CENTERS FOR ETHIO-MINES DEVELOPMENT,

ADDIS ABABA INSTITUTE OF TECHNOLOGY

PROVENANCE CONTROLS ON POROSITY EVOLUTION, ADIGRAT SANDSTONE, OGADEN BASIN, SOUTH EAST ETHIOPIA

BY MAHAMED HASSEN

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DECLARATION

This Project work entitled ***Provenance Controls on Porosity Evolution, Adigrat Sandstone, Ogaden Basin, SE Ethiopia,*** is my original master's degree under the supervision of **Dr. Solomon Kassa (PhD)**. I want to declare that this research work has not been presented or submitted for any degree at any University (institutions). All relevant source materials used for this project work have been duly acknowledged.

Name	**Signature**	**Date**
Mahamed Hassen	____________	___________

Approval Page

This is to certify that this Research Project was prepared by **Mahamed Hassen** which is entitled "***Provenance Controls On Porosity Evolution, Adigrat Sandstone, Ogaden Basin, SE Ethiopia***"**,** is submitted as a partial fulfillment for the award of the degree of master of Petroleum Engineering compiles with the regulation of Addis Ababa University and meets the accepted standards with respect to originality, content, and quality.

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DEDICATION

To My Family

ABBREVIATIONS

F	Feldspar
GSE	Geological Survey of Ethiopia
LEM	Light electronics microscope
MoM	Ministry of Mine
N	North
NE	North East
NW	North West
NNE	North North East
NNW	North North West
Qm	microcrystalline quartz
Qp	polycrystalline quartz
Qtz	Quartz
S	South
SE	South East
SW	South West
SSW	South South West
Sst	Sandstone
SE	South East
ENE	East North East
WSW	West South West

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ABSTRACT

The Ogaden basin is the largest sedimentary basin in Ethiopia, with 350,000 km^2 of areal coverage. Although it is the most studied region, so far 72 wells have been planned to be drilled in the area, i.e., the number of wells per area covered is 4861 km^2. This thesis investigates provenance based on petrography, facies analysis of Adigrat Sandstone in Calub-wells and Hilala-wells in the Ogaden Basin, Ethiopia. A Detailed laboratory petrographic analysis was done on 25 sandstone samples (15 sample from the Calub field wells and 10 sample from the Hilala field wells). Changes in the mineral composition and lithofacies of these sediments over time relate to the tectonic development of the region. When the different grain mineralogies are associated with different source rock types, the signals of at least two distinct sediment source regions emerge. The relative amounts of sand-sized material from the study areas indicate a shift in provenance over time; with the advance of the Calub-wells, a mixed provenance of sedimentary and metamorphic source terrains gave way to a depositional record characterized by sedimentary source rocks. Petrographic and modal composition of the sandstone classification displayed mostly quartz arenite with few subarkosic and sublithic arenite. The modal composition of sandstone revealed that the provenances are craton interior, recycled orogeny, and continental block provenance. From the Qt-F-L tectonic setting plot, all samples fall outside of the tectonic setting field as a result of intense weathering. According to the analyzed data, the porosity of the Adigrat sandstone of the two gas fields is medium therefore the reservoir is good.

CHAPTER ONE

1. INTRODUCTION

1.1. Background

There are various rock kinds in Ethiopia, each with a unique origin, age, and evolution. Sedimentary rocks are made up of those kinds of rocks, and they cover around 33% of Ethiopia's surface. There are five distinct sedimentary basins in Ethiopia, and they are the Southern Rift Basins (N-S striking), which include the Ogaden (350,000 km^2), Abay (63,000 km^2), Gambela (17,500 km^2), and Mekele (8000 km^2) (Assefa, 1988; Barnes, 1976; Beauchamp et al., 1990; Worku and Astin, 1992). According to Worku and Astin, (1992), the breakup of Gondwanaland in the Upper Paleozoic caused extensional forces that resulted in the formation of the Ogaden, Abay, and Mekele basins, which are thought to be intracontinental rift basins.

In the southeast of Ethiopia, you'll find the Ogaden Basin. The break-up of the massive continent Gondwanaland during the Permo-Triassic period is linked to the development of the basin. Southeast Ethiopia is home to a sizable portion of this Paleozoic-Mesozoic basin, which is distinguished by its internal highs and deep, asymmetrical grabens (MoM, 2011). The rifting of the NE-SW to ENE-WSW trending Calub Saddle in the east of the basin, the NNE-SSW oriented Mandera-Bodle Rift known as the Bodle Deep in the southern section, and the NW-SE trending Abay rift in the northwest of the basin resulted in the formation of the intra-cratonic Ogaden basin. According to Hinegnaw et al. (1998), this tri-radial rifting was active from the Late Paleozoic to the Mesozoic. Sedimentary successions from the Paleozoic and Tertiary span up to 10,000 meters. Karoo sediments (from the Permian to the Lower Jurassic) are the oldest sediments in the basin.

The Ogaden Basin is seen as having a promising petroleum future since it has drawn the interest of numerous oil corporations engaged in exploration. The Standard Oil Company of New Jersey's British subsidiary, Anglo American, began conducting petroleum research in Ethiopia in 1920 (John, 2016). Then, in 1945, Sinclair Petroleum Co. conducted mapping, gravity, magnetic, and reflection surveys, surface geology surveying, and aerial photography, but reported an oil show in 1952 despite seismic studies (Hunegnaw, 1998). As in Assefa (1988), the Ogaden Basin's possible organic-rich source rocks have been identified as the Permian Bokh Shale, Hamanlei Limestone, and Urandab Shale, while its potential reservoirs are the Permian Calub Sandstone, Adigrat Sandstone, and Hamanlei Carbonates (John, 2016).

Based on the data gathered during the petrographic study, rocks are classified. The origin of the sandstone's mineral grains (quartz, feldspar, lithic fragment, and heavy minerals) is known. Particularly, information from rock fragments, can provide insight into the lithology of provenance and the history of sediment transit (Dubey and Chatterjee, 1997). Four factors, including provenance, transportation, depositional environment, and diagenesis, affect the composition of detrital sediments (Suttner, 1974). After being first proposed by Crook (1974) (Cited in Basu, 2003), the ability to determine the tectonic setting of sandstones using the composition of the detrital framework minerals has since been demonstrated by numerous researchers, including Dickinson and Suczek (1979), Dickinson et al. (1983), Dickinson (1985), and Basu (2003). Additionally, they made the supposition that "the main assumption behind sandstone provenance studies is that different tectonic settings contain their own rock types, which when eroded produce sandstones with specific compositional ranges." The composition of sandstone provides information about its provenance and paleoclimate, while its internal structures and directional patterns provide information about paleocurrent direction and depositional settings. The aim of this research project is to establish and know the reservoir quality and how the provenance of sandstone affects the porosity of the reservoir using different techniques.

1.2. Geographic Setting of the Study Area

1.2.1. Location and Accessibility of the Study Area

Calub and Hilala gas fields are located in the Somalia region in the southeastern part of Ethiopia (**Figure 1.1**). The Calub gas field is about 700 kilometers directly southeast of the capital, Addis Ababa. The Hilala gas field is located 72 kilometers to the west of the Calub gas field. There is no village within 10 kilometers of the Calub gas field, that can connect to the outside through gravel roads and asphalt, so the traffic is relatively convenient, and currently the camp is in the field.

The study area belongs to the Ethiopian-Somalia plain, in which topography is high in the west and low in the east. The elevation is 450-480 m for the Calub gas field, 500-600 m for the Hilala gas field. The area's vegetation is dominated by bush and grass. There is a typical arid and semiarid climate, which is hot and dry, and the annual average temperature is 25°C. The rainy seasons are in March-June and October- November every year.

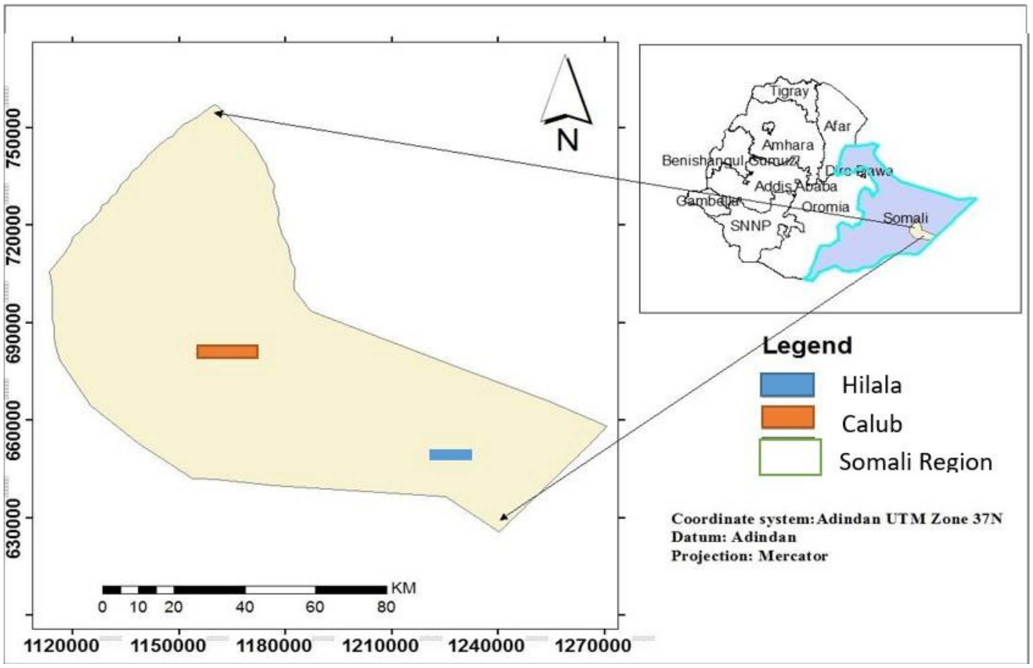


Figure 1.1 Location map Calub-Y and Hilala-X

1.2.2 Physiography and Drainage

The province appears to be divided into three informal physiographic feature groups. The Eastern Slope and Plains, as well as the Genale and Shebelle drainage basins are these. Outstanding upstream canyons in the drainage basins show the vertical movements that have gone hand in hand with the series of rifting episodes in the Ethiopian Rift, Afar, and the Gulf of Aden. The Eastern Slopes and Plains, in contrast, are soft and spread out over hundreds of kilometers to the southeast. They are blanketed with sheets of red sand.

1.3. Statement of the Problem

The Ogaden basin covers an area of 350,000 km^2, making it a sizable sedimentary basin. Despite being Ethiopia's most studied region, just 72 wells have been sunk there thus far, covering an area of roughly 4861 km^2. Numerous investigations should be carried out to better comprehend the reservoir rocks in an undrilled location.

The nature of the Adigrat sandstone reservoir rock with respect to provenance, which has an effect on the quality of the reservoir rock, is unknown because provenance studies have never been conducted in the Ogaden basin. In order to predict the similarities and differences between the Adigrat sandstone reservoir rock in drilled areas and undrilled or to be explored locations in the Ogaden basin, such a type of analysis is essential. Similar to Adigrat sandstone, which is referred to as low porosity reservoir rock, it is unknown how the rock's low porosity relates to its source.

1.4. Objective

1.4.1. General Objective

The main objective of this study is to determine the provenance of Adigrat sandstone in Calub and Hilala gas fields and identify its effect on reservoir quality.

1.4.2. Specific Objective

- To undertake compositional analysis and quantification of porosity
- To conduct the petrographic study of provenance analysis.

