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COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE

SCHOOL OF EARTH SCIENCE

**SEDIMENTOLOGICAL AND PETROGRAPHIC ANALYSIS OF ADIGRAT
SANDSTONE IN YEJUBE SECTION, CENTRAL NORTH WESTERN ETHIOPIA:
IMPLICATION FOR PALEOENVIRONMENT**



**A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL
FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS OF SCIENCE
IN STRATIGRAPHY AND SEDIMENTOLOGY**

By; Natinael Kasa

SEPTEMBER 2021

ADDIS ABABA, ETHIOPIA

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SEDIMENTOLOGY STREAM.

ADVISOR: BALEMWAL ATNAFU (PhD)

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCE

ADDIS ABABA, ETHIOPIA

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SEPTEMBER, 2021

Declaration

I hereby declare that the thesis entitled “Sedimentological and petrographic analysis of Adigrat sandstone in yejube section, Central North Western Ethiopia: implication for paleoenvironment “is submitted in partial fulfillment of the requirement for the award of the degree of Master in Earth Science (Stratigraphy and Sedimentology) to the school of Earth Science in Addis Ababa University under the supervision of Dr. Balemwal Atnafu. I certify that this thesis work contains no materials which have been accepted for the award of any other degree in any university and not does it contains any materials which previously published and written by any other persons, except where due reference is made in the reference list and there citations in the text.

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ADDIS ABABA, ETHIOPIA

SEPTEMEBER 2021

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ABSTRACT

This thesis is about the interpretation of the depositional environment of Adigrat sandstone from the neglected section of yejube in the Blue Nile sedimentary basin in central northwestern Ethiopia after following a detailed field investigation supported by petrographic and grain size analysis. The data obtained mainly field data that includes color, texture, sedimentary structure, the lateral and vertical continuity of lithology that were investigated. Additionally, the stratigraphic log of the section and geological mapping is conducted. Petrographic and grain size analysis was performed on 27 representative samples. A petrographic analysis result indicates that the studied sandstone is classified mainly as quartz arenite from the modal analysis following point counting of framework grain. The analysis indicating that the sandstone unit is both compositionally and texturally matured. Grain size analysis generally indicates that the sediment consisting of more than one provenance and sediment is deposited not in a restricted environment rather it is deposited in a mixed environment of a fluvial and marine process. Based on the field investigation supported by laboratory result nine lithofacies type has been identified, these are namely Fine-grained Trough cross-laminated sandstone, Medium grained mud crack developed sandstone Facies, Planar cross-bedded medium-grained sandstone facies from lower sub section, Medium grained herringbone cross stratified sandstone facies from the middle part of the section and Well sorted thinly bedded sandstone, Fine-grained hummocky cross stratified sandstone, Fine-grained well-sorted tool marked sandstone, Moderately sorted horizontal bedded sandstone facies, Medium to Coarse grain Bioturbated sandstone facies from lower sub- section. These identified lithofacies type has to be grouped into three facies association to interpret its depositional environment. These facies assemblages are the Meandering river deposit, tidal flats, and continental shelf deposit. The facies stacking pattern indicates that the retrogradational effect of Transgression process deposits this Formation.

Key Words: Adigrat sandstone, Blue Nile Basin, lithofacies, Petrography, Yejube section

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ACRONYMS

a.s.l= above sea level

Bi = Biotite

BSS=Bioturbated sandstone

C = Calcite

Cm = Centimeter

°C = degree Celsius

FTS = Fine-grained tool marked sandstone

GPS = Global position system

HCB=hummocky cross stratified sandstone

HS=herringbone cross stratified sandstone

Km= Kilometer

Kf = Potassium feldspar

m= Meter

HBS=horizontal bedded sandstone

MCS=mud crack developed sandstone

Mc = Microcline feldspar

NE= North East

NW=North west

PPL= Plain Polarized light

PCS=Planar cross-bedded sandstone

Qm = Monocrystalline quartz

Qp = Polycrystalline quartz

QFL= Quartz,Feldspar,Lithic fragment

Rf =Rock fragment

SE= South East

TBS=thinly bedded sandstone

TCS=Trough cross-laminated sandstone

TMS=tool marked sandstone

XPL= Crossed polarized light

CHAPTER ONE

1. BACKGROUND AND JUSTIFICATION

About the total of Ethiopia's surface Coverage, 33 % of it is covered by sedimentary rocks (Wolela, 2008). According to Bosellini (2001), the Paleozoic up to the tertiary extensional tectonic event as a result of the breaking apart of the Gondwanaland promote the development of the sedimentary basin of Ethiopia. The sedimentary rock of the country is located in five sedimentary basins. These include the Mekelle basin, the Blue Nile basin (Abay basin), Gambela basin, the South rift basin (Omo basin), and the Ogaden basin. The present studied section is part of the Blue Nile sedimentary basin.

The Blue Nile sedimentary basin is situated in the NW direction from the Capital Addis Ababa that contains thick sedimentary succession following along the gorge of Blue Nile (Abay) river and its tributary. This sedimentary basin which is part of the failed arms of the Karoo rift system developed by the extensional movement that is associated with the breakup of Gondwanaland is a major geological formation formed in the Late Paleozoic to Mesozoic during a period of crustal extension and which is filled with sedimentary deposits. Based on the recent studies carried by the Geological Survey of Ethiopia the basin has a total area coverage of 120,000 square km. According to Getane (1991), the stratigraphic sequence on the gorge of the Blue Nile is divided into five units; these are the Neoproterozoic basement rock, Early Jurassic Adigrat sandstone, middle Jurassic Antalo Limestone, Gypsum unit of Gohatsion formation, the late cretaceous Amba Aradom sandstone and the younger volcanic rock. Recently Dawit (2010) modifies these by adding three formations in which he named Pre Adigrat I, Pre Adigrat II, and Pre Adigrat III below the Adigrat sandstone formation.

Adigrat sandstone Formation distributed widely in the Blue Nile sedimentary basin. According to Wolela (2008), The Adigrat sandstone covers vast areas forming vertical cliff exposure in different sections including Yejube , Dejen , Amuru – Jarty , Gendebert –Jeldu ,Jemma, and Fincha locality. It is underlain unconformably by either pre-Adigrat unit or basement and overlain by either Gohastion formation of tertiary volcanic.

Sandstone rock units make up nearly one-quarter of the sedimentary rock in the geologic records and they are formed under a variety of depositional environments (Boggs, 2009). It is one of the siliciclastic rocks which consist of sand-size grains of mineral, rock, or organic material in which the framework of the sandstone binds together by cementing material and there is also silt or clay size particle that occupy the space between the sand grains which is

called matrix. The sedimentary textures and structures observed under the sandstone rock unit have the potential for environmental interpretation.

To explore important information obtained from sandstones detailed study of units by using different methods is needed. The petrographic and Sedimentological approach to study the origin and nature of sedimentary rocks particularly sandstone has been the fundamental source of information about the surface history of our planet. According to (Grazanti,2019) petrographic study and sediment characteristics of sandstone archives is one of the many keys to deciphering geologic history. The petrographic analysis of rock samples becoming an organized discipline with the development of thin section techniques and the polarized microscope. This Petrographic analysis is used to study detail compositional and textural property of the rock which is difficult to observe in the handspeciemment scale. According to Patric and Donald (1985), the environmental interpretation based on grain size analysis in the sedimentary deposit has been a fundamental goal to sedimentologists. According to [Henery Clifton Sorby \(1849\)](#), Facies analysis of Sandstone is used to study the specified characteristics of the rock unit that implicates under what condition it was formed in the past. This facies study in sedimentology includes interpretation from the rock textures, color, sedimentary structure, fossil content, and the lithological continuity of vertical and lateral relationships that gives clue under which conditions the rocks deposits. By combining the observed facies character on different lithofacies type identified to give us a huge clue for what the paleoenvironment looks like during the time of the rock deposition. The main objective of the study is to reconstruct the Palo environment in terms of the depositional environment of the sandstone in the study area by using sedimentological and petrographic analysis in addition to the field investigation.

1.1 GENERAL DESCRIPTION OF THE STUDY AREA

1.1.1 LOCATION

The study area is part of the Blue Nile sedimentary basin in the central NW part of Ethiopia near Yejube town along the Chemoga river canyon. The study area geographically it's bounded between 112150 m and 1132000 m N latitude and 352500 m and 358500 m E longitude (Fig 1.1). The approximate area coverage of the study area is around 36 squares Km. The average elevation of the area reaches up to 1625 m a.s.l. The study is undertaken on one locally selected stratigraphic section which is located in Gozamen woreda of East Gojam zone.

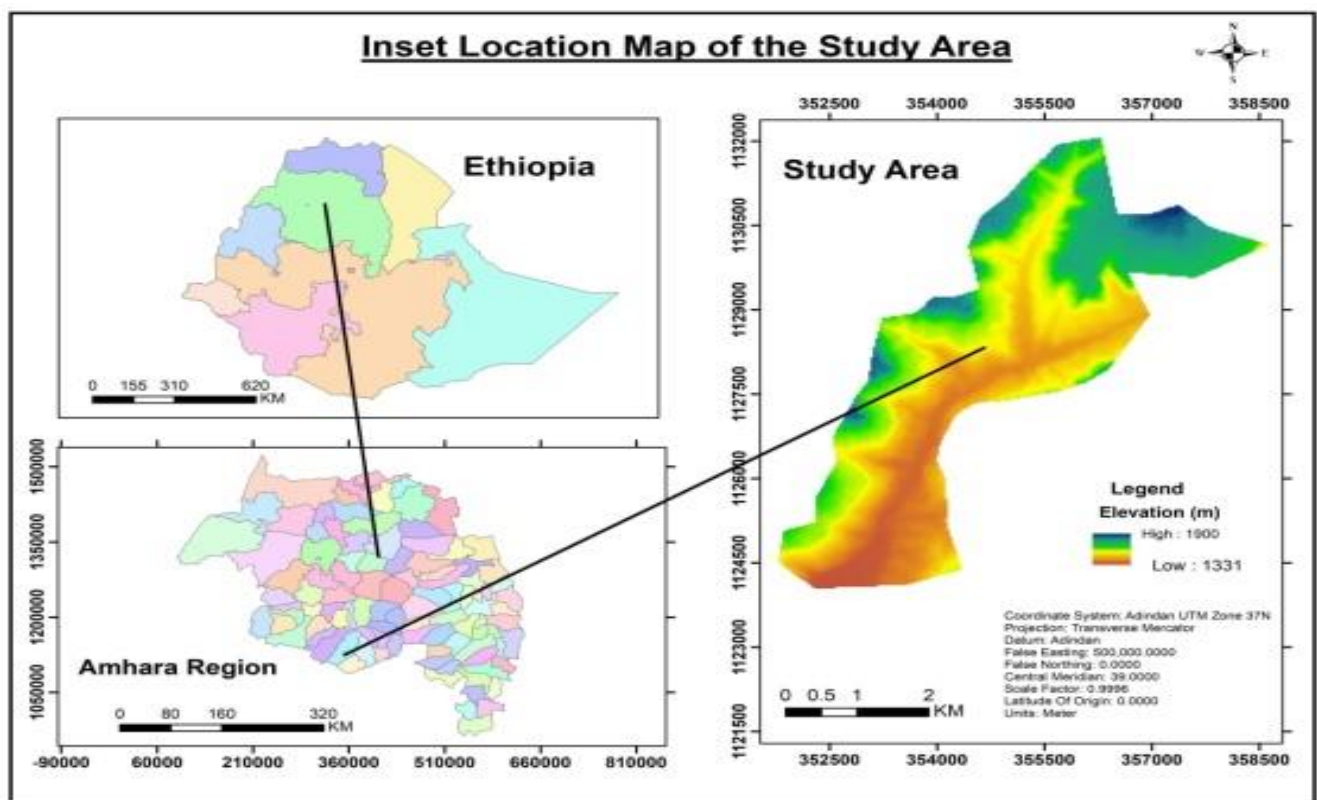


Figure 1.1 Location map of the study area

1.1.2 ACCESSIBILITY

The study area is accessed by a 16 km well-aligned gravel road that branched to the south direction from the main asphalt road that runs from Addis Ababa to Debremarkose city. There is also a good network of footpaths that connect the specific area of interest to the town of yejube and the nearby small villages.

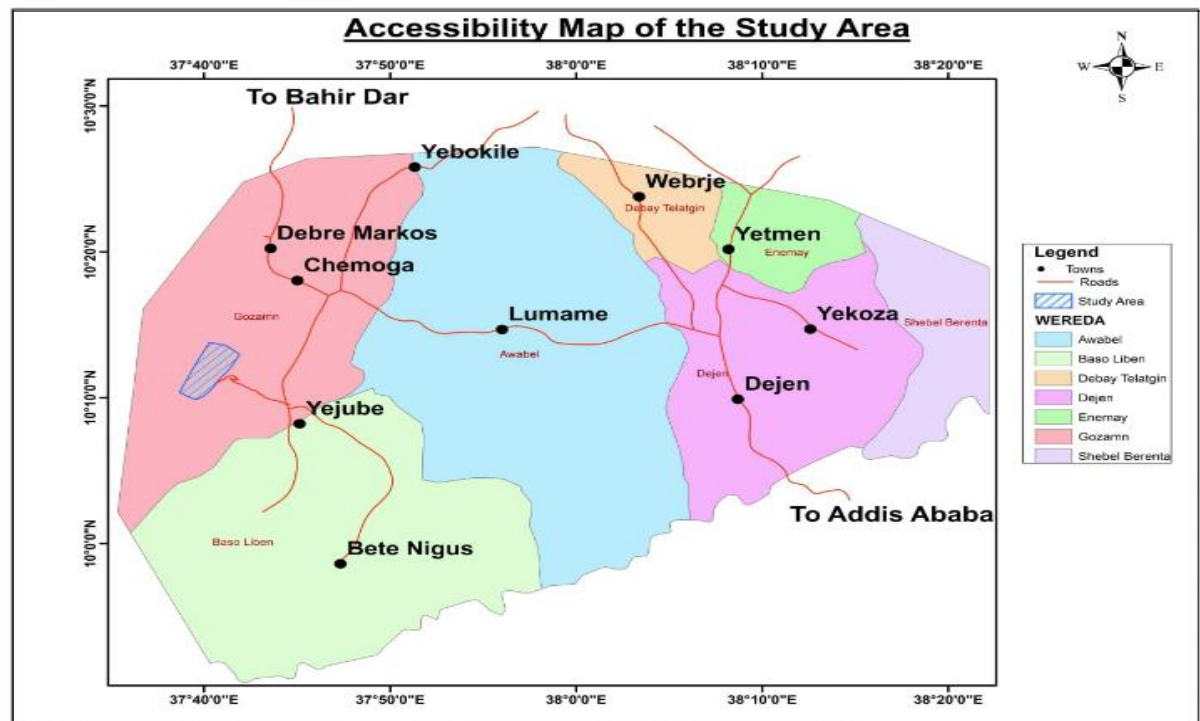


Figure 1. 2 Accessibility map of the study area

1.1.3 PHYSIOGRAPHY AND DRAINAGE PATTERN

The study area is located in Gozamin woreda of the zonal administration of the east Gojam zone. The area contains varied topography ranging from flat land that is used for Agricultural activity to river gorge valley. The flat surface of the area is covered by a Quaternary volcanic deposit at the edge of the gorge of the Chemoaga River and its tributaries. The Chemoaga River is the main river found in the area which is the tributary of the Abay(Blue Nile) River. The Yada and Sens small rivers are also downriver order of the Chemoaga River.

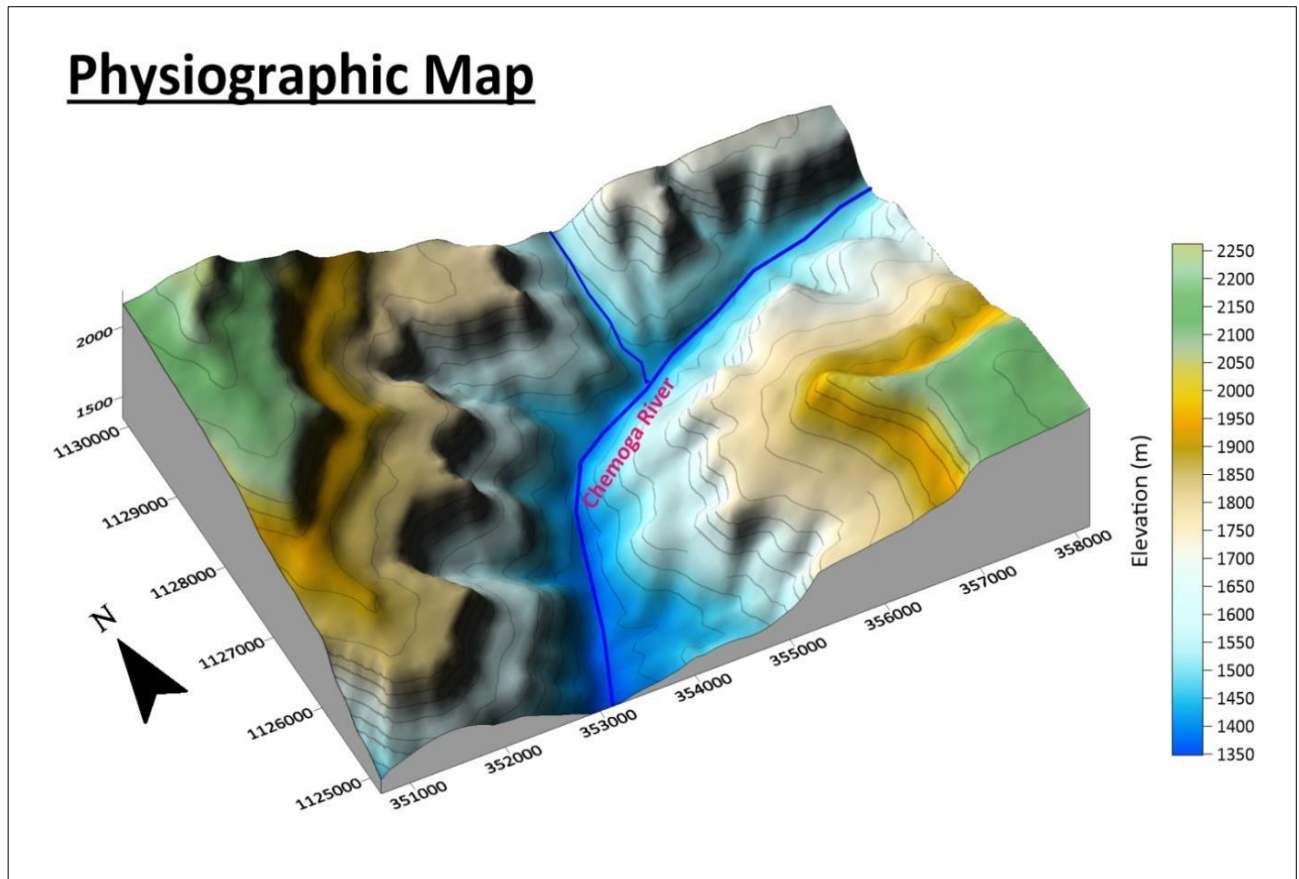


Figure 1. 3 Physiographic maps of the study area

1.1.4 CLIMATE

The nearby climate station to the study area is in Deberemarkose, which is the main city of the east Gojam zone which is approximately 16 km far from the study area. According to [climate-data.org](https://en.climate-data.org) the climate of the area is classified as warm and temperate. In winter, there is much less rainfall in the area than in summer. The temperature is highest on average in March at around 17.9 °C. July has the lowest average temperature of the year. The average annual temperature is 15.9 °C and the annual precipitation fall is about 132/mm/52.0 inch.

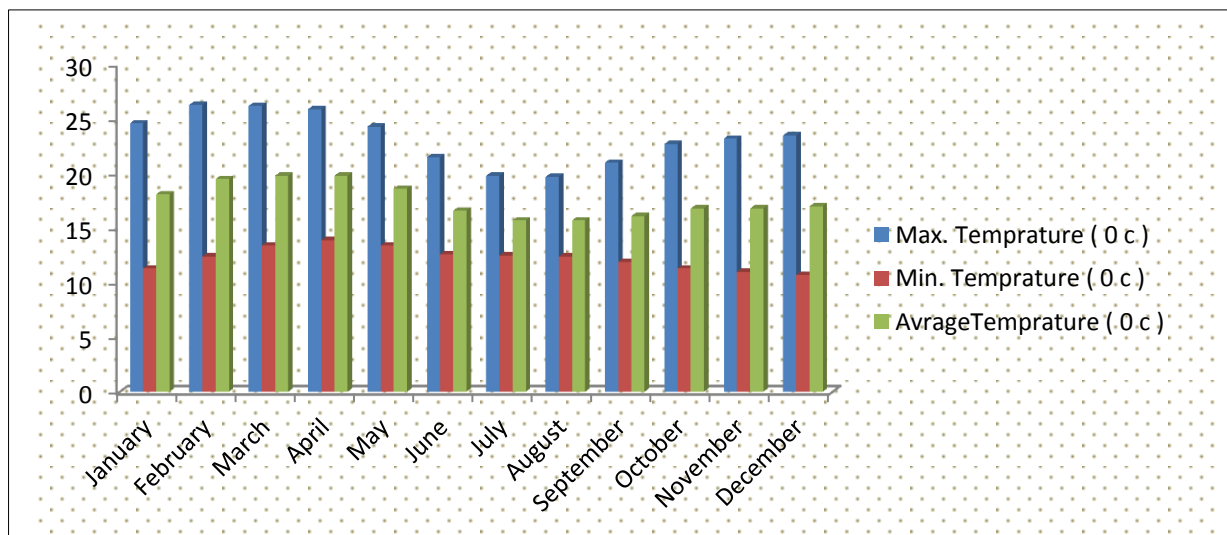


Figure 1. 4 A bar chart shows the climatic condition of DebreMarkose area, Source from climate Data.org in <https://en.climate-data.org/location/762997/>

1.1.5. POPULATION AND SETTELEMENT

In the study area, the largest ethnic group is the Amhara and the majority of the inhabitants practiced Ethiopian Orthodox Christianity while there is also a small proportion of Muslims found. Since most people live in remote areas and the flat topography of the area makes farming the main economic backbone for the society including the breeding of all domestic animals.

1.2 PROBLEM STATEMENT

Sandstones contain many kinds of sedimentary textures and structures that have potential in environmental interpretation (Boggs, 2009). To explore such important information's detailed study of units by using different methods is needed. Among this petrographic and sedimentological study of sandstone archives is one of the many keys to deciphering geological history (Garzanti, 2019). The Adigrat sandstone in the north and central Ethiopia was studied by different scholars who have different fields of specialization. In the case of paleoenvironmental reconstruction of Adigrat sandstone, some contradictions arise by some scholars in their previously conducted research related to depositional environment. For instance, Wolela (2008) conduct a study on the Adigrat sandstone in the Blue Nile basin and interpret the depositional environment as a mixture of lacustrine, alluvial fan, and meandering river. However later Dawit(2010) carried on the depositional environment of Adigrat sandstone based on stratigraphical and palynological evidence from both Blue Nile and Mekele basin and interpreted the paleoenvironment of Adigrat sandstone formation as an estuarine and shallow marine. Most of the previous work focused more on a Regional Scale. In the Yejube section, the formation is well exposed and there is not much detailed local investigation that is supported by using sedimentological and petrographic analysis.

1.3 OBJECTIVE

1.3.1 GENERAL OBJECTIVE

The thesis is intended to provide an investigation on sedimentological and petrographic analysis to reconstruct the paleoenvironment in terms of the depositional environment of Adigrat SandStone.

1.3.2 SPECIFIC OBJECTIVE

The main specific objective of this research is as follows

- Defining sedimentary structures and describing the observed field features
- Producing a geological map with its cross-section of the study area
- To construct a representative stratigraphic log
- To describe Lithofacies type

1.4 REVIEW OF PREVIOUS WORK

In the middle of the nineteenth century, the study of sedimentary rocks of Ethiopia was started. The pioneering works include (Blanford, 1870, Aubry, 1886, Dainelli (1943), Mohr (1943), Kazmin1973), Mohr (1963), and Beauchamp (1977). The sedimentary succession within the Blue Nile basin was studied by different scholars at different times, among this Getaneh Assefa (1980,1981, 1991), Russo et al (1994), Wolela (1997), Worash (2002), Dawit and Bussert (2009) conducted their works related to the sedimentary units in the basin of Blue Nile. The Stratigraphic and Structural evolution of the sedimentary basin of Blue Nile were studied by Gani et al.,(2009).

Specific studies that target the Mesozoic Adigrat sandstone of the Blue Nile basin include Wolela (2008) sedimentation of the Triassic – Jurassic Adigrat sandstone formation of the basin in which he focused the reservoir potential concerning the exploration of oil and gas. According to the research conducted by Bosellini (1989) and Russo et al., (1994) the Adigrat sandstone was formed on continental fluvial to the deltaic environment. Later Wolela (2010) modifies its own work with a new finding of the depositional environment of Adigrat sandstone formation is a mixture of alluvial fan, meandering river, and lacustrine deposit. Dawit and Bussert (2009) conducted their study related to facies architecture and stratigraphy of Adigrat sandstone of Blue Nile basin and also in 2010 Dawit makes a study on Adigrat sandstone on both the Blue Nile and Mekelle basin is studied based on the stratigraphy facies and palynological studies concluded that three depositional systems (fluvial-estuarine, barrier-lagoon, and strand plain systems) are also identified within the Adigrat Sandstone succession in the Blue Nile basin. According to Worash (2002), the geochemistry and provenance of this unit are silicic to intermediate basement rocks. Based on the paleocurrent analysis on the Adigrat sandstone inferring that the provenance of driven from mainly in the SE direction flowing water (Mandefro, 2019).

1.5 METHODOLOGY AND MATERIAL

To achieve the objective of this research work different methods and materials are used. The studied section is exposed following the river cut exposure, in which the detailed field investigation, facies analysis, sample collection, lithologic mapping, and the stratigraphic section logging were done. In the field studies of yejube section, both samples of consolidated sandstone sample for petrographic analysis and unconsolidated sample for grain size analysis are collected. Generally, we can categorize the phase of the entire work into three parts. This includes the first phase of pre-field, the actual fieldwork, and the post-field

activities. In the pre-field phase of the thesis work, the pro founding activity includes literature review, setting objectives, identifying the problem of a statement, preparing and identifying the methods used to implement, and the general logistical preparation for the fieldwork were conducted.

1.5.1 FIELDWORK

This is the second phase of the project following pre-field activity and it is carried on the February /2021 G.C. The fieldwork is conducted on the section near the town of Yejube area along the river gorge of Chemoga. By selecting the section with good exposure and suitable to see the vertical and lateral succession that have a well accessible footpath to the specific field activity conducted area. The fieldwork was accompanied by the collection of both consolidated sandstone and unconsolidated highly friable sediment sample from the section. Fifty consolidated samples were collected for petrographic analysis and twelve unconsolidated sediment samples were collected for grain size analysis. During the field, sedimentological data collected in addition to sample collection that includes a textural, lithological, and sedimentary structure within the sandstone unit were recorded. Based on textural and compositional data the stratigraphic log of the section is done. The geology of the area is mapped at the scale of 1:30,000. The photographic images of all important features and structures during the field are captured by a high-quality photo camera. During the field terrain, different materials were used these include a geological hammer, GPS, Brunton compass, sample bags, plastic sample bag, field notebook, pencils, and hand lens.

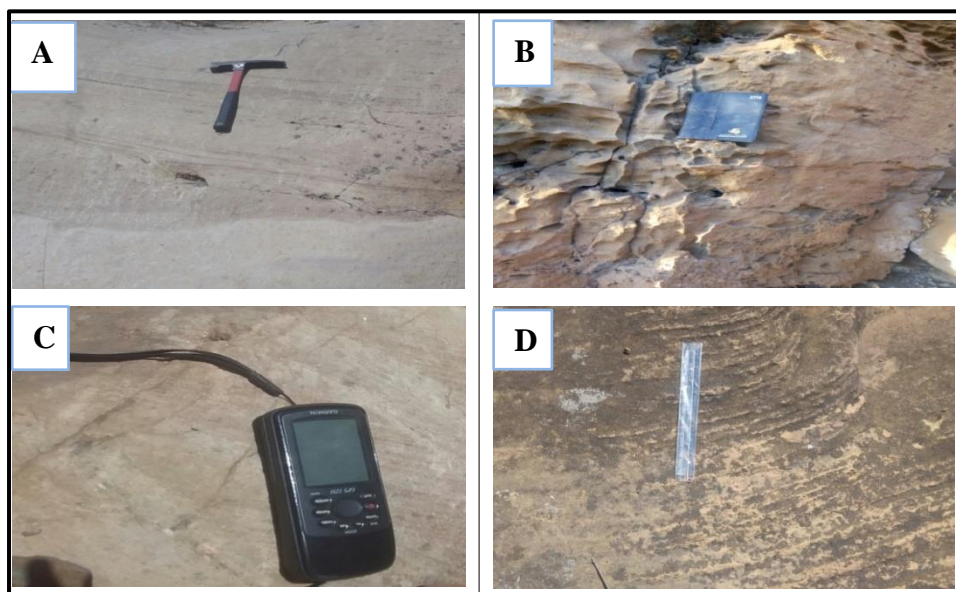


Figure 1. 5 Some of the Materials used during the fieldwork A, Geological hammer B, Field notebook C, GPS D, Ruler

1.5.2 LABORATORY WORK

Geological works need to confirm and analyze the data obtained from the field further by laboratory analysis. The sample collected from the field is placed in the laboratory for the petrographic and grain size analysis. The consolidated rock samples of thin sections were analyzed by using a petrographic microscope and the friable unconsolidated sediment samples were analyzed their grain size distribution by using the standard technique of sieve.

