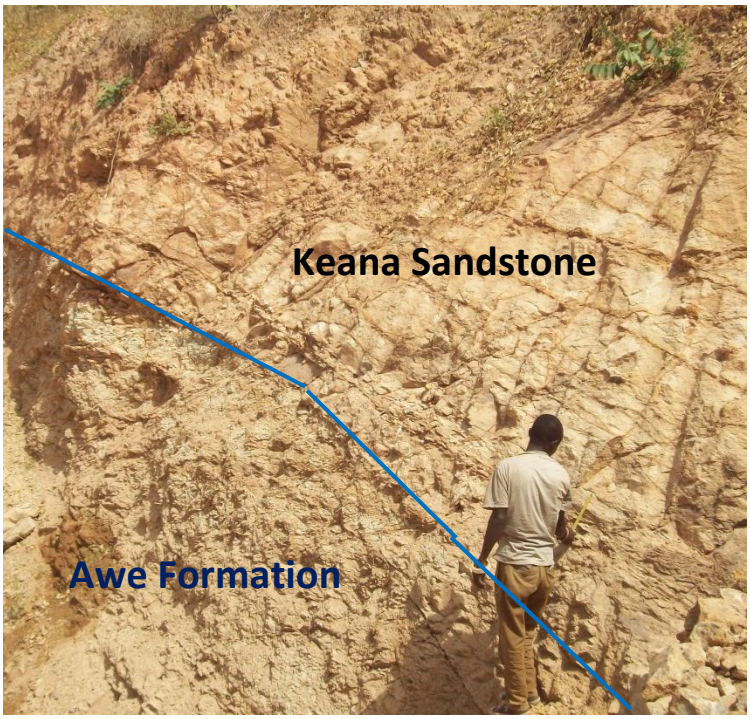


Figure 5.1: Exposed Awe Formation underlying Keana Sandstone at a Baryte mine site [8° 17' 47.3"N, 9° 53.3"E] showing an unconformity (paraconformity) between them. Formations are dipping due to the folding episode which affected the study area.

3. Keana Sandstone: The Keana Sandstone consists mainly of massive, indurated, current bedded, fine to very coarse, conglomeratic, gritty, arkosic sandstones (Offodile and Reyment, 1976). The Keana Sandstone is deposited in a fluviatile environment (Fig. 4.15, 4.16). In the study area, the Keana Sandstone is encountered at various places for example along the road to Gidan Soja [8° 25' 19.7"N, 9° 14' 44.0"E], at Ribi town [8° 22' 11.8"N, 9° 07' 36.6"E], and at Akondo settlement [8° 23' 50.8"N, 9° 06' 50.7"E]. At various places this formation occurs as a massive, flat-lying, extensive outcrop. It is very conglomeratic and quartz-veined.

The outcrops shows planar cross beddings (Fig. 4.17). The contact between this formation and the underlying Awe Formation is observed at the pit dug by the local baryte miners (Fig. 5.1). Plate XIIIa also shows a flat lying outcrop of massive sandstone with conglomerates and quartz veins near Ribi town within the Keana Sandstone.

4. Alluviums: Due to extensive and prolonged weathering of previously exposed rocks in the study area, there occurs a fairly thick overburden of alluvium in areas along River Ankwe. Its contact with underlying formation is not seen in the study area. Analysis of Landsat Imageries shows that the areas where alluvial deposits are found have the same tone as that which indicated the Keana Sandstone (Fig. 4.1). Thus, one can conclude that the alluvial deposits are formed as a result of the deposition of weathered regoliths from nearby Keana Sandstone. Along the banks of River Ankwe, the overburden reaches a height of about 10 meters (Fig. 5.2). The area covered by this overburden has been utilized by the villagers for farming purposes.



Figure 5.2: Alluvium – seen along River Ankwe

5.2.2 STRUCTURES

In the study area, the structures observed are syn-depositional and post-depositional structures. These structures are believed to result from the tectonic effect that affected the study

area and other parts of the Middle Benue Trough. The syn-depositional structures includes the bedding planes, graded beddings and laminated beddings of rock units seen in outcrops which generally is an indicator of the environment of deposition of the sediments. Post – depositional structures observed includes folds (represented by the various dips of rock units; Fig. 4.2), joints, quartz veins (Plate XIII a, c), hydrothermal mineralized veins and an unconformity between Awe and Keana Sandstones (Fig. 5.1).

The varying orientation of these dip values is as a result of the several folding episodes that these rocks have been subjected to. As observed in the field, Uomba Formation dips at an average angle of 9° towards the East, Keana Sandstone dips at an average angle of 20° while Awe Formation dips at an average dip angle of 14° either to the East or to the West depending on where it is exposed (Fig. 4.2). These varying dip directions confirm the presence of an anticline which cuts across the study area. This anticline is an extension of the Keana anticline. The variability of the strike trends reflects the sinuosity of the fold axes (Fig. 4.2) and it orientates averagely in a NE – SW direction coinciding with the direction of the Benue Trough axis.

Offodile (1976) reported with evidence, the existence of three folding episodes in the Keana – Awe area, the first of which is that of Nwachukwu (1972) who suggested the existence of a post Albian and pre – Turonian folding phase basing his inference on the "greater intensity of folding of the Albian sediments". This suggestion is confirmed with the tightness of measured dip values of the beds observed in the study area. However, evidences to confirm the two other episodes of folding as suggested by Offodile is not seen in this area probably because of the lack of very good exposures to identify the fold episodes.

The joint systems in-filled with silica, as observed within the study area, reflect the pattern of the faulting and are possibly genetically related to the fault system. The joints pattern

crisscross closely in the area. The few faults exposed in the study area trends NE – SW. The effect of this faulting is marked by the slicken-sliding of the Awe Formation which has dissected it into huge blocks though subjected to intense weathering. The presence of the quartz veins in the Keana Sandstone suggests the occurrence of tectonic activity in the area which is possibly as a result of the tectonic rifting reported by Benkhelil (1989).

The contact observed between Awe Formation and the overlying Keana Sandstone in the study area is depositional, gradational and para-conformity because there is no obvious evidence of erosion and the unconformity surface resembles a simple bedding plane (Fig. 5.1). The quartz veins and the mineralized hydrothermal baryte bearing veins observed in the study area orientates predominantly in the NW – SE and NNW-SSE directions. Various theories have been proposed for the origin of these hydrothermal fluids and brine such as those of Farrington (1952), Offodile (1976), Olade (1976) and Oden (2012).

5.2.3 DEPOSITIONAL HISTORY

The depositional history of the study area will be attempted by using the transgression - regression model. The sedimentation within the Middle Benue Trough during the Albian to Turonian has been identified to be part of three of the four Cretaceous sedimentary cycles of transgression and regression that are also recognized in the Lower Benue Trough (Murat, 1972). These four cycles are the Middle Albian to Middle Cenomanian; Upper Cenomanian to Middle Turonian; Upper Turonian to Coniacian; and Upper Campanian to Maastrichtian. Differential subsidence coupled with eustatic sea level rise in the Benue Trough has led to facies variations of the sediments within every part of the basin (Akande *et al.*, 2012).

Only one sedimentation cycle is identified in the study area and that is the first identified cycle which occurred between the Middle Albian to Middle Cenomanian (Fig. 5.3). This cycle began with a marine transgression which led to the deposition of the Uomba and Arufu Formations in the Middle Benue Trough (Obaje, 2009) and the Gboko Formation in the Lower Benue Trough (Najime, 2011). These are also age equivalent of the marine slumps and turbidites that made up the Ekebeligwe Formation (Abakaliki Shales of Reyment, 1965) in the Lower Benue Trough (Ojoh, 1990) and also equivalent to the alternating sequence of fissile shales, mudstone and micaceous siltstones of the Uomba Formation encountered in the study area.