1.5. Scope of the Study

This project is only applicable to the Calub and Hilala gas fields in the Ogaden basin. The project's scope is likewise limited to provenance restrictions on the Adigrat sandstone reservoir's porosity evolution in the Calub and Hilala gas fields. To assess how provenance affects reservoir quality, the study included laboratory analysis and petrology thin sections.

1.6. Significance of the study

Despite the Ogaden basin drilled many wells, just one well covers the entire 4861 km^2 of the basin. This suggests that the Ogaden basin's subsurface geology is still unknown. Studies like this one are essential to understanding whether or not the granite in the Adigrat reservoir comes from the same source. This will then provide information about whether the rock in the Adigrat reservoir in undrilled places is similar to the rock in drilled sites or if it is possible to correlate the two areas.

1.7. Project out Line

This research work contains six chapters. The first chapter deals with the general introduction, purpose and significance of the study. Chapter two briefly discusses literature reviews of the study. Whereas chapter three provides methods that the study followed to complete the study. Chapter four introduces the results. In chapter five, all the study results are discussed. The final chapter six includes a summary of the study and a recommendation.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Porosity in sandstone

Laboratory tests and visual methods were used to determine the porosity. Total porosity can be estimated using visual approaches; the more pore space that can be seen at a given magnification depends on the mode of observation. By utilizing a low-power microscope to visually analyze core slabs, porosity is frequently assessed (Jerry Lucia, F., 1999, 2007).

To determine total porosity, the Archie classification (Archie 1952) offers an approach that combines textural criteria with apparent porosity. By counting the visible pores in a thin section or by calculating the pore space using image analysis software, visible porosity can be determined. The bulk volume is assumed to be the thin portion. Without calibration against point-counted data, visual estimations can be extremely erroneous. Visual estimates of porosity frequently exceed point-counted measurements by a factor of two. Because very small pore spaces cannot be seen using visual observational techniques, laboratory porosity measurements are typically greater than visual estimations. However, point-counted values are comparable to measured values when all the pore space is substantial, as in grain stones. Knowing the bulk volume of the rock, as well as either its pore volume or the volume of the matrix material (mineral volume), is necessary for measuring the porosity of rock samples in the lab. Bulk volume is often assessed by direct measurement of a regularly shaped sample or by volumetric displacement of a strongly non-wetting fluid, like mercury. There are various methods for obtaining pore volume. Mineral volume can be determined from grain density and sample weight if the mineralogy is known; pore volume is derived as bulk volume less mineral volume (Archie 1952).

2.2. Importance of provenance

Sandstone can come from igneous rocks, metamorphic rocks, or other sedimentary rocks. Provenance is the source rocks before the reworking process. Finding the origin of an artwork, an old document, or a piece of sandstone is the goal of this investigation method. The term "provenance" in geology refers to the origin of sediments and sedimentary rocks. Provenance, at its most basic level, identifies the type of source rock that provided the loose sediment. However, provenance can also reveal details about: Paleotopography and Paleoclimate. Sandstones are categorized into three classes based on grain mineralogy: quartz arenite, fieldspathic arenite, and lithic arenite (Archie 1952).

A. Quartz arenite

It is a sandstone that contains quartz, chert, and quartzose rock fragments in greater than 90% of its granular silica composition. Its predominant hue is light gray. But it can happen. having iron oxide-induced pink, yellow, or brown coloring. Typically, silica and carbonate cement were used to lithify and cement this sandstone.

B. Feldspathic arenite

Feldspar is the major component and contains up to 25% quartz by composition. It might also have trace amounts of heavy minerals like mica and fragments of brittle rock.

C. Lithic arenite

contains a considerable amount of clastic rock pieces, including volcanic and metamorphic rocks. These sandstones may have less than 90% quartz grain and an assemblage of rock fragments that are more unstable than feldspar. Lithic arenite fragments can be comprised of chert.

Provenance studies have been used for a variety of purposes, some of which include aiding in the interpretation of basin evolution and tectonic setting (Dickinson 1985), aiding in the differentiation of sandstone petrofacies and source areas (Ingersoll 1990), and aiding in the improvement of stratigraphic correlation. Provenance has recently been employed by researchers to identify possible basins with improved reservoir quality potential (Vincent et al. 2010; 2013). In order to choose the best analogues for predicting reservoir quality, provenance reconstruction has grown to be a crucial stage (Dickinson 1985). The initial detrital composition and, to some degree, the textural characteristics of sandstone reservoirs at the start of burial are influenced by provenance, transport distance, climate, and depositional context. The rate and manner of compaction and other diagenetic processes that take place during burial are highly influenced by the texture and composition of the underlying deposits. The following specific subsurface processes are impacted by the initial sand composition: mechanical compaction, chemical compaction, dissolution of unstable minerals, quartz cement precipitation, and precipitation of other cements (such as carbonates, zeolites, and sulphates). Sand composition is frequently significantly influenced by provenance, which has an impact on compaction, diagenesis, and ultimately reservoir quality.

For evaluating sediment transit pathways and determining the presence and quality of possible sandstone reservoirs, provenance reconstruction is essential (Dickinson and Suczek, 1979; Dickinson et al., 1983; Dickinson, 1985).

2.3. Regional Geological Setting

Because Precambrian rocks have only been exposed to a limited extent, little is known about the Precambrian geology of the Ogaden Basin. Deep well drilling provides the majority of knowledge on the Precambrian rocks, with the exception of a few exposures in the basin's raised northern region. The Precambrian rocks exposed in the northern Ogaden Basin were divided into three groups, according to Berhe's (1985) proposal.These are the Boye Group, composed of meta-arkose, metapelite, quartzite, and marble; the Lower Complex, composed of high-grade gneiss and migmatites; and the Upper Complex of Kazmin, 1972, composed of phyllite, chlorite schist, metavolcanics, and lenses of ultramafic rocks. Precambrian rocks exposed between Hirna and Harar in the northern Ogaden Basin were studied using Pb-Pb zircon geochronology, which revealed Archean and Paleoproterozoic dates (Teklay et al., 1998). The Precambrian rocks of the Hirna and Harar area are correlatable with earlier (Paleoproterozoic and Archean) basement rocks of Somalia and Yemen, as well as Afif terrane of Saudi Arabia, according to the Neodymium isotopic data summarized for basement rocks of the Eastern Africa Orogen (EAO) (Stern, 2002).

The polyphase break-up of Gondwanaland can be seen as having a relationship to the Phanerozoic evolution of the Ogden Basin. From the late carboniferous onward, rifting related to the breakup of Gondwanaland was predominant (Karoo Rift), and basins emerged as a result of this extension both at the edges and within the continental African plate. In the Early-Middle Jurassic, a tri-radial system of north-south (Mandera-Bodle) rifting began in the Ogaden Basin. East and west Gondwana split apart as a result of the northeast-southwest (Calub Saddle) and northwest-southeast trending (Blue Nile) grabens, and the central Atlantic Ocean started to expand (bosworth, 1994; beicip-franlab, 1985, 1998). The ogaden basin's many rift development and sedimentation phases can be summed up as follows: (i) the initial stage of the rift: the breakup of Gondwanaland created continental rifts along the eastern edge of the African continent as a result of northwest-southeast tensional forces, likely with associated thinning of the continental crust (Karroo rift), (ii) Post-rift stage: This stage is distinguished by the deposition of basal sandstone in East Africa following rifting. (iii) Flooding of the craton: Subsidence of the continental margin was thought to happen as sea level increased following the rifting stage and syn-rift sediment deposition in the rift basins. Early Liassic flooding took place (Assefa, 1980; Wolela, 1997)Drowning of the Craton (iv): This stage is linked to a significant Collovain-Early Oxfordian transgression brought on by the breakup of Gondwanaland and the development of the African continental margin. This event resulted in the deposition of the Upper Sandstone and Muddy Sandstone (Amba Aradom clastics), and (v) Regression stage: The sea receded from northern and central Ethiopia in the late Jurassic to the early Cretaceous, most likely as a result of an intraplate event linked to the division of Africa and South America (Bosellini, 1989).

2.4. Ogaden Basin Stratigraphy

One of Ethiopia's three main sedimentary basins, the Ogaden Basin, has a high potential for hydrocarbons and is stratigraphically made up of volcanic rocks, Paleozoic-Cenozoic sediments, and sections of crystalline foundation rocks. The research of several oil tycoons, the EIGS, and other unpublished works served as the foundation for the overall stratigraphy of the Ogaden basin (Mohr, 1963; Kazmin, 1972, as referenced in Warku and Astin, 1992). The Ogaden basin's geological map is shown above, and according to its sedimentary surface geology, the Marda fault zone separates the basin into Mesozoic and Tertiary sedimentary divisions (Mega et al., 2015; Purcell, 1976a). Actually, Tertiary sediments fill the entire eastern part of the Ogaden basin and have an outcrop sequence that depicts the NNE-trending through the Somalia beach basin. Jurassic sediments cover the western portion of the basin, which is overlain by Cretaceous sediments at the basin edge and in the basin center. Drilled wells in the basin have revealed the underlying continental Karroo sediments, which preserve the Paleozoic history of the basin. Three Paleozoic Formations (Calub Sandstone, Bokh Shale, and Gumburo Sandstone) that are either Permian (Purcell, 1979) or later Paleozoic in age (Elwerath, 1967, as cited in Purcell, 1981) have been identified by Purcell (1979, 1981; Kazmin, 1972; Worku and Astin, 1992). All East African basins, including the Ogaden Basin, contain the following three main geological units, arranged in order of age: Precambrian basement complexes, Late Paleozoic Karroo Rift sediments, Mesozoic-Cenozoic sedimentary sequence, and Tertiary and Quaternary volcanic rocks that cover earlier deposition. In addition, Beicip (1998) and Petronas (2005) concluded that the Ogaden sedimentary succession's basic components were divided into three portions; hence, a thorough explanation of each unit, including the basement, is provided below.

A. Karoo Terrigenous clastic, which is likely carboniferous and Permian to Triassic in age, is deposited on top of the Precambrian foundation rocks.
B. The pots of Karoo the Karoo sequence is conformably overlain by the Jurassic and early Cretaceous succession, which is predominantly, composed of carbonates with some evaporites facies. The Hamanlei group of Shallow Marine Carbonates Evaporites, the Uarandab to top Korrahei unidentified group, and the Mustahil - Ferfer unnamed groups are the three lithostratigraphic subdivisions of this section.
C. Late Cretaceous to Early Tertiary, a mixed carbonate and terrigenous clastic interval that only occurs in the eastern Ogaden Basin and is overlain by the Early Cretaceous in an unconformable way.

2.4.1. The Precambrian Basement

The Ogden's north and west have outcrops of the Precambrian basement, which are broken up by a number of wells (Mengesha et al., 1996). Due to the limited exposure of Precambrian rocks in the Ogaden Basin, the geology of the Precambrian is poorly understood. A few exposures, including the Bur massif in the south, the Negele block in the southwest, and the Chercher block in the north, surrounded the perimeter of the basin

(Purcell, 1979). The majority of knowledge about Precambrian rocks comes from underground well drilling. According to Purcell (1979), the Pre-Cambrian strata under the Ogaden basin are assumed to make up the Mozambique Belt in southeast Africa (UNESCO, 1969).