1.5.2.1 PETROGRAPHIC ANALYSIS

The petrographic analysis is one of the laboratory methods used in this study. Thus, Petrographic analysis is a method used to study the rocks in thin sections with the help of a petrographic microscope. The rocks require processing before they can be used for analysis. The rock sample has to be thin enough for light to pass through it in a light microscope. At first, the rock is cut at a suitable size slab to form a piece of rock with a diamond saw then the slab is labeled on one side and the other side is lapped flat and smooth. After drying on a hot plate a glass slide is glued to the lapped face of the slab with epoxy, following by using a thin section saw the slab is cut off close to the slide and the thickness is further reduced on a thin section grinder. A finished thickness of 30 microns is achieved by lapping the section by hand on a glass plate with 600 grit carborundum.

Petrographic analysis of the thin section of the sandstone is used to make detail textural and compositional analysis in which the rock is composed that supports the data gained from the field observation. During this analysis both compositional and textural property of the sandstone is investigated with the help of petrographic analysis. By using a technique known as point counting the proportion of major rock-forming framework grain is counted and plotted on a QFL diagram.



Figure 1. 6 Laboratory Equipment's used in the preparation of the thin section of the rock, A, grinding machine B, Cutting slab C, petrographic Microscope D, petrographic light source E, hot plate

1.5.2.2 GRAIN SIZE ANALYSIS

Grain size or particle size is the diameter of individual grains of sediment or the lithified particles in clastic rocks. It is a fundamental tool for classifying unconsolidated material, sediment, and sedimentary rock which has a significant role in interpreting the sedimentary environment. The analysis provides an important clue for the transport and depositional condition of sediment (Folk and Ward, 1957). Quantitative analysis of the percentage of different particulate sizes yields one of the most fundamental physical properties of clastic sediment and sedimentary rocks. Sieve analysis is one of the laboratory technics of grain size analysis in which particles will move vertically through different mesh that has different sieve openings. During these sieve analyses, different standard sieve mesh is used with sieve opening of 2 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.16 mm, 0.063 mm, and 0.053 mm are used. Other important materials in this analysis include the oven, porcelain dish, and spatula, clock, cleaning brush, receiving pan, and hand lens has been used. The procedure of preparation includes cleaning, recording the weight of each sieve and the receiving pan then arranging the sieves in ascending order of the sieve numbers, following that sample is placed in an oven for a day. When it is ready to be sieved, by weighing 200mg of the sample we put it on the top of the sieve stacking pattern and allow the mechanical shaker to work up to ten minutes. Finally by removing the sieve stack from the shaker and the weight of retained sample in each class of sieve is recorded and data is ready for further sedimentological statistical description.

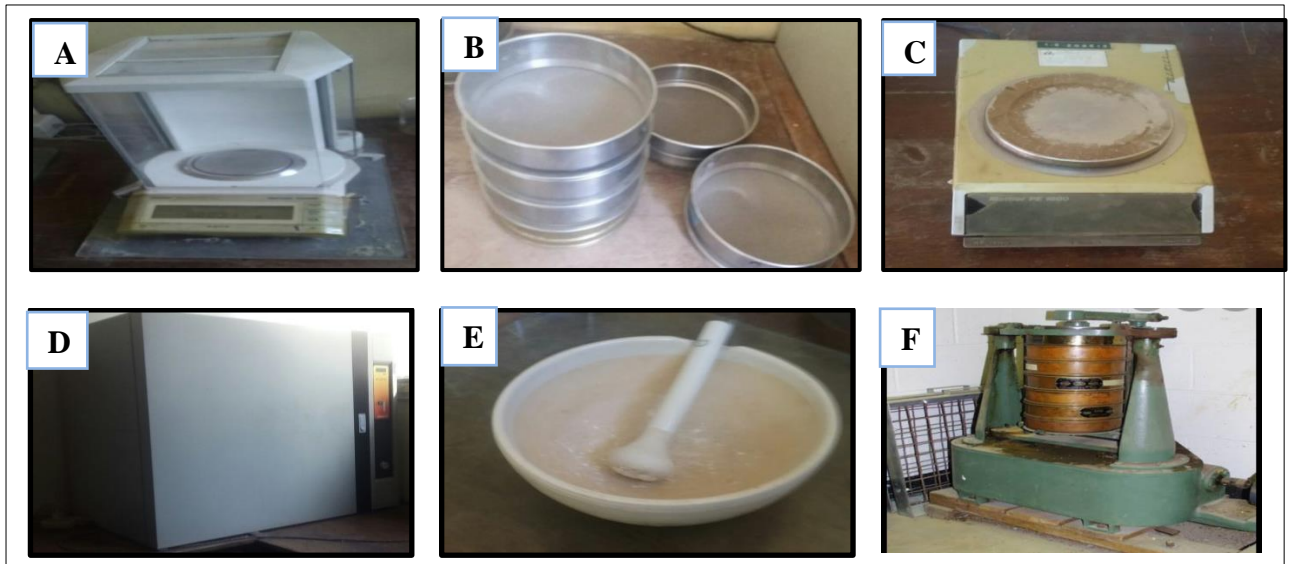


Figure 1. 7 Laboratory materials used in the grain size analysis A, weighting tool B, Sieve mesh C, weighing tool D, Oven E, Grinding tool F, Mechanical shaker

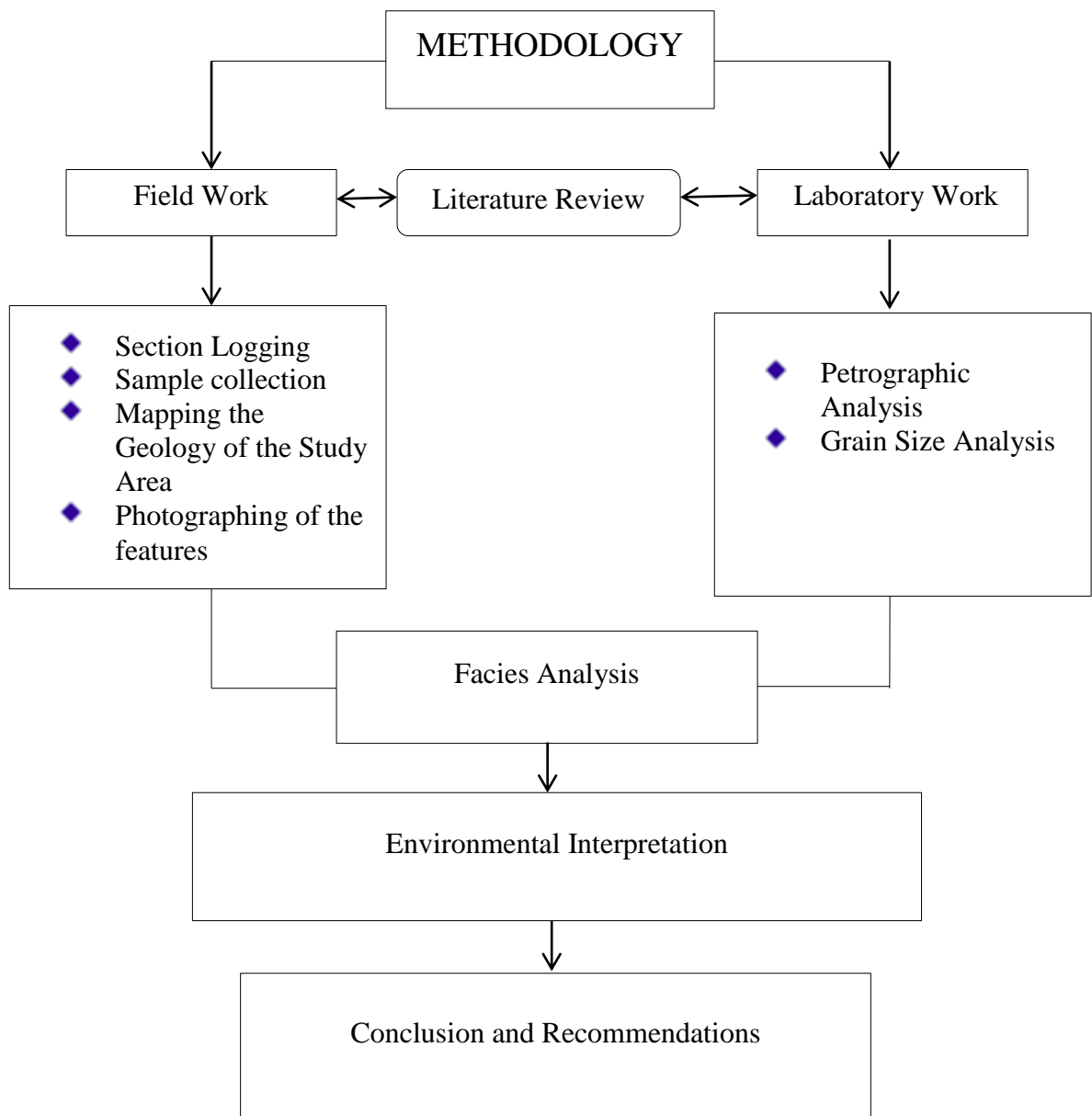


Figure 1. 8 Flowchart of the generalized methods used in the study

1.6 SIGNIFICANCE OF THE RESEARCH

This research is conducted to try to implicate what the Paleoenvironments were during the time of sediment deposition. This work also has a great significance in introducing of one of the neglected thick siliclastic section of yejube and the importance of sedimentological studies in environmental interpretation. Even if there was previously researched by different scholars at different times there raised controversies between their work and this work tries to fill the gap that differences and try to value add to the general understanding about the sedimentary basin on which it's located. This work may used as a tool for further studies for the related investigations made in the future.

1.7 LIMITATION

The Adigrat sandstone unit is exposed with a very large continuity and vast coverage in the Blue Nile basin and other sedimentary basins found in Ethiopia. Paleoenvironmental reconstruction is to make a generalized picture of what the environment was in the past, especially during the time of deposition, since the rock unit is exposed in a large coverage in the basin to interpret the paleoenvironment of deposition more data from different sections exposed in a different area is needed to be studied, unlikely this thesis only focused on the one stratigraphic section selected and also due to cliff-forming nature the formation it makes it difficult to traverse in some areas of the section especially on the upper part.

1.8 THESIS OUTLINE

The thesis is structured into seven chapters. The first chapter is about the general overview and justification of this thesis work. Chapter two gives the general highlight of the literature review on the regional geology of the basin in which the study is conducted. Chapter Three deals with the geology of the study area containing geological mapping and section logging. Chapter four deals with the laboratory analyzed result and interpretation of petrographic and grain size analysis. Chapter five dealing with the facies analysis and in chapter six of the thesis discussion and interpretation of the entire work in addition to correlation to previous work is discussed. The last chapter of this work is about making a conclusion and recommendation which is under chapter seven.

CHAPTER – TWO

2, REGIONAL GEOLOGICAL SETTING

2.1 INTRODUCTION TO GEOLOGY OF ETHIOPIA

The Ethiopian region records about billion years of geological history (Abbate et al., 2015). It includes rocks of the Neoproterozoic East African orogeny, Jurassic marine and continental siliciclastic sediment, and rift-related volcanism. The assembly and break up of Gondwana and rifting of the continents greatly shaped the geology of east African geology in which Ethiopia is included (Kazimin, 1973).

The Precambrian basement rocks are the oldest rock upon which all the younger formations were deposited (Mogessie et al., 2002). Different researchers investigate the basement rocks of Ethiopia Ayalew (1988), Alene(1991), Kazimin, et al., (1978) in which the basement rock contains a wide variety of sedimentary, volcanic, and intrusive rocks that have been metamorphosed to varying degrees. They are exposed in areas where the younger cover rocks have been eroded. This basement constitutes the crustal backbone of Ethiopia, which is exposed in southern and western Ethiopia also with less extent of northern Ethiopia (Abbate et al., 2015). According to Kazmin (1973), the basement rocks age over 600 million years. In southern Ethiopia, the East African orogeny constitutes the Mozambique belt, and in the northern part of the country, it's the Arabian Nubian shield. According to kazimin (1971, 1975), the Precambrian basement rocks of Ethiopia are classified into three forms from the oldest to the youngest the lower complex, the middle complex, and the upper complex (Tefera et al., 1996).

Basement rocks during parts of the upper Paleozoic were peneplain in most parts of Ethiopia. There was a long period of erosion at the end of Precambrian time due to the uplift that leads huge sediment deposition during the Paleozoic time interval. Early Jurassic marine sediment covers much of the older sediment including a planation surface of the Triassic age. According to Getaneh (1991), sedimentary history of the horn of Africa began between late carboniferous to Ordovician and Early Triassic time due to the development of NE and NW trending graben by continental sediment. Nowadays a large part of these Mesozoic sediments is exposed in the eastern Ogaden, the central part in the Blue Nile river basin, and the northern in Tigray of the Mekelle basin.

According to [Abbate and Sagri \(1980\)](#), the volcanic rocks of Ethiopia based on their lithological development subdivided into five major provinces. These are volcanic of northern plateau, volcanoes of the southern plateau volcanic of the Somali plateau, Afar volcanic, and the main Ethiopian rift volcanite. The source of volcanism during the Tertiary was the Rift valley and the Afar depressions ([Kazmin, 1975](#)). In the Early Miocene, the volcanism resulted from the east African rift development covers the Mesozoic sedimentary succession of Ethiopia ([Serawit et al., 1999](#)).

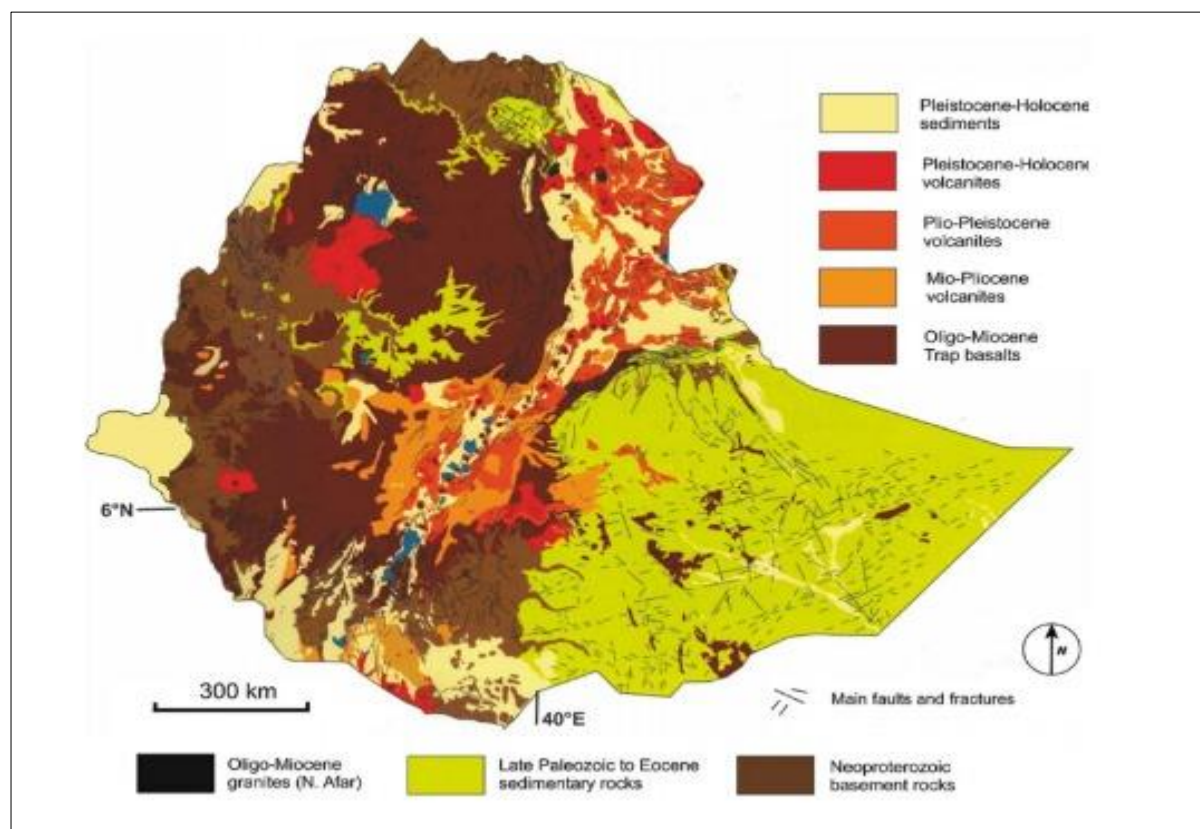


Figure 2. 1 Regional geologic map of Ethiopia adopted from [Tefera et al., \(1996\)](#)

2.2 THE BLUE NILE SEDIMENTARY BASIN

In Ethiopia, Sedimentary Rocks cover one third percent portion of the areal coverage and comprise five sedimentary Basins ([Beyth, 1972](#)). These are Blue Nile Basin, Ogaden Basin, Mekele Basin, Gambela Basin, and South Rift Basin. Along the western margin of the northwestern Ethiopian plateau in the gorges of Blue Nile River and its tributaries up to 2000 m section of Mesozoic strata capped by tertiary volcanic which is called the Blue Nile basin ([Mogessie et al., 2002](#)). This Blue Nile basin is part of the failed arms of the rift system of the karoo system ([Hunegnaw et al., 1998](#)), which covers a large area that it covers a total area of 120,000 square Km ([wolela, 2008](#)). This sedimentary basin contains a thick Paleozoic and Mesozoic sedimentary succession that reaches up to a thickness of 2600 m ([Dawit, 2010](#)).

The Ethiopian rift valley separates the northwestern and southeastern plateaus of the country. According to [Gani et al ., \(2008\)](#) the Blue Nile basin located in the northwestern plateau of Ethiopia bounded by the tectonic escarpment on the east and southeast, to the west by the main Ethiopian rift, in the north by Axum – Adigrat lineament, also the Ambo lineament bounded to the south. According to [wolela \(2009\)](#), the Blue Nile basin is coeval to Ogaden and Mekele outlier consists of karoo sediment, evaporates, and Jurassic carbonates.

The Blue Nile sedimentary basin is previously studied by different scholars at different times. Among the studies includes [Krenkel \(1926\)](#) described limestone, gypsum, and shale unit of the Blue Nile, [Mohr \(1962\)](#) described the regional geology of Ethiopia, [Kazmin \(1973, 1975\)](#) explain the geological map of Ethiopia, [Canuti, and Radrizzani \(1975\)](#) described microfacies of the limestone in the Blue Nile Basin, [Assefa \(1979,1980,1981,1991\)](#) established lithostratigraphic units of the Blue Nile Basin, [Russo et al. \(1994\)](#) outlined the sedimentary evolution of the Abay River Basin, [Gani, and Abdelsalam \(2006\)](#) Produced geological map of Dejen–Gohatsion region of the Gorge of the Nile, [Serawit and Tamrat \(1995,1996\)](#) studies the geology of Jimma River, [Wolela \(1997,2002\)](#) investigate the source Rock potential of Blue Nile basin and [Dawit \(2010\)](#) works recently on Adigrat sandstone in the north and central Ethiopia: Stratigraphy, facies, depositional environments, and palynology. The Mesozoic sedimentary succession section of the Blue Nile sedimentary is overlain by the quaternary trap volcanic rock and underlain by the Neoproterozoic basement rock. The Blue Nile basin consists of Karoo sediments, Jurassic carbonate and evaporates cretaceous siliciclastic sediment, and volcanic rocks ([wolela, 2009](#)).

2.3 LITHOLOGICAL UNIT IN THE BLUE NILE BASIN

According to [Getaneh \(1991\)](#), the stratigraphic lithology of the basin is informally classified into five distinct formations. These include from the bottom to the top as the lower sandstone unit (Adigrat sandstone), the shale gypsum unit (Gohatsion formation), the Limestone unit (Antalo limestone), shaly sandstone unit (Muger mudstone), and upper sandstone (Debrelibanos sandstone). [Dawit \(2010\)](#) recently modifies these by adding three formations in which he named Pre Adigrat I, Pre Adigrat II, and Pre Adigrat III. A brief overview of these lithological units is described below.

2.3.1 BASEMENT ROCK

In Ethiopia, the Precambrian basement contains a variety of sedimentary, volcanic, and intrusive rocks which were metamorphosed to varying degrees (kazmin, 1992; Getaneh, 1991). In the Blue Nile basin, this rock unit is overlain unconformably by Adigrat sandstones or by the Paleozoic sediment. The basement unit consists of metamorphosed quartz feldspathic schist and gneisses, migmatites, and plutonic rock. According to Ayalew et al.,(1990) the basement rock is considered to be Neoproterozoic and from geochronologic studies age ranging from 850 to 550 Ma. According to Kazmin (1975), this unit in this basin consists of rocks of basic to acidic Precambrian rocks that forms the base of the Blue Nile basin and crop out within rugged topography at 900 – 1500 m altitude along the entire NW – Flowing segment of the Blue Nile. According to Asfaowssen Asrat et al., (2001) the high-grade and low-grade metamorphic rock assemblage is named as Algehe group and Tulu Dimtu group in the Blue Nile basin.

2.3.2 PALEOZOIC AND MESOZOIC SEDIMENTARY SUCCESSION

According to Getaneh (1999), the history of sedimentation of East Africa probably began between the late carboniferous – Ordovician and early Triassic time. The Blue Nile basin consists of horizontal to sub-horizontal succession up to 1400 m of a thickness of continental siliciclastics and marine carbonate rocks (Gani et al., 2009). The Mesozoic sediments of the Blue Nile basin are not exposed in all areas but it is outcropped in areas of deep valleys and the river canyon of Abay River and its tributaries. Due to the development of the East African rift system is associated with the volcanism of vast quantities of lava which masks the Mesozoic sedimentary strata (Serawit and Tamerat, 1999).

2.3.2.1 PRE-ADIGRAT SANDSTONE

Before the work of Dawit (2009) the pre-Adigrat sandstone was considered to be a single formation based on previous studies. Unlikely recently Dawit (2010) comes with new founding in which he classified the pre-Adigrat sandstone into pre-Adigrat I, Pre Adigrat II, and Pre Adigrat III from the bottom to the top respectively. According to Dawit (2010) work, the three subunits of pre-Adigrat are discussed below.

- ◆ **Pre- Adigrat I:** This unit reaches up to 50 m thickness and it is the oldest of others pre Adigrat and overlies the crystalline basement (Dawit, 2010). It is composed of poorly sorted, massive to cross-bedded medium to coarse-grained sandstone and conglomerates.

- ◆ **Pre – Adigrat II:** This formation overlain either the crystalline basement or the pre-Adigrat I. It reaches its maximum thickness up to 400m (Dawit, 2010).
- ◆ **Pre – Adigrat III:** This unit is composed of three cycles of stacked, multi-story sandstone (Dawit2010). The sandstone unit is composed of unstable minerals like feldspar and mica. According to Dawit (2010), the environment of deposition is interpreted to be alluvial and lacustrine to the deltaic environment and attains its maximum thickness of 350 m that is dominated by low angle cross-bedding and horizontal lamination (Dawit and Bussert, 2009).

2.3.2.2 ADIGRAT SANDSTONE (LOWER SANDSTONE)

Adigrat sandstone age is believed to be Triassic – Early Jurassic based on the evidence from biostratigraphic data and with supported fossil evidence of adjacent areas (Gani et al.,2009). In the Blue Nile basin the Adigrat sandstone is distributed to a large area and forms a vertical cliff in the sections of Dejen –Gohastion, Amuru –Jarty, Fincha, Gendebret – Jeldu,Fincha, Yejube and around Jemma river (wolela,1991). The Adigrat sandstone formation in the Blue Nile basin attains a thickness of 100m in the Jemma river section (Mohr,1962); 120m in the Arjo area (Gethaneh Assefa, 1987); 450m in the Dejen - Gohatsion section (Wolela Ahmed, 1994); 800m in Amuru - Jarty; 450m in Gindeberet - Jeldu (Tamrat and Tibebe,1997); and 150m in Ejere area (Serawit and Tamrat, 1994). This rock unit is overlying either the basement rock or the pre Adigrat and overlain by volcanic rocks in the Blue Nile basin of the NW flowing segment, but the SW flowing segment of the basin is overlain by the lower limestone unit (Gani et al., 2009). There exists a controversy between scholars about the formation of this sandstone unit. According to Danielli (1943) the Adigrat sandstone formed as a result of the marine transgression of the Indian ocean, however, some scholars define this unit as formed under a continental siliciclastic sediment environment (Russo et al., 1994; Bosellini, 2001). According to Worash (2002), the geochemistry and provenance of this unit are silicic to intermediate basement rocks. In the Blue Nile basin, the formations are mainly represented by texturally and compositionally sub mature to mature sandstone.

3.2.3 GOHATSION FORMATION

This type section identified in central Ethiopia near the town of Gohastion in which very well exposed named and identified by Getaneh (1998). Gohastion formation consists of lower limestone and gypsum unit. It has a thickness of 450 m and it is the early – middle Jurassic age according to the study by Getaneh (1981). The formation overlain conformably by Antalo limestone formation and underlain by lower sandstone unit (Getaneh , 1991).

Gohastion formation consists of lower bedded limestone and upper interval alternating limestone and gypsum bed, the limestone are grey in colour which is fossiliferous with burrows, and also the gypsum bed characterized by mottled texture. It is interbedded with glauconitic mudstone and a rare thin sandstone bed (Gani et al., 2009). Getaneh (1991) interpreted the depositional environment of this formation as super tidal for the gypsum, shale, and limestone and terrigenous clastic deposit as the deltaic environment.

2.3.2.4 ANTALO LIMESTONE

Antalo Limestone is believed to be deposited in the Callovian – early Oxfordian due to east Africa was exposed to the transgression that leads to up to 450 m thick. This formation in the Sedimentary basin of Blue Nile found between the early – Middle Jurassic lower sandstone unit and the Late Jurassic – Early cretaceous upper sandstone unit Nile (Bosellin 1989; Russo et al., 1994; wolela 1997). This carbonate formation can be subdivided into three-part (Greitzer, 1970). The bottom part contains coquinoid limestone, limestone intercalated with marl and mudstone. This lower part of the rock unit has a thickness of 180 m and also contains fossils like corals and stromatoporoid. The Middle parts contain Marl and limestone marl intercalation has 200 m thickness. The upper part contains limestone and thick laminated oolitic limestone up to 60 m thick and formed by sea transgression (Samuel, 2018). According to (Russo et al., 1994) its was deposited in a marine environment. Antalo Limestone in the Blue Nile basin is considered to be correlated with the Urandab formation of the Ogaden basin (Dawit, 2010).

2.3.2.5 MUGER MUDSTONE UNIT

The name Muger mudstone is named after the profound work of Getaneh (1991) who defines the type section. This unit is exposed along the river bed of sodoble in the west margin of the Blue Nile sedimentary basin. According to wolela (1993), the unit is also exposed in the Abay river canyon along the highway to Gojam. This unit stratigraphically overlays conformably the Antalo Limestone and is overlain by the Debre Libanos sandstone unit. According to Getaneh (1991), this rock unit is classified into two, namely the lower and upper parts of the unit. The lower part of the unit consisting of gypsum of both beds of nodular vein filling, shale and dolomite assigned to be lagonal and supper tidal environment that reaches up to 15m thickness (Getaneh, 1991). The other part known as being upper part consists of mudstone and sand–silt interbedded which reaches 240m thickness in which part of the unit represents a Meandering river system (Getaneh, 1991). The age of mugger

mudstone is assumed as in the interval of post-Kimmeridgian to pre-Middle Eocene (Getaneh, 1991).

2.3.2.6 DEBRE LIBANOS SANDSTONE

This unit was named after the discovery of the type section by Getaneh (1991) near the area of Debre Libanos town (Dawit, 2010). According to Getaneh(1991), the age of this unit was determined to be late Jurassic to early cretaceous based on the relationship of the unit which is underlying and it is overlying. Debrelibanos sandstone unconformably overlies the upper limestone unit (Gani,2009). The unit is unfossiliferous, yellowish to white colored, fine to medium-grained massive at the near contact with the underlying limestone unit (Serawit and Tamrat,1990). The sandstone unit has a variable thickness with 280 m maximum thickness near the Lemi area (Getaneh,1991; as cited in Barsisa,2011). It is dominated by planar, tabular, and asymmetrical through cross-beds sedimentary structures (Getaneh, 1991). The depositional environment of this unit is interpreted to be continental alluvial to fluvial (Gani et al.,2009). The unit is regionally correlated to the Amba Aradom sandstone of the Mekele basin (Dawit, 2010).

2.3.3 THE TERTIARY VOLCANIC

This Volcanic rock unit is conformably overlaid with either Debra Lebanose sandstone, the Antalo limestone and the Adigrat sandstone.. The age of this formation is believed to be post-Oligocene and attain over 5500 m in thickness (Getaneh, 1991; as cited in Serawit and Tamerat,1999). According to Getaneh (1991), this unit consists of trachyte, rhyolite, basalt, paleosoil, and lacustrine sediment.

2.4 BASIN EVOLUTION

The Blue Nile sedimentary basin which is located in the northwestern part of Ethiopia is a geologically interested area formed concerning the extension which is caused by Gondwana. According to Gani et al.,(2008) in the Paleozoic time the basement and uplifted Paleozoic rocks were subjected for a substantial extension. In Triassic to Jurassic eastern Africa due to the breakup of Gondwana the NE-SW extension has printed its effect on the Blue Nile sedimentary basin as a series of NW trending rift basin.