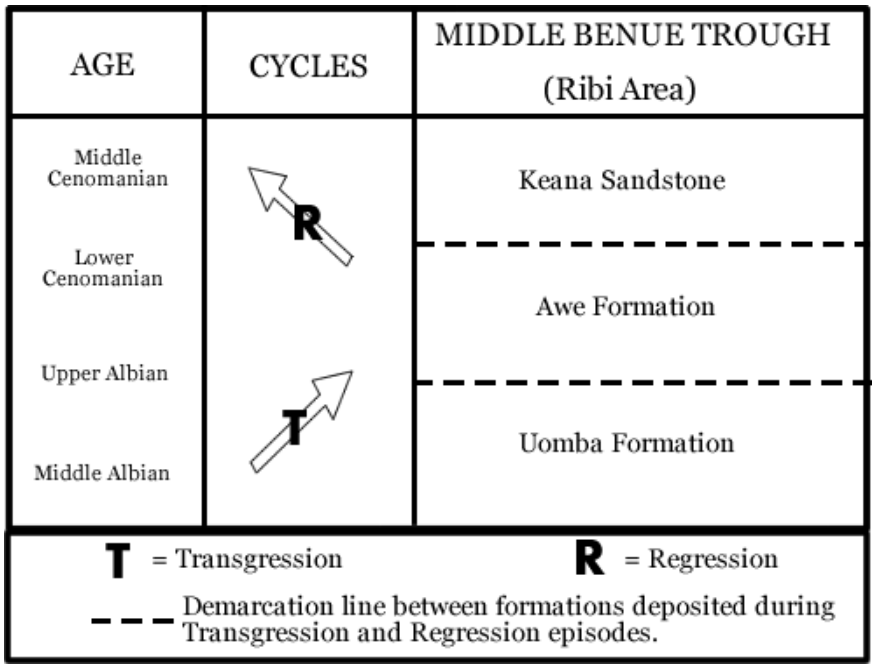


Figure 5.3. Transgression-Regression cycles and the stratigraphic chart of the study area.

From field observations, the change in constituent rock units making the Uomba Formation of the Asu River Group in this area is believed to be as a result of the location of the study area within the Middle Benue Trough. This means the causative marine transgression which entered this part of the Benue Trough from the newly opened Equatorial Atlantic Ocean

and reached its peak towards the Late – Middle Albian did not have enough energy flow to move much marine sediments into this part of the Middle Benue Trough. Thus, small quantities of marine sediments are deposited together with the accompanying mudstones.

Akande *et al* (2012) opined that this Albian transgression which flooded the Lower and Middle Benue Trough and led to the deposition of thick shales of the Asu River Group at the basin center and carbonates at the basin margins is consequent to the erosion and continental sedimentation of the Aptian and older periods. Offodile and Reyment (1977), however believed that the sea apparently shoaled somewhere towards the north-eastern boundary of the Middle – Upper Benue Trough with the sediments being fossiliferous, containing Late Middle Albian ammonites *Oxytropidoceras*. The constituent finely laminated shales of this Asu River Group have been suggested to be a potential source rock for hydrocarbon in the Middle Benue Trough (Akande *et al.*, 2012).

The Upper Albian to Lower Cenomanian saw a regressive phase that eventually ended this first sedimentation cycle. However, between this transgression and the concluding regression, there definitely occurred a transitional period which is believed to have led to the deposition of carbonaceous, flaggy, medium to coarse – grained calcareous sandstones and clays of the Awe Formation which was deposited as passage (transitional) beds (Offodile, 1976) in the Keana – Awe area of the Middle Benue Trough. During this period, deposition of the regressive Albian marine episode occurred in a transitional environment between predominantly marine and fluviatile conditions. In the study area, this transitional period defined by the minor forward and backward movement of the coastline, resulted in interplay of shallow marine and transitional marine conditions with the deposition of alternating mudstones, siltstones and fine grained,

arkosic, feldspathic sandstones, greywackes and quartz – arenitic sandstones series. The presence of glauconite in these rocks confirms their marine origin.

The final withdrawal of the sea during the Lower Cenomanian to Middle Cenomanian gave way to the process of erosion that occurred hinterland and thereby causing a large detritus to be deposited in a restricted delta (Bima Delta). These fluviodeltaic sediments moved southwards to form the Keana Sandstone (Offodile, 1976; Akande *et al.*, 2012) also encountered in this area. Other formations were not encountered in this area of study and as such, the possibility of other transgression – regression cycles could not be ascertained.

5.3 ECONOMIC GEOLOGY

The name Azara has become synonymous with the mining of baryte in Nigeria. Tate (1959) gave a reserve estimate of 40,000 tons to a depth of 20 m in Azara locality. In 1976, the defunct Nigerian Mining Corporation identified eighteen major hydrothermal veins in Azara and its environs (Chaanda, Obaje, Moumouni, Goki and Lar, 2010). Baryte is the primary source of the element barium. Most baryte is mined from layers of sedimentary rock which formed when baryte precipitated onto the bottom of the ocean. Some smaller mines utilize baryte from veins, which formed when barium sulfate is precipitated from hot subterranean waters. Baryte could also be formed in hydrothermal veins which are often found with copper, silver, lead ore and also associated with limestone. In some cases, baryte is won as a by-product of mining lead, zinc, silver, or other metal ores.

The baryte deposits in the study area occur as hydrothermal veins hosted within the Awe Formation of the Middle Benue Trough. Oden (2012) believed that hydrothermal fluid pressure

and sustained baryte availability over a long period of time (over a million years) produced a fairly to very wide mineral veins in host rocks. Farrington (1952) regarded the mineralization as of mesothermal, magmatic hydrothermal origin emplaced at some time during the Late Albian to Early Turonian interval. Olade (1976) was of the opinion that tectonic activities are responsible for creating pathways through which hydrothermal veins of possibly magmatic origin or remobilized meteoric waters enriched in Pb, Zn and Na percolated.

Two sets of fractures were recognized in the Keana – Azara area, one of which is associated with the Pb - Zn mineralization trending NE – SW while the other is associated with the baryte mineralization trending NW – SE (Offodile, 1976; Farrington, 1952). The baryte bearing veins are consistent and trends mostly in the NW-SE parallel direction to the axis of the Benue Trough with few veins trending in the NNW - SSE direction (Oden, 2012). These two vein directions indicate the presence of post sedimentary deformation phase in the trough and are formed from the ac-tension joints.

Benkhelil (1981) suggested that the veins trending NW - SE are older and formed during the first phase of deformation while those veins trending NNW - SSE are younger and formed during the second phase of deformation which caused the breciation of the earlier NW - SE veins thereby resulting into joints which are invaded by neo-mineralization fluids of this second deformation. This is as observed in the field where many baryte veins show the presence of small scale fracturing with secondary minerals such as quartz, feldspars serving as binding cements.

Also within the study area, local mining of salt is undertaken by the indigenes. This is seen at Rufai (Ribi) (Fig. 5.4). Offodile (1976) suggested that during the regression of the Albian Sea, parts of the sea could have been cut off with the formation of hypersaline lakes and swamps.

He also believes there is the possibility of the salt mineralization being formed as a result of arenaceous detritals infilling the ponds and sponging the brine, or bittern, if evaporites had been formed.



Figure 5.4: Local Salt mining at Ribi.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMENDATIONS

6.1 SUMMARY

The geology of the study area is made up of three formations – the Uomba Formation, Awe Formation and Keana Sandstone. However, the Uomba and Awe Formations show variations in constituent units to others elsewhere within the Middle Benue Trough due to the location and distance of the study area to the transgressing Atlantic Sea. This is because as the sea transgressed, it deposited more marine sediments within the south western part of the Middle Benue Trough and less of it towards the upper North Eastern part of the Middle Benue Trough.

The effect of this transgression in this area led to the deposition of an alternating fissile shales, mudstone and micaceous siltstones series which represents the Uomba Formation of the Asu River Group. The transitional period led to the deposition of alternating sandstones, siltstones and mudstones series which in the study area represents the Awe Formation. The regressive phase led to the deposition of the conglomeratic, fractured and quartz-veined sandstones which represents the Keana Sandstone in the study area. The Keana anticline is the main structural element in this part of the trough.

6.2 CONCLUSIONS

Field observations in the study area has shown the effect of the location and distance of the study area to the transgressing Atlantic sea which is evident by the type of rock series deposited. It is expected that geological studies done further in the eastern half of the Middle Benue Trough will show a thinning out of the shale constituent of the Uomba Formation of the Asu River Group and Awe Formation might thins out eventually. This will invariably mean that more of the overlying Keana Sandstone in the study area will be found as the base formation of the Middle Benue Trough further north east. This will therefore serve as a lateral continuation

between the Middle Benue Trough and the basal deposits of the Upper Benue Trough that is, the Bima Sandstone.

6.3 CONTRIBUTIONS TO KNOWLEDGE

i. A detailed geological map of the area on a scale of 1:50,000 has been produced.

ii. The stratigraphy of the study area has been shown and contacts highlighted.

iii. The depositional environment of the sediments in the study area has been established – Awe Formation sediments being marine and Keana Sandstone sediments being river sands.

iv. The sedimentation cycle which occurred within this study area has been established.

v. The effect of the proximity of the study area to the transgressing Albian Sea – which has led to variations in rock series for Uomba and Awe Formation – has been exposed.