2.4.2. Late Paleozoic Sedimentary Succession

According to popular wisdom, the Paleozoic era in the Horn of Africa was one of siltation, during which time erosion steadily flattened the region's Precambrian topography (Purcell, 1981), raising questions about the scale relevance implications of the area's upper Paleozoic deposits. By comparing the western Ogaden sub-basin's strata to those of the Mandera-Lugh basin, Purcell (1979) demonstrated the existence of substantial Permian strata, which are estimated to be about 4000 meters thick. The sedimentary strata of the continental Karroo Rift are therefore the oldest in the basin. Clastic layers from the Carboniferous to the Liassic are known as "Karroo" in south and east Africa. The Karroo Basin in South Africa, which serves as its type locality, gave it its name (Warku and Astin, 1992). Zimbabwe, Tanzania, Madagascar, Somalia, Kenya, Ethiopia, and Mozambique may have similar rock layers in the same rifts, both above and below the surface (Mayne, 1971; Flores, 1973; Kent, 1974; Kamen Kaye, 1978; Cannon et al., 1981, as mentioned in Warku and Astin, 1992). Paleozoic outcrops have been seen in Negele and the Ramis river valley in the Ogaden basin, despite the fact that drilled wells have shown deep Upper Paleozoic strata below the surface (Purcell, 1979). According to Warku and Astin (1992), the Karroo sedimentary pattern in the Ogaden basin is classified into four Formations (Calub Sandstone, Bokh Shale, Gumburo Sandstone, and Adigrat Sandstone).

Deep wells drilled for oil prospecting in the Ogaden sedimentary basin's southeast and center have revealed these Formations. This subdivision implies that continental clastic sediments will continue to be deposited until they are replaced by middle to low Jurassic carbonate deposits and takes into consideration the entire gradation between the Gumburo Sandstone and the Adigrat Sandstone. According to Ethiopian Palaeozoic sediment records, Adigrat Sandstone's presence led to the discovery of Pre-Adigrat sediments in Gumburo Sandstone (Permian age), and Gumburo Sandstone has been recognized in deeper units in the basin with Calub Sandstone and Bokh Shale. Other upper Paleozoic sedimentary rocks discovered in Ethiopia, such as the Enticho Sandstone in the north, the Pre-Adigrat Sandstone in the center, and the Gumburo Sandstone in the southwest, are comparable to the Calub Sandstone, Bokh Shale, and Gumburo Sandstone (John, 2016).

A. Gumburo formation

The Gumburo formation thickens to 390 meters in the Calub area before clamping out to the east. Alluvial, river-produced sandstone with a significant amount of carbonaceous material from the soil is known as the Gumburo formation. The greatest sandy unit is produced at a quick overall rate of sedimentation from rivers, and it is predominantly the result of sand-braided river deposition (John, 2016).

B. Bokh formation

The Bokh formation's organic-rich, black to brown shales and bedded sandstones correspond to early rift-phase deposits that were deposited in a basinal setting. The Bokh is primarily composed of lacustrine, biological, and silty shale from the continent, with some sandstone and dolomite sedimentary formations. Interface is gradual and conformable with formations above and below. The dark shale has a variable organic carbon content of up to 5% and is abundant in pyrite. (1992; Worku and Astin).

C. Calub Formation

The Calub formation is an arkosic sandstone with coarse grains and fairly sorted grains that contains layers of clastic sandstone rich in elementary volcanic clasts and intermediate to elementary explosive tuffs, as well as some granulated conglomerate and minor layers of reddish-brown siltstone. According to Assefa (1988), Worku and Astin (1992), as well as John (2016), the Calub formation is the first deposit to fill the Ogaden groove and lies irregularly on the Pre-Cambrian crystalline base. This formation is made up of pre-rift sandstones and aggregates that were deposited in a glacial to fluviatile environment (Assefa 1988).

2.4.3. Mesozoic to Cenozoic Sedimentary Sequence

A. Middle Hamanlei

The Ogaden and Blue Nile basins both include this evaporite-carbonate sequence. The nation's primary sedimentary basins are where one can find the Mesozoic sedimentary sequence. They are believed to have emerged as a result of a known sea intrusion with a SE-NW pattern (Kazmin, 1973). The Ogaden basin's mesozoic strata are arranged in chronological order from oldest to youngest as follows:

B) Adigrat Sandstone

It is thought to slightly overlie the karroo series in the Ogaden Basin, where it climbs upward through a transitional area into the carbonate Hamanlei Formation. In almost every borehole in the Ogaden basin, it is present, and its depth varies. It is found in Ethiopia (Karroo sediments) either unconformably or conformably on top of Precambrian basements or Paleozoic deposits. In northern Ethiopia, close to the town of Adigrat, Blandford discovered it and called it there (1870; quoted in Purcell, 1979). According to John (2016), the Adigrat sandstone is a typical fluvial series with braided-stream deposits at the base, point-bar stages in the middle, and a coastal plain with lagoonal materials at the top. As a result, it is possible to interpret the Adigrat Sandstone as a time-regressive unit that marks the beginning of the Jurassic Sea invasion into the Horn of Africa (Purcell, 1979).

C**) The Hamanlei Formation**

At the type locality in the northern part of the basin, the Hamanlei Formation was initially found close to the town of Hamanlei (Purcell, 1979). Although a transitional zone between these two Formations has been identified (John, 2016; Purcell, 1979; Kazmin, 1972), it overlaps and partially intercalates the Adigrat Sandstone in some areas and immediately covers basement rocks in others, such as the western part of the basin and the Harrer region. In general, the transgression carbonate-evaporite sequence of the Hamanlei Formation moves uphill toward the basinal shale and marl of the Uarandab Formation. In the region's center and northern regions, the Jurassic limestone of the Hamanlei Formation is identical to that of the Antalo Formation (Kazmin, 1973; Purcell, 1979).

D) Lower Hamanlei Formation

The Transitional unit is atop it. The fine-grained-skeletal limestone and shale limestone make up the formation's upward-coarsening succession. This sub formation is deposited in a maritime environment within a small lagoon. According to Gebreyohannes (1989, as referenced in John, 2016), it is a carbonate-clastic that is only present in the Ogaden basin and has been referred to as a transitional sand facies in the Abay basin. Oolites, algal stromatolites, green algae, foraminifera, echinoids, gastropods, and other organisms are plentiful. The lithology alternates between limestone, dolostone, and evaporites. According to John (2016), the depositional habitat is a shallow inner shelf with a locally constrained shelf and an enclosed brackish environment.

E) Upper Hamanlei

Mudstones, skeletal, and peloidal grainstones make up the majority of it, with some high-energy oolitic grainstones at the base. This portion of the Hamanlei Formation overlies Middle Hamanlei in the Ogaden Basin and is conformably underlain by the Uarandab Formation. The thickness of the upper Hamanlei varies between 396 and 488 meters, reaching a maximum of 544 meters close to Hilala-1 (BEICIP, 1985 as reported in John, 2016). This unit was classified as Liassic-Bathonian in the basin axis (Purcell, 1979).

1) Uarandab Formation

It conformably overlies the Hamanlei Formation and is characterized by a deeper greenish gray carbonaceous fissionable shale, argillaceous lime with marl, and gypsiferous limestone with a thickness of around 400m (Mengesha et al., 1996; Purcell, 1979). It shows an ecosystem with low energy, openness, and some anoxia in deep water. According to Purcell (1976), the widespread shale facies in Ethiopia and Northern Somalia represent calm water conditions at the height of the Jurassic incursion. As the unit travels northeasterly across the basin, its overall thickness decreases until it reaches the Gumboro-1 well, where it measures about 115m thick. Its type corner near the Ogaden basin's Uarandab hamlet has a thickness of 55 meters (John, 2016).

2) Gabredarre Formation

The Ogaden basin's topmost Jurassic sequences are included in the Gabredarre series, which Kazmin (1975; 1972) first classified. It has a thickness of 410 meters in the type section at Gabredarre and is composed of marl, lamp oolitic limestone, and shale that transitions to brecciated pisolitic limestone with marl and gypsiferous through the east (Kazmin, 1972; Purcell, 1979). On top of the Uarandab Formation, it is located. According to Purcell (1976), the Jurassic-Cretaceous boundary is gradational, and deposition persisted into the Lower Cretaceous for the majority of the middle Ogaden Basin. The Formation is dated as Kimerdgian-Portlandian (Kazmin, 1972).

2.4.4 Cretaceous

Several shear zones formed along and within the East African continental coast as the South Atlantic Ocean began to open up during the Cretaceous Period (Bosworth, 1994). Regressions and transgressions alternated throughout the Ogaden platform area during this post-rift period, and the Gorrahei, Mustahil, Ferfer, Belet Uen, and Jesomma Formations are representative of the associated sedimentary rocks

A) Korrahei Formation

The lowest level of Cretaceous silt in the basin is the Korrahei Formation, or significant gypsum as Kazmin (1972, 1975) called it. It was deposited during a period of sea regression and shoreline progradation toward the sea. Additionally, the Main Gypsum Formation, also known as the typical part at Gabredarre in South Eastern Ethiopia, is made up of 200 meters of gypsum intercalated with limestone, marls, and shale (Purcell, 1976). The unit, which is made up of interbedded shale and gypsum and limestone, is exposed in large portions of the western Ogaden basin and extends into the Mandera-Lugh trough. According to Mengesha et al. (1996), Kazmin (1972, 1975), Purcell (1979), and John (2016), the lower portion of the Korrahei Formation is primarily made up of limestone, dolomitic marl, anhydrite, and shale in sandstone for the west, while the upper portion of the sub-Formation is made up of massive, white-gray anhydrite with inter beds of shale and dolomite. The entire thickness of the Korrahei formation dips north-eastward from more than 5,500M in the Bodle-1 well to 2,234M in the Shilabo-1 well. The formation doesn't go past 836 feet in the Galadi -1 well and isn't present in the Bokh -1 well or the Sinclair boreholes, where cretaceous erosion has gradually shortened it in the northern Ogaden basin and in Somalia (Beicip, 1989).

B) Mustahil Formation

This formation, which rests on the Korrahei Formation, may be found in the Fafan stream and the lowerparts of the Shabele river in the Ogaden basin. It consists of alternating light grey limestone interbeddedwith shale and marl in the lower portion and fossiliferous limestone rich in Orbitolina in the upper portion near Mustahil village (Mengesha et al., 1996; Purcell, 1979; Russo et al., 1991). It has an Aptian-Albian age and was deposited in an inner to outer shelf habitat, according to paleontology (Kazmin, 1975, 1972; Russo et al., 1991; John, 2016). This Formation marks a Cretaceous Sea transgression across the East Africa and

Middle East. For the Aptian limestone, which largely overlain on sandstone unit, located along the western edges of the Ogaden basin, notably at Sheik husein and Gramulata hills surrounding Harar, indicates the aerial expanse of the Cretaceous re-established ocean incursion. The overlaying sandstone (Amba Aradam Sandstone) is from the Korrahei Formation's coastline facies (Purcell, 1979).

C) Ferfer formation

The Ferfer Gypsum Formation, which alternates dolomites, limestone, marls, and gypsum, is lithologically similar to the Main Gypsum Formation. It combines through intercalation with the underlying Belet Uen Formation and has an outcrop thickness of around 200 meters (Purcell, 1976). According to John (2016), the facies are thought to indicate a constrained Lagoona ecosystem.

D) Formation of Belet Uen,

According to Purcell (1976), it is made up of light-colored limestones, some of which are reefal, with intercalations of grey-green glauconitic shale and green and brown sandstones. Older units cannot be contacted at its lower contact, while the Jessoma Sandstone can be contacted at its summit (John, 2016).

2.4.5. Tertiary

A) Jesomma Sandstone

The fluvial, shallow-marine depositional habitat that this Upper Cretaceous-Paleocene sandstone represents. Age is determined by the age of the sediments below and above. According to John (2016), the Jessoma may be related to Amba Aradam Sandstone deposits in the Harer region.