According to the previous studies the stage and events of the evolution of the basin of Blue Nile are classified as below

Peneplain stage: This is the stage before the break up of Gondwanaland. According to (Russo et al.,1994) this stage is associated with pan – African metamorphic peneplain.

Intra continental rift stage: This is the stage after the breakup of the Gondwana. During the Jurassic, the disintegration of Gondwanaland into separate blocks was a result of the second phase of Karro rifting (Wolela, 2008). A sedimentary basin of Blue Nile and Ogaden with an orientation of N-S, NE-SW, and NW-SW is responsible due to the early stage of karoo rifting (Wolela,1997).

Post rifting: This is the stage consisting of early flooding and drowning of the craton in which the early flooding the deposition of the formation Adigrat sandstone(basal clastic sediments). Therma subsidence and rifting of east Africa was responsible for early flooding in which another stage was drowning of craton responsible to the Africa continental margin of Callovian – Oxfordian transgression due to the evidence from Antalo limestone (Russo et al.,1994).

The Ethiopian rift valley separates the Blue Nile basin from that of the Ogaden basin. In the eastern flanks of the Blue Nile basin the NE-SW AND N-S trending systems of fault as a result of the Ethiopian rift exposure (Wolela, 2008).


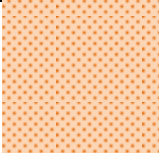

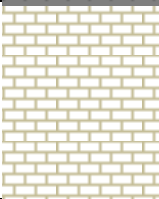

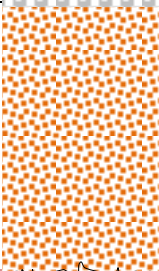

| Era | Period | Formation | Thick (m) | Lithology | Description |
|--------------|---------------------------------|--------------------------|----------------|--|---|
| Cenozoic | Tertiary | Trap Series | 0 - 2500 |  | Basalt bed with tuff rare agglomerates and rhyolite and quaternary alluvium covers the top part |
| Mesozoic | Cretaceous | Debre Libanose sandstone | 0 - 280 |  | Fine to coarse grained cross-bedded sandstone |
| | | Muger Mud Stone | 0 - 360 |  | Mainly mudstone with alternation of thinly bedded dolomite, siltstone, sandstone, and gypsum at the base. |
| | Upper Jurassic | Antalo Limestone | 0 - 1070 |  | Crystalline limestone with fossils marly limestone and shale beds. |
| | Middle Jurassic | Gohastion formation | 0 - 250 |  | Upper part alternation of shale, limestone, and gypsum with rare beds of dolomite and traces of paleosol. |
| | Late Triassic - Middle Jurassic | Adigrat sandstone | 0 - 850 |  | Mostly quartz-dominated, dense, moderately rounded fine to medium sandstone. |
| Pre Cambrian | | | |  | A complex of gneiss and granite. |

Figure 2. 2 General stratigraphies of the Blue Nile Basin (After wolela 2009).

CHAPTER THREE

LOCAL GEOLOGY

3.1 INTRODUCTION

Yejube section is found in eastern gojam of central northwestern Ethiopian plateau. In this section, a thick Mesozoic siliciclastic particularly of sandstone of late Triassic – middle Jurassic age was deposited. During the field to interpret the depositional environment of this sandstone formation detailed field investigation of the section based on lithological, compositional, textural, and sedimentary structures are investigated. The lithological unit found in the section described according to their stratigraphic succession as composite stratigraphy based on the vertical relationship observed during the fieldwork.

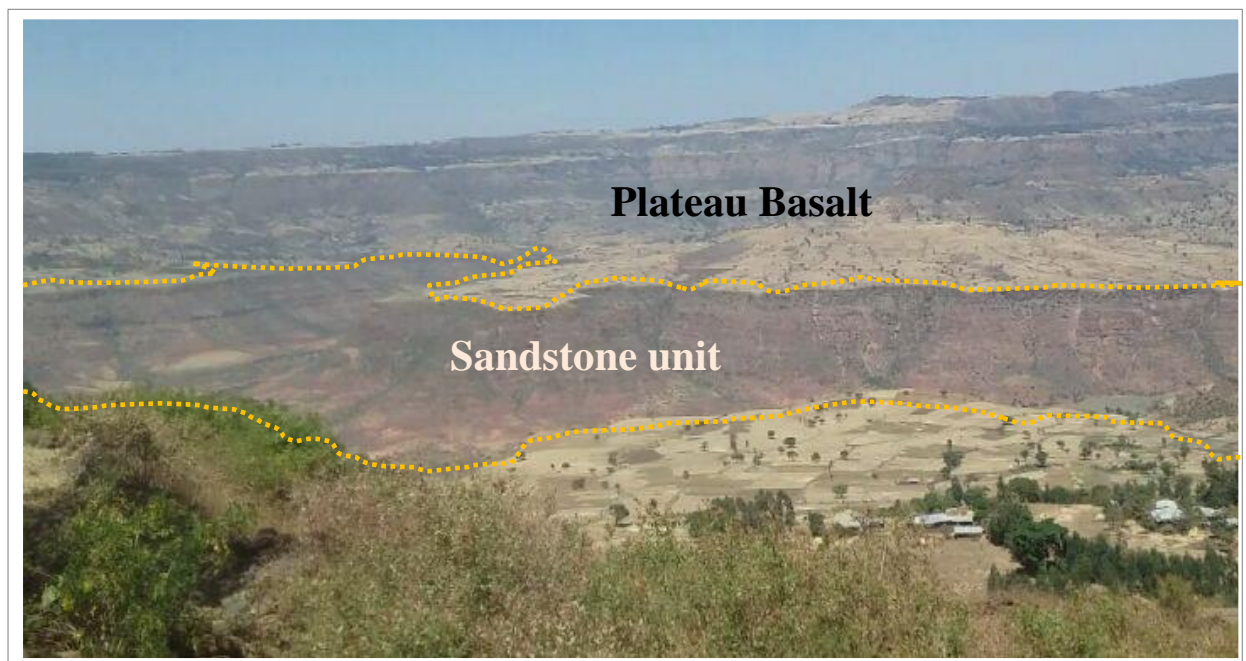


Figure 3. 1 photograph showing the topography of the study area

In the studied section, the sandstone unit exposed by the gorge formed following parallel to the flow of the river chemoga and its small tributary. Based on the field observation detailed local stratigraphy is studied. The thickness of the section containing the siliciclastic unit reaches a maximum thickness of 220 m.

The sandstone unit of this section ranges from fine to coarse-grained size, reddish to white in color and different facies change is observed vertically. The sequence of the sandstone unit consists of very fine-grained thinly bedded sandstone unit, fine-grained cross-bedded sandstone facies, horizontally bedded medium-grained sandstone, sandstone containing desiccation crack in the lower part of the section, slightly bioturbated medium to coarse-

grained sandstone facies, planner cross-bedded sandstone unit, unconsolidated muddy facies in the middle of the section and the upper part of the section a coarse-grained cross-bedded sandstone unit facies.

Generally, the geology of the studied area investigated during the field is described briefly supported by the geological map of the area including its cross-sectional view, the detailed lithological, textural, compositional property of the section including different lithofacies type of the formation is identified which helps in the interpretation of depositional system by grouping to associated facies assemblage.



Fig 3.2 Filed outcrop image showing thick Silsiclastiic sedimentary exposure in Yejube section

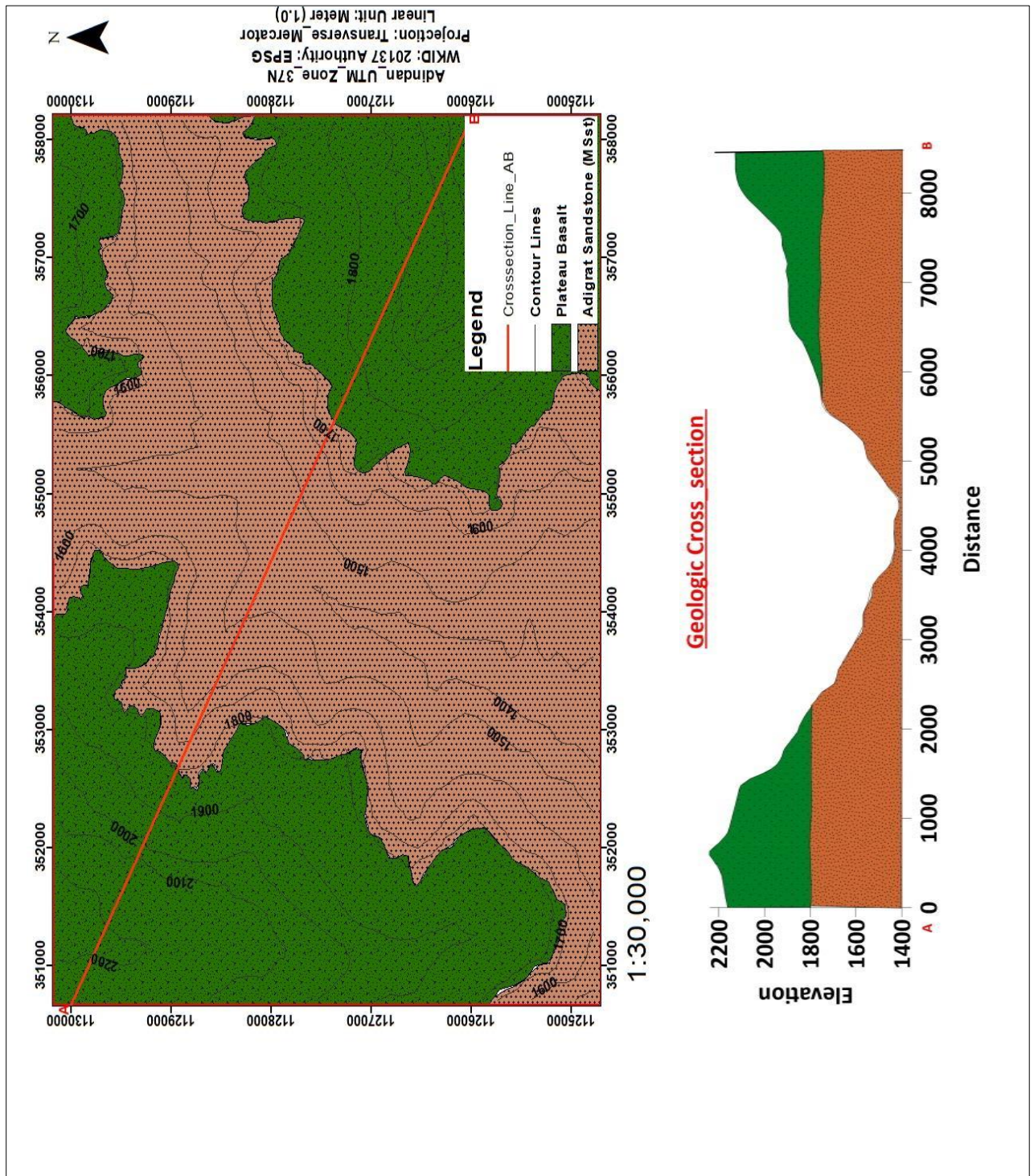


Figure 3. 3 Geological Map of the study area

3.2 LITHOSTRATIGRAPHY OF YEJUBE SECTION

The studied section is located 13 km west of town yejube. It is geographically bounded by 355540 Easting, 1120274 northings, and averagely at elevation of about 1625 m above sea level. The sandstone rock unit overlain by the volcanic deposit and river chemoga defines the base of the exposed section. This section is selected based on the accessibility and good exposure to observe sandstone unit succession. During the field, the section was logged, measured, and described based on their lithology, texture, composition, sedimentary structure, and the stratigraphic relationship. The siliciclastic sediment mainly of the sandstone unit in the yejube section is well exposed and generally characterized by both cliffs forming steeply sloped and gently exposed. The section reaches a thickness of 220 m and having different specific characters including their grain size, color, sedimentary structure within the unit. The studied section is subdivided into the lower part, middle part, and upper part of the subsection.

3.1.1 UPPER SECTION

This sub section has a thickness of 85 m that is overlain by the plateau quaternary deposit. when it is compared with the middle and lower part of the sub-section it is characterized by a cliff-forming appearance. Lithologically consists of medium to coarse-grained sandstone with the existence of mudstone in between. In this part of the section as shown in [figure 3.4](#) different sedimentary structures are observed. From this upper, most section different lithofacies types identified that have a significant role in environmental interpretation. These lithofacies types include horizontally bedded sandstone, Bioturbated sandstone, thinly bedded sandstone, mud crack developed sandstone and tool marked sandstone.

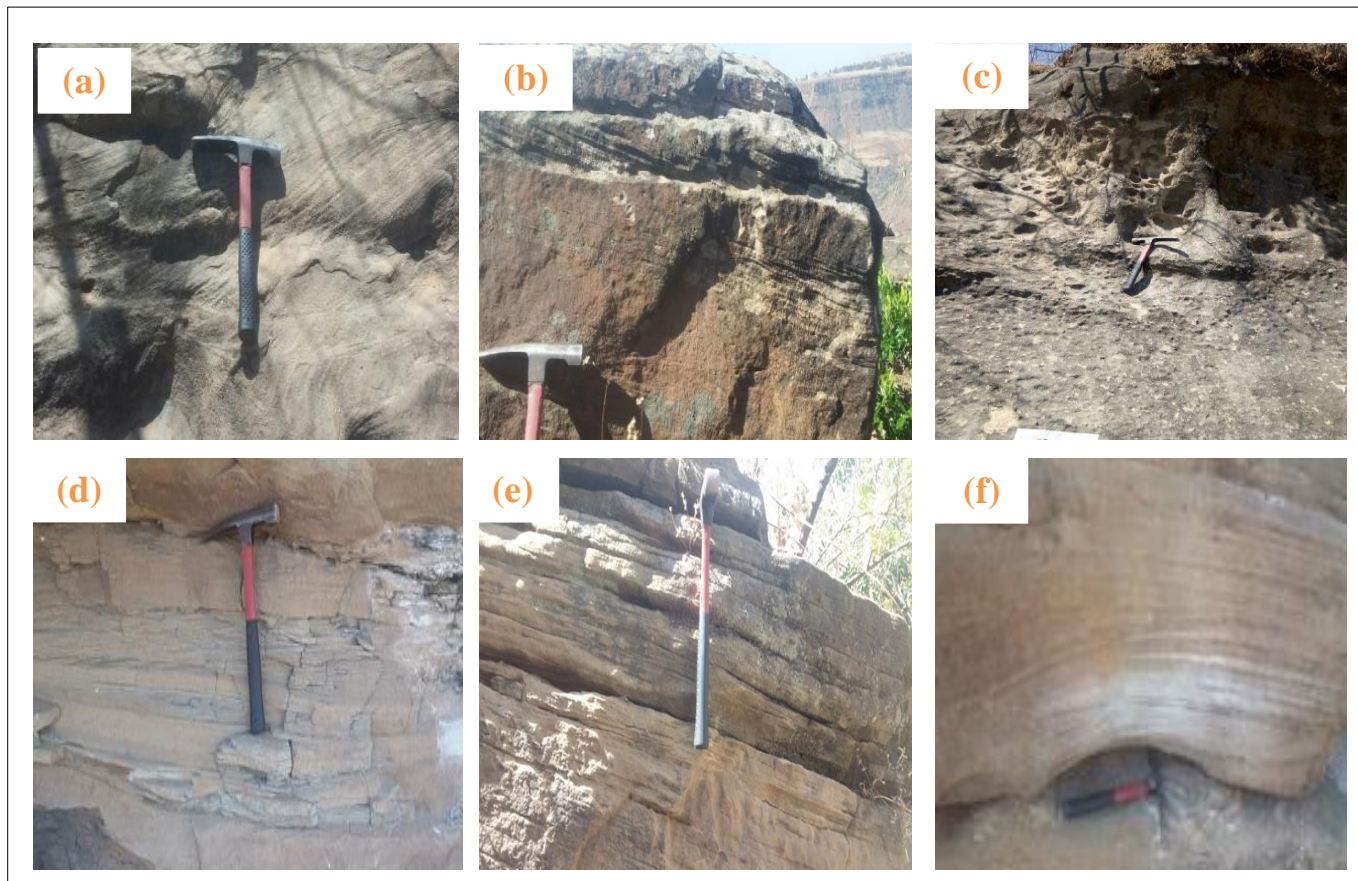


Figure 3.4 Field outcrop features on the upper part of the section showing A. Bidirectional trough cross-bedded sandstone (b) High angle planar – tabular cross-bedded sandstone (C), highly bioturbated sandstone D. thinly bedded sandstone (e) Horizontally bedded sandstone (f), hummocky cross-stratification sedimentary structure

3.1.2 MIDDLE SECTION

This sub section found on the middle part consists relatively gentle slope that reaches a thickness of 55 m. From this part of the section different sedimentary features and structures are observed as shown in [figure 3.5](#). From the identified lithofacies type Herringbone cross-stratification sandstone facies are observed in this sub section that gives a clue of tidal environmental deposition.



Figure 3.5 Field outcrop features on the middle part of the section showing A. Fine to medium-grained semi consolidated sand deposit B. Large-scale laminated inclined sandstone unit C. Light greenish mudstone overlain by sandstone horizontal laminated sandstone D .horizontal lamination sedimentary structure E, Herringbone cross-stratification

3.1.3 LOWER SECTION

This sub section is found at the near bottom of the studied section that has a total thickness of 80 m. This sub section consisting of fine to medium grained white to grey colored sandstone unit which contain sedimentary structure of sandstone with clast imbrication Planer cross-bedded sandstone , and Desiccation mud crack structure as showed in [figure 3.6](#) Different lithofacies type identified from the lower section that has a huge role in environmental implication. This lithofacies type includes Trough cross-laminated sandstone , Planar cross-bedded sandstone and mud crack developed sandstone.



Figure 3.6 Field out crop features on the lower part of the section indicating A. Medium grained sandstone with clast imbrication B, Desiccation mud crack structure C. cross-stratification on the sandstone D. Overbank deposit of sandstone with cross-laminated E, Planar cross-bedded sandstone, F, light-colored sandstone with massive structure

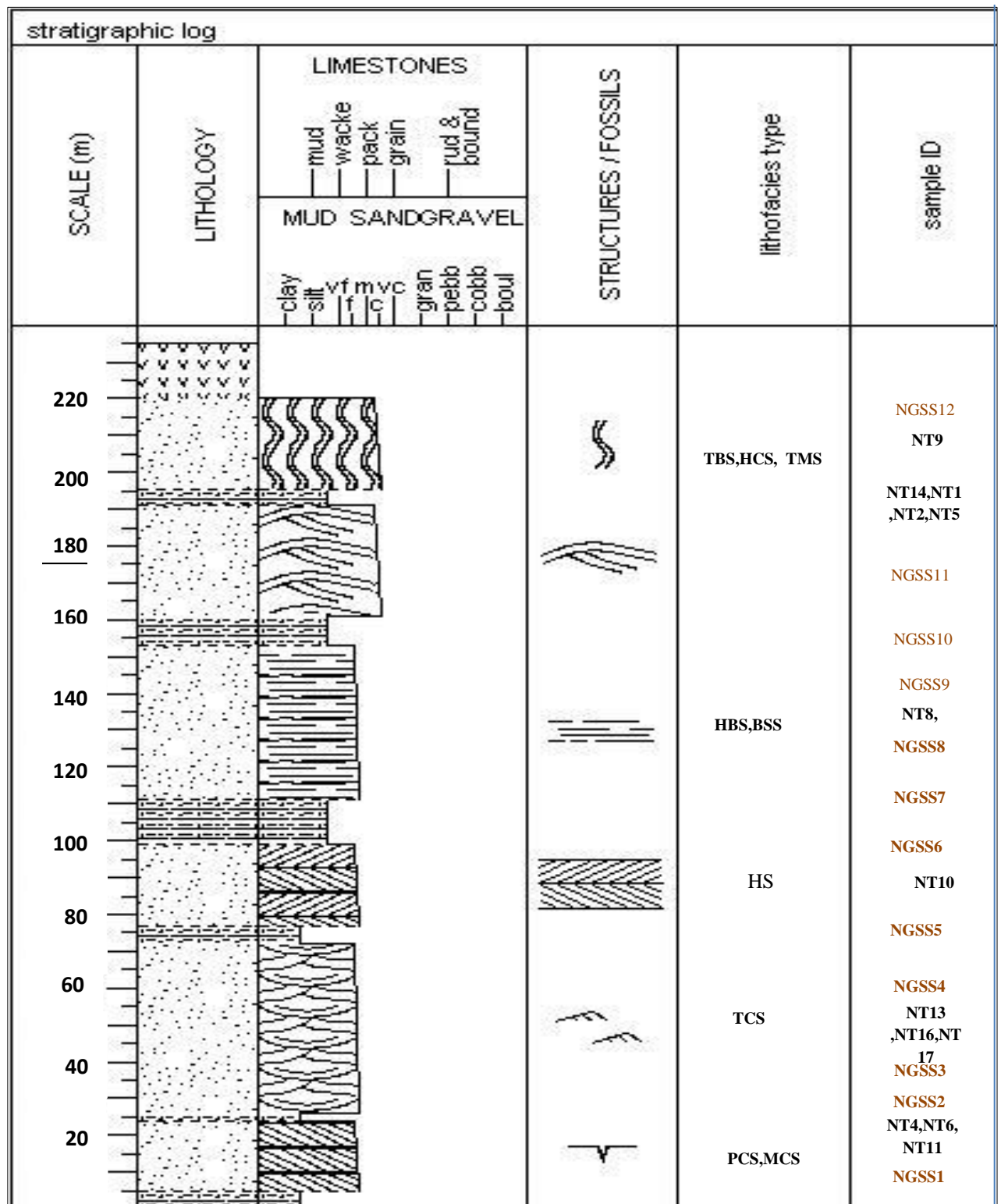


Figure 3.7 The stratigraphic log of Yejube section

Section Legend

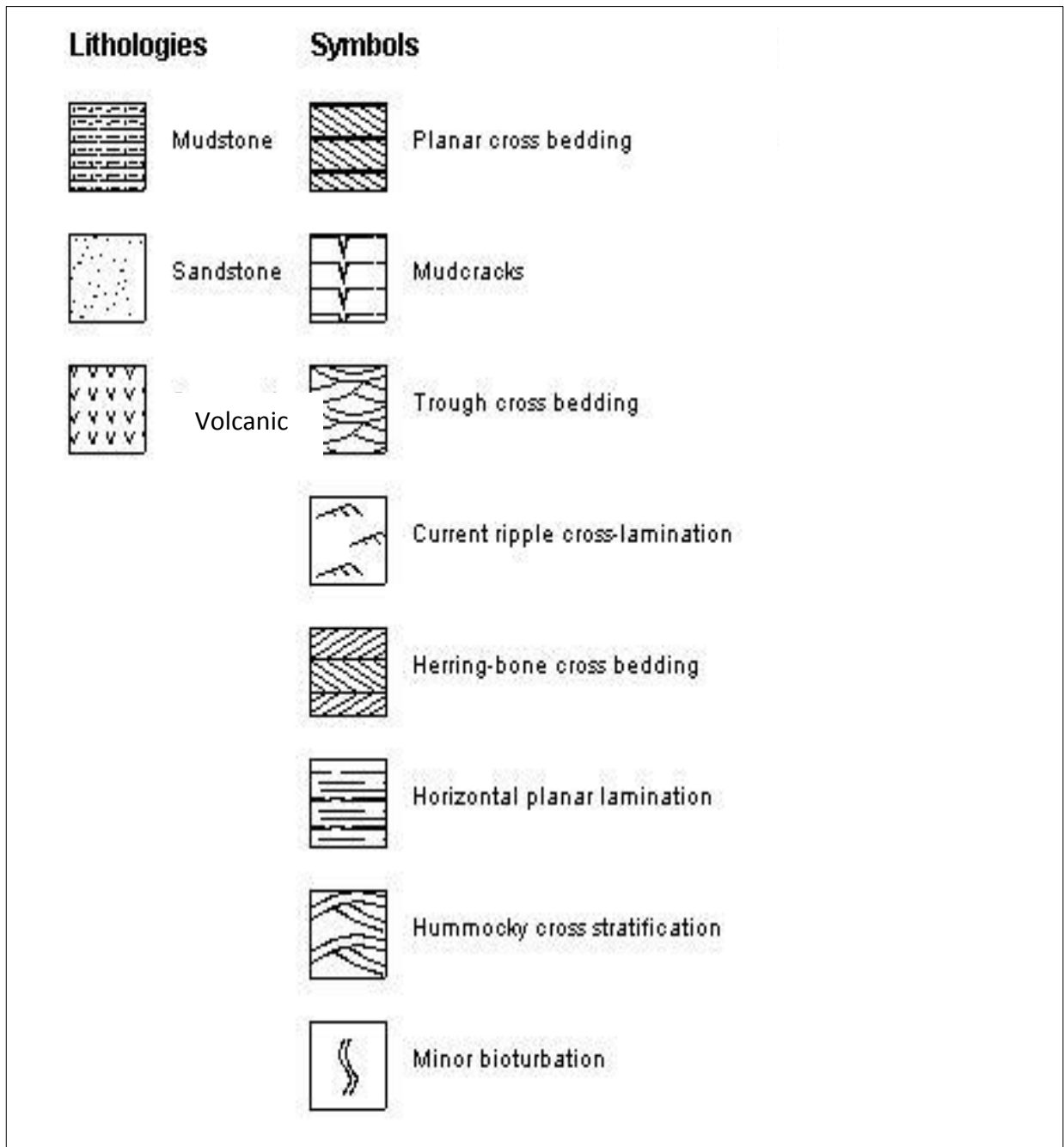


Figure 3. 8 Legends of the stratigraphic log of yejube section

CHAPTER FOUR

PETROGRAPHIC AND GRAIN SIZE ANALYSIS

4.1 PETROGRAPHY

In geological science petrographic analysis is conducted to support the data obtained from the field observation to see the detailed compositional and textural properties of rock samples. In this analysis, a total of 15 samples were analyzed by the petrographic microscope. During the thin section analysis, the composition of rock-forming minerals is identified, and by using a technique called point counting the modal proportion of the framework grain is calculated and plotted on a QFL diagram according to Folk (1980) and Pettijohn et al., (1987) classification scheme. In addition to the compositional study, the detailed textural and diagenetic features observed in the rock are discussed. The matrix and cementing minerals are fine-grained material that sticks the framework grain together including the materials which fill the pore space between grains identified respectively. There is also some amount of Accessory minerals including a sheet of mica (biotite and muscovite) flakes, a little number of opaque minerals observed in some thin section samples, and the diagenetic features are also discussed.

4.1.1 COMPOSITIONAL DESCRIPTION

In this analysis of thin section different kinds of detrital mineral composition of the sandstone were identified and these include that the framework grain in which the majority dominated by mineral quartz. Unlike quartz feldspar and lithic fragment covers small percent of framework mineralogy of the sandstone. In addition to the framework grains sheets of mica, heavy minerals and opaque minerals observed in the analysis as minor accessories. The space between the grains of sandstone is filled by a much fine muddy matrix mixed with very fine quartz, feldspar, and quartz. Cementing material observed under thin sections includes mineral calcite, silt-sized quartz, and red-colored iron oxide minerals.

4.1.1.1 QUARTZ

These minerals dominated the sandstone mineralogy in which the percentage estimation from point counting investigation indicating that quartz grain has an average of 90 % and above the framework grains in most of the analyzed samples. The grains of quartz consists of both monocrystalline and polycrystalline grains. When polycrystalline quartz grain compared with that of monocrystalline contains a small proportion. The majority of the quartz grain shows

extinction under the xpl. In the case of polycrystalline quartz grain, Undulose extinction is observed, which is an indication of deformation due to the stress Subjected. In some thin section samples, the quartz grain shows a vacuole, According to [Scholle \(1979\)](#) vacuole rich quartz is derived from a hydrothermal source.

4.1.1.2 FELDSPAR

Feldspar is one of the framework mineral grains in the analyzed sandstone samples. Relative to the quartz mineral grain the feldspar grain contains a very small proportion from the modal analysis result obtained from point counting. The feldspar grain shows an alteration due to weathering and polysynthetic twinning's in the case of plagioclase feldspar observed clearly in xpl . In some samples, a microcline feldspar grain possesses a cross-hatched twinning. Out of the feldspar group, potassium (k – feldspar) is observed dominantly than plagioclase feldspar because potassium has to weather resistance nature.

4.1.1.3 LITHIC FRAGMENTS

This is one of the framework grains in the sandstone which is a fragment of rock that is not broken down into a single mineral. From the petrographic analysis lithic fragment is the second dominant framework grain next to mineral quartz based on the modal analysis conducted. Lithic fragments of sedimentary, and metamorphic rocks observed in the studied samples..

4.1.1.4 MICA FLAKS

Mica sheets are other minerals identified from this analysis, in addition to that of the framework grains. Both muscovite and biotite micas are observed in the analysis. Mica most of the time found along the weak zones like that of the lamina, parting, and bedding. During the analysis, the micas mineral shows a perfect cleavage under xpl and exhibits speckled extinction. Both biotite and muscovite show the pleochroism property in that biotite differentiated by its pleochroism property it exhibits brown to weak green color. The muscovite mineral is unaltered and dominating over the biotite in the analysis.

4.1.1.5 CEMENTING MATERIAL

These minerals are fine-grained and used in the process of porosity reduction process formed after the deposition of the rock. The mineral was seen in the thin section as cement includes calcites mineral, very fine silt-sized quartz, and the red hematite mineral.