6.4 RECOMMENDATIONS

a. A detailed geological study of areas north-east of the study area including that which connects the Middle and Upper Benue Trough should be embarked upon so as to produce a comprehensive geology of the whole Middle Benue Trough.

b. Due to the relative shallowness of most sections exposed in the study area, bore holes should be drilled and logged to help in better understanding of the geology of the area and the Middle Benue Trough so as to be able to highlight changes in facies of encountered formation(s).

c. The name “Asu River Formation” of Offodile (1976) is inappropriate as you cannot have the same name for a formation and the group it is found thus “Uomba Formation” of Reyment (1964) is used in this work until new proposals are made.

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APPENDICES

Appendix I: Statistical Parameters of the Analysed Samples

Sample A (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	47	47.47	47.47
0.600	0.75	21	21.21	68.68
0.300	1.75	19	19.19	87.87
0.150	2.75	7	7.07	94.94
0.075	3.75	4	4.04	98.98
Pan	5.0	1	1.01	99.99
Total		99	99.9	

Sample B (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	6	6	6
0.600	0.75	12	12	18
0.300	1.75	35	35	53
0.150	2.75	29	29	82
0.075	3.75	9	9	91
Pan	5.0	9	9	100
Total		100	100	

Sample C (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	32	31.68	31.68
0.600	0.75	10	9.09	40.77
0.300	1.75	27	26.73	67.50
0.150	2.75	19	18.81	86.31

0.075	3.75	7	6.93	93.24
Pan	5.0	6	5.94	99.18
Total		101	100	

Sample D (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	22	22	22
0.600	0.75	26	26	48
0.300	1.75	33	33	81
0.150	2.75	8	8	89
0.075	3.75	3	3	92
Pan	5.0	8	8	100
Total		100	100	

Sample E (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	12	11.88	11.88
0.600	0.75	14	13.86	25.74
0.300	1.75	28	27.72	53.46
0.150	2.75	26	25.74	79.20
0.075	3.75	11	10.89	90.09
Pan	5.0	10	9.90	99.99
Total		101	99.99	

Sample F (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	15	15	15
0.600	0.75	15	15	30
0.300	1.75	27	27	57
0.150	2.75	20	20	77
0.075	3.75	11	11	88

Pan	5.0	12	12	100
Total		100	100	

Sample G (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	18	18	18
0.600	0.75	17	17	35
0.300	1.75	35	35	70
0.150	2.75	17	17	87
0.075	3.75	5	5	92
Pan	5.0	8	8	100
Total		100	100	

Sample H (Awe Formation)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	55	55.56	55.56
0.600	0.75	12	12.12	67.68
0.300	1.75	14	14.14	81.82
0.150	2.75	7	07.07	88.89
0.075	3.75	5	05.05	93.94
Pan	5.0	6	06.06	100
Total		99	100	

Sample I (Keana Sandstone)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	1	1	1
0.600	0.75	5	5	6
0.300	1.75	37	37	43

0.150	2.75	42	42	85
0.075	3.75	7	7	92
Pan	5.0	8	8	100
Total		100	100	

Sample J (Keana Sandstone)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	64	64	64
0.600	0.75	13	13	77
0.300	1.75	13	13	90
0.150	2.75	4	4	94
0.075	3.75	3	3	97
Pan	5.0	3	3	100
Total		100	100	

Sample K (Keana Sandstone)

Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	88	88	88
0.600	0.75	5	5	93
0.300	1.75	3	3	96
0.150	2.75	2	2	98
0.075	3.75	1	1	99
Pan	5.0	1	1	100
Total		100	100	

Sample L (Keana Sandstone)

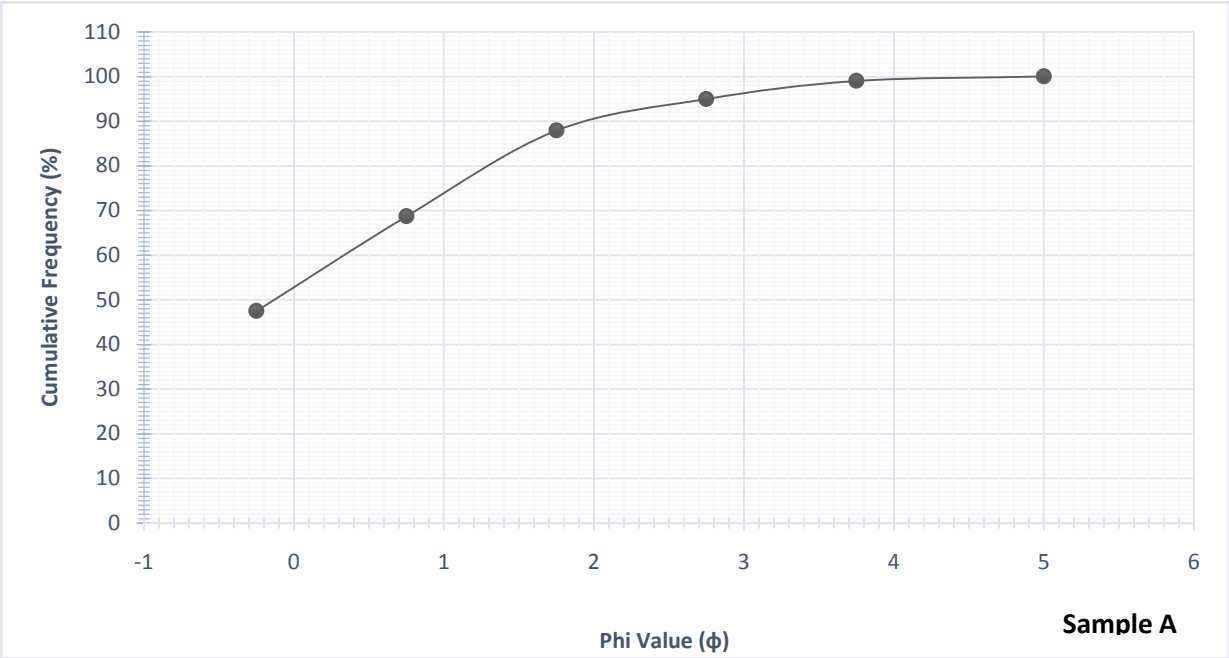
Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	69	69.69	69.69
0.600	0.75	7	7.07	76.76
0.300	1.75	11	11.11	87.87
0.150	2.75	4	4.08	91.95

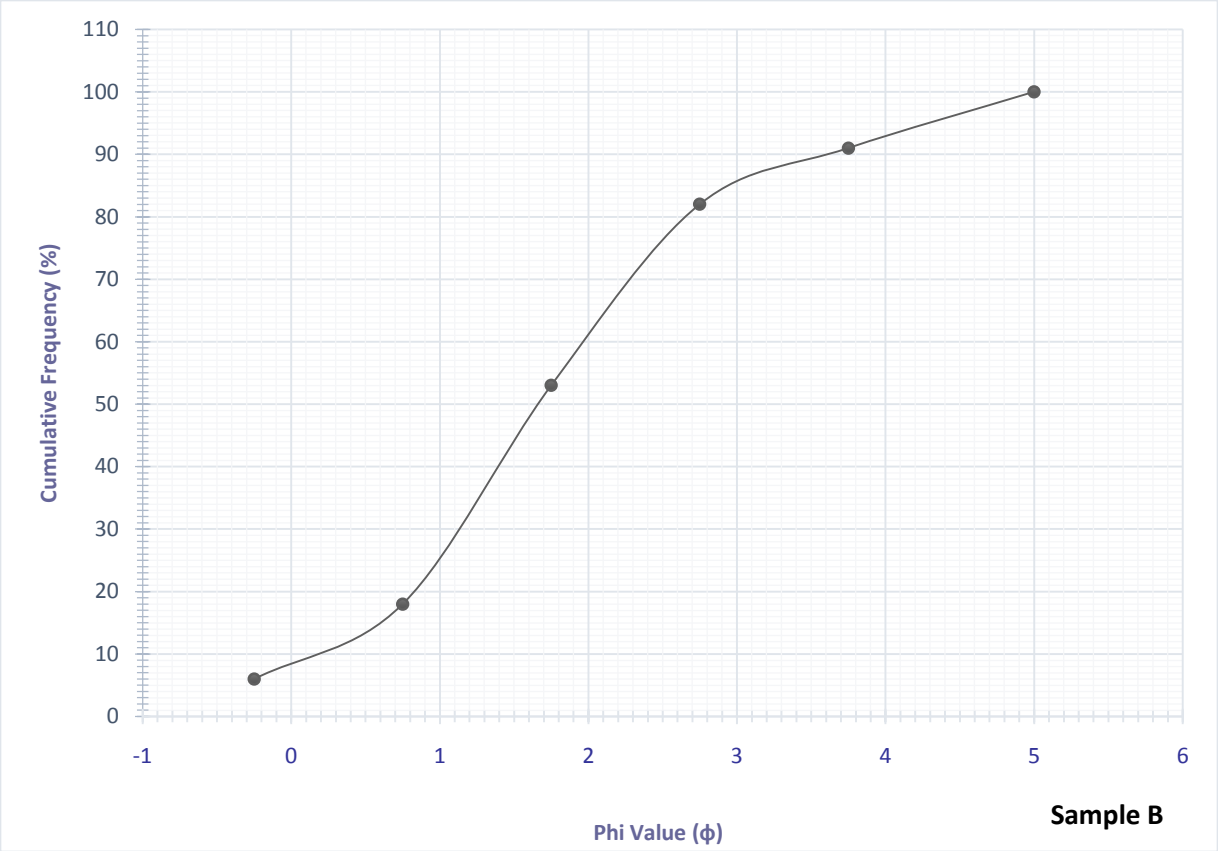
0.075	3.75	2	2.02	93.97
Pan	5.0	6	6.06	100.03
Total		99	100.03	