B) Auradu Formation

According to Purcell (1976), the Auradu Formation is a transgressive fossiliferous mudstone to dolomitic packstone that was deposited in an environment ranging from the inner to the outer shelf.

C) **Taleh Formation**

According to John (2016), the Taleh Formation is composed of cherty limestone, clay, gypsum, dolomite, and anhydrite from the lower to middle Eocene. According to Purcell (1976), the Taleh Formation facies shows that regional sea depths have been shallowing, possibly as a result of both regional uplift and the prograding continental edge.

D) Karkar Formation

Middle to upper Eocene limestone with marl intercalations and clay make up the Karkar Formation (John, 2016). The formation, the latest marine series in the Ethiopian Ogaden region, signifies a transgression cycle (Purcell, 1976).

E) Trap series

The thin Paleocene-Eocene Auradu, Taleh formations in the eastern Ogaden Basin, Oligocene- to Pliocene Trap Series (volcanic flows), and thicker sedimentary layers in the Red Sea region to the NE make up the tertiary portion. During the completion of this research, several field materials and methodologies were used to meet the aforementioned aims. The techniques used are:

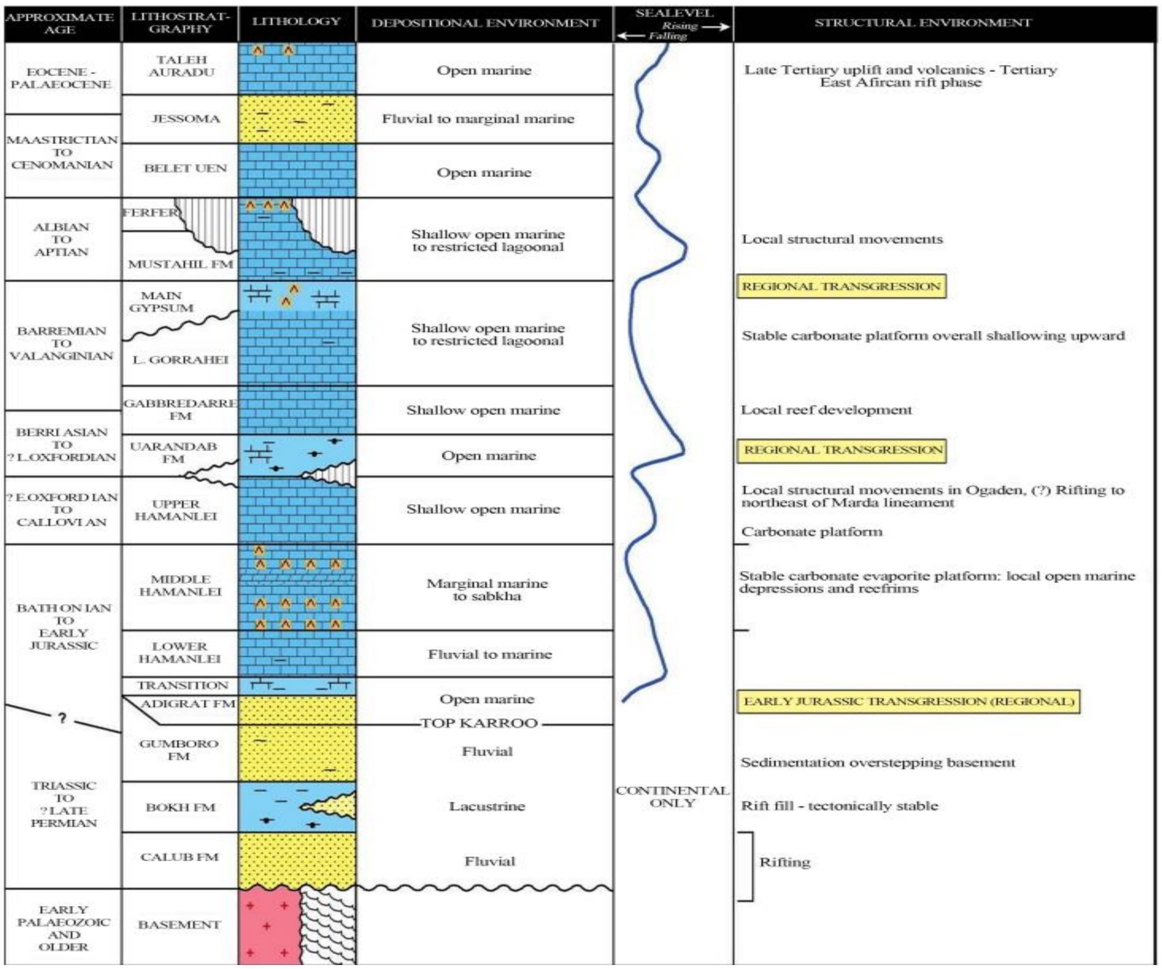


Figure 2.1 Stratigraphy and petroleum system of Ogaden basin (Assefa. 1988).

CHAPTER THREE

3. METHODS AND MATERIALS

To achieve the above-stated objectives during the accomplishment of this research, different field materials were used and different methods had been followed. The methods employed are

3.1 Image Acquisition

Image acquisition from thin section is the process of taking pictures with a microscope or another imaging tool of thin slices of an object, like a rock. Typically, thin sections are made by taking a thin slice of the material, putting it on a glass slide, and examining it under a microscope. Thin section imaging can be used to capture pictures that can be utilized to characterize rock fabrics and detect mineral grains.

The sample must be carefully prepared before picture acquisition from a thin segment in order for it to be placed and aligned with the imaging instrument. To guarantee that the photographs are of good quality and precisely depict the sample, imaging settings like the magnification, focus, and lighting must also be carefully calibrated. Several authors have employed image analysis to assess pore system features using images taken using various microscopy techniques, such as optical microscopy (Grove and Jerram, 2011).

3.2 Image processing and Analysis

Analyzing digital images is nothing new. Analyzing the qualities of digital photographs after they have been captured is all that is required. In recent years, following the introduction of high-speed desktop computers, this has become a standard practice. Geoscientists today employ image acquisition and analysis tools for a wide range of petrographic applications, including as textural, mineralogical, fabric, and porosity investigations. Using conventional petrographic techniques, thin sections employed in investigations by Hammel (1996) and Roy (1998) were investigated. On each thin segment, 250 points were counted to determine the number and kind of pores. Under a polarized light microscope, 25 core samples from the Calub-Y and Hilala-X wells were examined in total. The visible porosity, grains, cements, and matrix (clay or lime mud) in thin slices were all inspected. To estimate pore size, the major and minor axis dimensions of counted pores were measured. Pore area served as a proxy for pore size. The eye evaluated the form of the pores to be a circle, square, elliptical, or rectangle. The pores were finally categorized using the appropriate genetic system. ImageJ in the Fiji version (figure 3.1b) and Jmicrovision (figure 3.1a) were the programs utilized for image analysis. For the purpose of identifying the grains, matrix, and cement, a petrographic microscope was utilized.

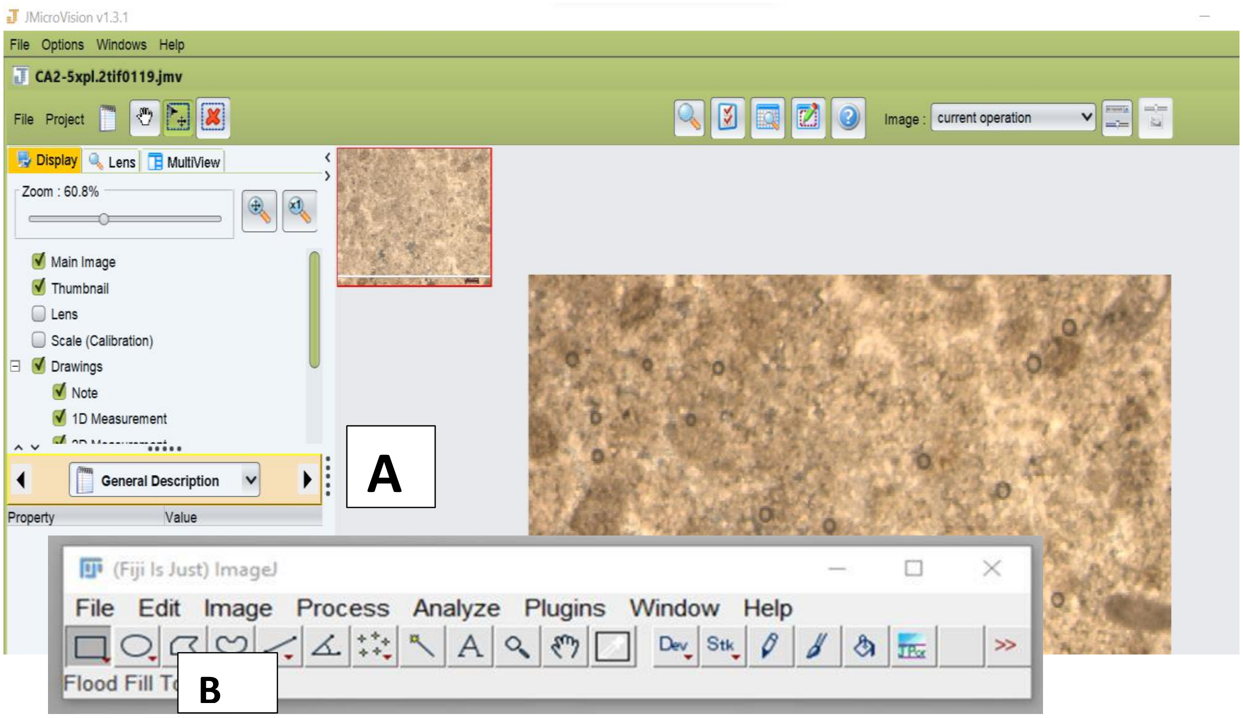


Figure 3.1 A) Jmicrovision software with thin section image display, and B) tools of Image software

3.3 sampling

A total of 25 samples were obtained from the ministry of mines in May 2023 for additional petrographic study and image interpretation. Although the number of samples was limited, they were gathered from the bottom, middle, and higher portions of each well whenever possible in order to cover a meaningful stratigraphic range for Calub-Y (15 samples) and Hilala-X (10 samples).