4.1.1.6 MATRIX

It is fine-grained clay and silt-sized material in which the framework grained is embedded and sticks together. From the analysis, the matrix content is relatively lower. The are very fine-grained nature of the matrix makes it very difficult to study their compositions in detail from the petrographic analysis.

4.1.2 TEXTURAL DESCRIPTION

Textural description of sandstone is a function of grain shape, size, roundness, and sorting of each grain. The shape of most grain is dicoid – bladed, and the shapes of the framework grain particularly range from rounded to sub-rounded is also moderately sorted. The thin section sample analysis showed that the sandstone is texturally sub matured to mature. This is because the relative abundance of a matrix is very low compared with that of quartz minerals. As described in the hand specimen the size of the grains of the sandstone ranges from fine-grained up to coarse sand grain and the surface feature of most quartz minerals is highly fractured.

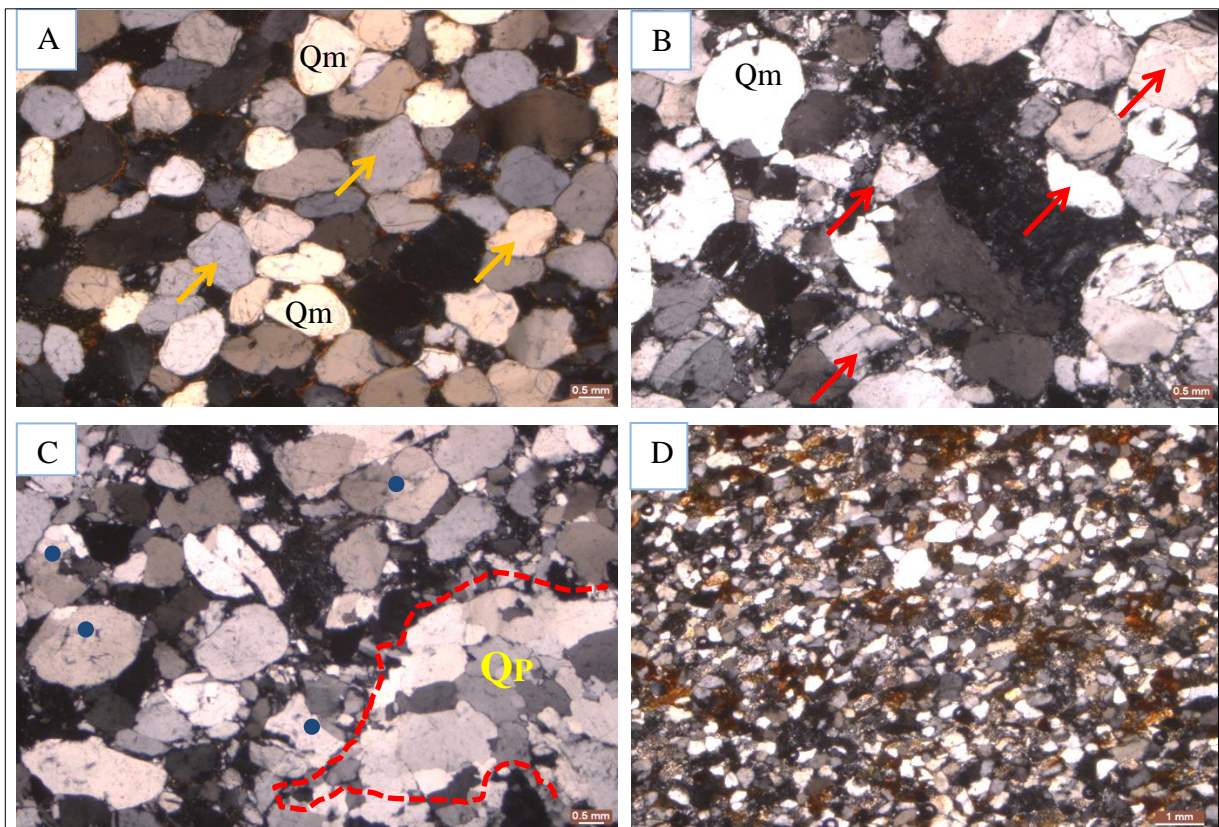


Figure 4.1 Photomicrographs of Quartz grains in the sandstone thin section showing A. Rounded grain monocrystalline quartz (yellow arrow)(sample NT-5)(xpl) B.sub rounded shaped medium to coarse-grained quartz (red arrow)(sample NT-1)(xpl) C. polycrystalline quartz grain (blue dot)(NT-8)(xpl) D.Fine grained Monocrystalsquartz quartzmagnification(sample NT-7)(xpl)

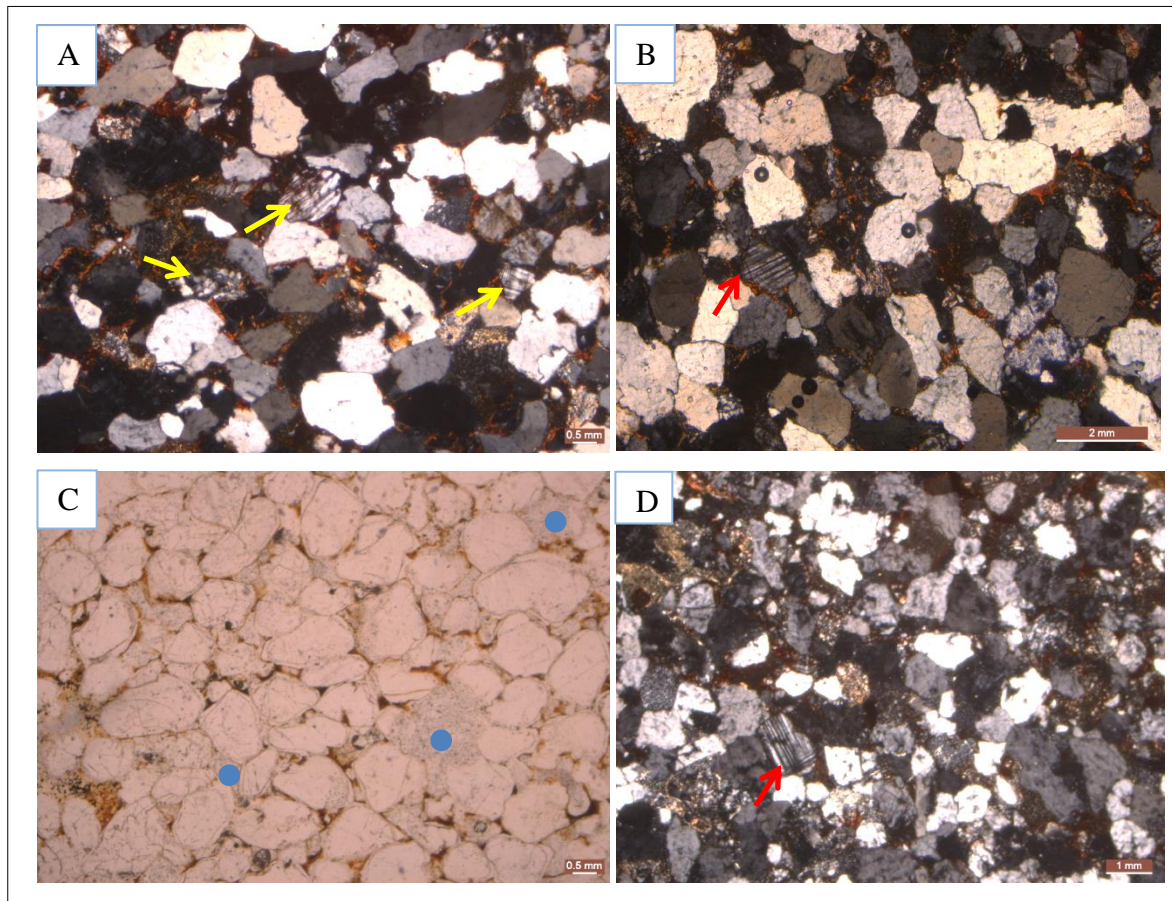


Figure 4. 2 Photomicrographs of Feldspar grains in the sandstone thin section showing A.microcline feldspar grain with cross-hatched structure (yellow grain)(Sample NT-18)(xpl) B.the red arrow showing plagioclase feldspar(xpl) C. grains with the blue dot showing orthoclase potassium feldspar(Sample NT-5)(ppl) D.the red arrow showing microcline potassium feldspar(sample NT-13)(xpl)

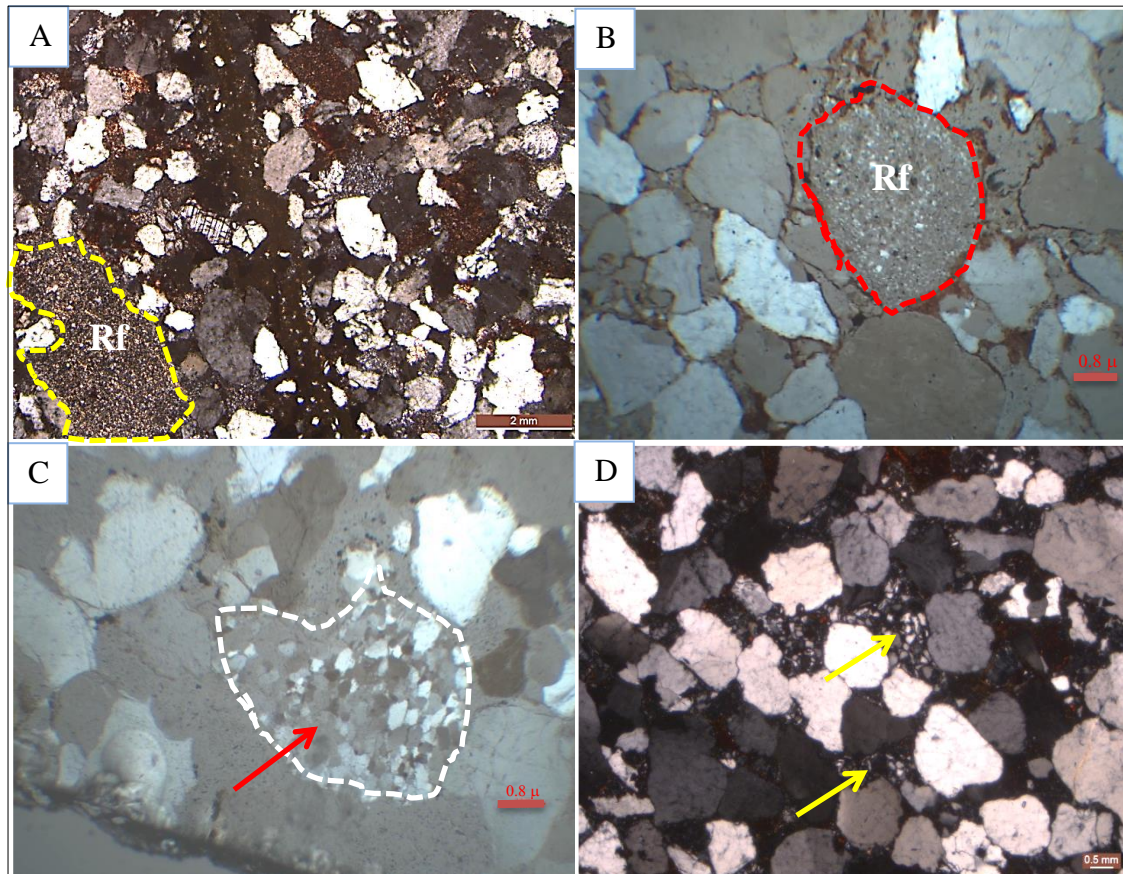


Figure 4.3 Photomicrographs of Lithic Fragment in the sandstone thin section showing A. lithic fragment with the alignment of grain that is encircled with yellow color(sample NT-11) (xpl) B. sedimentary lithic fragments in the center of the thin section which is encircled by red color (sample NT-17(xpl)) C. The red arrow showing the lithic fragment of sandstone(sample NT-10)(ppl) D.the yellow arrow indicating lithic fragment of sedimentary Provenance(sample NT-15)(xpl)

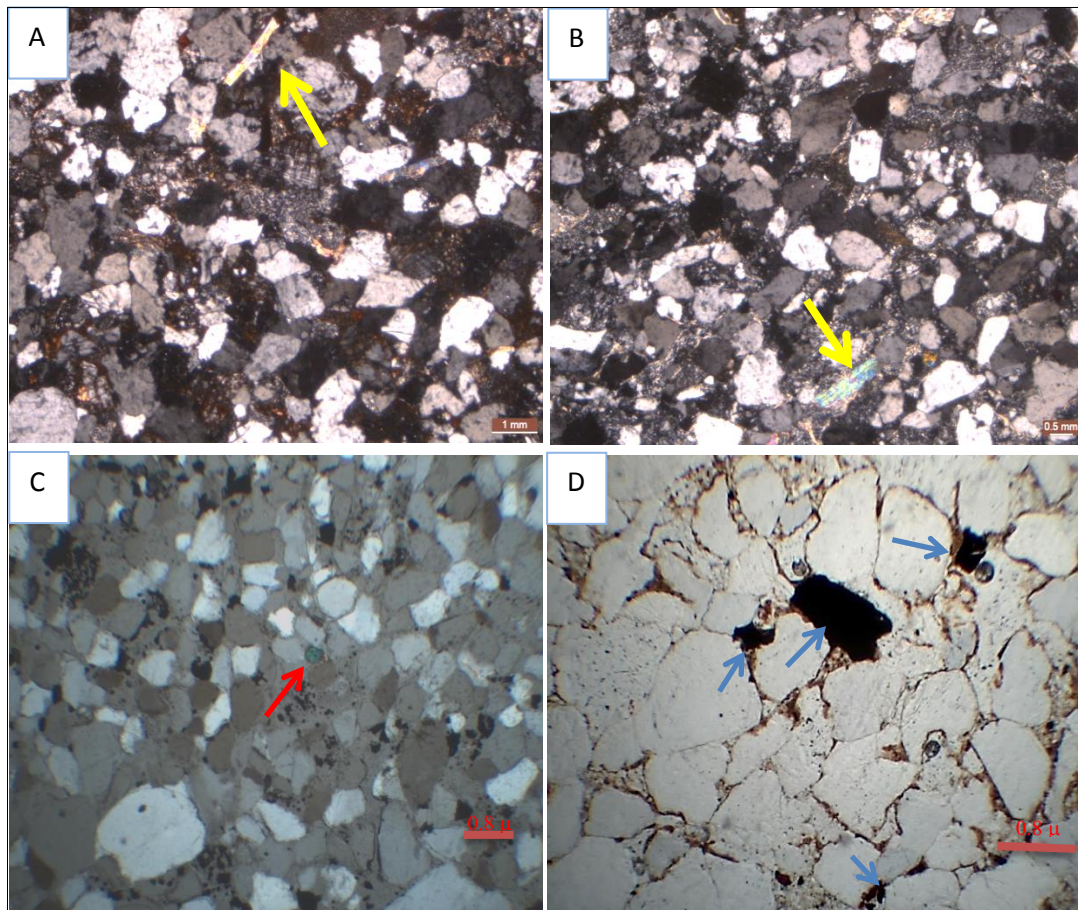


Figure 4.4. Photomicrographs of in the sandstone thin section showing A. the yellow arrow indicating muscovite mica shit in the upper part of the section(sample NT-13)(xpl) B.Biotite mineral In the lower part of the thin section image indicated by yellow arrow(sample NT-16)(xpl) C. in the central part the red arrow indicating the zircon heavy mineral(sample NT-12)(xpl) D.The dark minerals indicated by an arrow showing an opaque mineral(sample NT-5)(ppl)

4.1. 3 DIAGENETIC PROPERTIES

Diagenesis is the process that affects sediment after the time of its deposition. In sedimentary rocks, it is the fundamental suite of the biological, chemical, and physical process which controls the texture, mineralogy, and fluid flow properties of the rock. The diagenetic processes that have affected the sandstone are cementation, compaction, recrystallization, replacement, mineral overgrowth, and dissolution (Hayes, 1979).

4.1.3.1 Grain deformation and fracturing

Under the petrographic analysis, slight grain fracturing was observed but not intense. Some of the grains of the sandstone particularly quartz mineral are deformed slightly and point to long contact between frameworks of grains are observed. In some grains of quartz sutured grain contact is seen particularly on polycrystalline quartz. Due to the overburden pressure, the grains packed close together showing linear to convex-concave contact between them as a result of compaction.

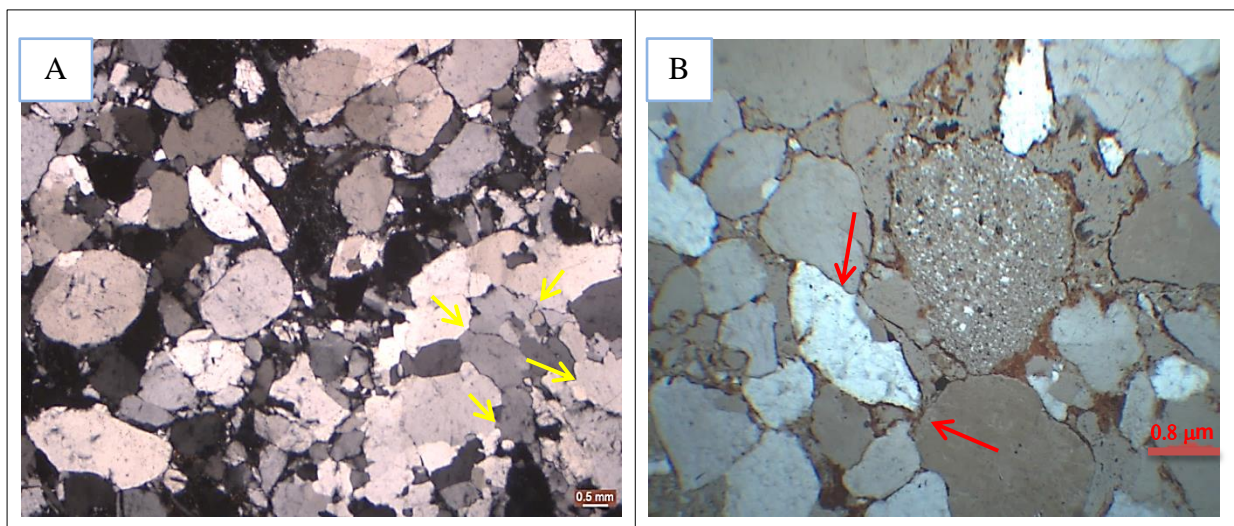


Figure 4. 5 Photomicrograph of sandstone (a) sutured grain contact in polycrystalline quartz and concave-convex grain contact(indicated in Yellow arrow) (sample NT-8) (ppl) (b) point, long contact between grains(sample NT-17)(ppl)

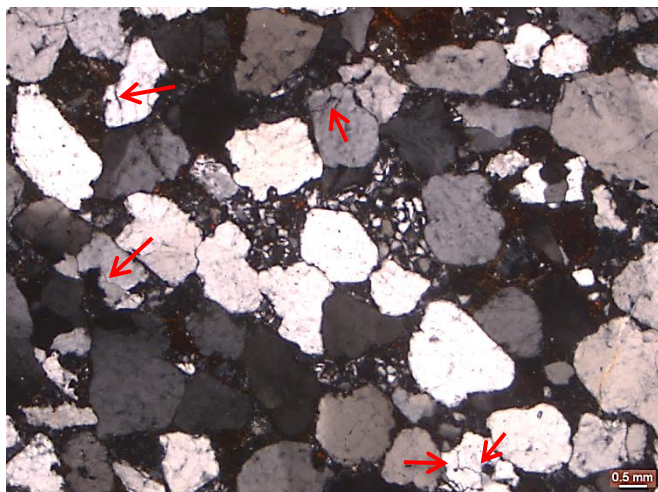


Figure 4. 6 Photomicrograph of fractured grains (red arrows) as a result of burial pressure(sample NT-15)(xpl)

4.1.3.2 Cementation

It is a process of welding the clastic sediment of framework grain by the precipitation of mineral matter in the pore space. It is a diagenetic process in which autogenic minerals are precipitated in the pores space of loose sediment. Cementation is the primary process that involves porosity reduction.

In the thin section analysis, there are three types of cementation identified from the analysis, these include silica/quartz cementation, calcite cementation, and hematite cementation. Silica cementation: originated from silica enriched pore fluids. Quartz mineral overgrowth is the common silica cement in this study, this fine-grained quartz mineral fills the open space between the framework grains. Calcite cement is one of the types of cement used in the porosity reduction between framework grains. It fills the large crystal with poikilitic texture, as a grain replacing and grain overgrowth. Hematite cementation is the process in which hematite acts in some sandstone as a cement coating the framework grains particularly quartz and involves the porosity reduction by filling the open space between grains. Most clay minerals and framework grain are stained by iron oxide that results in reddish color.

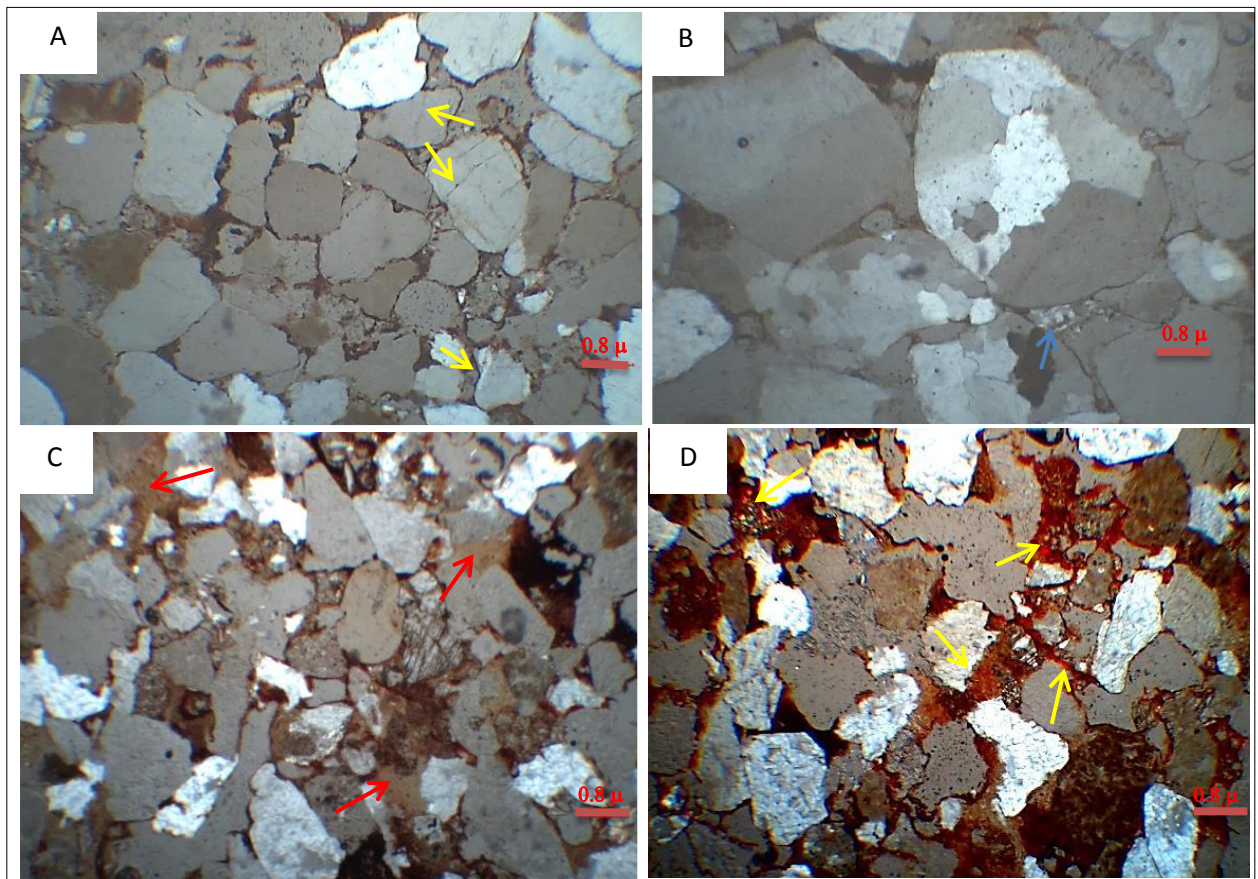


Figure 4.7 Microphotographs of sandstone sample in thin section (a), shows overgrowth of quartz (yellow arrow) (ppl) (b), indicates the silica cementation in which quartz act as a cementing role(blue arrow) (ppl) (c) images in which the red arrow indicating calcite cement (ppl) (d), photomicrograph in which the hematite cement indicated by the yellow arrow.(ppl)

| Diagenetic Features (Process) | Sandstone formation of Yejube section |
|-------------------------------|---------------------------------------|
| Compaction | Intense |
| Hematite cement | Common |
| Quartz cement | Moderate |
| Porosity | Moderate |
| Feldspar cementation | Low |
| Calcite replacement | Moderate |

Table 4. 1 The generalized Diagenetic summary of petrographic analysis

4.1.4 SANDSTONE CLASSIFICATION

The sandstone classification system is a broad concept in that there exist many different systems of classification of sandstone. In the very broadest context sandstone can be classified as epiclastic and volcanoclastic, where the former is formed from a fragment of preexisting rock by the process of weathering and transportation and the latter group is that sandstone formed from the volcanic debris.

The classification of sandstone based on the modal proportion of framework grain is made in this analysis by using a technique called point counting. During point counting software called j Microvision is used to facilitate the counting and a relative percentage of the three major framework grains is calculated in percentage.

By using Folk 1974 classification scheme the modal analysis of (QFL) where Q indicates quartz mineral including both monocrystalline and polycrystalline quartz grain, F is for feldspar and L is for lithic fragments.

| Sample code | Q (m + p) | F | L | Total | Q (%) | F (%) | L (%) |
|-------------|------------|----|----|-------|-------|---------|---------|
| NT-1 | 298 | 2 | 0 | 300 | 99.3 | 0.7 | 0 |
| NT-2 | 300 | 0 | 0 | 300 | 100 | 0 | 0 |
| NT-4 | 295 | 5 | 0 | 300 | 98.3 | 1.7 | 0 |
| NT-5 | 297 | 0 | 3 | 300 | 99 | 0 | 1 |
| NT-7 | 246 | 12 | 42 | 300 | 82 | 4 | 14 |
| NT-8 | 300 | 0 | 0 | 300 | 100 | 0 | 0 |
| NT-10 | 266 | 6 | 28 | 300 | 88.6 | 2 | 9.33 |
| NT-11 | 282 | 11 | 7 | 300 | 94 | 3.66 | 2.33 |
| NT-12 | 297 | 3 | 0 | 300 | 99 | 1 | 0 |
| NT-13 | 286 | 14 | 0 | 300 | 95.33 | 4.66 | 0 |
| NT-14 | 271 | 7 | 22 | 300 | 90.3 | 2.33 | 7.33 |
| NT-15 | 293 | 4 | 3 | 300 | 97.66 | 1.33 | 1 |
| NT-16 | 277 | 0 | 23 | 300 | 92.33 | 0 | 7.66 |
| NT-17 | 298 | 0 | 2 | 300 | 99.3 | 0 | 0.7 |
| NT-18 | 286 | 9 | 5 | 300 | 95.33 | 3 | 1.66 |

Table 4. 2 Point counting data from the sandstone sample of yejue area

Based on the data obtained by point counting of sandstones framework mineralogy classification is made by using [Folks \(1974\)](#) classification schemes. The sandstone classified by modal analysis (QFL) where Q is generally indicating both mono and polycrystalline quartz, F is indicating feldspar grains and L is for the lithic fragment. Most of the selected sample of sandstone represents quartz arenite in which contains a quartz proportion of > 95% according to the classification made by [Folk \(1980\)](#). The modal analysis made is dominated by quartz arenite unlikely there exists one sample classified under sub feldsarenite and four samples under sublitharenite.