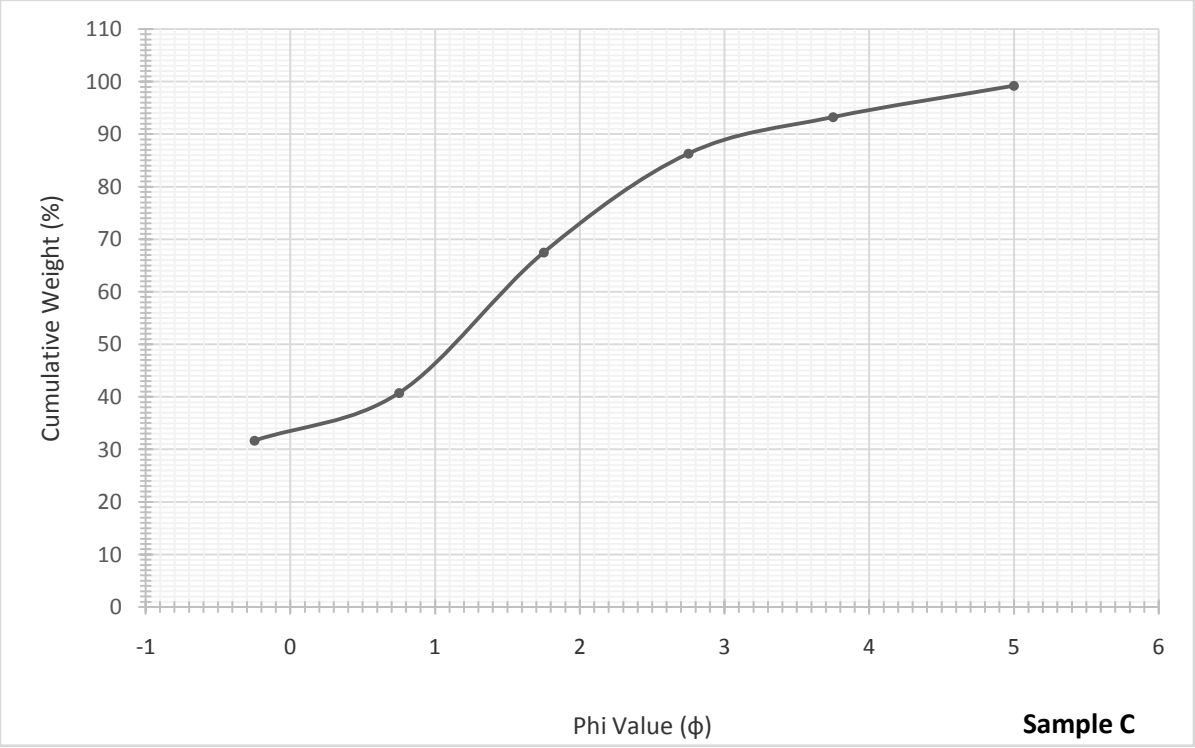
Sample M (Keana Sandstone)

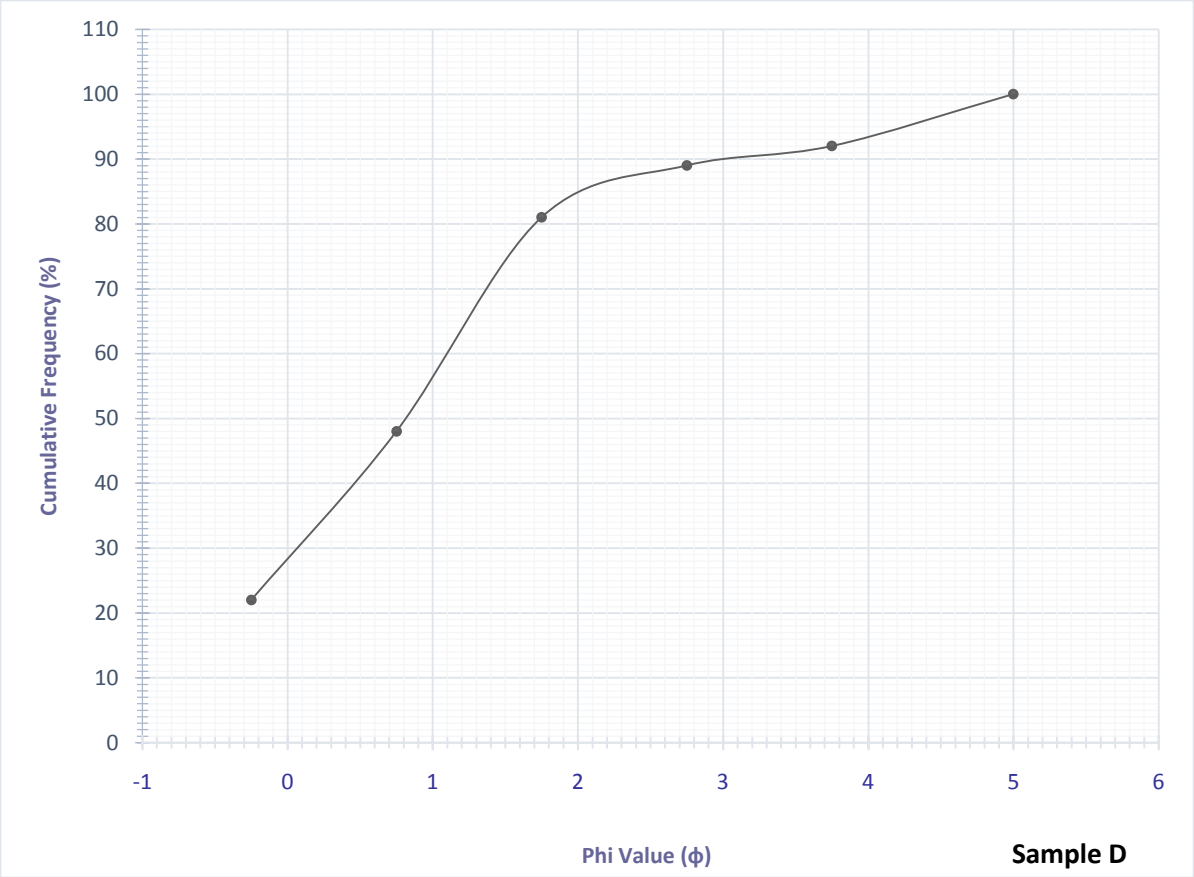
Sieve Size (mm)	Phi (ϕ) Value	Weight of Sample (g)	Weight (%)	Cumulative Weight (%)
1.800	-0.25	73	73	73
0.600	0.75	14	14	87
0.300	1.75	8	8	95
0.150	2.75	4	4	99
0.075	3.75	1	1	100
Pan	5.0	0	0	100
Total		100	100	