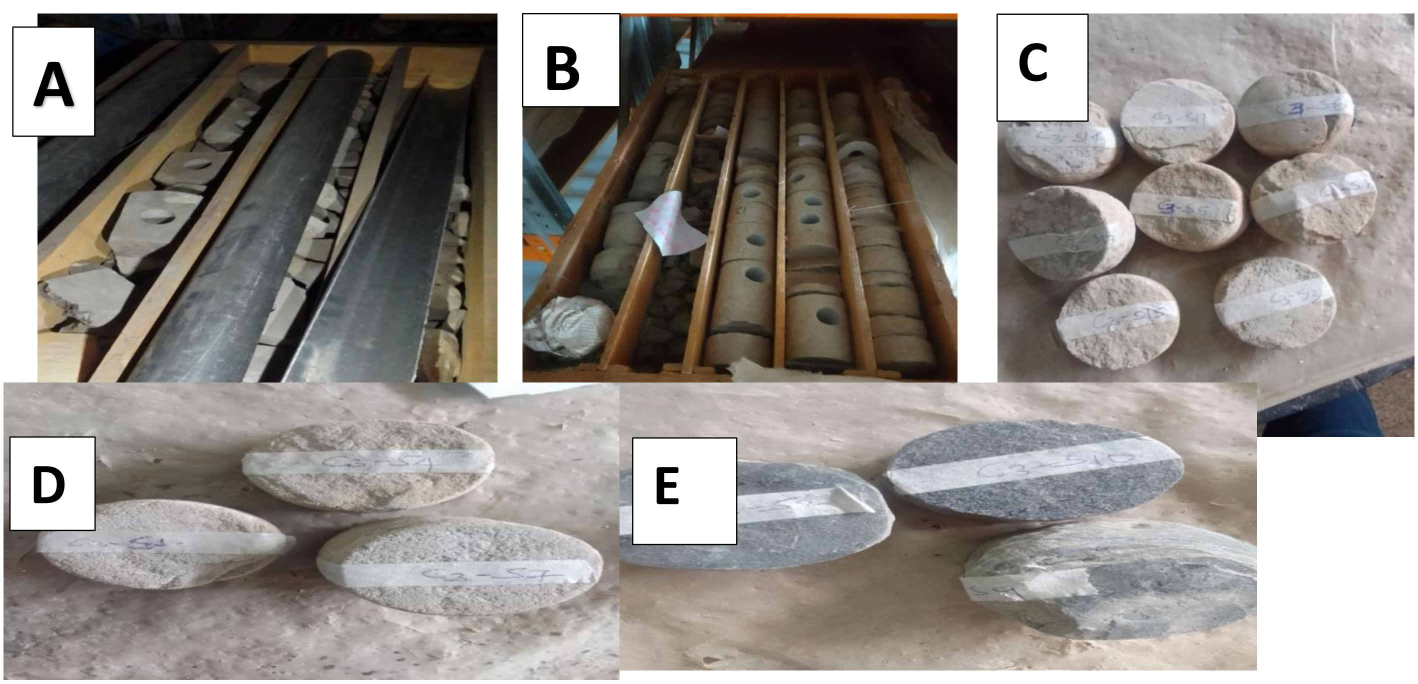


Figure 3.2 core samples from Calub-Y with depth of 2762M-2776M (Ministry of Mines, 2023)

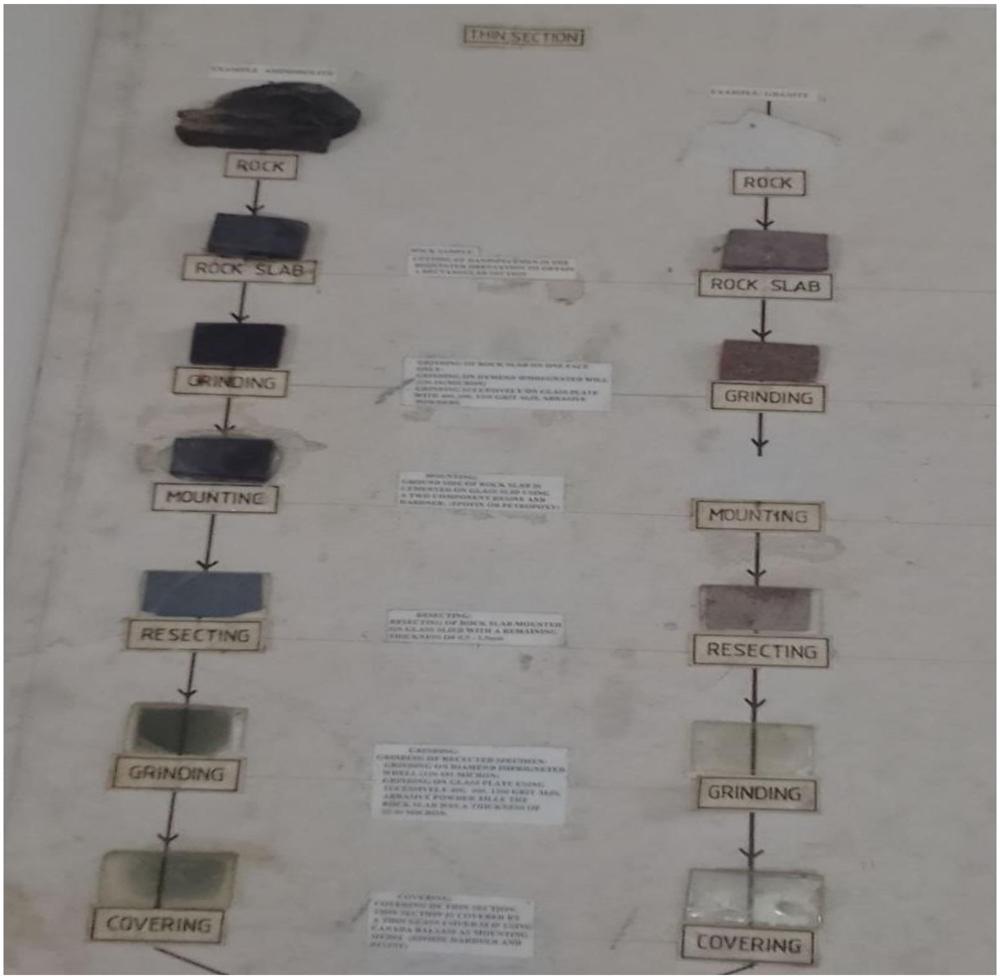


Figure 3.3 Thin section preparation Process (Ethiopian Geological Survey)

3.4 Laboratory Activity

The Ethiopian Geological Survey's Central Laboratory is where the thin sections were created. Rock samples were cut into rectangular blocks for thin section preparation, and the surfaces were then ground smooth and flat to allow for adhesion to glass specimen plates. After samples were attached to the glass slide, the surface was rough ground and polished once more till the thickness reached 0.3mm.

3.5 Sandstone Porosity

The significant degree of form irregularity in the sand grains and particles that make up sandstone reservoirs means that they rarely fit together precisely (Tiab & Donaldson, 2015). The pore space or interstice, a void gap between grains formed throughout the beds, is inhabited by liquids or gases. According to Tiab and Donaldson (2015), a reservoir rock's porosity is the percentage of the reservoir's overall volume that is not taken up by its solid framework. The quantity of empty space between the sand grains is what determines how porous sandstone is. The proportion of the rock that is vacant was obtained by point counting the vacuum space in order to calculate this empty area.

The quantity of empty space between the sand grains determines sandstone's porosity. In order to calculate the proportion of the rock that is vacant, the empty emptiness space was point counted. Optical Microscope was used to analyze the petrography.

3.6 Point Counting

An abridged version of the earlier Gazzi-Dickinson approach for sandstone point counts was used for the porosity point count (Ingersoll et al., 1984). Based on pore space abundance, standard point count data can be used to quantitatively analyze the levels of porosity (Lundegard, 1992). According to accepted standards for structure, texture, and composition, each sample was described and recorded. The following details were noted: grainsize, shape, rounding, and sorting. Both a hand sample and a petrographic analysis were used for this. This was done in order to determine the quality of the reservoir, as the porosity and permeability of the sediment might be affected by its texture (Allen & Allen, 2013; Tiab & Donaldson, 2015).

For quantification of mineralogical composition, Rock AR2/Jmicrovision application (Fig 3.4) was used. For mineralogical quantification, point counting was employed. This technique was used for all thin sections, and per thin section 250 counts were made.

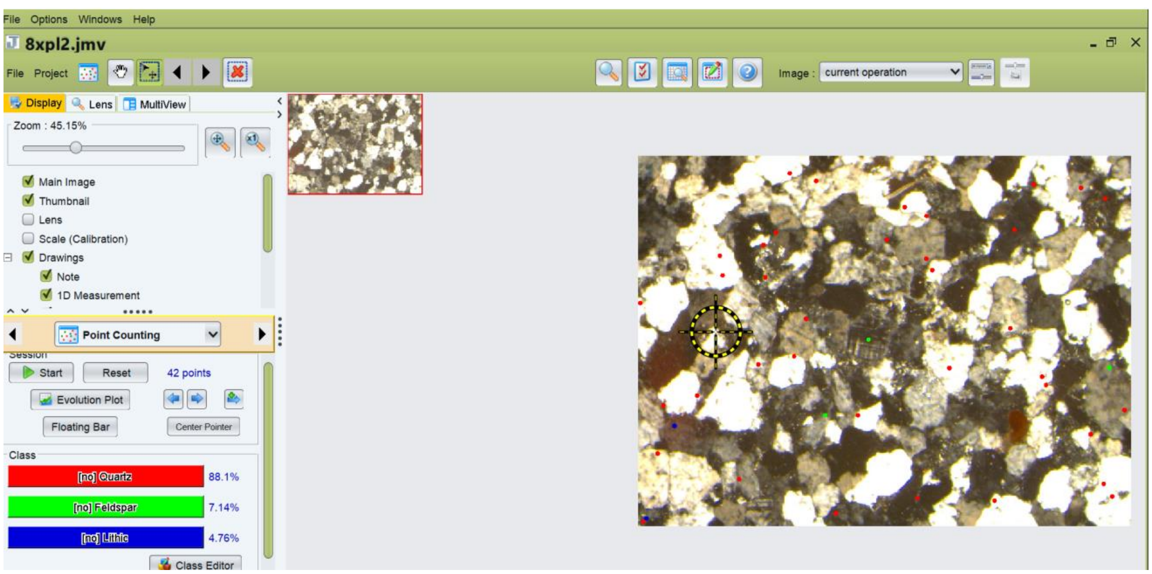


Figure 3.4 point counting software results

3.7 Porosity Measurement

The porosity of the thin section samples was assessed to determine the reservoir quality of the sandstone formation. The two essential components of reservoir quality are permeability and porosity. The apps Jmicro Vision and ImageJ were used in combination with two different methodologies to measure the porosity of the thin sections. For each pore that showed non-clay porosity, the cumulative area of the hand-drawn outlines was then estimated as a proportion of the total area of the thin section photograph.

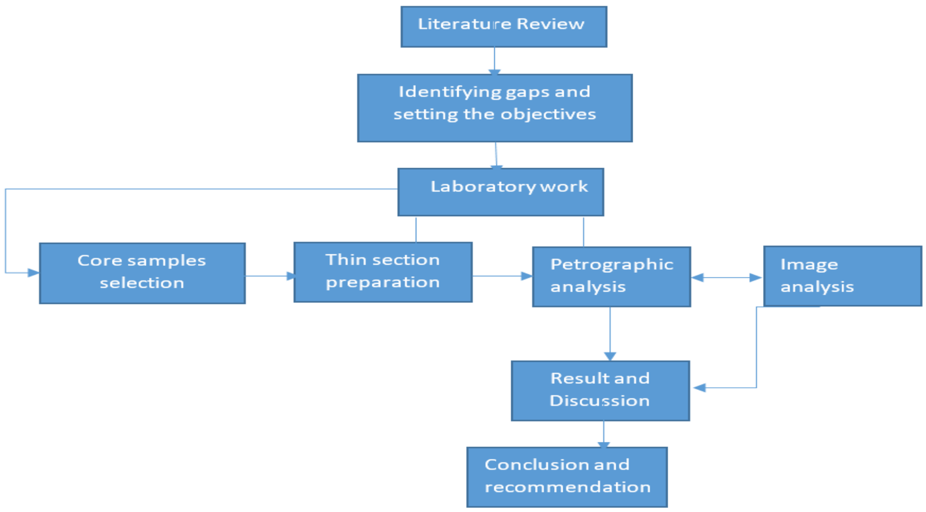


Figure 3.5 Project flow diagram

CHAPITER FOUR

4. Results and Discussions

4.1Results

4.1.1Petrographic analysis

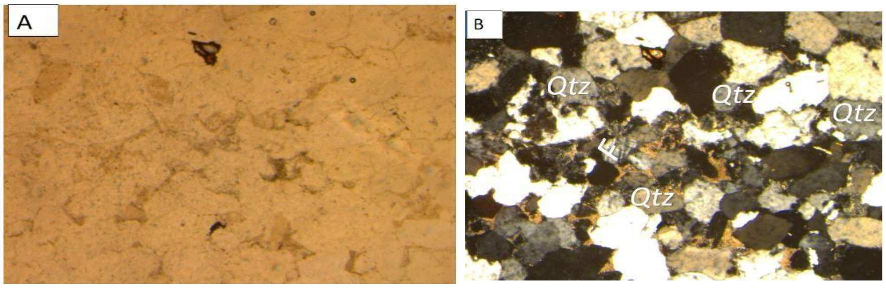
Sandstone has been studied in the lab, including petrographic mineral analysis. To ascertain the sandstone's origin, this study was conducted. Twenty-five samples of sandstone were examined for the petrographic study. The following is a presentation of the petrographic mineral analysis findings.