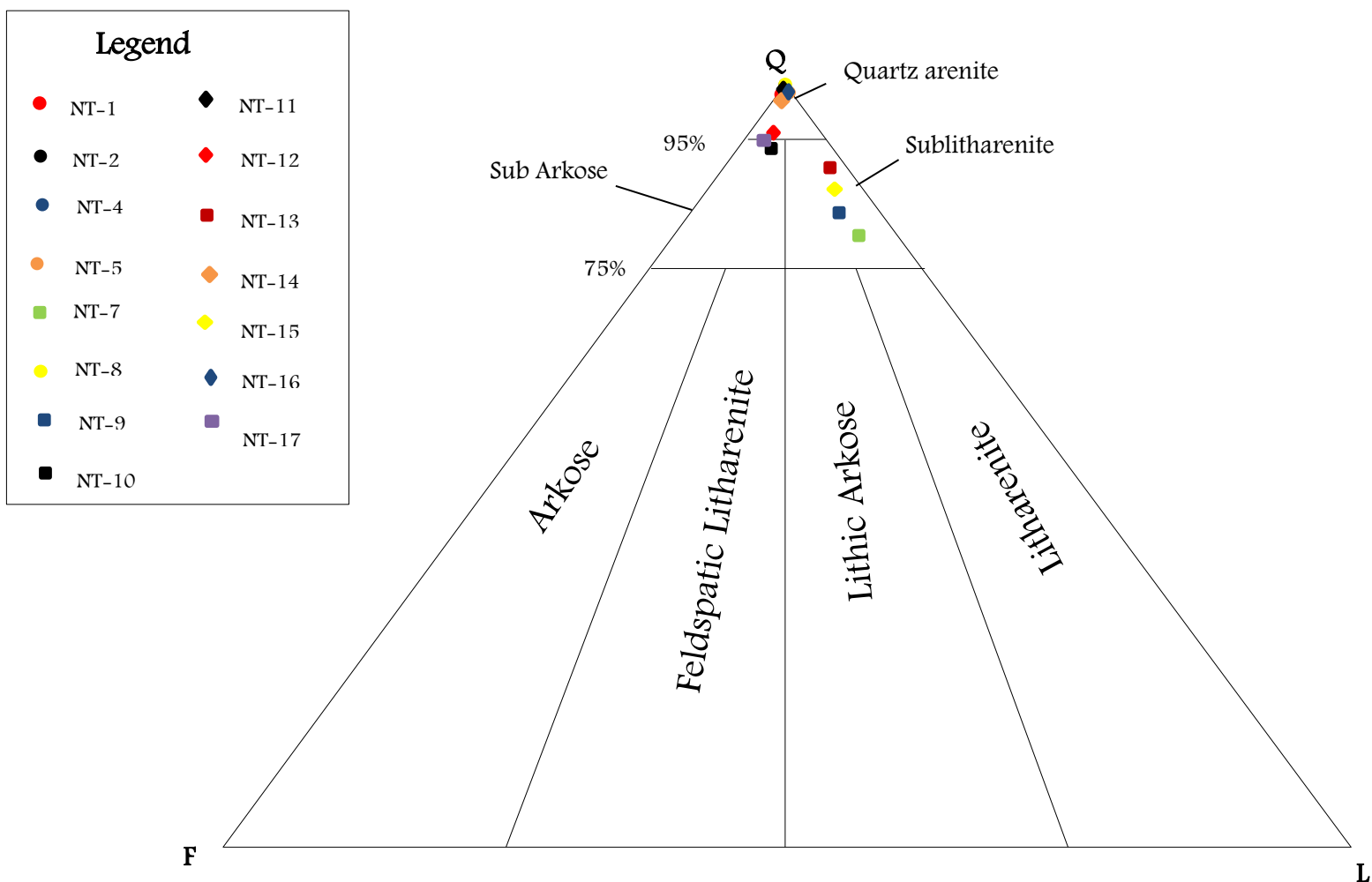


Figure 4.9 QLF ternary diagram showing the compositional classification of Adigrat sandstone of yejube area (After Folk, 1980),

4.1.5 MATURITY

The sandstone maturity of the studied section can be described in two ways. The first one from the petrographic analysis made the framework grain dominated by the stable minerals of grains particularly quartz including both mono and polycrystalline grains which indicates that the samples are compositionally matured. The second parameter of maturity analysis is that in textural perspective in which from the analysis made in petrographic microscope there exists little amount of clay, the grains are medium to well sorted, subrounded to rounded indicating texturally its classified under matured.

4.1.6 CONCLUSION

From the modal analysis result, the studied sandstone samples are more or less classified as quartz arenite sandstone. According to [Boggs \(2009\)](#), quartz arenite occurred in association assemblage of rocks deposited in stable cratonic environments. The grain shape of the framework mostly of quartz is rounded to subrounded indicating its transported a long distance before it deposits and the grains of the sandstone indicate well sorting which tells us the energy of the transporting medium was constant. Generally from the analysis made the sandstone is both compositional and texturally matured.

4.2 GRAIN SIZE ANALYSIS

Grain size analysis is one of the important methods particularly for unconsolidated sediment for classifying and interpreting the energy of sediment transporting medium and sedimentary environments. According to [Patric and Donald \(1985\)](#), the fundamental goal grain size analysis is environmental interpretation.

In this study grain size analysis of 12 representative samples of unconsolidated sand-size sediment was carried out by using the conventional method of dry sieve analysis. . This analysis aims to represent the grain size distribution of the studied section by using the representative selected sample to implicate mode of sediment transportation history and in general depositional history of its formation.

The sieve analysis follows a consecutive procedure to obtain the result. In this study, the unconsolidated sand-sized sample that weighs 200 g is taken to be analyzed. The stacked grains were disaggregated using a porcelain mortar and pestle after the sample was thoroughly split into quarters. After that, the sample was placed in an oven for 24 hours to make it dry. Following the sample taken off from the oven and its mass is weighed again to make sure it is not changed. Then it is placed in a stacked sieve mesh of having an opening of 2mm, 1.8 mm, 0.6 mm, 0.3 mm, 0.16mm, 0.063 mm and below 0.063mm bottom receiver placed in ascending pattern and shacked for 10 minutes in a mechanical shaker. The fraction of grains in each sieve and receiving pan were weighted in a balance then its values were recorded properly and tabulated.

In the grain size analysis, some statistical parameters are used which has a significant role in the sedimentological analysis. These include sample sorting (the standard deviation of grain size), mean (average grain size), kurtosis (degree of curvature near the mode of grain size distribution), and skewness (the deviation of grain size distribution from symmetrical) of sediment calculated by the Microsoft Excel spreadsheet program of GRADISTAT (Version-8) by the graphical method of [folk and ward \(1957\)](#).

| Parameter | Description | |
|---|--|---|
| Median | Indicates that diameter corresponds to the 50 percentile (50 % mark) from the cumulative curve | |
| Graphic Mean | Parameter indicating the average grain size $Mz = \frac{\phi (16+50+84)}{3}$ | |
| Standard deviation (sorting) | $\frac{\phi(84-16)}{4} + \frac{\phi(95-5)}{6.6}$ | < 0.35 (φ) Very wellsorted |
| | | 0.35 to 0.5 (φ) Wellsorted |
| | | 0.5 to 0.71 (φ) Moderately well sorted |
| | | 0.71 to 1.0 (φ) Moderately sorted |
| | | 1.0 to 2.0(φ) Poorly sorted |
| | | 2.0 to 4.0 (φ) Very poorly sorted |
| | | >4.0 (φ) Extremely poorly sorted |
| Skewness | $Sk = \frac{\phi 16+\phi 84-2\phi 50}{2(\phi 84-\phi 16)} + \frac{\phi 5+\phi 95-2\phi 50}{2(\phi 95-\phi 5)}$ | 1.0 to 3.0 (φ) Very fineSkewed |
| | | 0.3 to 0.1 (φ) FineSkewed |
| | | 0.1 to -0.1 (φ) NearSymmetrical |
| | | -0.1 to -0.3 (φ) Coarse Skewed |
| | | -0.3 to -1.3 (φ) Very coarse skewed |
| Graphic kurtosis | $KG = \frac{\phi 95-\phi 5}{2.44(\phi 75-\phi 25)}$ | < 0.67 (φ) VeryPlatykurtic |
| | | 0.67 to 0.90 (φ) Platykurtic |
| | | 0.90 to 1.11 (φ) Mesokurtic |
| | | 1.11 to 1.50 (φ) Leptokurtic |
| | | 1.50 to ø 3.00 (φ) Very leptokurtic |
| | | > 3.00 (φ) Extremely leptokurtic |

Table 4. 3 Folk and Ward (1957) graphical measures and statistical formulas used to
Calculate the grain size parameters

| Milimeters | Phi (ϕ) | Wentworth size scale | |
|------------|----------------|----------------------|--------|
| | | Boulder | Gravel |
| 256 | -8 | Cobble | |
| 64 | -4 | Pebble | |
| 2.0 | -1 | Very coarse sand | Sand |
| 1.0 | 0 | Coarse sand | |
| 0.5 | 1 | Medium sand | |
| 0.25 | 2 | Fine sand | |
| 0.125 | 3 | Very fine sand | |
| 0.0625 | 4 | Coarse silt | Mud |
| 0.0310 | 5 | Medium silt | |
| 0.0156 | 6 | Fine silt | |
| 0.0078 | 7 | Very fine silt | |
| 0.0039 | 8 | Clay | |

Table 4. 4 The Udden (1914) and Wentworth (1922) Grain size scale for clastic

4.2.1 Result

4.2.1.1 Grain size distribution

Grain size distribution is a method used to classify sediments based on the size of the individual grains of sediment. In the analyzed sample the percentage of different sizes of the grain contained from 200mg within the sample is calculated by using the GRADISTAT excel software program. Twelve analyzed samples show a different grain size distribution. The grain size distribution indicates that most of the sample is dominated by medium to coarse grain size particles having the largest percentage of the total weight analyzed.

Table 4. 5 Grain size distribution of sediment of yejube section

| Sample code | VFG (%) | VSC (%) | CS (%) | MS (%) | FS (%) | VFS (%) | VCS (%) | CSI (%) |
|-------------|---------|---------|--------|--------|--------|---------|---------|---------|
| NGSS 1 | 0.0 | 47.2 | 12.4 | 17.7 | 14.2 | 8.2 | 0.3 | 0.0 |
| NGSS 2 | 0.0 | 25.9 | 15.6 | 31.5 | 17.5 | 5.5 | 4.1 | 0.0 |
| NGSS 3 | 0.0 | 13.6 | 24.7 | 54.5 | 5.4 | 1.3 | 0.5 | 0.0 |
| NGSS 4 | 0.0 | 30.6 | 23.6 | 30.9 | 11.1 | 2.6 | 1.3 | 0.0 |
| NGSS 5 | 0.0 | 9.9 | 20.6 | 50.7 | 17.8 | 0.8 | 0.2 | 0.0 |
| NGSS 6 | 0.0 | 60.6 | 20.5 | 14.3 | 3.2 | 0.9 | 0.4 | 0.0 |
| NGSS 7 | 0.0 | 6.8 | 11.5 | 41.0 | 31.8 | 7.4 | 1.6 | 0.0 |
| NGSS 8 | 0.0 | 40.0 | 22.9 | 24.4 | 7.4 | 3.2 | 1.6 | 0.0 |
| NGSS 9 | 0.0 | 28.5 | 22.6 | 32.8 | 11.8 | 3.9 | 0.5 | 0.0 |
| NGSS 10 | 0.0 | 32.5 | 18.6 | 29.1 | 14.5 | 4.5 | 0.8 | 0.0 |
| NGSS 11 | 0.0 | 0.8 | 4.2 | 29.3 | 49.5 | 14.6 | 1.7 | 0.0 |
| NGSS 12 | 0.0 | 6.8 | 11.5 | 41.0 | 31.8 | 7.4 | 1.6 | 0.0 |

Note NGSS1- NGSS12 sediment sample, **VFG** ; Very fine gravel, **VSC**; Very coarse sand, **CS**; coarse sand, **MS**: Medium sand, **FS**; Fine sand, **VFS**: Very fine sand, **VCS**; Very coarse silt, **CSI** : Coarse silt

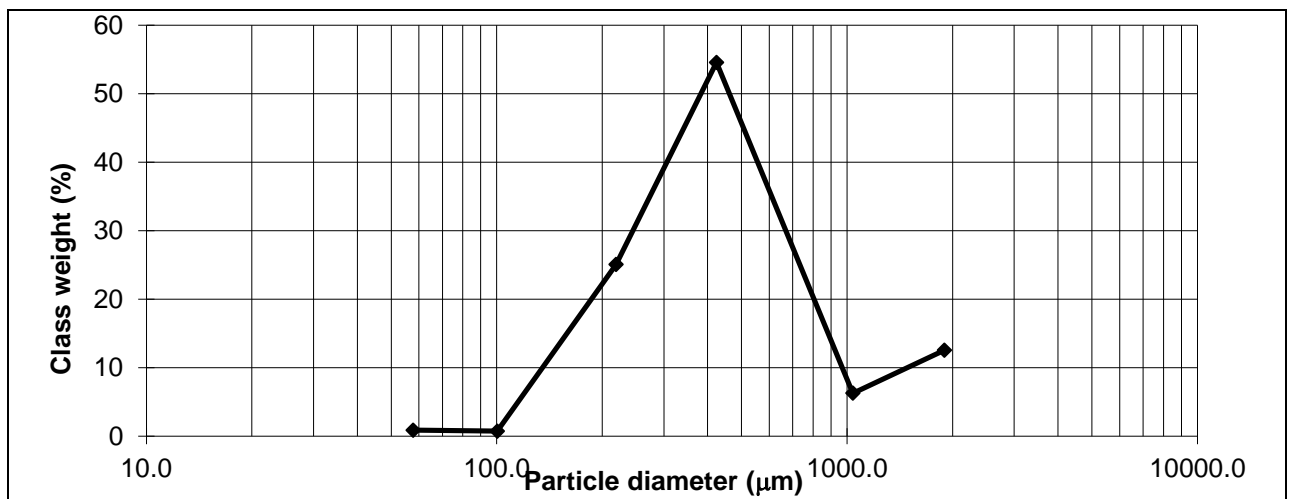


Figure 4. 10 Frequency curve showing the grain size distribution of sample NGSS5 with bio modal distribution of grains ((Folk and Ward, 1957)

4.2.1.2 Graphic Mean

Graphic mean is the average of the grains of available material and it is the result of the energy amount of the transporting medium (Okeyode and Nnamdi, 2012). The mean grain size value of the analyzed sample ranges from -0.111ϕ to 2.322ϕ . The mean value of the average grain size of the analyzed sample is 0.9ϕ .

| Sample ID | D10 (ϕ) | D50 (ϕ) | D90 (ϕ) | (D90 / D10) (ϕ) | (D90 - D10) (ϕ) | D75 / D25 (ϕ) | (D75 - D25) (ϕ) 3 |
|-----------|-------------------|-------------------|-------------------|---------------------------|---------------------------|-------------------------|--------------------------------|
| NGSS1 | -1.523 | 0.269 | 2.823 | -1.854 | 4.345 | -1.950 | 2.825 |
| NGSS2 | -1.001 | 1.250 | 2.921 | -2.917 | 3.922 | -20.175 | 2.188 |
| NGSS3 | -0.450 | -1.164 | -1.726 | -3.836 | 2.175 | 1.864 | 0.721 |
| NGSS4 | -0.992 | 0.885 | 2.312 | -2.507 | 3.234 | -5.351 | 1.869 |
| NGSS5 | 0.018 | 1.331 | 2.324 | 129.7 | 2.306 | 1.952 | 0.865 |
| NGSS6 | -1.208 | -0.493 | 1.498 | -1.240 | 2.705 | -0.707 | 1.618 |
| NGSS7 | -1.035 | 0.121 | 2.247 | -2.174 | 3.280 | -1.520 | 2.243 |
| NGSS8 | -1.216 | 0.469 | 2.229 | -1.834 | 3.445 | -1.855 | 2.147 |
| NGSS9 | -0.935 | 0.973 | 2.382 | -2.548 | 3.317 | -7.852 | 1.825 |
| NGSS10 | -1.278 | 0.966 | 2.487 | -1.946 | 3.764 | -3.142 | 2.293 |
| NGSS11 | 1.327 | 2.229 | 3.426 | 2.581 | 2.098 | 1.390 | 0.728 |
| NGSS12 | 0.790 | 1.796 | 2.861 | 3.621 | 2.071 | 2.006 | 1.177 |

Table 4. 6 Percentile values of each sample analyzed

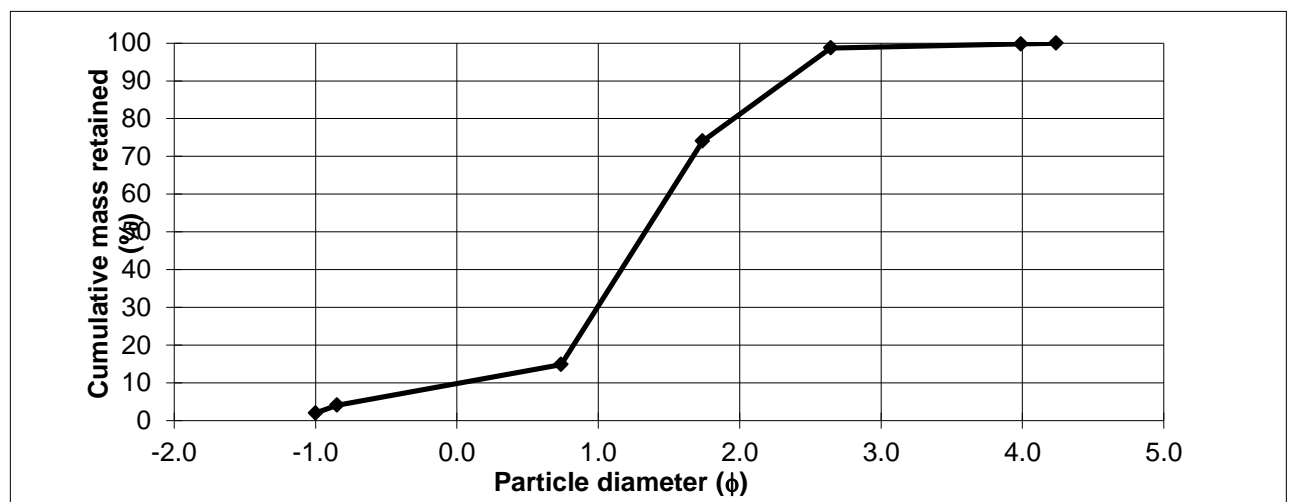


Figure 4. 11 The cumulative frequency curve of Sample code NGSS5

4.2.1.3 The standard deviation (sorting)

This is the statistical parameter in which the measure of the variation of particle size or sorting in phi scale and its value gives a reflection of the capability of transporting agents to disintegrate grains during the time of sediment deposition.

The standard deviation of the sample analyzed ranges from 0.74 – 1.307 ϕ and its mean value of all analyzed samples is 1.10 ϕ . The sample having the standard deviation of 1.10 ϕ is

grouped under moderately sorted class and interpreted as deposited possibly under shallow marine shelf and transitional environment (Friedman, 1961).

Table 4.7. Classification of sands based on sorting used as a tool in the interpretation of environment (Friedman, 1961)

| Standard deviation value in (ϕ) unit | Sorting | Environmental interpretation |
|---|-------------------------|--|
| <0.35 | Very well sorted | Coastal and lake dunes; many beaches (foreshore), common on shallow marine shelf |
| 0.35-0.50 | Well sorted | Most beaches(foreshore); shallow marine shelf, many inland dunes |
| 0.50-0.80 | Moderately well sorted | Most inland dunes; most rivers; most lagoons, distal marine shelf |
| 0.80-1.40 | Moderately sorted | Many glacial-fluvial settings; many rivers; some lagoons; some distal marine shelf |
| 1.40-2.00 | Poorly sorted | Many glacio-fluvial settings |
| 2.00-2.60 | Very poorly sorted | Many glacio-fluvial settings |
| >2.60 | Extremely poorly sorted | Some glacio – fluvial setting |

4.2.1.4 Skewness

Skewness is the statistical parameter used in grain size analysis in which it is the quality, state, or condition of being distorted or lacking symmetry. In sedimentology, it's the degree to which symmetry or symmetry of grain size is distributed and it's a function of mean, median, and kurtosis of grain distribution. Skewness is an implication of the depositional process and energy of transporting the medium.

From the analyzed sample the values of skewness range from -0.062 to 0.847 ϕ and the mean value of the all analyzed sample are 0.117 ϕ . The positive and negative results of the skewness indicating that the value is towards the fine grains and to the coarse grain respectively. From the analyzed sample half of the result shows it's negatively skewed, this indicates that the grains of the sediment are neither extremely finer nor coarse possibly it's dominated by medium-sized grain.

4.2.1.4 Kurtosis

Statistically, kurtosis is defined as the quality, state of condition of flatness, or peakedness of the graphic representation in the frequency distribution. In sedimentology, kurtosis gives meaning in which the peakedness of the size distribution curves towards the coarse grain (Friedman, 1961).

In this analysis, the value of kurtosis ranges from 0.534 to 1.871 ϕ value and its mean value of the kurtosis from all analyzed samples is 0.98 ϕ . In general, from the analyzed samples 41.6 % is Very platykurtic, 33. % is very leptokurtic and the rest of 25 % is platykurtic.

| Sample code | Sand (%) | Mud (%) | Median (ϕ) | Mean (ϕ) | Standard Deviation (ϕ) | Skewness (ϕ) | Kurtosis (ϕ) | Mode |
|-------------|----------|---------|-------------------|-----------------|-------------------------------|---------------------|---------------------|----------|
| NGSS1 | 99.7 | 0.3 | 2.723 | 0.616 | 1.355 | 0.522 | 0.534 | Unimodal |
| NGSS2 | 96.9 | 4.1 | 1.250 | 0.939 | 1.497 | -0.041 | 0.816 | Trimodal |
| NGSS3 | 99.5 | 0.5 | 1.164 | 1.032 | 0.823 | -0.299 | 1.871 | Bimodal |
| NGSS4 | 98.7 | 1.3 | 0.885 | 0.684 | 1.217 | -0.124 | 0.783 | Bimodal |
| NGSS5 | 99.8 | 0.2 | 1.331 | 1.397 | 0.826 | -0.062 | 1.529 | Bimodal |
| NGSS6 | 99.6 | 0.4 | -0.493 | -0.111 | 0.876 | 0.847 | 0.561 | Unimodal |
| NGSS7 | 99.2 | 0.8 | 0.121 | 0.327 | 1.159 | 0.421 | 0.559 | Bimodal |
| NGSS8 | 98.4 | 1.6 | 0.469 | 0.967 | 1.165 | 0.213 | 0.626 | Bimodal |
| NGSS9 | 99.5 | 0.5 | 0.973 | 0.747 | 1.229 | -0.100 | 0.802 | Bimodal |
| NGSS10 | 99.2 | 0.8 | 0.966 | 0.719 | 1.307 | 0.004 | 0.603 | Bimodal |
| NGSS11 | 98.3 | 1.7 | 2.229 | 2.322 | 0.743 | 0.164 | 1.558 | Unimodal |
| NGSS12 | 98.4 | 1.6 | 1.796 | 1.762 | 1.074 | -0.140 | 1.546 | Bimodal |

Table 4. 8 Result obtained from grain size analysis of yejube section

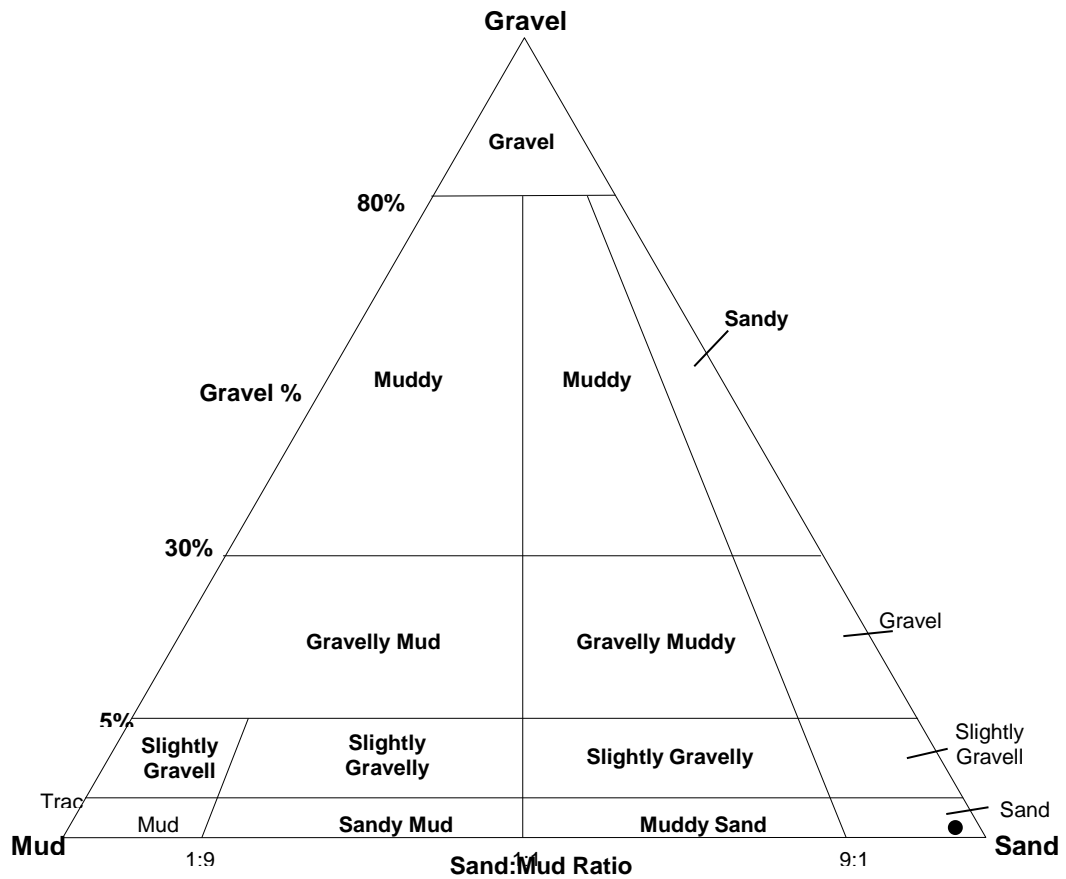


Figure 4. 12 Diagram showing Gravel, Mud and Sand proportion of the sample ID of NGSS12

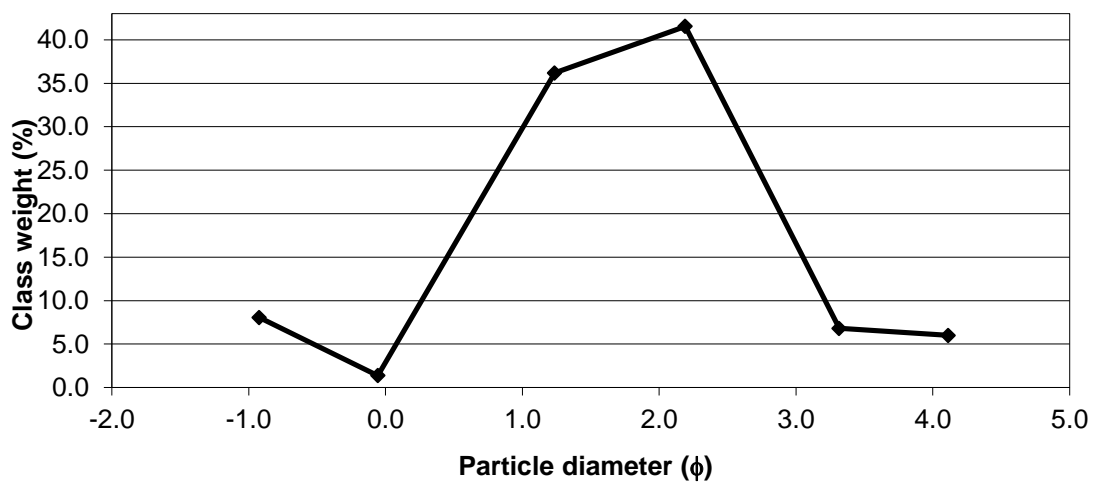
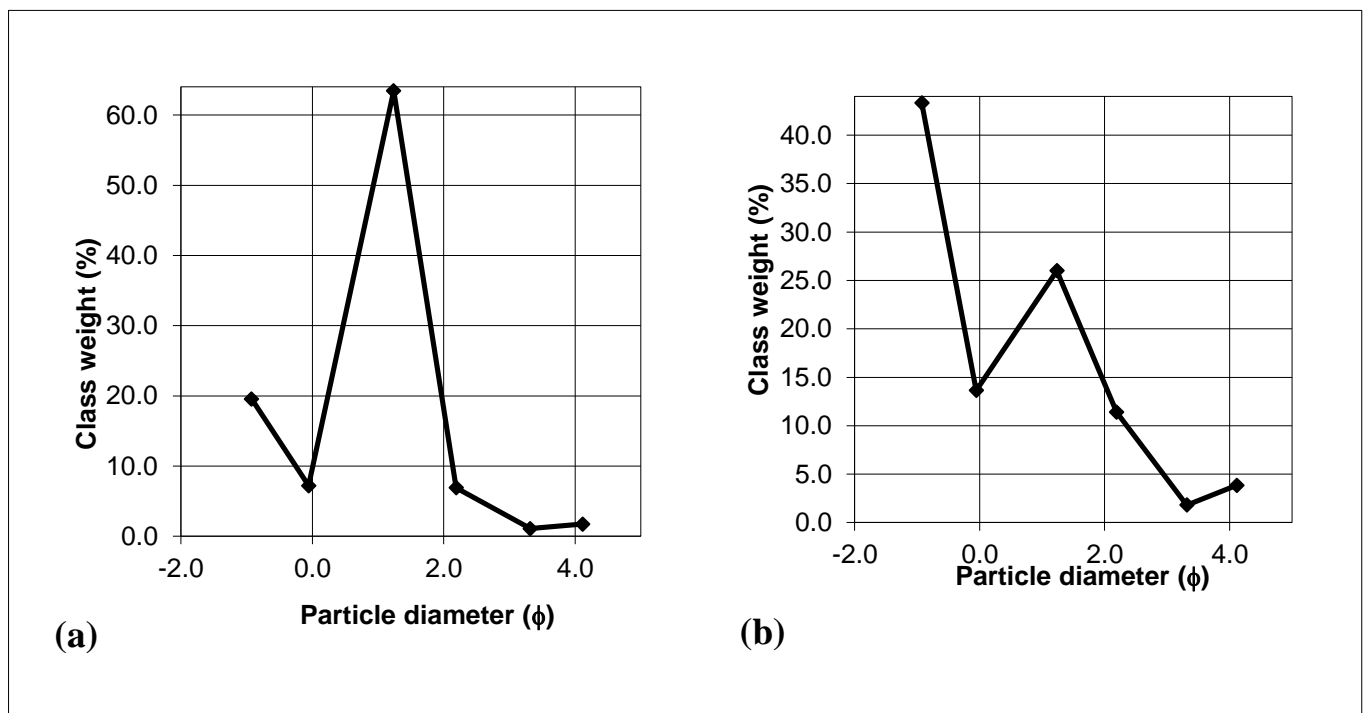