Appendix II: Cumulative Frequency curves for the Analysed Samples

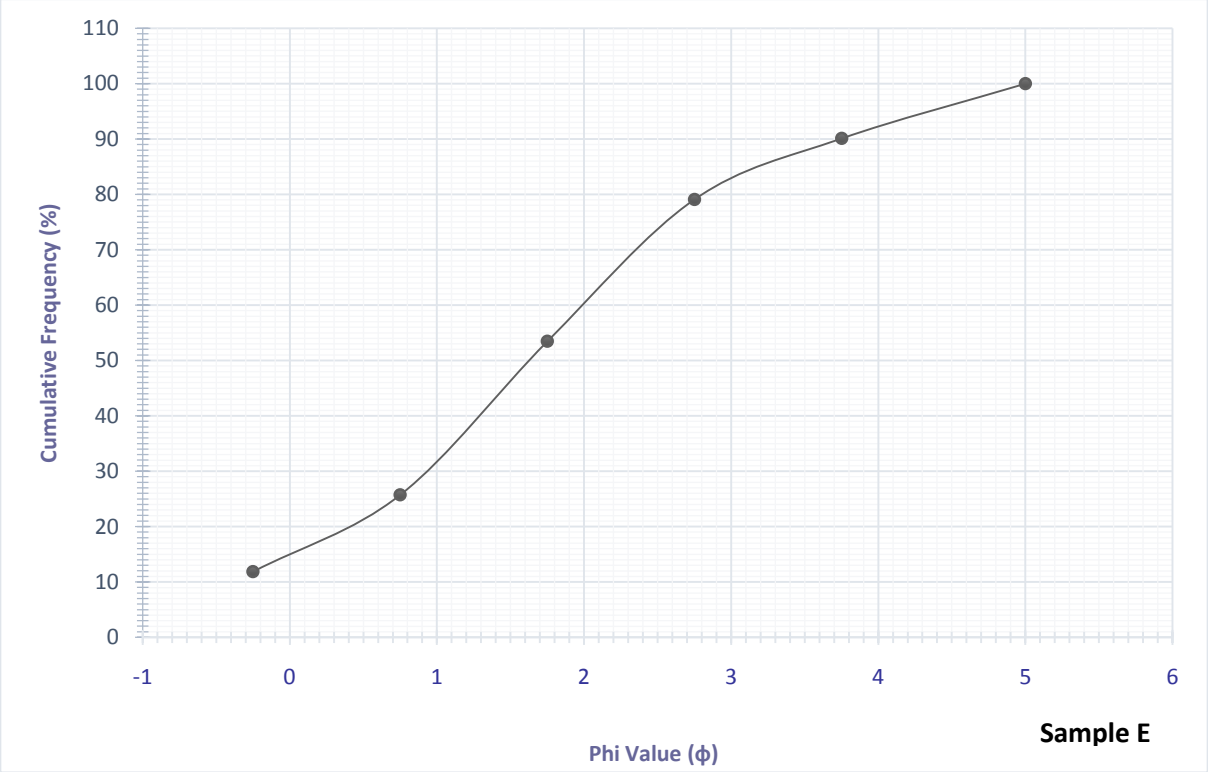



110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Frequency (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample B

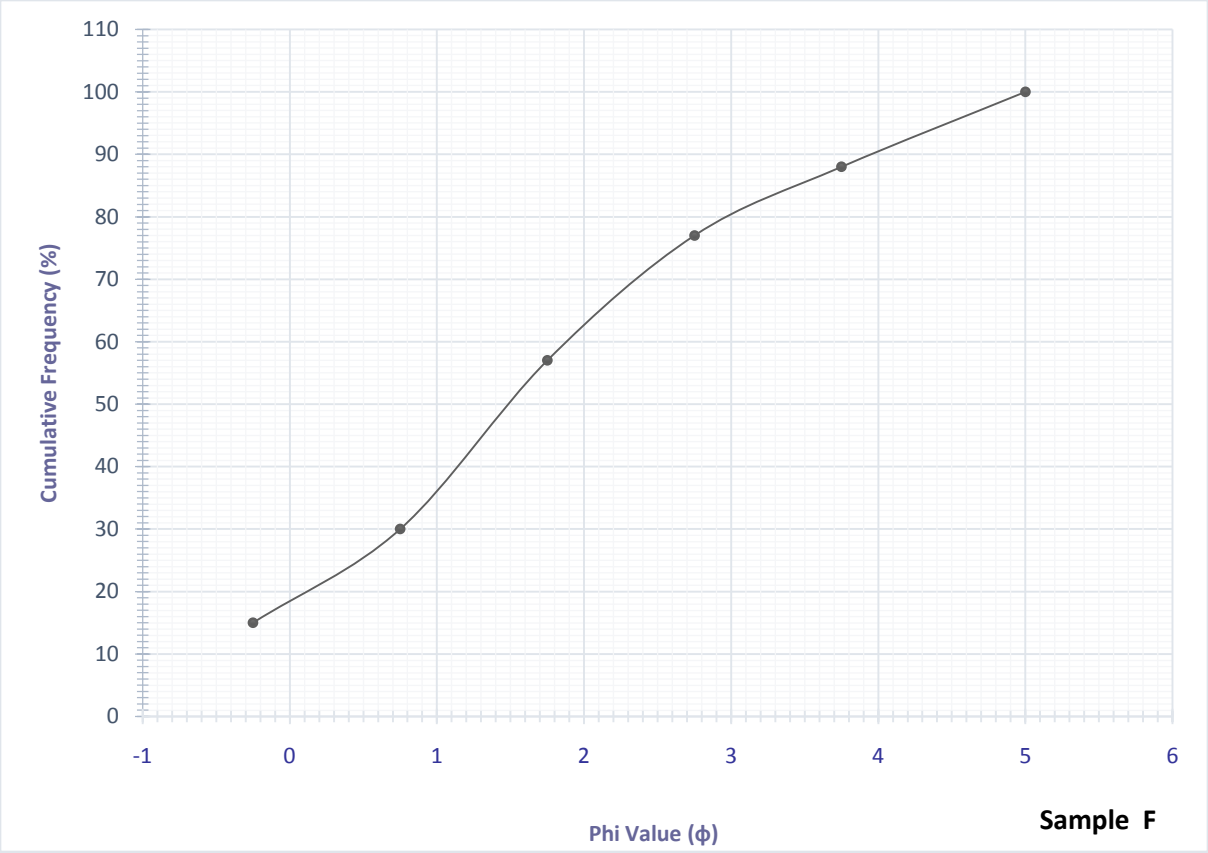

110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Weight (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample C