4.1.1.1. Quartz

Quartz, the most stable mineral under sedimentary circumstances, makes up a significant portion of the detrital grains in the calub-Y sandstones (Tucker, 2001). Adigrat Sandstones in Calub-Y and Hilala-X have total quartz contents that range from 62 to 81% and 74 to 86%, respectively, with typical quartz contents of 72% and 80% Table (4.1).

The sandstones contain quartz grains that are both monocrystalline and polycrystalline. The analyzed samples' grain sizes range from fine to medium to coarse grained, with medium-grained samples predominating. Individual quartz grains' observed interaction with one another is almost sub-parallel to parallel with some sutured borders. Quartz often occurs as polycrystalline grains and is thought to have metamorphic origins.

In Hilala-X, quartz is the main mineral grain that is seen in all of the thin-sections of sandstone. The two types of quartz grains are monocrystalline and polycrystalline. The primary difference between the two varieties of quartz is that one quartz crystal makes up monocrystalline quartz, whereas two or more quartz crystals make up polycrystalline quartz. In some of the samples, the quartz grains are extensively broken and have tiny holes (vacuoles).



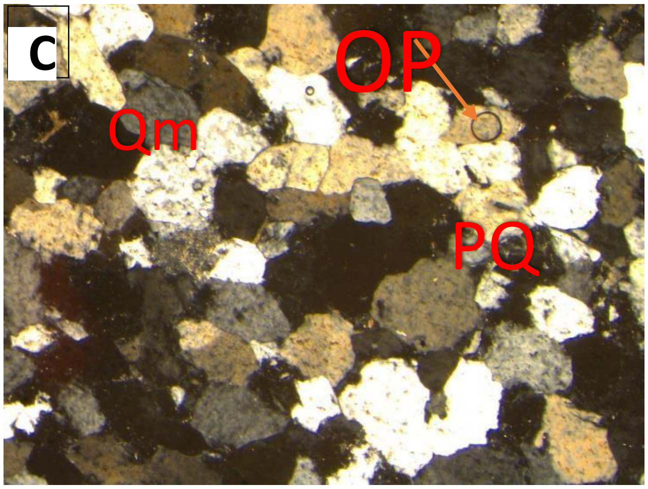


Figure 4.1 Photomicrograph of quartz grains both ppl(A) and xpl(B) displaying both monocrystalline quartz (MQ) and polycrystalline quartz (PQ).

4.1.1.2. Feldspar

Both regions Compared to quartz and lithic pieces, feldspar makes up a relatively tiny portion of the Adigrat Sandstone; the amounts of feldspar minerals in Calub-Y and Hilala-X are both less than 3% (Table 4.1). Though they are small in this case the feldspar minerals found in sandstones include alkali feldspar (orthoclase) and plagioclase feldspar (albite), with plagioclase feldspar predominating in the sample under study. The feldspar granules have undergone some alteration.

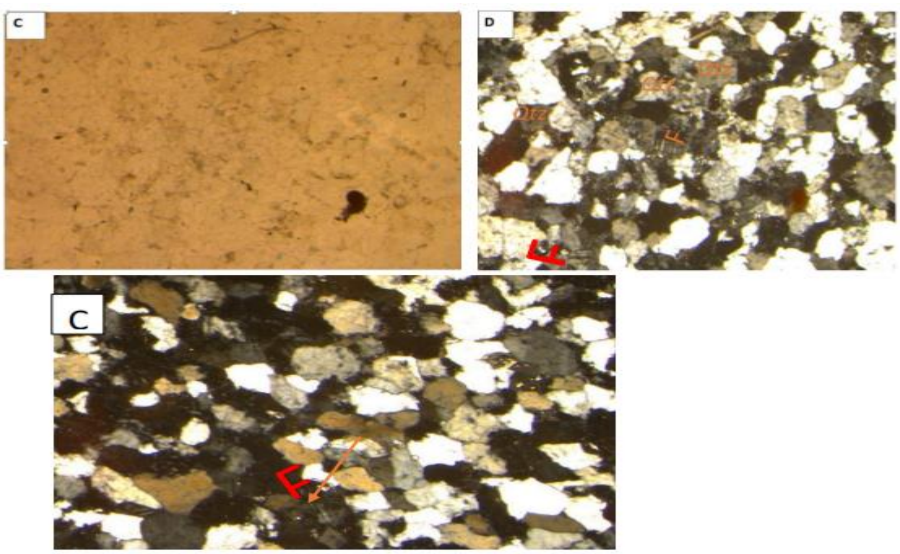


Fig 4.2 Photomicrograph of Feldspar both ppl(A) and xpl(B), (C).

4.1.1.3. Rock Fragment

Lithic fragments are pieces of other rocks that have been eroded down to sand size and now are sand grains in sedimentary rock. They were first named and described by Dickinson in 1970. It can be derived from recycled sedimentary,igneous or metamorphic rock. There are fewer sedimentary lithic fragments. But there are also infrequent bits of quartz siltstone, lithic sandstone, and fine-grained quartzose sandstone (Fig. 4.3).

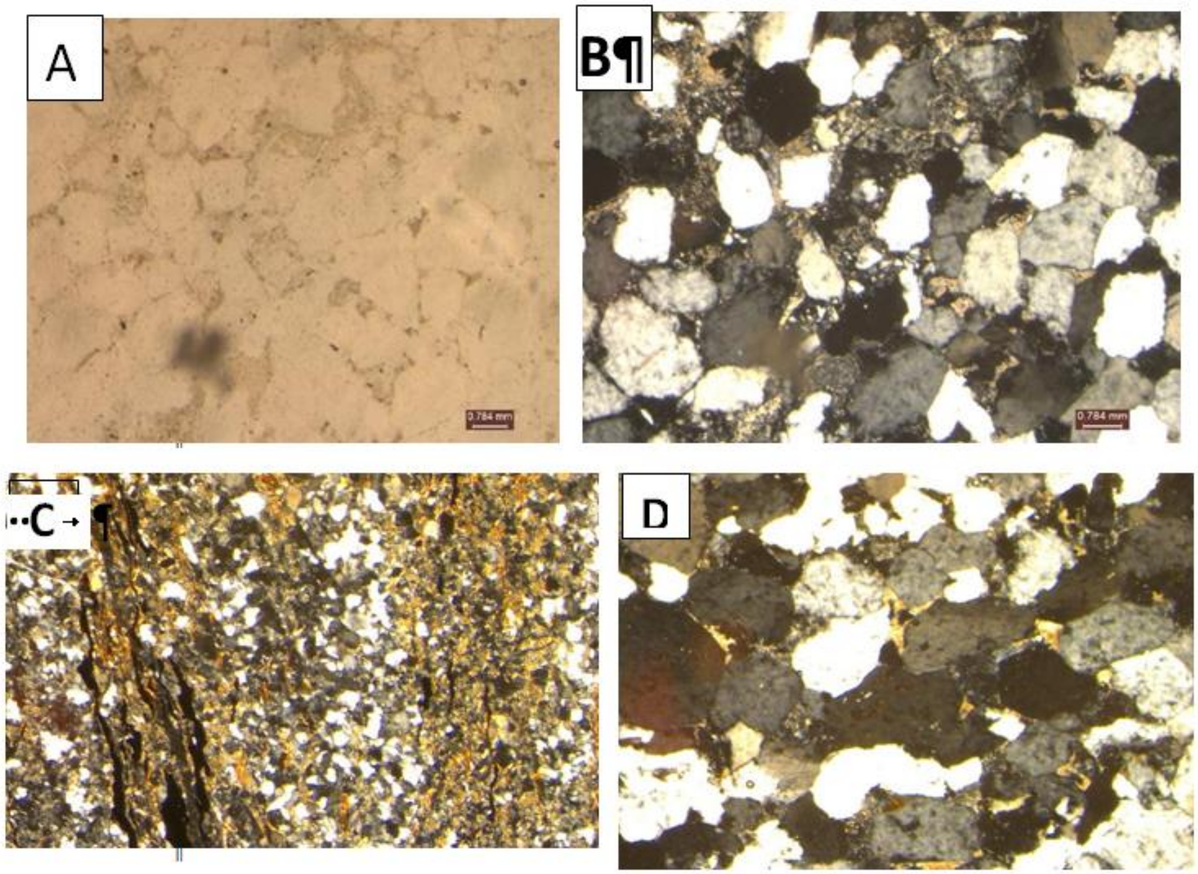


Fig 4.3 Photomicrograph of Lithic fragments both Ppl(A) and Xpl(B), (C), D). In C biotite and schist is seen

4.1.1.4. Matrix and Cement

Cement has a tendency to fill up the pore spaces within the sandstone grains (both matrix and framework grains), whilst the matrix acts as binding materials around bigger or framework grains (Boggs, 2006). Adigrat Sandstone's modest matrix of clay minerals and fine-grained quartz surrounds the detrital framework grains. The majority of the quartz cement that forms in the pore space between the original detrital grains is made up of the quartz overgrowths. Clay minerals, which make up the majority of the matrix, are either detrital or evolved diagenesis. The minerals in the diagenetic matrix In the examined sandstone, the framework grains undergo modification and precipitation in addition to other matrix minerals re-crystallizing (Baiyegunhi et al., 2020).

4.1.2. Diagenetic properties:

Diagenesis is a process that occurs after sediment has been deposited. It is the basic set of biological, chemical, and physical processes that regulates the texture, mineralogy, and fluid flow features of sedimentary rocks. Cementation, compaction, recrystallization, replacement, mineral overgrowth, and dissolution are diagenetic processes that have altered the sandstone (Hayes, 1979). The study of sandstone in petrographic shows, slight grain fracturing was observed but not intense. Some sandstone grains, particularly quartz mineral grains, are slightly distorted, indicating long interaction between grain frameworks. Sutured grain contact can be visible in some quartz grains, especially in polycrystalline quartz. The grains packed close together as a result of compaction due to the overburden pressure, resulting in linear to convex-concave contact between them.