Figure 4. 13 Grain size-frequency curve of sediment sample NGSS12 with two peaks showing the sediment is Bimodal (indicating two populations of grains)

| Sample ID | Description | Sediment Name |
|-----------|---|------------------------------------|
| NGSS1 | Poorly sorted, very fine skewed and very platykurtic | Poorly sorted coarse sand |
| NGSS2 | Poorly sorted, symmetrical, and platykurtic | Poorly sorted medium sand |
| NGSS3 | Moderately sorted, coarse skewed, and very leptokurtic | Moderately sorted medium sand |
| NGSS4 | Poorly sorted, coarse skewed, and platykurtic | Poorly sorted medium sand |
| NGSS5 | Moderately sorted, symmetrical, and very leptokurtic | Moderately sorted medium sand |
| NGSS6 | Moderately sorted, very fine skewed, and very platykurtic | Moderately sorted very coarse sand |
| NGSS7 | Poorly sorted, very fine skewed, and very platykurtic | Poorly sorted very coarse sand |
| NGSS8 | Poorly sorted, fine skewed, and very platykurtic | Poorly sorted very coarse sand |
| NGSS9 | Poorly sorted, symmetrical, and platykurtic | Poorly sorted medium sand |
| NGSS10 | Poorly sorted, symmetrical, and very platykurtic | Poorly sorted very coarse sand |
| NGSS11 | Moderately sorted, fine skewed, and very leptokurtic | Moderately sorted fine sand |
| NGSS12 | Poorly sorted, coarse skewed, and very leptokurtic | Poorly sorted medium sand |

Table 4. 9 Generalized grain size description of the analysis



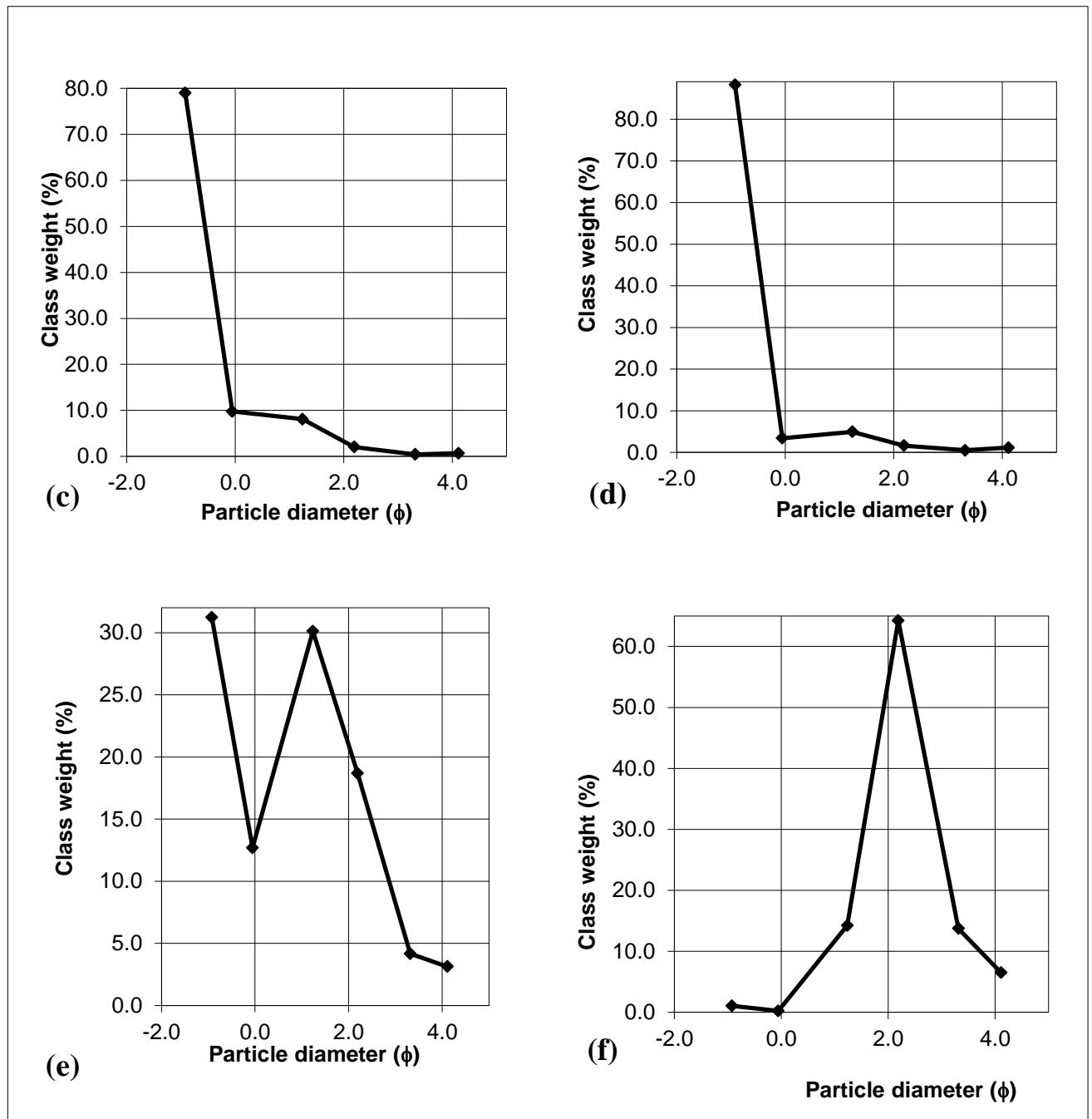


Figure 4.14 Graphical grain size distribution of selected samples showing (a), Moderately sorted medium sandstone having positively skewed and very leptokurtic (b), poorly sorted medium grain sand which is coarse skewed and platykurtic (c), finely skewed, very platykurtic moderately sorted sand (d), Poorly sorted coarse sand with finely skewed and very platykurtic (e), symmetrically skewed very platykurtic poorly sorted very coarse sand (f), finely skewed moderately sorted with very leptokurtic fine sand

4.2.2 Interpretation of Scatter Diagrams

Mean versus Kurtosis

Kurtosis indicates the degree of concentration of the grain relative to the average mean size. Its dependant on the value of the mean (folk and ward, 1957). The binary scatters plot means to kurtosis of the studied samples indicating that the sandstone is coarse to medium-grained and very platykurtic to leptokurtic, in which platykurtic character dominating. The sample at the bottom of the scatter diagram having kurtosis value $< 0.9 \phi$ of samples NGSS1, NGSS2, NGSS3, NGSS7, and NGSS 8 gives a very platykurtic curve. Most of the sample having coarse-grained sand shows kurtosis to mean curve of very platykurtic to platykurtic. Sample with medium grains ranges from the mean value of 1ϕ to 2ϕ shows leptokurtic curve.

Mean versus Skewness

Skewness is the measure of the symmetry of the distribution and it is related to the grain of fine and coarse tails of the distribution of the size from the mean (Folk and Ward, 1957). The binary plot of mean against the skewness shows that the sandstone is dominated by coarse to medium-grained and near-symmetrical. The figure shows that the curve of mean against skewness indicating that the sample plotted was dominated by coarse grain. The sample plotted to have a mean size ranging from $0.111 (\phi)$ to $2.322 (\phi)$ shows positively skewed showing its fine-grained. However, some samples show negative skewness ranging from $-0.0062 (\phi)$ to $-0.1 (\phi)$ coarse skewed.

Mean versus Standard deviation

Standard deviation is a parameter of the size of the grain and their spread around to the average. The distinct sample of NGSS1 has a moderately well sorted with standard deviation value of 0.743ϕ with unimodal distribution having to mean size of 2.229ϕ . Most of the sample consisting of more range of size of grain having a relatively high number of standard deviation ranging from $1 \phi - 2 \phi$ showing it's poorly sorted. From the mean against sorting plotted curve two samples which are NGSS3 and NGSS6 showing standard deviation value of 0.823ϕ and 0.876ϕ respectively indicating moderately sorted distribution.

Sorting versus Skewness

The binary plot of sorting against skewness shows the sandstone unit is near-symmetrical; moderately to poorly sorted. The analyzed samples according to Friedman's (1967) classification they are located in the river sand part from the graph of standard deviation against skewness.

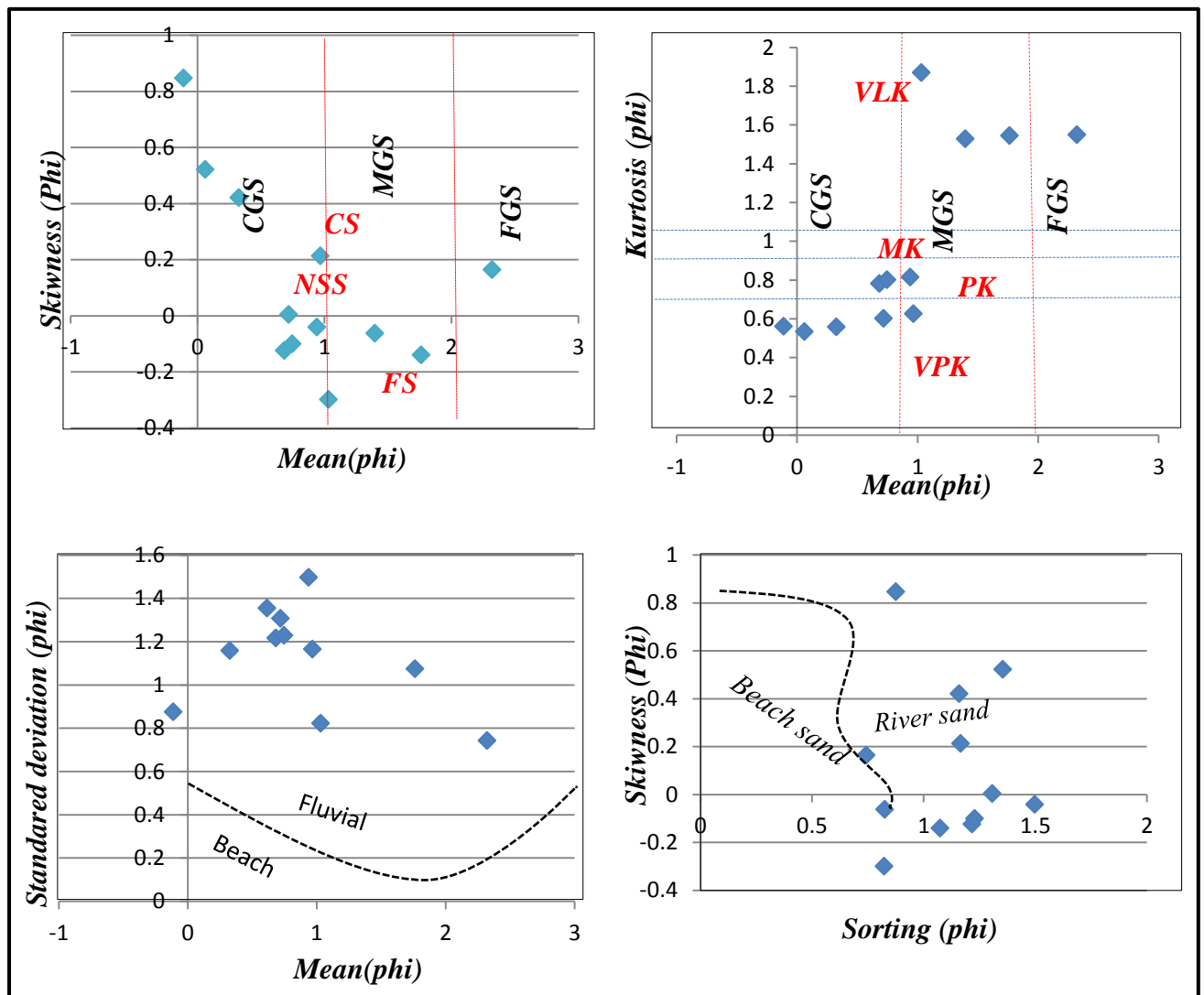


Figure 4.15 Scatter plots of the grain size parameters (a) binary plot of the statistical parameter of mean against skewness (b) binary plot of the statistical parameter of mean against Kurtosis (c) binary plot of the statistical parameter of mean against standard deviation (d) binary plot of a statistical parameter of Skewness against sorting where VLK (very leptokurtic), MK (mesokurtic), PK (platy kurtic), VPK (very platy kurtic), CGS (coarse-grained sand), MGS (medium-grained sand), FGS (fine-grained sand), CS (coarse skewed), NSS (near to symmetrical) and FS (fine skewed)

4.2.3 Conclusion of grain size analysis

The grain size analysis of the studied section from twelve representative samples was taken for the laboratory sieve analysis. The analysis gives an important clue which is summarized as follows.

From the grain size distribution curve showing of most samples have a bimodal nature of distribution showing that simultaneously consisting of a mixture of grains of both fine to coarse and this bimodality of the grain size distribution except to some unimodal and trimodal which indicate the provenance be more than one source. The graphic mean size ranges from the value of -0.001ϕ (very coarse sand) to 2.322ϕ (fine sand) from which the all analyzed sample 66.6 % consists of a coarse sand grain, 16 % and 8.3 % are medium and fine consequently indicating that the possibly deposited in high energy environment. The frequency curve of grain size shows that both the negatively skewed and positive skewed sample is almost in equal proportion showing that both marine and fluvial process plays its part during the depositional period. The value of the skewness varies from -0.2299ϕ (coarse skewed) to 0.826ϕ (very fine skewed) showing that a mixed environment ϕ . The standard deviation value indicating the degree of sorting in the sediment, in which its value ranges from 1.497ϕ (poorly sorted) to 0.743ϕ (moderately sorted). This variation in sorting indicating of the change in the energy of sediment transport as a result of the mixed depositional environment. The value of kurtosis indicates 1.871ϕ (very leptokurtic) to 0.559ϕ (very platykurtic) this wide range of values indicates fluctuation in the energy of the deposition. The gravel, sand, and mud proportion of the analyzed sample showing the sand size sediment dominated at all except a very insignificant mud presence. The scatter plot between the statistical parameter used in the grain size analysis gives supportive evidence in environmental interpretation. According to Friedman, the scatter plot of mean versus standard deviation and standard deviation versus skewness of the samples analyzed falls under the fluvial and the river sand field respectively.

CHAPTER FIVE

FACIES ANALYSIS

In sedimentology, facies is about the characteristics of the rock bed or unit in which it reflects its origin and the overall characteristics that distinguish it from others. According to (Nichol,2009) Facies is a body of rocks with a specified character that reflects the condition under which it is formed by describing and interpreting the texture, sedimentary structure, fossil, and lithologic associations of sedimentary rocks on the scale of an outcrop, well section and a small segment of the basin. During the fieldwork, the facies succession is studied by investigating the lateral and vertical lithologic unit by identifying different lithofacies type that has a significant meaning in environmental interpretation.

5.1 LITHOFACIES DESCRIPTION

Lithofacies is facies characterized by a particular lithologic feature including both physical and organic characteristics on which a particular lithology show. The lower sandstone units of the studied section can be broadly classified into two parts. The upper part of the section is a cliff-forming and consists of more than half of the total thickness of the section consisting of both compositional and texturally matured sandstone with the sedimentary structure of cross-stratification, bioturbated and muddy facies in between the sandstone. Below the upper part of the section unit, there is relatively gently exposed 60 m unconsolidated sediment that separates the upper and the lower part of the sandstone unit of the section. In The lower part of the section, the sandstone contains a fine to medium-grained sandstone unit consisting of a relatively unconsolidated and gently exposed sandstone unit compared with the upper part of the section. The sandstone unit in the lower part of the section contains sedimentary structures like that of hummocky cross-stratification, herringbone cross-stratification, the erosional structure of tool marks, and planar cross strata is observed.

To identify and describe the lithofacies type detail vertical and lateral investigation is conducted on the studied section. Generally based upon the lithological, textural property and sedimentary structures observed during the field investigation nine lithofacies types are identified. The identified lithofacies types are described in detail as below.

Facies 1: Fine-grained Trough cross-laminated sandstone

Description: This body of rock is semi consolidated sandstone found on the lower part of the section. The facies consists of a Sedimentary structure of trough stratification in its lower surface which is curved and truncated to the underlying bed that merges tangentially with the lower surface. There is a gradual fining upward of grain size change indicating the decrease in the energy of deposition. The facies unit has a thickness ranging from 80 cm up to 100 cm.



Figure 5.1 Field image of cross-stratification on the sandstone unit of the section

Interpretation: Trough cross bedding forms through the migration of dunes in subareal or subaqueous environments. According to [Tucker 2005](#), trough cross lamination and bedding is formed in a meandering stream of the point bar. Point bar is a depositional feature made of alluvium that accumulates on the inside bend of stream and river. Sample NT-11 of thinsection represent this facies in which it is characterized by comprises quartz, feldspar particularly microcline and lithic fragment calcite, and hematite used as a cementing material between framework grains. From point counting result it shows this thin section sample categorized under the quartz arenite sandstone.

Facies 2: Medium grained mud crack developed sandstone Facies

Description This facies unit is found on the lower part of the bottom section in the overbank of the river chemoga. It is a consolidated medium-grained sandstone at the base of the mud crack which has a thickness of 2m.



Figure 5.2 well-developed desiccation crack in medium-grained sandstone facies

Interpretation: The alternating wet and dry conditions in the exposure of subaerial on the overbank of the river caused the development of desiccation crack on the sandstone facies. According to (Elliott 1986), the desiccation crack on muddy facies interpreted a floodplain environ Sample NT-4 of thinsection represent this facies in which it is characterized by moderate sorting and quartz mineral grain having a subrounded shape is dominated the framework mineralogy and a small proportion of feldspar grain is observed. Point counting result indicates it is classified as a quartz arenite sandstone.

Facies 3: Planar cross-bedded medium-grained sandstone facies

Description: It is a slightly reddish consolidated well-sorted fine to moderately grained sandstone facies on the lower part of the section. the set thickness has increased upward on the facies.



Figure 5.3 Field Photograph of Planar cross-bedded sandstone facies

Interpretation: Planar cross-bedding is a group of inclined layers formed on a sloping surface where the interset boundary is generally planar and interpreted as a fluvial depositional environment in which water movement is fast and deep to develop a large scale inclined bed. In the fluvial environment of the stream, the water loses energy and its ability to transport sediment due to the sediment deposited along a point bar over a long time that water dries up and sediment in the point bar preserved as cross-bedding. NT-13 of thinsection represent this facies in which it is characterized by it comprises monocrystalline quartz, lithic rock fragment, and feldspar particularly microcline and some mica sheets also observed. The quartz grain dominating the framework mineralogy by possessing 95% of the total framework mineralogy.

Facies 4: Medium grained herringbone cross stratified sandstone facies

Description: It is medium-grained reddish consolidated sandstone facies found on the middle part of the section. It has a thickness of 10 cm and is overlain by cross-bedded sandstone also that underlain by unconsolidated sediment. It is characterized by a structure of herringbone cross-stratification which resembles the shape of the bones of fish in which the forests in successive sets are directed in opposite directions.

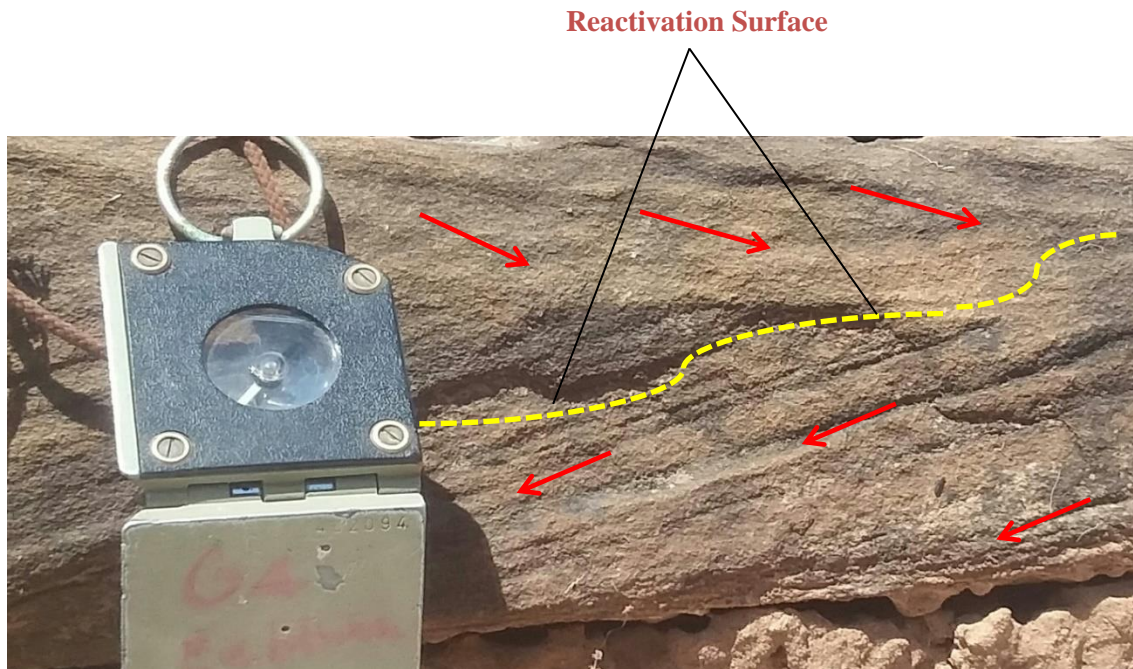


Figure 5.4 Herringbone cross-stratification medium-grained sandstone beds

Interpretation: Herringbone cross-stratification is a type of sedimentary structure formed in tidal areas when the current periodically flows in the opposite direction. The bipolar orientation of foresets seen in herringbone cross-bedding is commonly generated by the reversing current developed in many tidal environments. NT-10 of this section represents this facies in which it is grouped in Sublitharenite in sandstone classification containing more lithic fragments next to the quartz mineral. Generally, it has moderate sorting; the red color seen between framework grains is an indicator of hematite cement.

Facies 5: Well sorted thinly bedded sandstone

Description; These sandstone facies are found on the upper part of the section with whitish-colored thinly bedded sandstone that reaches a thickness of 40-60 cm. The grain size of the sandstone ranges from fine to moderate with finning upward rounded grain size shape. In the upper part of the facies, a thick lamination is observed. It is overlain by a massive sandstone unit above it.



Figure 5.5 field photograph of thinly bedded sandstone from the bottom of the section

Interpretation: Bedding produced by changes in the pattern of sedimentation may be defined by changes in sediment grain, color, or composition. Bedding on sandstone can form in almost any depositional environment. In submarine fan succession, an upward increase in bed thickness shows a turbidite bed (Tucker,2005). According to Elliott 1986, horizontally bedded fine sandstone grain is interpreted as upper shoreface facies. NT-12 of thinsection represent this facies which is Well, sorted quartz dominated fine to medium-grained sandstone sample, the opaque and heavy mineral is also observed. The quartz grain fine to medium in size and rounded. This sample grouped under quartz arenite based on modal analysis of framework grain.

Facies 6: Fine-grained hummocky cross stratified sandstone

Description: This rock facies is well sorted fine-grained whitish sandstone formed on the upper part of the section. There is a gently undulating low angle cross lamination with concaving downward which indicates sedimentary structures called hummocky cross-stratification.



Figure 5.6 Fine sandstone unit with hummocky cross-stratification

Interpretation: Hummocky cross-stratification is characterized by the gently undulating low angle cross lamination with the convex upward parts of the hummock and concave downward parts of the swell. Lithofacies with this type of sedimentary structure are widely interpreted as the sedimentary records of an oscillatory current caused by storm waves on the continental shelf (Nichols, 2009, Tucker 2005, Elliott 1986). NT-7 of thinsection represent this facies which is fine grain moderately sorted sandstone sample. It comprises monocrystalline quartz, feldspar, and lithic fragments. It's one of the few analyzed samples that deviate from the quartz arenite group and is grouped under sublitharenite.

Facies 7: Fine-grained well-sorted tool marked sandstone

Description: This facies unit is located in the lower part of the section with medium-grained sandstone which is characterized by a preserved cast during the time of deposition. The sandstone unit is consolidated and reaches up to 1.5 m thickness and is overlain by a massive sandstone unit above it.



Figure 5.7 Very fine quartz-rich sandstone with the erosional structure of tool mark

Interpretation: This facies has an erosional structure that occurs on the sole of the bed that formed when objects come in contact with the sediment surface. According to [Tuckers \(2005\)](#) tool marked sandstone facies is commonly on the base of turbidite bed that was formed on the sea bottom deposits when river flowing into the ocean deposits particularly sediment on the continental shelf environment. NT-5 of thinsection represent this facies which is typical example of quartz arenite sandstone-dominated mineral quartz with a rounded shape. From the modal analysis result, it is almost all covered by monocrystalline quartz minerals. Between the grains of mineral reddish color act as cementing material is an indicator of hematite cement.

Facies 8: Moderately sorted horizontal bedded sandstone facies

Description: This facies unit has a thickness of up to 1m located on the upper part of the section. It is a moderately sorted medium-grained brown-reddish colored sandstone unit containing a horizontally bedded sedimentary structure. According to (tucker 2005) shore facies sandstone is characterized by fine and horizontally bedded.



Figure 5.8 Field photograph of Horizontally bedded sandstone facies

Petrographic studies confirmed that it consists of framework grains (Quartz, Feldspar, and lithic fragment) and the grains are held together by mostly by hematite cement. NT-14 of thin section represent this facies It contains a relatively high amount of lithic fragment next to the mineral quartz. K feldspar and mica fragments are also observed. The data obtained from point counting technique indicating that its grouped under litharenite sandstone containing lithic fragments next to mineral quartz in its framework mineralogy.

Facies 9: Medium to Coarse grain Bioturbated sandstone facies

Description: It is located on the upper part of the section which has a thickness of 50 cm and texturally poorly sorted reddish colored sandstone facies. It is semi-consolidated bioturbated sandstone that is affected by the reworking of the organism during the time of deposition. The size of the larger grain in this facies unit has a thickness up to 1.5 cm and is dominated by sub-angular grain shapes.

Interpretation: Bioturbation on sandstone is the disruption of sediment by the activity of organisms living during the time of the sediment deposited. Coarse-grained sandstone is an indication of the facies deposited in a high-energy environment. According to [tucker 2005](#) coarse sandstone with trace, organism activity was interpreted as an environment of shoreface.



Figure 5.9. Coarse to medium-grained sandstone affected by bioturbation

NT-2 of thinsection represent this facies which is moderately sorted medium grained sandstone thin section dominated by mineral quartz point-counting data showing that is grouped under quartz arenite sandstone, the grains of quartz has subangular to subrounded shape and small grains of quartz act as a cementing material. Suture contact in the polycrystalline quart indicating metamorphic provenance.

CHAPTER SIX

DISCUSSION AND INTERPRETATION

Based on the detailed field outcrop investigation, petrographic analysis of fifteen representative thin section samples and grain size analysis from twelve unconsolidated sand sediment, the yejube section particularly the lower sandstone (Adigrat sandstone) were investigated.

In yejube section, the Adigrat sandstone unit is very well exposed along the river Canyon of Chemoga River which is the tributary of the Blue Nile (Abay) river. The sandstone unit overlain by the tertiary volcanic in which it is composed of both cliff-forming mostly on the upper part of the section and relatively gently exposed with semi consolidated to a consolidated unit is observed down to the bottom of the section. Even if there is a color variation on the Adigrat sandstone in the studied section red color is dominant over the other which is the result of the effect of iron oxide. There is also white to whitish-grey color is observed in the section indicating less amount of iron oxide as a cementing material. During the field investigation, different lithofacies types were identified that have strong evidence in the interpretation of the depositional environment.

From the petrographic analysis, the Adigrat sandstone mineralogy is dominated by the mineral quartz. The result from the point-counting data indicating above 90 percent of the framework mineralogy is quartz grain the rest accessory part is contained by feldspar mineral and lithic fragments. Sutured contact from polycrystalline quartz grain and sedimentary lithic fragment gives a clue the basement rocks and sedimentary rocks were the possible provenance for this formation. The diagenetic property indicates that the Adigrat sandstone of the section is moderate to high porous that indicating the possibility of being a reservoir for petroleum. From the modal analysis after point counting the compositional classification of the QLF diagram above 87 percent of the analyzed sample is quartz arenite. Petrographic analysis shows that the Adigrat sandstone is both compositionally and texturally matured as a result of a high amount of stable mineral and little amount of clay content respectively. During the depositional time particle were transported a long distance before its deposited evidence from its rounded to subrounded shapes of grains in the sandstone and the moderate to well-sorted grain distribution indicating that they were transported within a constant transporting medium before it deposit.

Grain size analysis is one of the important methods to identify and classify sedimentary depositional environments. This study attempts to interpret the mode of transport and environment of deposition of Adigrat sandstone of yejube section along the river gorge of chemoga. Detailed fieldwork is conducted in which twelve representative sediment samples were collected for the standard sieve analysis.