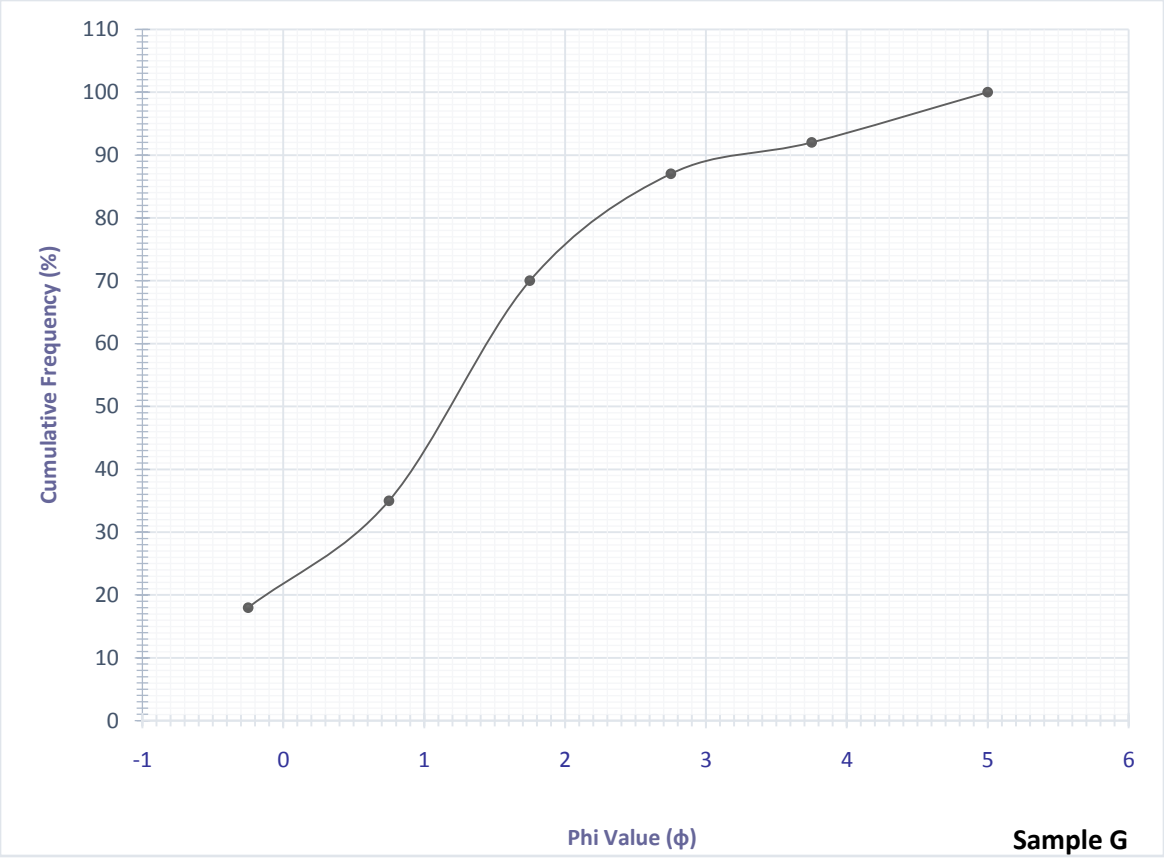


Sample D

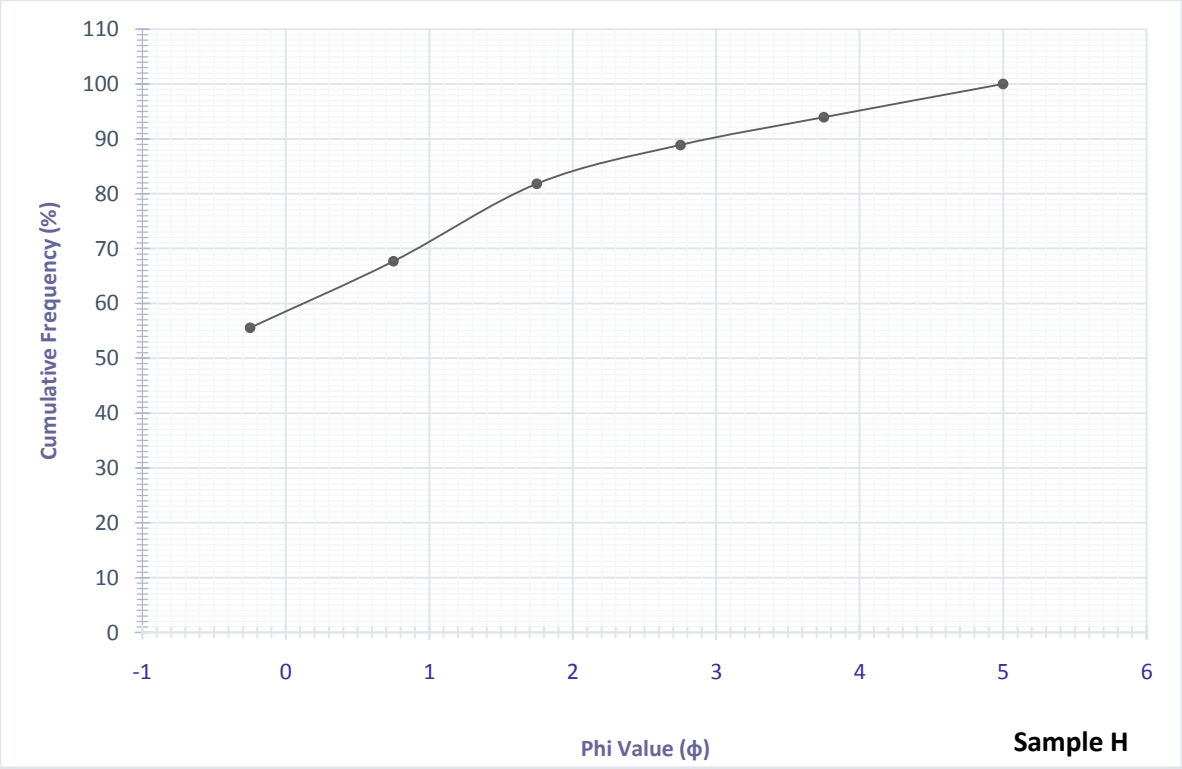


Sample E

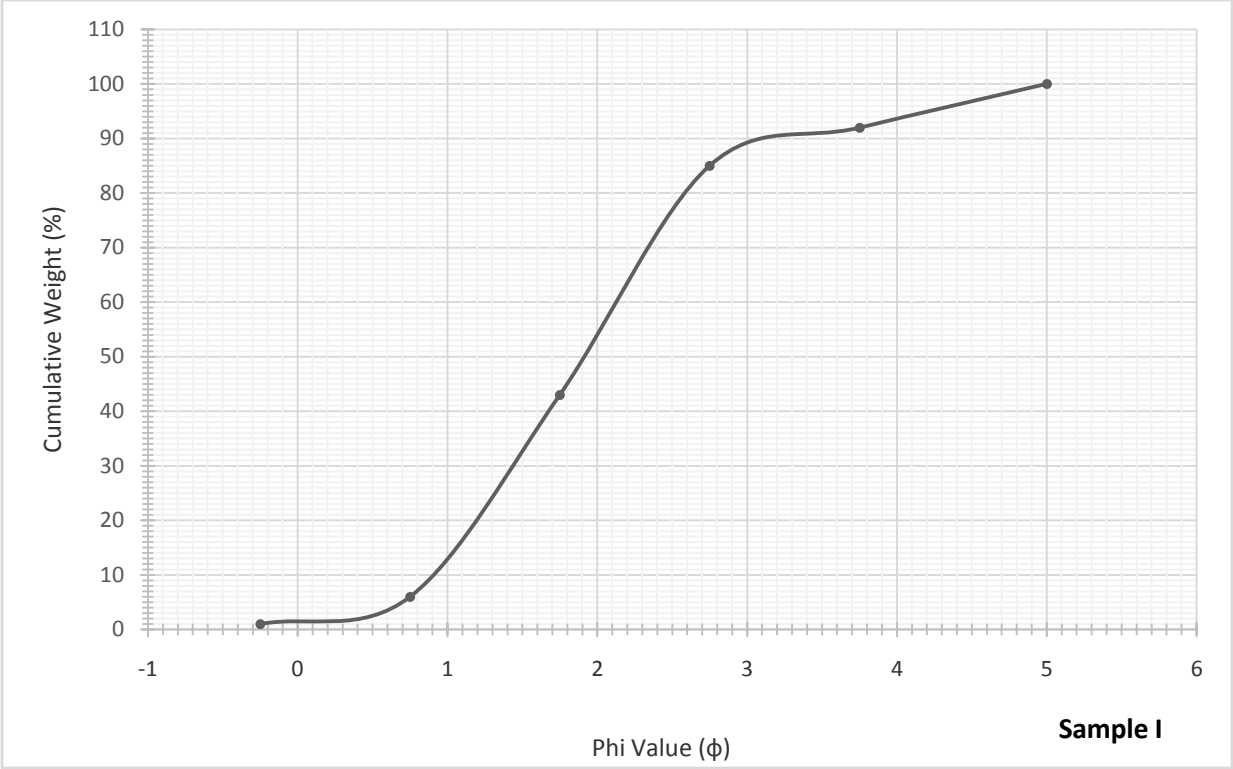

110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Frequency (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample F