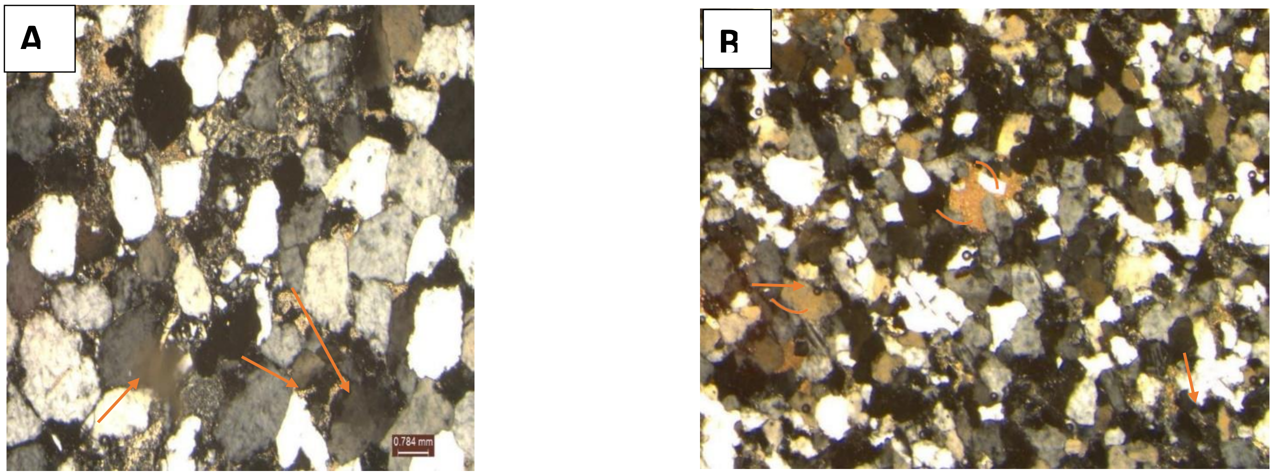


Fig 4.4: Photomicrograph of Matrix and Cement A) and B) with colored arrows

4.1.3. Classification of Adigrat sandstone in Calub-Y and Hilala-X

The Main detrital framework grains of Calub-Y and Hilala-X of Adigrat sandstone as we mentioned above includes; quartz, feldspar, rock fragments. To classify the target sandstone of the two area the framework grains (quartz, feldspar and lithic fragment) were normalized to 100%. This means that other constituents like cement type, which do not fit for classification are disregarded. Then the clan name was given. The analysis has been done using point counting of framework grains for Jmicrivision software and calculating various parameters, i.e., Qt, F, and Lt see that Table 4.1. The parameters recalculated to 100 percent and used in triangular diagrams Qt- F-Lt, for provenance study and for classification and this study used the folk (1974) triangle for such classification. Dickinson and Suczek (1979), Dickinson (1983 &1985) classified sandstone on the basis of their characteristic petrofacies, which is primarily controlled by the tectonic setting of their provenance and thus the present it is used them as a reference to locate the framework grains of Adigrat sandstone in the two area.

Table 4.1 Percentage of framework grain

Sample Code	Quartz(%)	Feldspar(%)	Lithic Fragment(%)
C3S1	75	8	17
C3S2	62	14	22
C3S3	75	11	14
C3S4	70	11	19

C3S5	75	9	16
C3S6	77	6	17
C3S7	80	8	12
C3S8	76	9	15
C3S9	64	17	19
C3S10	59	18	23
C3S11	70	11	18
C3S12	62	15	23
C3S13	74	9	17
C3S14	79	8	13
C3S15	81	6	13
H4S1	84	6	10
H4S2	79	10	11
H4S3	76	5	19
H4S4	86	6	8
H4S5	81	7	12
H4S6	78	13	9
H4S7	83	6	11
H4S8	79	8	13
H4S9	81	5	14
H4S10	74	11	15

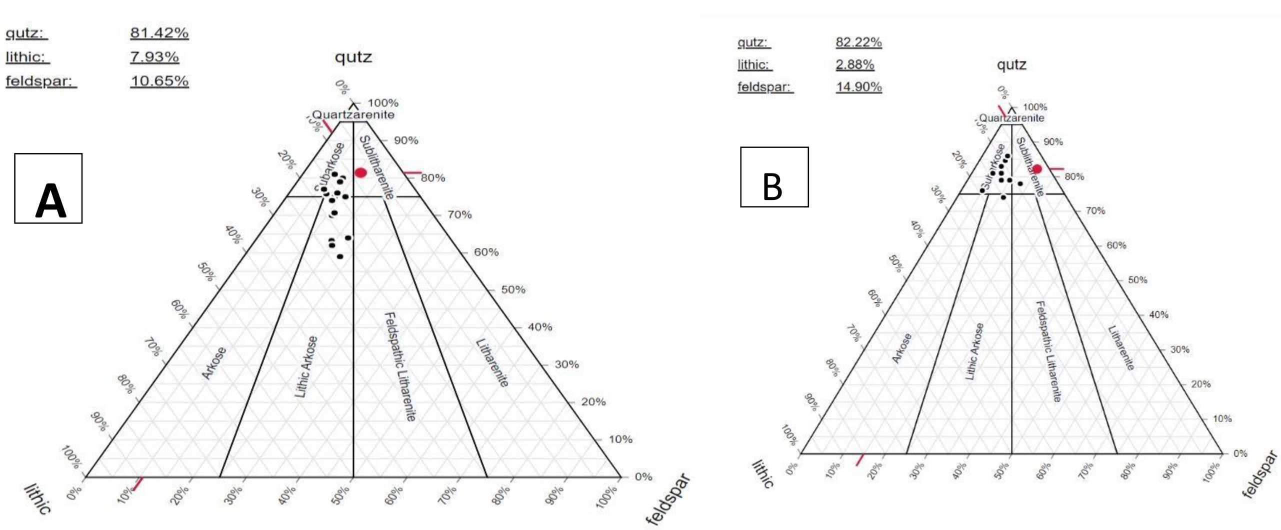


Figure 4.5: Q-F-L ternary presents classification of Adigart Sandstone from Calub-Y A) and Hilala-X (After Folk, 1980)

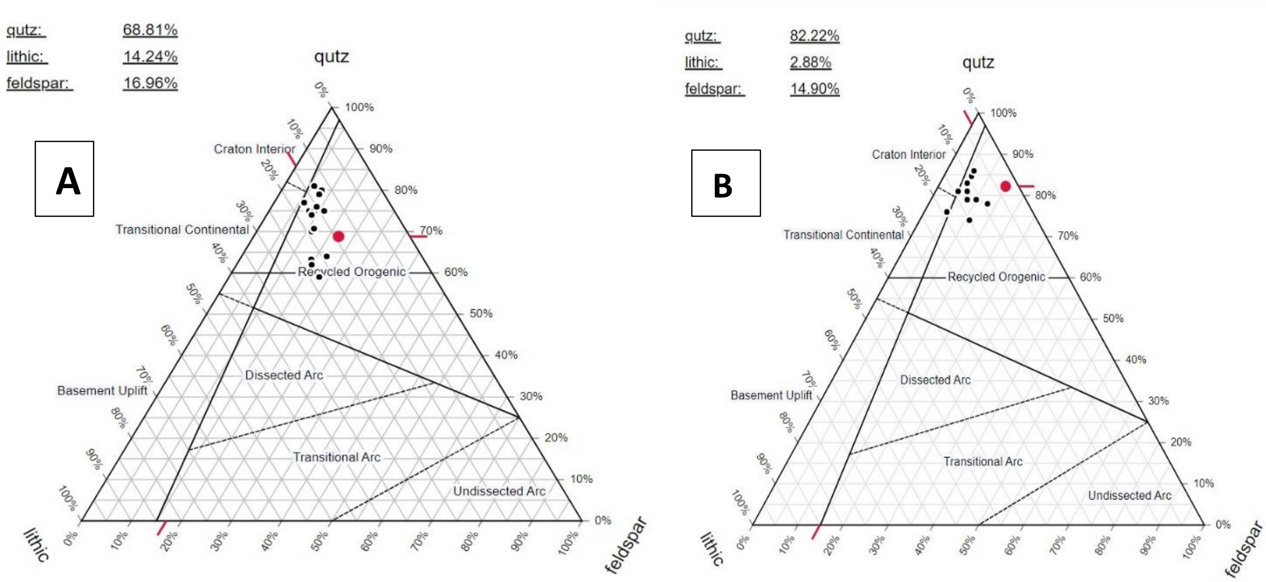


Figure 4.6: Qt-F-L ternary plot of data presented in (Table 4.1.) display provenance of Calub-Y and Hilala-X for Adigrat Sandstone Formations (After Folk, 1980).

Table 4.2 Hand specimen Description, Mineral composition, Textural Descriptions and Given rock nameof Calub-Y

Sample Number	**Hand Specimen Description**	**Mineral composition**	**Textural Descriptions**	**Rock Name**
C3S1	-Gray in color -Fine to coarse grained intexture	Minerals qtz(81%), cal(10%), cl(5%), op(4%)	-Grain supported text -Quartz grains are the major component of matrix and minor amountof calcite, clay and opaque minerals	Sandstone
C3S2	-gray in color, with a texture ranging from fine to coarse.	Qtz(62%), Biotite(32%), opaque(6%)	-Quartz, biotite, and opaque minerals exhibit high parallel alignment. Schistose Texture	-Biotite-Quatz Schist
C3S3	Gray to Light in color and Fine to Medium Grained	Minerals qtz(89%), cal(2%),cl(6%), op(3%)	- Grain supported text -Quartz grains are themajor component of matrix	-Sandstone
C3S4	Fine to medium grained with a light gray color	Minerals qtz(85%), cal(7%),cl(3%), op(5%)	- Grain supported text -Quartz grains are dominant	-Sandstone
C3S5	-Light in color -Medium grained in texture	Minerals qtz(85%), cal(7%),fel(3%), op(5%)	- Grain supported text -Major grains are quartzMinors are calcite and feldspar	-Sandstone

C356	-Gray in color -Medium grained in texture	Minerals qtz(84%), cal(7%),fel(6%), op(3%)	- Grain supported text -Quartz grains are themajor component of matrix	-Sandstone
C3S7	-Gray in color - medium to coarse grained intexture	Minerals qtz(81%), cal(9%), cl(4%), op(6%)	- Grain supported texture -Major matrix its Quartzgrains -Minor amount of clay,calcite and opaque minerals	-Sandstone
C3S8	gray in color, with a texture ranging from fine to coarse.	Minerals qtz(85%), cal(7%),fel(5%), op(3%)	- Grain supported text -Quartz grains are themajor component of matrix	-Sandstone
C3S9	-Dark gray in color -Fine to Medium grainedtexture	Qtz(60%), Biotite(34%), opaque(6%)	-Schistose Texture -Quartz, biotite and opaque are dominant	-Biotite-Quatz Schist
C3S10	-Dark gray in color -Medium grained texture	Qtz(65%), Biotite(30%), opaque(5%)	- Quartz, biotite, and opaque minerals exhibit parallel alignment in the schistose texture.	-Biotite-Quatz Schist
C3S11	- Light gray in color and with a texture ranging from fine to coarse.	Minerals qtz(85%), cal(7%),fel(5%), op(3%)	- Grain supported text -Quartz grains are themajor component of matrix	-Sandstone
C3S12	-Dark gray in color -Fine to Medium grainedtexture	Qtz(62%), Biotite(31%), opaque(7%)	-Schistose Texture -Quartz, biotite and opaque minerals are present	-Biotite-Quatz Schist
C3S13	-Gray in color, with fine to medium-sized grains.	Minerals qtz(88%), cal(7%),clay(2%), op(3%)	Grain supported text -Quartz grains are the major component of matrix and minor amountof calcite, clay and opaque minerals	-Sandstone
C3S14	-Gray in color -Medium grained in texture	Minerals qtz(86%), cal(6%),fel(4%), op(4%)	- Grain supported text -Quartz grains are themajor component of matrix	-Sandstone
C3S15	-Gray in color -Medium to course grained in Texture	Minerals qtz(84%), cal(6%),clay(6%), op(4%)	- Grain supported text -Quartz grains are the major minerals	-Sandstone

According to analyzed data for the given depth, the mineral composition seems the same that is dominated by quartz mineral except Sample C3S2, C3S9, C3S10 and C3S12.