In this study area, the sediment is mostly dominated by sand-sized particles with a mixture of very small silt-sized particles. From the distribution curve of particle diameter against a class weight, most of the samples have bimodal nature with the frequency distribution curve has two peaks around to $2(\phi)$. This bimodality of the grain size distribution chart except a few limited unimodal and trimodal samples indicating the sands were derived from more than one source area. The mean size of particles from the analyzed sample ranges from phi value of $-.011(\phi)$ to which is very coarse sand to $2.32(\phi)$ of fine sand. Generally having the average size of $1(\phi)$ from all analyzed samples indicating medium sand grain size. The sorting of the particles from the analyzed sample ranges from $0.74(\phi)$ (Moderately well sorted) to $1.3.07(\phi)$ (moderately sorted) with an average sorting value of $1.10(\phi)$ which is grouped under moderately sorted class. The variation in the sorting from moderately well sorted to moderately sorted gives a clue for there is high energy fluctuation of a depositing agent in a mixed environment. The skewness value of the analysis ranges from $-0.062(\phi)$ to $0.847(\phi)$ and with an average value of $0.117(\phi)$ indicating that the all analyzed sample showing nearly symmetrical skewness. . From the analyzed sample half of the result shows it's negatively skewed, this indicates that grains of the sediment is neither extremely finer nor coarse possibly it's dominated with medium-sized grain. From the analysis, the value of Kurtosis ranges from $0.5344(\phi)$ (very platykurtic) to $1.871(\phi)$ (very leptokurtic). Generally from the analysis 41.6 % is Very platykurtic, 33.% is very leptokurtic and the rest of 25 % is platykurtic. According to Friedman (1967), the scatter plot of skewness against standard deviation showing the sediment is mostly river sand of fluvial system.

6.1 Facies Association

Facies association is a combination of different facies that has a significant role in environment interpretation in sedimentary rocks. It is an interpretation of an environment of a body of rock from the specified character and features it shows, these include sedimentary structure, texture, lithological association and fossils. The variation on facies succession both on lateral and vertical extension with specified lithological and paleontological features reflecting the depositional environment change. According to the [Welters law \(1894\)](#), the environment of deposition can shift the changes in condition laterally, indicating the laterally related environment becoming superimposed.

The Adigrat Sandstone in the studied section after conducting a detailed field investigation divided into different lithofacies types based upon texture, sedimentary structure, and sedimentological features. The identified lithofacies from this study includes horizontal bedded sandstone, Bioturbated sandstone, thinly bedded sandstone, mud crack developed sandstone and tool marked sandstone from the upper sub section, Herringbone cross stratification sandstone facies from the middle part of the section and Trough cross-laminated sandstone, Planar crossbedded sandstone and mud crack developed sandstone facies from the lower part of the sub section are environmentally interpreted from the strong evidence they contain as discussed on chapter five in detail for each. The identified lithofacies type is grouped on the generalized three facies association in which they belong. This facies association is meandering river environment, tidal flat deposits, continental shelf environment particularly shoreface deposit.

6.1.1 Meandering River deposit

Meandering river deposit is part of the fluvial depositional system which is formed in the terrestrial environment. Within the flood plain in this environment, there is one channel that erodes over the bank of the riverside which cut the bank of the river and deposits fine-grained material alongside the river on the flood plain. Generally, meandering river sedimentation consisted of alternative cyclic sedimentation, flood plain sediment, and fining upward sequence ([Wolela, 2008](#)). From the lithofacies observed from the section medium-grained mud crack developed sandstone, planar cross-bedded medium-grained sandstone and Fine-grained Trough cross-laminated sandstone are grouped under this lithofacies association.

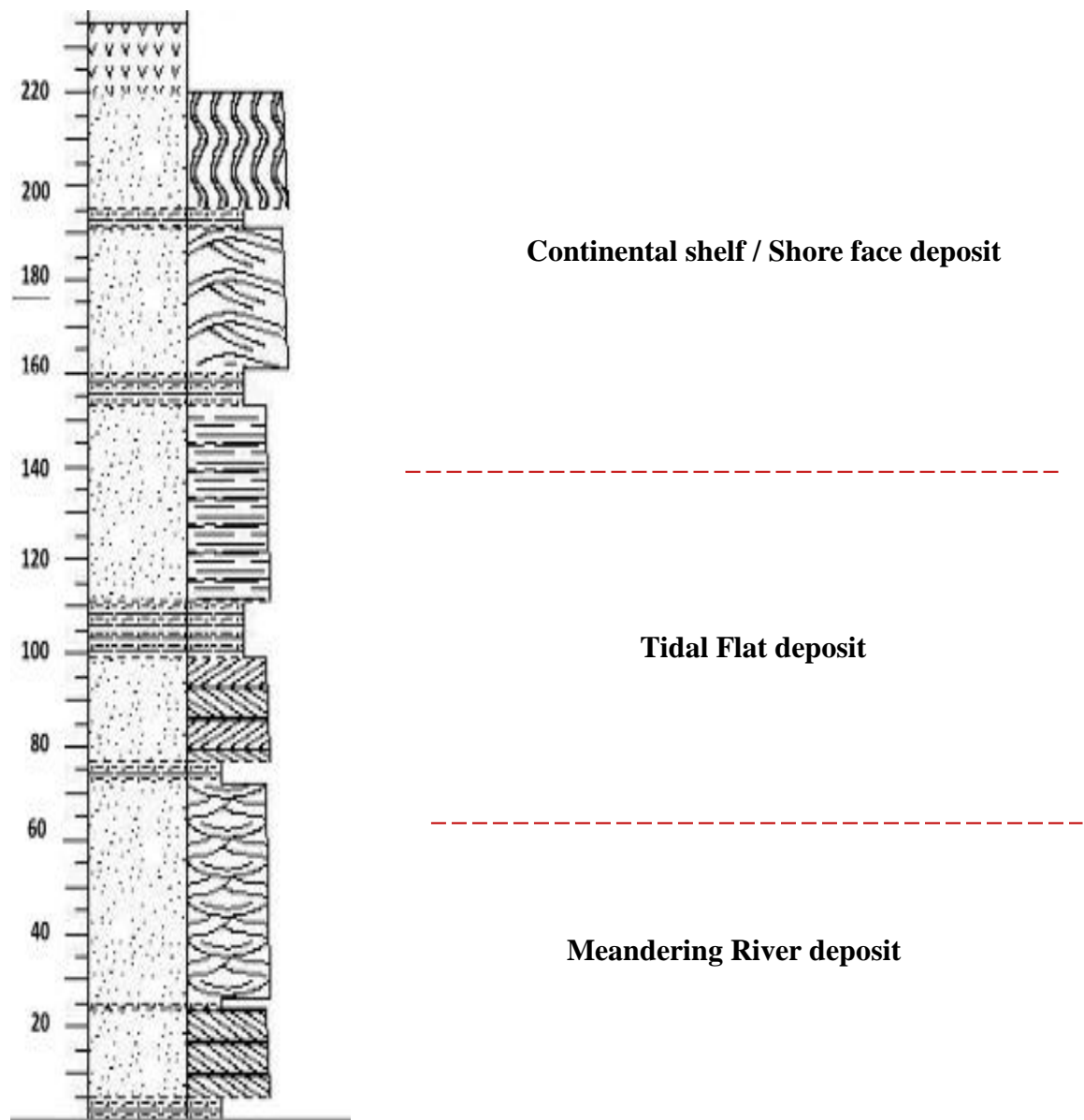


Figure 6.1 facies assemblage in the studied stratigraphic section

Generally the lithofacies type identified from this facies assemblage shows fining upward succession which is a particular point bar deposits of meandering river deposit.

6.1.2 Tidal Flat deposit

This deposit is part of the transitional depositional environment which is dominated by sand flat and mudflat deposits formed in a non-embayed or linear tide-dominated coasts of marine sediment supply. The medium-grained herringbone cross stratified sandstone lithofacies identified from studied section giving strong evidence of tidal deposit.

6.1.3 Continental shelf deposit

These depositional environments are under the continental plate margin where there is no noticeable slope submerged under the area of a shelf sea. From the identified lithofacies type five of them are grouped under this facies association. These lithofacies namely well-sorted thinly bedded sandstone ,Fine-grained hummocky cross-stratification sandstone ,fine-grained tool marked sandstone,medium to coarse-grained bioturbated sandstone facies and moderately sorted horizontal bedded sandstone facies .

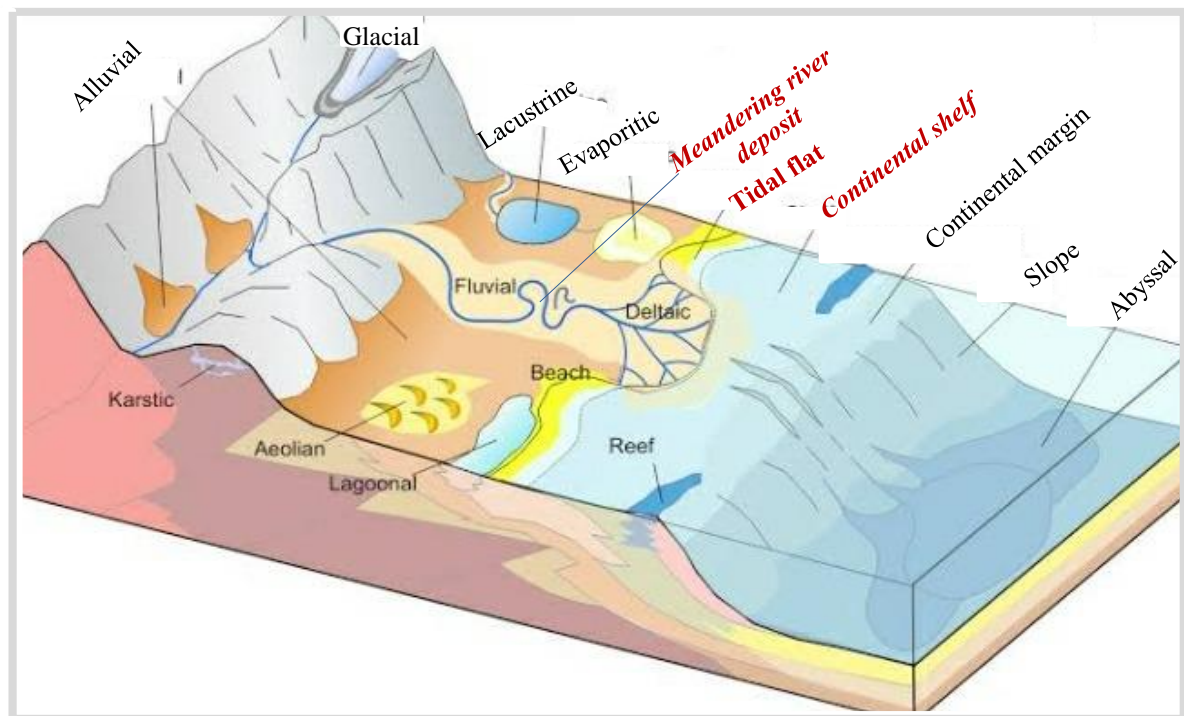


Figure 6.2 depositional model of sedimentary environment where the particular deposit written in red color showing the interpreted environment of Adigrat Sandstone from the present studies (source <https://en.m.wikipedia.org>)

6.2 Correlation

The present studied section is located in the central NW Ethiopia of the Blue Nile sedimentary basin. The siliciclastic units of yejube section which reaches the thickness of 220 m are logged in this study. It's grouped in different lithofacies types after a detailed lateral and vertical investigation of fieldwork. Both intra basinal correlation and regional correlation of Adigrat sandstone are made by referring to the previously worked sections by different scholars over time.

6.2.1 Intrabasinal Correlation

The siliciclastic sedimentary rocks in the Blue Nile (Abay) basin Particularly Adigrat sandstone are previously studied by different scholars at different times from different perspectives. The early Triassic to Jurassic Adigrat sandstone unit having 220 m thickness in yejube section is studied in this work, based on the lithological basis particularly vertical succession the present studied section is correlated with sections of Dejen, Dedu , Fincha, Eere and Bekotabo located in Blue Nile basin of central northwestern Ethiopia.

In the Dejen section located near the town of Dejen northwestern side of the Abay River bridge. It is around 60 km to the south direction from yejube section of the present study area. The Adigrat sandstone reach at the thickness of 195 m is exposed (Dawit, 2010). It overlies unconformably by Karro – group sediment and the evaporate deposit of Gohastion formation overlain above it (Dawit, 2010).

Dedu section is found near the town of Dedu in the western side of the river gorge of Guder, within that the Adigrat sandstone reaches up to 100 m thickness (Dawit, 2010). According to Dawit (2010) Tertiary basalt overlain the sandstone unit and the sandstone, unit overlies the Karoo Group. The succession starts with 25 m thick fluvial-estuarine deposits containing tidal flat, marsh, tidal bar, and isolated shallow tidal creek channel facies (Dawit, 2010).

Fincha section is also another section in which the Adigrat sandstone unit is exposed situated in the Blue Nile sedimentary basin. This section is located near the town of fincha with a section thickness of 80 m in which the Adigrat sandstone unit is bounded in between karoo group sediment and tertiary flood basalt (Dawit, 2010). In Dedu and Fincha Section the similarity in facies composition and section thickness indicating by a similar transgression process (Dawit, 2010).

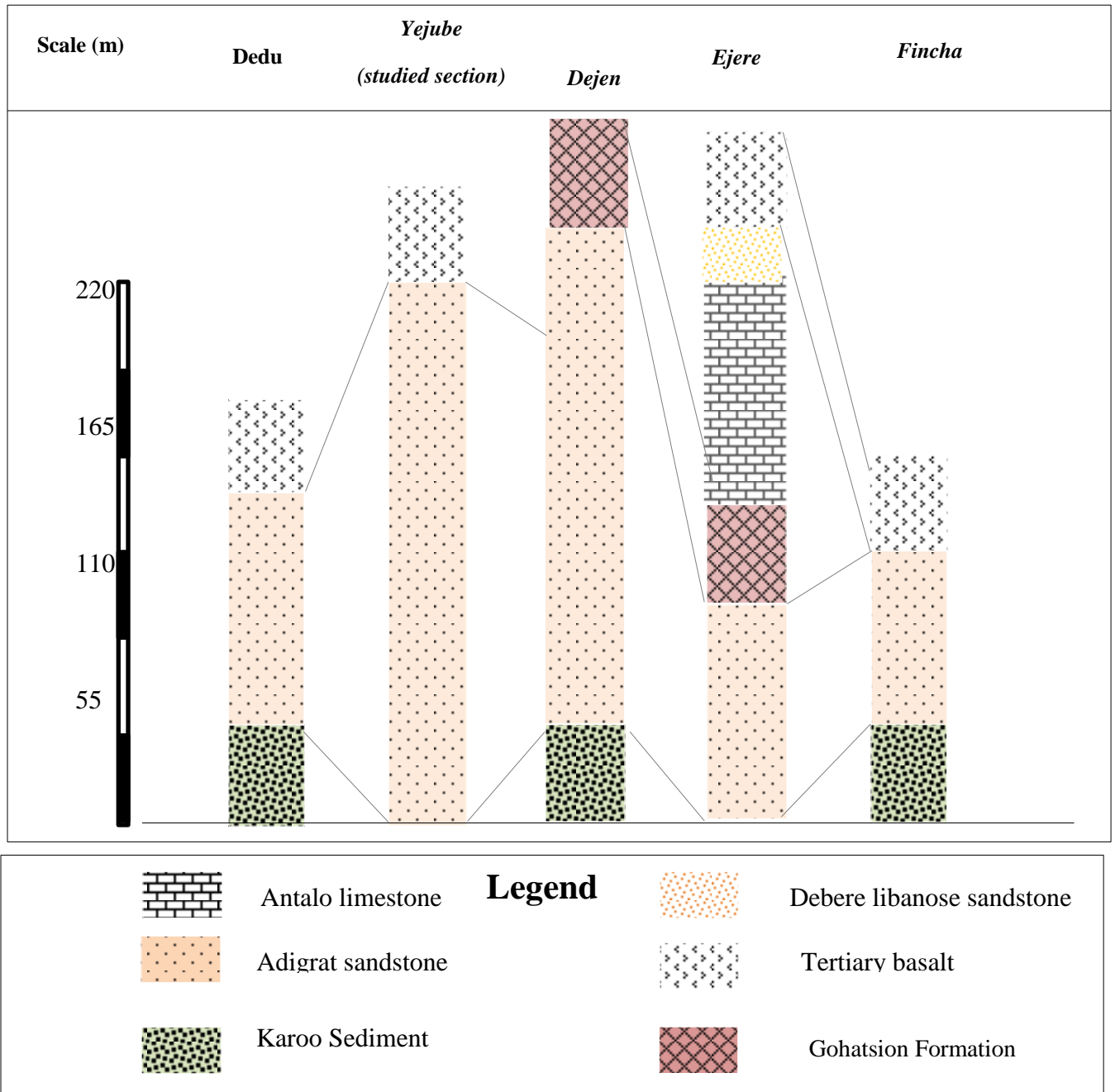


Figure 6.2 Intrabasinal correlation of Adigrat sandstone in a different section (Dejen ,Dedu , Fincha and Yejube (present study) Source: Dawit (2010).(The scale works for Adigrat sandstone formation).

6.2.2 Regional Correlation of Adigrat Sandstone

The Late Triassic – middle Jurassic Adigrat sandstone is formed out of the Blue Nile basin on a regional scale in other sedimentary basins of Ethiopia and East Africa. The Blue Nile and Mekelle basin of Ethiopia is a relatively studied sedimentary basin including this Adigrat sandstone unit than the Ogaden basin. In the Blue Nile basin the unit consists of a mixed clastic- evaporate sediment whereas the mekele basin this unit is composed of entirely sediment of siliciclastic (Dawit,2010).

In Mekelle sedimentary basin the Adigrat sandstone reaches up to a thickness of 670 m. According to Bosellini et al., (1997) the Adigrat sandstone deposited in the lacustrine – deltaic or estuarine as a result of an abundance of lacustrine bed interpret the continental depositional environment.

In Ogaden, the clastic deposit that overlies unconformably the basement rock in the southeastern of Ogaden basin is named as Adigrat sandstone with a maximum thickness reaching 250 m and According to (Damenu,2014) the depositional environment of southeastern Adigrat sandstone formation be continental to the continental margin. According to (work und Astin,1992) this formation in the Ogaden basin is classified into six lithofacies types namely massive to thinly laminated siltstone, massive to parallel laminated sandstone, cross-bedded fine sandstone, tabular cross-bedded conglomerate, cross-bedded medium-grained sandstone, and massive pebbly conglomerate. The formation in the Ogaden basin is containing microflora of the Rhaeto – Liassic age (Worku and Astin,1992).

The Adigrat sandstone formation extension not only bounded in Ethiopia but extended up to the Red sea, North Somalia, Kenya, and Tanzania (wolela,2008). The coast of the Red Sea of Eritrea reaches its maximum thickness of 1775 m (Bossellini et al., 1997). Generally The Negrenegre sandstone of Tanzania, the Mazera sandstone of Kenya, the Minjur sandstone of Saudi Arabia, and Kohan formation of Yemen (Bosellini,1989, Wolela ,2008).

| Age | | BlueNile Basin | Mekele Basin | Ogaden Basin | Somalia | Kenya | Tanzania |
|----------------------|--------|------------------------------|--|------------------------------|------------------------------|---|----------------------|
| Jurassic | Upper | Transitional Facies | Agula shale | Urandab shale | Hamanlei Limestone Formation | Kambe limestone | Station Limestone |
| | Middle | Hamanlei Limestone Formation | Hamanlei (Antalo) Limestone Formation | Hamanlei Limestone Formation | | | Negrenegre Sandstone |
| | Lower | Transitional facies | Transitional Facies | Transitional Facies | | | Mazera Sand stone |
| Triassic | Upper | Adigrat Sand stone | Adigrat Sandstone | Adigrat Sand stone | Adigrat Sand stone | Maria kuni Sand Stone | Karoo sediment |
| | Middle | Adigrat Sand stone Formation | Adigrat Sandstone Formation | Adigrat Sand stone Formation | Adigrat Sand stone Formation | | |
| | Lower | | | | | | |
| Permian - Ordovician | | Pre Adigrat Sediment | Edaga Arbi Glacial Enticho Sand Stone | Karoo Sediment | Pre Adigrat Formation | Maj ya chumri Formation Taru Formation | Karoo sediment |
| Pre Cambrian | | Basement rock | Basement Rock | Basement rock | Basement rock | Basement Rock | Basemen rock |

Figure 6.3 Regional correlation chart of Adigrat sandstone (After Wolela,2008)

6.3 Paleogeographic setting

The early Jurassic of Neotetethys which is forming the first Tethys sea caused the formation of east and west Gondwana (Reynolds et al.1997). In the middle Jurassic, the eustatic rise in sea level was enhanced by the rifting and crustal extension (Haq et al, 1987). According to (Haq et al.,1987) the pre rifting stage of Gondwana in Permian to Triassic and the actual break up takes place during Toarcian – Aalenian which caused the development of the east Africa-Madagascar margin.

There were two assumptions created by scholars which contradict each other. According to (Haq et al.,1987) the oldest crust dated in the Indian Ocean was the oceanic crust along the Somalia and Madagascar flanks. Unlike the previous others argue that the initial phase of separation causes the flooding of the continental margin of Africa and Madagascar in early Bajocian (Hankel 1994, Geiger et al.,2004).

In the late Triassic the east African affected by the karoo rifts that developed in the East African margin along the southern flanks, in which the crustal uplifting takes place after the karoo rift (Hankel,1994). In North-East Africa including the north and central Ethiopia also Arabian plate formed under the stable margin of the Neotethyan Ocean. According to Dawit(2010) in the Rhaeto –Norian age of prograding estuarine to shallow marine siliciclastics of Abay and Mekelle sedimentary basin of Ethiopia indicating the seaway widening to the northeast.

In this studied section the facies succession indicates the change from continental to shallow marine facies. According to Dawit (2010) in the Blue Nile and Mekelle basin., the age Adigrat sandstone was identified to be Late Triassic to Middle Jurassic from the palynological evidence. Therefore, by considering these facts, the formation of the basin, as well as the subsequent sediment accumulation to form this unit, could be related to the Late Triassic-Early Jurassic paleogeography of East Africa and Norian-Callovian sea-level fluctuation.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

- In the northwestern part of the Blue Nile sedimentary basin, there exists a section near to yejube of a thick 220 m Adigrat sandstone formation is exposed in the chemoga river valley.
- This sedimentological study, which includes a detailed lithofacies analysis in the field supported by petrographic and grain size analysis suggesting that the depositional environment of this formation is not restricted to a particular environment, rather it is deposited in a mixed sub environment.
- The section is subdivided into the upper, middle, and lower parts of the section based on the texture, stratigraphic position, and lithofacies type it contains. The lower part of the section is 80 m thick, fine to medium-grained sandstone with mudstone facies intercalated in between the sandstone. This subsection consists of lithofacies types of planar cross-bedded sandstone, Desiccation crack developed sandstone, and Trough cross-laminated sandstone facies. The middle part of the section which consisted of herringbone cross stratified sandstone and also is relatively gently exposed consists of 55 m thickness lithologically it is covered by unconsolidated mud and friable sandstone. The upper part of the section is dominated by a cliff-forming sandstone unit that has 85 m thickness which is overlain by Trap volcanics containing lithofacies type Well sorted thinly bedded sandstone, Fine-grained hummocky cross stratified sandstone, Fine-grained well-sorted tool marked sandstone, Moderately sorted horizontal bedded sandstone facies and Medium grained mud crack developed sandstone Facies.
- From petrographic studies, the sandstone is classified under the quartz arenite from the result obtained by modal analysis in which it suggests that its occurrence in an assemblage of rocks deposited in a stable cratonic environment (Boggs, 2009). The rounded-subrounded siliciclastic grains are interpreted to travel far distance before being deposited in their final destination (depositional environment) by fluvial action from uplifted sediment source area and further reworking by waves along shelf environment . The studied sandstone formation is both compositional and texturally matured as a result of the dominance of stable minerals like quartz in its framework grain and the existence of a very insignificant amount of clay minerals respectively.

- The grain size study indicates that from bimodal nature of grain size distribution indicating the sediment has more than one provenance. The range of the value of standard deviation from poorly sorted to medium sorted shows the effect of mixed depositional environment. The Wide range of the kurtosis value from very leptokurtic to very platykurtic indicating fluctuation in the energy of the deposition.
- Generally the deposition of the sediment is not restricted to a single depositional environment; rather it interpreted the sediment deposited in a mixed environment. Unlike its mixed environmental interpretation, the scatter plot of mean versus standard deviation and standard deviation versus skewness shows that the fluvial process dominates over the marine process.
- The identified lithofacies types in the field are grouped in the following facies assemblage.
 - Meandering river deposits: Planar cross-bedded medium-grained sandstone facies, Medium grained mud crack developed sandstone Facies and Fine-grained Trough cross-laminated sandstone
 - Tidal Flat deposit: Medium grained herringbone cross stratified sandstone facies
 - Continental shelf deposit: Well sorted thinly bedded sandstone, Fine-grained hummocky cross stratified sandstone, Fine-grained well-sorted tool marked sandstone, Moderately sorted horizontal bedded sandstone facies, and Medium to Coarse grain Bioturbated sandstone facies.
- From Lithofacies assemblage succession in the studied section, it gives a clue that transgression were responsible for the deposition during its formation.
- The yejube sandstone formation (Yejube Section) are correlated with sections from the blue Nile sedimentary basin of northwestern Ethiopia including Dejen, Dedu, Bekotabo, and Fincha section and with Mekelle and Ogaden sedimentary basin of Ethiopia and also correlated with Adigrat sandstone formation of Somalia, Mazara sandstone of Kenya and Negrenegre sandstone of Tanzania on the regional scale.

7.2. Recommendation

- The attempt has been made to reconstruct the depositional environment of the Late Triassic-Middle Jurassic Adigrat sandstone from yejube section of the Blue Nile sedimentary basin. Even if the present studies was the first local investigation on this section, to create a complete depositional picture of this formation in the basin a detailed study from different sections has to be conducted and to create a broad understanding of the formation of Adigrat sandstone in the studied section the provenance should have to be studied.
- Since Grain size analysis has a significant siliclastic sedimentological tool in environmental reconstruction using this method in the future studies is recommended.
- To assess the basin's petroleum potential and promote petroleum exploration more laboratory analysis from the sandstone unit with many samples as possible needed to be analyzed to assess its reservoir potential.