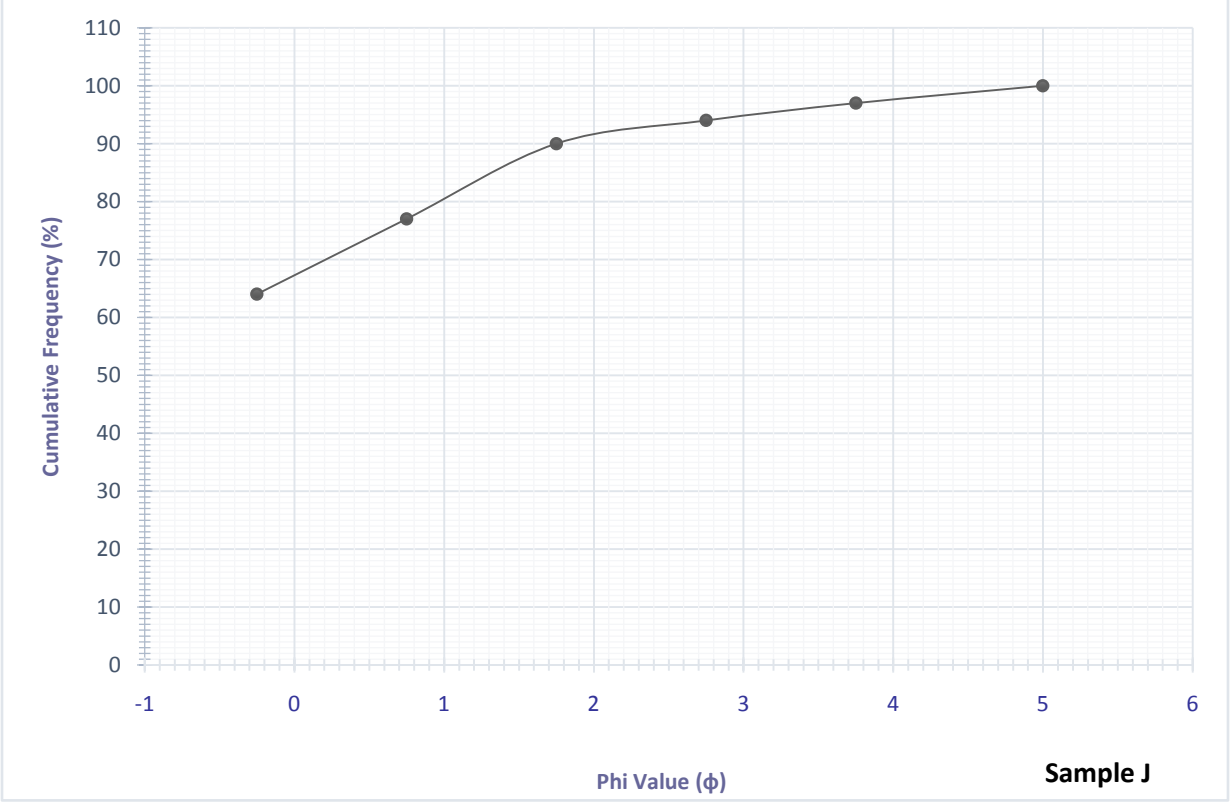


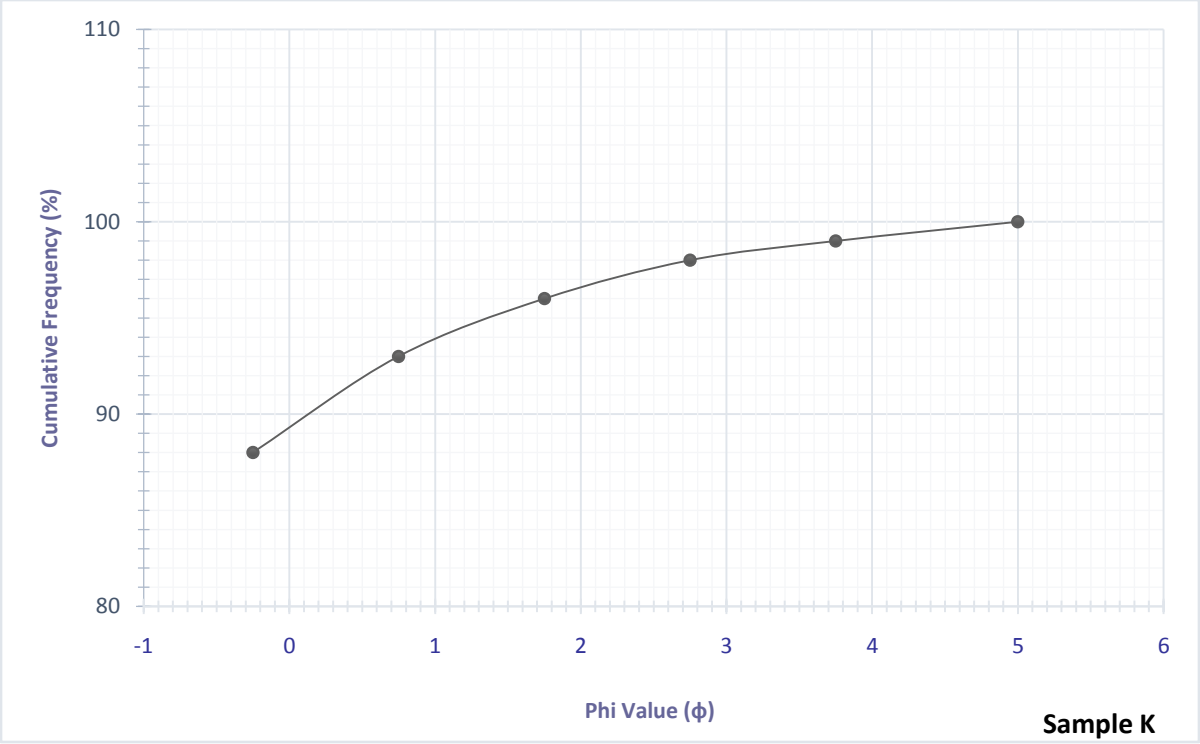
Sample G



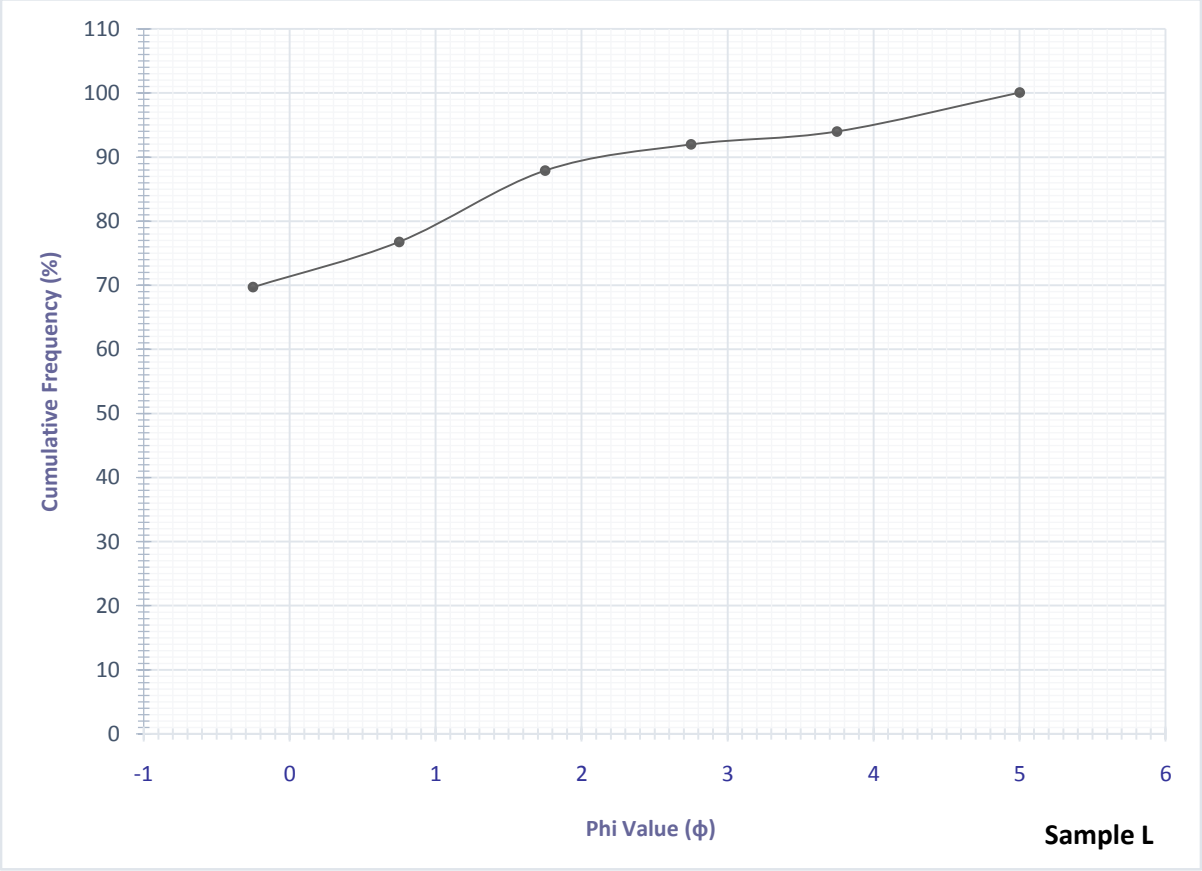
Sample H


110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Weight (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample I

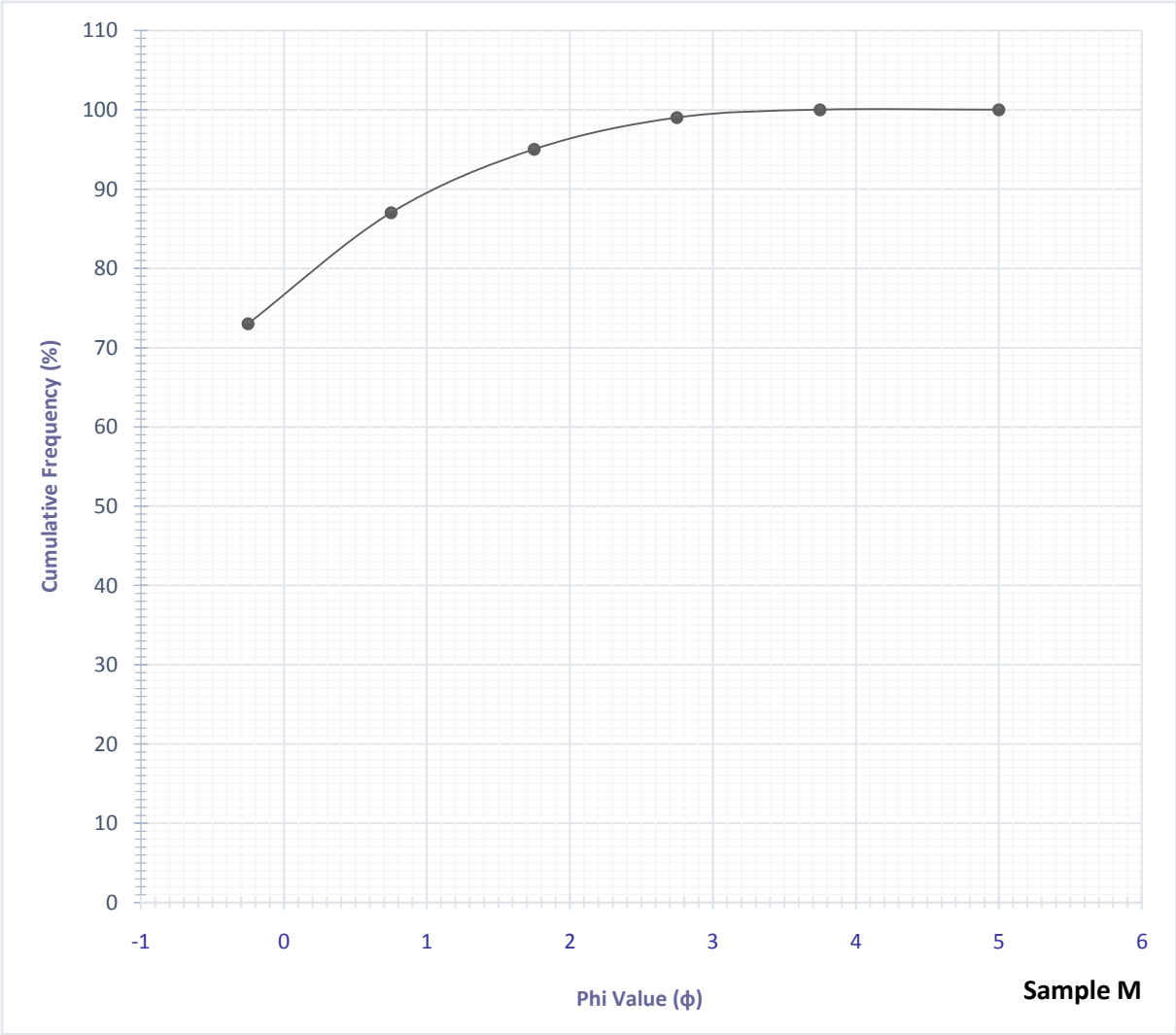

110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Frequency (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample J



Sample K



Sample L


110
100
90
80
70
60
50
40
30
20
10
0
Cumulative Frequency (%)
-1
0
1
2
3
4
5
6
Phi Value (ϕ)
Sample M

APPENDIX III: Percentiles, Grain Sizes, and Interpretation of Statistical parameters.

Table 1: Percentile values derived from cumulative frequency curve plots

Samples		Φ 5	Φ 16	Φ 25	Φ 50	Φ 75	Φ 84	Φ 95
Awe Formation	A	0.00	0.00	0.00	- 0.15	1.075	1.50	2.75
	B	0.00	0.65	1.00	1.65	2.45	2.85	4.24
	C	0.00	0.00	0.00	1.15	2.11	2.60	4.00
	D	0.00	0.00	-0.12	0.80	1.52	1.90	4.25
	E	0.00	0.09	0.71	1.63	2.58	3.10	4.30
	F	0.00	-0.18	0.48	1.51	2.62	3.38	4.45
	G	0.00	0.00	0.24	1.20	1.96	2.49	4.20
	H	0.00	0.00	0.00	0.00	1.25	2.00	3.95
Keana Sandstone	I	0.70	1.10	1.35	1.90	2.48	2.72	4.22
	J	0.00	0.00	0.00	0.00	0.60	1.27	3.00
	K	0.00	0.00	0.00	0.00	0.00	0.00	1.39
	L	0.00	0.00	0.00	0.00	0.56	1.40	4.00
	M	0.00	0.00	0.00	0.00	-0.09	0.50	1.75

Table 2: Grain size distribution and statistical parameters

Samples		Mean	Sorting	Skewness
Awe Formation	A	0.45 Coarse Grained Sand	0.79 Moderately Sorted	1.15 Strongly Positively Skewed
	B	1.72 Medium Grained Sand	1.19 Poorly Sorted	0.16 Positively Skewed
	C	1.25 Medium Grained Sand	1.26 Poorly Sorted	0.27 Positively Skewed
	D	0.90 Coarse Grained Sand	1.12 Poorly Sorted	0.39 Strongly Positively Skewed
	E	1.61 Medium Grained Sand	1.40 Poorly Sorted	0.11 Positively Skewed

Awe Formation	**F**	1.57 Medium Grained Sand	1.56 Poorly Sorted	0.19 Positively Skewed
	G	1.23 Medium Grained Sand	1.26 Poorly Sorted	0.23 Positively Skewed
	H	0.67 Coarse Grained Sand	1.10 Poorly Sorted	1.0 Strongly Positively Skewed
Keana Sandstone	**I**	1.91 Medium Grained Sand	0.94 Moderately Sorted	0.17 Positively Skewed
	J	0.42 Coarse Grained Sand	0.77 Moderately Sorted	1.00 Strongly Positively Skewed
	K	0.00 Very Coarse Grained Sand – Coarse Grained Sand	0.21 Very Well Sorted	0.50 Strongly Positively Skewed
	L	0.47 Coarse Grained Sand	0.96 Moderately Sorted	1.00 Strongly Positively Skewed
	M	0.17 Coarse Grained Sand	0.39 Well Sorted	1.00 Strongly Positively Skewed

Table 3a: Interpretations for the Graphical Mean values of grain sizes

Values from	To	Equal
∞	–1 ϕ	gravel
-1	0 ϕ	very coarse sand
+0	+1 ϕ	coarse sand
+1	+2 ϕ	medium sand
+2	+3 ϕ	fine sand
+3	+4 ϕ	very fine sand
+4	+8 ϕ	silt
+8	∞ ϕ	clay

Table 3b: Interpretations for the Sorting values of grain sizes

Values from	To	Equal
0.00	0.35 ϕ	very well sorted
0.35	0.50 ϕ	well sorted
0.50	0.71 ϕ	moderately well sorted
0.71	1.00 ϕ	moderately sorted
1.00	2.00 ϕ	poorly sorted
2.00	4.00 ϕ	very poorly sorted
4.00	∞ ϕ	extremely poorly sorted

Table 3c Interpretations for the Graphical Skewness values of grain sizes

Values from	To	Mathematically:	Graphically Skewed to the:
+1.00	+0.30	Strongly positive skewed	Very Negative phi values, coarse
+0.30	+0.10	Positive skewed	Negative phi values
+0.10	- 0.10	Near symmetrical	Symmetrical
- 0.10	- 0.30	Negative skewed	Positive phi values
- 0.30	- 1.00	Strongly negative skewed	Very Positive phi values, fine

APPENDIX IV: Direction of joints exposed on various formations within the study area.

Location 1	Location 2	Location 3	Location 4	Location 5
Awe Formation	Keana Sandstone	Awe Formation	Keana Sandstone	Keana Sandstone
34°	313°	333°	55°	65°
65°	298°	225°	60°	170°
75°	238°	230°	240°	175°
93°	176°	170°	230°	175°
184°	153°	155°	210°	172°
220°	100°	130°	240°	150°
220°	10°	25°	218°	220°
245°	50°	40°	185°	220°
200°	85°		220°	235°
190°	60°		220°	295°
	70°		190°	
	30°		200°	
			290°	
			315°	
			346°	
			330°	