References

- Abbate, E., Bruni P. and Sagri, M (2015) *Geology of Ethiopia: A Review Geomorphological perspective* Springer Netherlands, 8:33-64.
- Abbate, E, Bruni, P & sagri, M 1987, *The Mesozoic to Tertiary deposits. Int. Meeting on the Geology of Somalia and surrounding regions, Excursion B guidebook*: 12-22
- Ayalew T, Bell K, Moore JM, Parrish RR (1990): U-Pb and Rb-Sr geochronology of the western Ethiopian shields. *Geol. Soci. of Am. Bull.* 102, 1309–1316.
- Ayalew, T. & Gichile, S. 1990. Preliminary U-Pb ages from southern Ethiopia. 15th Colloq. Afr. Geol. Extended abstracts: 127–130. Nancy.
- Asfawossen Asrat, Barbey, P. and Gleizes, G. (2001). *The Precambrian geology of Ethiopia: a review. African Geosciences Review*, 8: 271-288.
- Aubry, A. 1886. *Obsérvations géologiques sur les pays Danakils, Somalis, le Royaume de . Choa et lesl payes Gallas. Bull. Soc. Geol. Fr.* 14: 201–222.
- Barsisa Bekele (2011). *Geochemistry of Lower sandstone in Blue Nile gorge Mesozoic sedimentary sequences: Implication for provenance composition and paleoclimate*, Unpublished MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia, 103pp.
- Baldwin, C.T. and Johnson, H.D. (1996). *Shallow clastic Seas. In: Sedimentary. Environments: Processes, Facies and Stratigraphy*, Reading H.G. (edn), 3rd edn, Blackwell, USA, .pp. 232-280.
- Beyth, M. (1972a). *Paleozoic-Mesozoic sedimentary basin of Mekele Outlier, Northern Ethiopia. American Association Petroleum Geologists Bulletin.* 56:2426- 2439.
- Beauchamp, J. 1977. *La série sédimentaire en Éthiopie centrale et orientale. Lyon: Thèse de . Doctorat, Univ. Claude Bernard.*
- Blandford, W.T. (1870). *Observations on the Geology and Zoology of Abyssinia, made During British Expedition to that country in 1867-68. With Illustrations and a Geological Map.* Macmillan & Co, London.
- Boggs, J.r. (2009). *Petrology of the Sedimentary rocks*, 2nd ed. Cambridge, New York. 612pp
- Bosellini, A. (1989). *The continental margins of Somalia: Their structural evolution and Sequence stratigraphy, Mem. Sci. Geol.* 41: 373–458.
- Bosellini, A., Russo A. and Getaneh Assefa (2001). *The Mesozoic succession of Dire Dawa*, Bosellini, A., Russo, A., Fantozzi, P.L., Assefa, G. & Tadesse, S. 1997. *The Mesozoic*

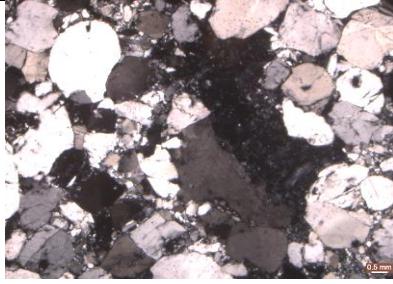
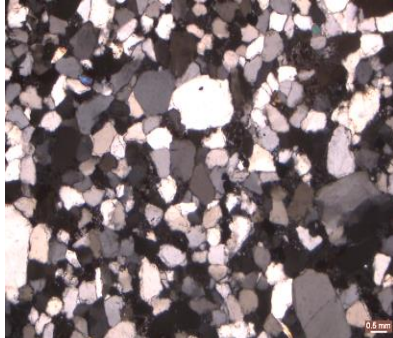
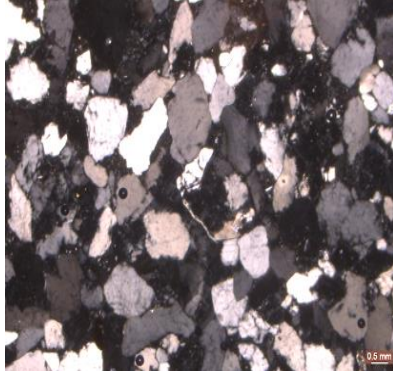
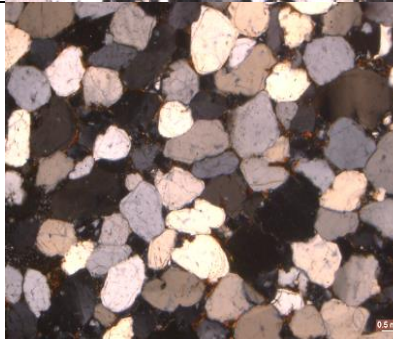
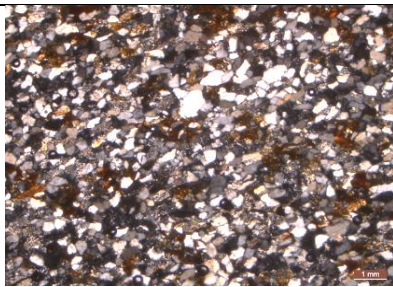
- succession of the Mekele Outlier (Tigray Province, Ethiopia). *Mem. Sci. Geol.* 49: 95–116. Harar Province, Ethiopia. *Journal of African Earth Sciences*, 32: 403-417pp
- Canuti P., Radrizzani C.P. (1975). Microfacies from the upper portion of the Antalo limestone Blue Nile sequence, Ethiopia. *Revista Espanõla de Micropaleontologia* 7: 131–147.
- Dainelli, G., 1943. *Geologia dell’Africa orientale*. Rome: Real Accad. Italia
- Damenu Adefris (2014). Paleoenvironmental reconstruction of Adigrat sandstone formation around Diredawa area southeast Ethiopia, Unpublished MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia, 75pp.
- Dawit, E.L. & Bussert, R. (2009). Latest Ordovician-Early Silurian postglacial tide-dominated shelf sediments in northern Ethiopia.
- Dawit, L. (2010). Adigrat Sandstone in Northern and Central Ethiopia: Stratigraphy, Facies Depositional Environments, and palynology. Unpublished Ph.D. Thesis, Technische university of Berlin. 166pp.
- Garzanti, E. (2019). Petrographic classification of sandstone. *Earth science review* 192(2019). 545 -563
- Elliott, T. (1986). Siliciclastic Shorelines. In: *Sedimentary Environments and Facies*, Reading H.G. (edn), Blackwell, Oxford, London, pp. 175-188.
- Friedman, G. M. (1961a). The distinction between dune, beach, and river sands from textural characteristics. *Jour. Sed. Petrology*, 31, 514-529.
- Folk, R. L. & Ward, W. C. (1957). Brazos river bar: A study in the significance of grain size parameters. *J. Sediment. Petrol.*, 27, 3-26.
- Folk, R.L. (1974). *Petrology of sedimentary Rocks* Austin, Hemphill, publishing co, USA (182pp)
- Getaneh Assefa (1991): Lithostratigraphy and environment of deposition of the Late Jurassic-Early Cretaceous sequence of the central part of the Northwestern Plateau, Ethiopia *NJb.geol.* 182, 255-284
- Getaneh Assefa (1975): Stratigraphy and sedimentology of the Mesozoic sequence in the upper Abay (Blue Nile) River Valley region, Ethiopia. PH.D. thesis University of Minnesota, USA
- Getaneh Assefa (1981): Gohatsion formation the A new Lias –Malm lithostratigraphic unit form Abay river basin, Ethiop.-*Geoscience*. 2, 63-88.
- Getaneh Assefa (1990): Stratigraphy and sedimentation of the type Gohatsion formation (Lias-Malm): Abay river basin, -Sinet, Ethiopia. *J.Sci.* 3, 87-110.

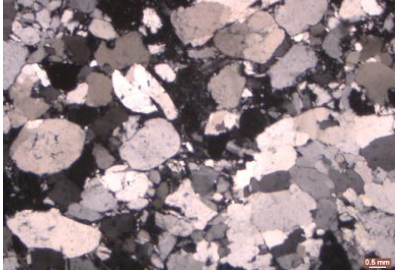

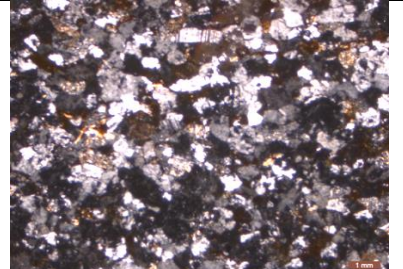
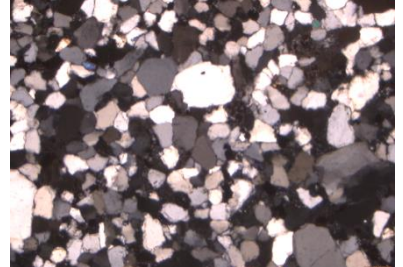
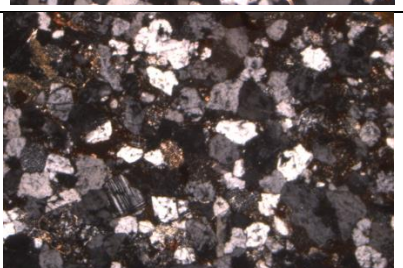
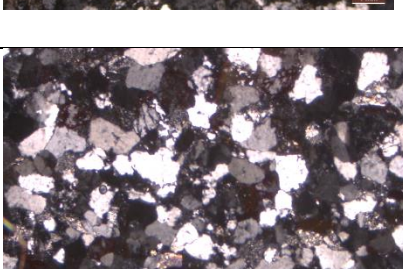
- Gani N.DS Abdeselam M.G, Gera.S Gani M.R. (2009).stratigraphic and structural evolution of The Blue Nile basin, Northwestern Ethiopian plateau.Geol.J.44:30-56.
- Geiger, M., Clark, D.N. & Mette, W. 2004. Reappraisal of the timing of the breakup of Gondwana based on sedimentological and seismic evidence from the Morondava Basin, Madagascar. *J. Afr. Earth Sci.* 38: 363–381.
- Hankel, O. 1994. Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar. *Geol. Rdsch.* 83: 703–710.
- Haq, B.U., Hardenbol, J. & Vail, P.R. 1987. Chronology of the fluctuating sea level since the Triassic. *Science* 235: 1156–1167.
- Hayes, M.O. 1980. General morphology and sediment patterns in tidal inlets. *Sediment. Geol.* 26: 139-156.
- Hunegnaw, A.,Sage,L and Gonnard, R. (1998).Hydrocarbon potential of the intracratonic Ogaden Basin.SE Ethiopia. *J. Petrol. Geol.* 21: 401-425.
- Kazmin, V., 1975. Explanatory Note to the Geology of Ethiopia. E.I.G.S, Bull.no.2, Addis Ababa, Ethiopia.
- Kazmin, V. (1973).Geology of Ethiopia (explanatory note to the geological map of Ethiopia 1:200000 scale), unpublished report Ministry of Mines, geological survey Of Ethiopia. Addis Ababa
- Kazmin, V. (1975). Explanation of the Geological Map of Ethiopia. Unpublished Korme, T., Acocella, V., Abebe, B., 2004. The role of pre-existing structures in origin, .propagation and architecture of faults in the Main Ethiopian Rift. *Gondwana Research.* 7. 467-479 technical report, Geological Survey of Ethiopia, Addis Ababa, Ethiopia, 18 pp.
- Krenkel, E. 1925. *Geologie Afrikas*. Berlin: Gebrüder Bomträger.
- Mohr.p.A. (1943).The geology of Ethiopia. Addis Ababa University press, Addis Ababa.
- Mohr, P.A. (1962). The geology of Ethiopia. University College of Addis Ababa Press, Addis Ababa, Ethiopia.
- Mandefro Gebeyehu (2019).Provenance and depositional tectonic setting of Late Triassic – Early Jurassic Adigrat Sandstone formation ,Blue Nile Basin ,NW Ethiopia : Evidence from petrographic and geochemistry (Unpublished MSc Thesis), Bahirdar, Ethiopia 103pp.
- Mengesha Tefera, Chernet Tewodros and Workineh Haro (1996). Geological Map of Ethiopia, 1:2000000, 2nd ed., Ethiopian Institute of Geological Survey, Addis Ababa.

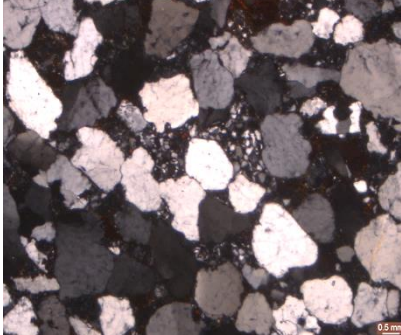
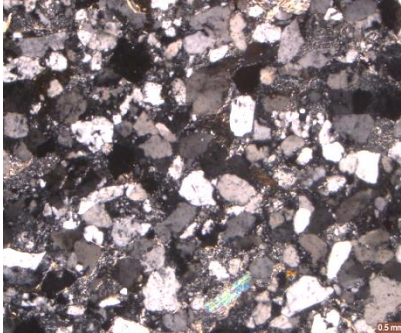
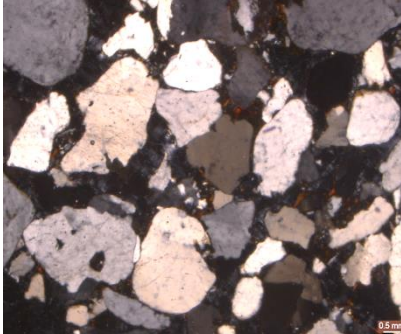
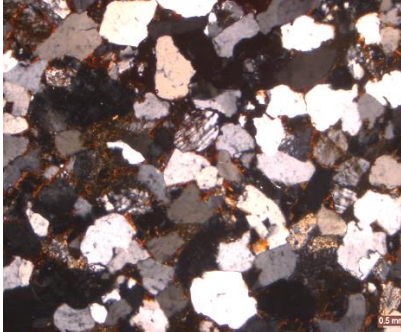
- Mogessie.A, Krenn.K, Schaflechner.J, Koch.U, Egger.T.Goritchin.B, Kosednar.B,Pichler.H, Ofner.L, Bauernfeind.D, Tadesse.S, Hailu.K and Demessie..M. (2002).a Geological excursion to the Mesozoic sediments of the Abay basin (Blue Nile), Recent volcanics of the Ethiopian main rift and basement rocks of the adola Area, Ethiopia.mitt.osterr.miner.Ges.147.
- Mulugeta.A (1991). Tectonometamorphic evolution of the Moyale region, southern Ethiopia, University of Southampton. P 200
- Mulugeta.A (1991). Tectonometamorphic evolution of the Moyale region, southern Ethiopia University of Southampton. P 200
- Nichols, G. (2009). Clastic Coasts and Estuaries. In: Stratigraphy and Sedimentology, Gary Nichols (edn), 2nd ed., John Wiley & Sons, pp. 199-214.
- Okeyode and Nnamdi (2012). Grain size analysis of the sediment from Ogun River, Southwestern Nigeria, University of Ibadan, Ibadan, Nigeria.
- Patric.M and Donald, B.(1985). The effects of sediment transport on grain size distribution.
- Pettijohn, F.H., Potter, P.E., and Siever, R., (1987). Sand and sandstone. Springer-Verlag, New York, 618p
- Reynolds, P.O., Schandelmeier, H. & Semtner, A.K. 1997. Chapter 8. The Early Jurassic (Toarcian, ca. 180 Ma). In H. Schandelmeier & P.O. Reynolds (eds.), PalaeogeographicPalaeotectonic Atlas of Northeastern Africa, Arabia, and Adjacent Areas: 51–54. Rotterdam: Balkema.
- Russo, A., Getaneh Assefa & Balemwal Atnafu (1994): Sedimentary evolution of the Abay River.(Blue Nile) Basin, Ethiopia.-N.Jb.Geol.16: 91-107.
- Samuel Getachew (2018), Stratigraphic, Petrographic and geochemical characteristics of the Gohatsion formation in the Blue Nile basin, Central Ethiopia Implication for paleoenvironmental reconstruction MSc Thesis, Addis Ababa University, Addis Ababa Ethiopia,103pp.
- Scholle,P.A(1979). A color illustrated guide to constituents, Texture, cement, and porosities of sandstones and Associated Rocks,28 American Association of Petroleum Geologist, Memoir(201 pp).
- Serawit Amene and Tamrat Mojo (1999).The Geology of Mughher Cement Factory Area, Aba Serawit A., and Tamrat M., (1999). The geology of Mughher cement factory area. Abay basin, North Shoa. Ministry of mines and energy. Petroleum operations department. (unpublished report) y Basin, North Showa.

- Serawit A., and Tamrat M., (1995).The Geology of Jema river valley, North showa, Abay Basin: Ministry of Mines and energy: Petroleum operations department: Addis Ababa, (unpublished report).
- Serawit A., and Tamrat M., (1995).The Geology of Jema river valley, North showa, Abay Basin: Ministry of Mines and energy: Petroleum operations department: Addis Ababa, Serawit, A., and Tamrat, M., (1999). The Geology of Mughher cement Factory area, North Shoa, Abay Basin: Ministry of Mines and energy: Petroleum Operations Department, Addis Ababa, p. 12. (Unpublished report). (unpublished report).
- Sorby, Henry Clifton: on the Microscopical structure of the calcareous grit of the York shire coast, Geol, SOC London Quart; Jour 1-6 (1851).
- Tamrat Mojo and Tibebe, G.S. (1997) The Geology of Gendiberit- Jeldu and Amuru-jarti areas (East Wellega and Western Shoa), Ministry of mines and Control, Petroleum. operations Department, Addis Ababa, Ethiopia.
- Tucker (2003). Sedimentary rock in the field 3rd ed.234 pp
- Wentworth CK. (1922). A scale of grade and class terms for clastic sediments. Journal of Geology 30: 377–392.
- Wolela, A. M, (1997): Sedimentology, Diagenesis and Hydrocarbon Potential of Sandstone in the hydrocarbon perspective rift basins (Ethiopia, UK, USA).-Ph.D. Thesis, The Queen’s Univ., Belfast, 238p.
- Wolela, A. M. (2008): Sedimentation of the Triassic-Jurassic Adigrat sandstone formation, Blue Nile (Abay) Basin, Ethiop. 52: 30-42.
- Worash Getaneh (2002). Geochemistry provenance and depositional tectonic setting of Adigrat Sandstone northern Ethiopia. Journal of African Earth Sciences, 35: 185-198.
- Worku, T. & Astin, T.R. 1992. The Karoo sediments (Late Palaeozoic to Early Jurassic) of the Ogaden Basin, Ethiopia. Sediment. Geol. 76: 7–21.
- Udden JA. (1914). Mechanical composition of clastic sediments. Bulletin of the Geological Society of America 25: 655–744.

Appendix I

| | | |
|------|---|--|
| NT-1 |  | <p><i>Moderately sorted sandstone thin section dominated by mineral quartz point-counting data showing that is grouped under quartz arenite sandstone, the grains of quartz has subangular to subrounded shape and small grains of quartz act as a cementing material. Suture contact in the polycrystalline quartz indicating metamorphic provenance.</i></p> |
| NT-2 |  | <p><i>Well, sorted quartz dominated fine to medium-grained sandstone sample, the opaque and heavy mineral is seen. The quartz grain is monocrystalline almost at all in which pressure solution, undulose extinction is observed. This sample grouped under quartz arenite based on modal analysis of framework grain.</i></p> |
| NT-4 |  | <p><i>Sample of sandstone under thin section having significant porous space. quartz grain having a subrounded shape is dominated the framework mineralogy and a small proportion of feldspar grain is observed. Around the center of the thin section, a sheet of muscovite flake is observed.</i></p> |
| NT-5 |  | <p><i>This sample typical example of quartz arenite sandstone-dominated mineral quartz, with a rounded shape. From the modal analysis result, it is almost all covered by monocrystalline quartz minerals. Between the grain of mineral reddish color act as cementing material is an indicator of hematite cement.</i></p> |
| NT-7 |  | <p><i>It is fine grain moderately sorted sandstone sample. It comprises monocrystalline quartz, feldspar, and lithic fragments. It's one of the few analyzed samples that deviate from the quartz arenite group and is grouped under sublitharenite.</i></p> |

| | | |
|-------|---|---|
| NT-8 |  | <p><i>It consists of both monocrystalline and polycrystalline quartz-dominated sandstone. in polycrystalline quartz, the grains have sutured contact between them. There is a dark muddy matrix is observed in between the quartz grain.</i></p> |
| NT-10 |  | <p><i>It is grouped in Sublitharenite in sandstone classification containing more lithic fragments next to the quartz mineral. Generally, it has moderate sorting; the red color seen between framework grain is an indicator of hematite cement.</i></p> |
| NT-11 |  | <p><i>It comprises quartz, feldspar particularly microcline and lithic fragment calcite, and hematite used in the cementation between framework grains.</i></p> |
| NT-12 |  | <p><i>It comprises a large number of sub-rounded to rounded, Mono-crystalline quartz grains with variable grain sizes, it is grouped under quartz arenite (100X magnification under XPL).</i></p> |
| NT-13 |  | <p><i>It comprises monocrystalline quartz, lithic rock fragment, and feldspar particularly microcline and at the upper part, the mica sheet is observed.</i></p> |
| NT-14 |  | <p><i>It contains a relatively high amount of lithic fragment next to the mineral quartz. K feldspar and mica fragments are also observed, hematite and calcite cementation is observed.</i></p> |

| | | |
|-------|---|---|
| NT-15 |  | <p><i>It contains a large number of monocrystalline quartz minerals, the fine quartz grain act as a cementing role in between a large grain in addition with hematite cement. According to the modal analysis, the sample grouped under quartz arenite.</i></p> |
| NT-16 |  | <p><i>It comprises minerals of quartz(monocrystalline) sedimentary lithic fragment and a small amount of K-feldspar. At the bottom, part Biotite sheet is observed. According to the modal analysis, its grouped under the sublitharenite.</i></p> |
| NT-17 |  | <p><i>It contains large grain monocrystalline quartz minerals with insignificant feldspar and lithic fragment the grains are mainly cemented by hematite.</i></p> |
| NT-18 |  | <p><i>It includes quartz (both monocrystalline and polycrystalline), microcline feldspar, and an insignificant amount of Lithic fragment. Calcite minerals and hematite are used to cement the framework grain of the sandstone.</i></p> |

Appendix II

| Grain Size Analysis Data | | Sample ID: <u>NGS11</u> | | |
|----------------------------------|---------------------------|-------------------------|------------------------------------|-------------------------------------|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 0.9345 | 0.46725 | 0.46725 | 100 |
| 2-1.18 | 0.3463 | 0.17315 | 0.6404 | 99.53275 |
| 1.18-0.6 | 0.7514 | 0.3757 | 1.0161 | 99.3596 |
| 0.6-0.3 | 30.4328 | 15.2164 | 16.2325 | 98.9839 |
| 0.3-0.16 | 124.5759 | 62.28795 | 78.52045 | 83.7675 |
| 0.16-0.063 | 39.489 | 19.7445 | 98.26495 | 21.47955 |
| <0.063 | 3.4701 | 1.73505 | 100 | 1.73505 |

| Grain Size Analysis Data | | Sample ID ; <u>NGS10</u> | | |
|-----------------------------------|---------------------------|--------------------------|------------------------------------|-------------------------------------|
| Type of Analysis : Sieve Analysis | | | | |
| Sieve Opening Mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 31.7731 | 15.88655 | 15.88655 | 100 |
| 2-1.18 | 10.2005 | 5.10025 | 20.9868 | 84.11345 |
| 1.18-0.6 | 43.2032 | 21.6016 | 42.5884 | 79.0132 |
| 0.6-0.3 | 64.7267 | 32.36335 | 74.95175 | 57.4116 |
| 0.3-0.16 | 36.4061 | 18.20305 | 93.1548 | 25.04825 |
| 0.16-0.063 | 12.0168 | 6.0084 | 99.1632 | 6.8452 |
| <0.063 | 1.6736 | 0.8368 | 100 | 0.8368 |

| Grain Size Analysis Data | | | Sample ID ; NGS7 | |
|-----------------------------------|---------------------------------|----------------------|---------------------------------------|--|
| Type of Analysis : Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 41.7531 | 20.87655 | 20.87655 | 100 |
| 2-1.18 | 34.0206 | 17.0103 | 37.88685 | 79.12345 |
| 1.18-0.6 | 59.15 | 29.575 | 67.46185 | 62.11315 |
| 0.6-0.3 | 35.7082 | 17.8541 | 85.31595 | 32.53815 |
| 0.3-0.16 | 20.5726 | 10.2863 | 95.60225 | 14.68405 |
| 0.16-0.063 | 7.0968 | 3.5484 | 99.15065 | 4.39775 |
| <0.063 | 1.6987 | 0.84935 | 100 | 0.84935 |

| Grain Size Analysis Data | | | Sample ID ; NGS8 | |
|-----------------------------------|---------------------------------|----------------------|---------------------------------------|--|
| Type of Analysis : Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 29.3917 | 14.69585 | 14.69585 | 100 |
| 2-1.18 | 16.6759 | 8.33795 | 23.0338 | 85.30415 |
| 1.18-0.6 | 64.9121 | 32.45605 | 55.48985 | 76.9662 |
| 0.6-0.3 | 59.3258 | 29.6629 | 85.15275 | 44.51015 |
| 0.3-0.16 | 17.8535 | 8.92675 | 94.0795 | 14.84725 |
| 0.16-0.063 | 8.3821 | 4.19105 | 98.27055 | 5.9205 |
| <0.063 | 3.4589 | 1.72945 | 100 | 1.72945 |

| Grain Size Analysis Data | | | Sample ID ; NGS2 | |
|-----------------------------------|---------------------------|-------------------|------------------------------------|-------------------------------------|
| Type of Analysis : Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 60.0576 | 30.0288 | 30.0288 | 100 |
| 2-1.18 | 9.9197 | 4.95985 | 34.98865 | 69.9712 |
| 1.18-0.6 | 21.7601 | 10.88005 | 45.8687 | 65.01135 |
| 0.6-0.3 | 61.467 | 30.7335 | 76.6022 | 54.1313 |
| 0.3-0.16 | 37.1696 | 18.5848 | 95.187 | 23.3978 |
| 0.16-0.063 | 7.7125 | 3.85625 | 99.04325 | 4.813 |
| <0.063 | 1.9135 | 0.95675 | 100 | 0.95675 |

| Grain Size Analysis Data | | | Sample ID ; NGS9 | |
|----------------------------------|---------------------------|-------------------|------------------------------------|-------------------------------------|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 28.6928 | 14.3464 | 14.3464 | 100 |
| 2-1.18 | 11.7257 | 5.86285 | 20.20925 | 85.6536 |
| 1.18-0.6 | 50.294 | 25.147 | 45.35625 | 79.79075 |
| 0.6-0.3 | 74.4362 | 37.2181 | 82.57435 | 54.64375 |
| 0.3-0.16 | 26.321 | 13.1605 | 95.73485 | 17.42565 |
| 0.16-0.063 | 7.431 | 3.7155 | 99.45035 | 4.26515 |
| <0.063 | 1.0993 | 0.54965 | 100 | 0.54965 |

| Grain Size Analysis Data | | | Sample ID; NGS5 | |
|----------------------------------|---------------------------------|----------------------|---------------------------------------|--|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 4.09 | 2.045 | 2.045 | 100 |
| 2-1.18 | 4.1429 | 2.07145 | 4.11645 | 97.955 |
| 1.18-0.6 | 21.5383 | 10.76915 | 14.8856 | 95.88355 |
| 0.6-0.3 | 118.2954 | 59.1477 | 74.0333 | 85.1144 |
| 0.3-0.16 | 49.3611 | 24.68055 | 98.71385 | 25.9667 |
| 0.16-0.063 | 2.1023 | 1.05115 | 99.765 | 1.28615 |
| <0.063 | 0.47 | 0.235 | 100 | 0.235 |

| Grain Size Analysis Data | | | Sample ID; - NGS1 | |
|----------------------------------|---------------------------------|----------------------|---------------------------------------|--|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 139.6976 | 69.8488 | 69.8488 | 100 |
| 2-1.18 | 16.953 | 8.4765 | 78.3253 | 30.1512 |
| 1.18-0.6 | 13.1364 | 6.5682 | 84.8935 | 21.6747 |
| 0.6-0.3 | 15.684 | 7.842 | 92.7355 | 15.1065 |
| 0.3-0.16 | 11.5697 | 5.78485 | 98.52035 | 7.2645 |
| 0.16-0.063 | 2.2406 | 1.1203 | 99.64065 | 1.47965 |
| <0.063 | 0.7187 | 0.35935 | 100 | 0.35935 |

| Grain Size Analysis Data | | | | Sample ID; NGS3 | |
|----------------------------------|---------------------------------|----------------------|---------------------------------------|--|--|
| Type of Analysis: Sieve Analysis | | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize | |
| >2 | 6.8811 | 3.44055 | 3.44055 | 100 | |
| 2-1.18 | 6.6715 | 3.33575 | 6.7763 | 96.55945 | |
| 1.18-0.6 | 25.6627 | 12.83135 | 19.60765 | 93.2237 | |
| 0.6-0.3 | 142.397 | 71.1985 | 90.80615 | 80.39235 | |
| 0.3-0.16 | 14.0683 | 7.03415 | 97.8403 | 9.19385 | |
| 0.16-0.063 | 3.3441 | 1.67205 | 99.51235 | 2.1597 | |
| <0.063 | 0.9753 | 0.48765 | 100 | 0.48765 | |

| Grain Size Analysis Data | | | | Sample ID; NGS12 | |
|----------------------------------|---------------------------------|----------------------|---------------------------------------|--|--|
| Type of Analysis: Sieve Analysis | | | | | |
| Sieve Opening mm | Sample weight retained gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize | |
| >2 | 8.347 | 4.1735 | 4.1735 | 100 | |
| 2-1.18 | 2.6675 | 1.33375 | 5.50725 | 95.8265 | |
| 1.18-0.6 | 4.7825 | 2.39125 | 7.8985 | 94.49275 | |
| 0.6-0.3 | 78.8519 | 39.42595 | 47.32445 | 92.1015 | |
| 0.3-0.16 | 82.1218 | 41.0609 | 88.38535 | 52.67555 | |
| 0.16-0.063 | 19.9695 | 9.98475 | 98.3701 | 11.61465 | |
| <0.063 | 3.2598 | 1.6299 | 100 | 1.6299 | |

| Grain Size Analysis Data | | | Sample ID; NGS6 | |
|----------------------------------|---------------------------|-------------------|------------------------------------|-------------------------------------|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained Gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 31.8793 | 15.93965 | 15.93965 | 100 |
| 2-1.18 | 52.8787 | 26.43935 | 42.379 | 84.06035 |
| 1.18-0.6 | 68.109 | 34.0545 | 76.4335 | 57.621 |
| 0.6-0.3 | 35.663 | 17.8315 | 94.265 | 23.5665 |
| 0.3-0.16 | 8.2061 | 4.10305 | 98.36805 | 5.735 |
| 0.16-0.063 | 2.5254 | 1.2627 | 99.63075 | 1.63195 |
| <0.063 | 0.7385 | 0.36925 | 100 | 0.36925 |

| Grain Size Analysis Data | | | Sample ID; NGS4 | |
|----------------------------------|---------------------------|-------------------|------------------------------------|-------------------------------------|
| Type of Analysis: Sieve Analysis | | | | |
| Sieve Opening mm | Sample weight retained Gm | Weight % Retained | Cumulative weight percent oversize | Cumulative weight percent undersize |
| >2 | 10.5764 | 11.2882 | 11.2882 | 100 |
| 2-1.18 | 18.3602 | 8.1801 | 19.4683 | 88.7118 |
| 1.18-0.6 | 60.2994 | 29.1497 | 48.618 | 80.5317 |
| 0.6-0.3 | 72.5128 | 35.2564 | 83.8744 | 51.382 |
| 0.3-0.16 | 28.7931 | 13.39655 | 97.27095 | 16.1256 |
| 0.16-0.063 | 6.7901 | 2.39505 | 99.666 | 2.72905 |
| <0.063 | 2.668 | 0.334 | 100 | 0.334 |

Appendix III

| Month | Maximum Temperature | Minimum Temperature | Average Temperature |
|--------------|----------------------------|----------------------------|----------------------------|
| January | 24.6 | 11.3 | 18.1 |
| February | 26.3 | 12.4 | 19.5 |
| March | 26.2 | 13.9 | 19.8 |
| April | 25.9 | 13.9 | 19.8 |
| May | 24.3 | 13.4 | 18.6 |
| June | 21.5 | 12.6 | 16.6 |
| July | 19.8 | 12.5 | 15.7 |
| August | 19.7 | 12.4 | 15.7 |
| September | 21 | 11.9 | 16.1 |
| October | 22.7 | 11.3 | 16.8 |
| November | 23.2 | 11 | 16.8 |
| December | 23.2 | 10.7 | 17 |