Table 4.3 Mineral composition, grain shape and sorting with given Depth(m), Calub-Y.

Sample Code	Depth(M)	Mineral composition	Grain shape	Sorting
C3S1	2776	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Poorly sorted
C3S2	2775	Quartz	Xenoblastic	Well sorted
		Biotite	Flaky	Poor to moderately sorted
		Opaque	Xenoblastic	moderately sorted
C3S3	2774	Quartz	Angular	Well sorted
		Calcite	Angular	Well sorted
		Opaque	Angular	moderately sorted
		Clay	Fine	poorly sorted
C3S4	2773	Quartz	Angular	well sorted
		Calcite	Angular	moderately sorted
		Opaque	Angular	moderately sorted
		Clay	Fine	well sorted
C3S5	2772	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Poorly sorted
C3S6	2771	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Poorly sorted
C3S7	2770	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Poorly sorted
C3S8	2769	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Moderately sorted
C3S9	2768	Quartz	Xenoblastic	Well sorted
		Biotite	Flaky	Poor to moderately sorted
		Opaque	Xenoblastic	moderately sorted
C3S10	2767	Quartz	Xenoblastic	Well sorted
		Biotite	Flaky	Poor to moderately sorted
		Opaque	Xenoblastic	moderately sorted
C3S11	2766	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Moderately sorted

C3S12	2765	Quartz	Xenoblastic	Well sorted
		Biotite	Flaky	Poor to moderately sorted
		Opaque	Xenoblastic	moderately sorted
C3S13	2764	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Poorly sorted
C3S14	2763	Quartz	Angular	Well sorted
		Calcite	Angular	Moderately sorted
		Opaque	Angular	Well sorted
		Clay	Fine	Moderately sorted
C3S15	2762	Quartz	Angular	Well sorted
		Calcite Opaque	Angular Angular	Moderately sorted Well sorted
		Clay	Fine	Moderately sorted

Table 4.4 Hand specimen Description, Mineral composition, Textural Descriptions and Given rock name of Hilala-X

Sample number	**Hand Specimen Description**	**Mineral composition**	**Textural Descriptions**	**Rock Name**
H4S1	- light gray in color and fine tomedium grained in texture	Minerals qtz(86%), clay(10%), op(4%)	-Grain Supported Texture -Matrix mainly composed of quartz grains and minor amount of clay and opaque minerals	**-Sandstone**
H4S2	- Dark gray in color and finegrained in texture.	Qtz(85%), clay(11%) opaque(5%)	-Mud Supported Texture -Clay is the major constituent of the matrix and minor amount of quartz, sericite and opaque minerals	**-Mudstone**
H4S3	- Dark gray in color and finegrained in texture	Minerals qtz(15%), clay(80%), op(5%)	-Mud Supported Texture -Clay is the major constituent of the matrixand minor amount of quartz and opaque minerals	**Mudstone**
H4S4	- Dark gray in color and finegrained in texture.	Minerals qtz(13%), clay(79%), op(5%), sericite(3%)	-Mud Supported Texture -Clay is the major constituent of the matrixand minor amount of quartz and opaque minerals	**-Mudstone**

4.1.4 Porosity evaluation

Table 4.5 the major characteristics that affect the quality of reservoir rocks are the relationship and percentages of porosity and permeability. The textural traits of grain size, shape, packing, and arrangement have some impact on porosity and permeability. The arkose sandstones typically have higher porosity levels. Each borehole, at varying depths, and with varied sand units responded differently to the various controls (such as detrital matrix and cements) on reservoir quality. The vast matrix in some of the samples prevents the nucleation of overgrowths, despite the presence of both primary and secondary pore types in the sandstones at various depth intervals.

Intergranular (pore space between grains) and microporous (matrix micropores) are the major porosities that have been discovered, while secondary porosities include secondary intragranular, dissolution, and fractured pores (Table 4.5). The sandstones' point count porosity values range from 0.723% to 13.103%, with an average of 8.211% (Table 4.6). The table below provides a summary of the sandstones' reservoir qualities as they were observed.

The two sets of clastic rocks in the Calub-Y well primarily consist of pores, including primary pores, secondary pores, intergranular dissolution pores, and intragranular dissolution pores. intergranular pores first appear, followed by moldy pores and extra-large pores. Grain fractures and intragranular pores are frequently observed. when less than 30% of the pores are secondary.

Calub-Y has a core porosity that, when paired with core analysis, ranging from 6.0% to 17.6% with an average of 10.6%, which indicates that it has medium porosity.

Intergranular and intragranular dissolving pores primarily arise in Hilala-X Adigrat production. The calcite and kaolinite in the cement dissolve to form the intergranular pores. In some areas of the Adigrat sandstone, such pores are frequently produced and have high connection.

Table 4.5: Summary of the reservoir properties of Adigrat sand stone

	Types of pores	Method of formation	Characteristics
Primary pores	Primary intergranular pores	Contraction and compaction between grain	Point to line contact of grain
	Micro porosity	pores created by the continued interaction of matrix grains	Pores between authigenic clay minerals
Secondary pores	Solution pores	formed as a result of framework grains and cements dissolving	Corrosion of cements' and grains' edges
	Secondary intragranular pores	Pores created by the dissolution of calcite cement, lithic pieces, and detrital feldspar	Corrosion inside of feldspar grains
	Fracture pores	Rocks are fractured by tectonic pressures and differential compaction.	the grains are bent or there are fissures

4.2 Discussions

4.2.1 Sandstone Petrography and Mineralogy

Quartz predominates in the Adigrat Sandstone at Calub-Y and Hilala-X, with low amounts of feldspar, rock fragments, cement, matrix, and other minerals as opaque, Sericite, and biotite. The Adigrat Sandstones' typical quartz grain percentages and features suggest the origins of igneous, metamorphic, and pre-existing sedimentary rocks in the studied area. The general variation in the relative abundance of the various varieties of quartz and feldspar grains lends credence to this hypothesis. Quartz can be found in both monocrystalline (Qm) and polycrystalline (Qp) forms, indicating that it may have originated from both igneous and metamorphic processes (Tucker, 2001). Monocrystalline quartz grains are mostly plutonic, according to Folk (1974) and McBride's (1985) genetic and empirical classification of the quartz kinds, whereas polycrystalline quartz is made up of recrystallized and stretched metamorphic types. According to Adams (1977), the predominance of monocrystalline quartz grains in sandstones suggests that they were primarily formed from agranitic sources. The abundance of monocrystalline grains in the sandstone samples, on the other hand, may be the result of the original polycrystalline quartz grain disintegrating after a long-distance travel from the metamorphic source, according to Dabbagh and Rogers (1983). Sandstones were derived from plutonic igneous rocks, as evidenced by the fact that some of the polycrystalline quartz grains include two or more crystals with straight to slightly curved inter-crystalline borders. (Blatt,1973). Indicating a granitic and/or metamorphic source for the quartz grains, the presence of strained and unstrained quartz grains suggests separate source rocks and that some of the strain was inherited (Young, 1976). Similar to this, certain monocrystalline quartz grains display undulatory extinction, which is a sign of metamorphic and earlier sedimentary rocks in the provenance (Blatt, 1973). Additionally, Basu, et al. (1975) demonstrated that changed feldspar grains are primarily from metamorphic sources, whereas pristine shards of feldspar grains in sandstones imply an igneous source area. After examining the various traits we noticed in terms of the minerals contained in the core samples and the thin sections. The research area's sandstones include both altered and a few isolated grains of pure feldspar, suggesting that they likely had both igneous and metamorphic origins. Low percentages of feldspar and lithic pieces in sandstones are generally preferred by a mature transport regime and a cratonic source (Akarish & Gohary, 2008).

4.2.2 Sandstone classification

According to Dott (1964), Pettijohn (1972), Pettijohn (1973), Folk (1974), Dickinson (1983), and Johnson (1991), the most popular and successful methods for classifying sandstones combine the textural criteria (i.e., the proportion of the matrix) with the compositional criteria (i.e., percentages of the framework grains). Classification techniques based on percentages of the framework grains (total quartz, feldspar, and lithic fragments) are based on the percentages of the framework grains. They will be displayed in a triangle-shaped plot, with these three elements acting as the last elements of a Q-F-L ternary diagram. (Raymond 1995).

Important information regarding provenance is provided by Folk's classification scheme, with the name of the rock revealing specifics of its composition. Based on the classification schemes put forward by Pettinjohn (1975), Folk (1980), and Dickinson (1983), the Adigrat Sandstones in the Calub-Y well and Hilala-X well were categorized in this study. The QFL ternary diagram proposed by (Folk 1980) showed that approximately 75–80% of sandstones were categorized as quartz arenite, with the remaining 20–25% being plotted in the subarkose and sublithic arenite field.

The classification of the Adigrat Sandstone as quartz arenite, subarkose, and sublithic arenite is also shown. According to Pettijohn (1987) and Nichols (2009), sandstone can be classified as arenite if it contains less than 15% matrix, and as a wacke if it contains between 15 and 75% matrix. The sandstones can be categorized as arenites based on the matrix percentages shown in (Table 4.6.). Furthermore, according to (Pettijohn, 1987; Nichols, 2009), sandstone cannot be referred to as a feldspathic arenite or an arkosic arenite unless at least 25% of the rock is composed of feldspar. According to the same rules, sandstone becomes a lithic arenite when it contains at least 25% lithic pieces. Similar to subarkosic arenite, sublithic arenite is a kind of sandstone that contains feldspar or lithic particles in proportions between 5 and 25% (Pettijohnb et al., 1987; Nichols, 2009). The sandstones are categorized as arenites, subarkosic, and sublithic arenites based on the matrix composition displayed in (Table 4.6), which is consistent with the findings of the QFL ternary plot. The QFL sandstone categorization diagram did not reveal any differences in the samples retrieved from Calub-Y and Hilala-X, indicating that they had similar source and transportation histories.

4.2.3 Sandstone Provenance and Tectonic Setting

The study of sandstone provenance can show the distinctive properties of rock types that are typically found in tectonic contexts (Dickinson, 1985). Pettijohn (1975), Folk (1980), Dickinson (1983), Yerino and Maynard (1984), Dickinson (1988), Kumon et al.et al., 1992; Baiyegunh et al., 2017) have used the Q-F-Lternary diagram to connect the detrital framework grains of sandstone to various provenance settings, such as stable cratons, recycling orogenies, basement uplifts, and magmatic arcs. One technique used to determine the origin of specific sandstone is Q-F-L (quartz- feldspar-lithic fragment) analysis (Mohammedyasin and Wudie, 2018). The Q-F-L ternary diagram suggested by (Pettijohn, 1975; Folk, 1980; Dickinson, 1983) was used to depict the Adigrat Sandstone.

Dickinson et al.'s (1983) Qt-F-L diagram (Fig. 6). Additionally, it demonstrates that the sandstone primarily falls in the field of continental block provenances (with stable craton origins and uplifting in the basement complexes), while some samples do as well. Sandstones plotted in the craton field may be formed from relatively low-lying granitoid and gneissic sources, with the addition of recycled sands from an adjacent platform, according to Dickinson et al. (1983). The petrographic and modal compositional analyses' findings indicated that the examined sandstones share traits with the passive margin setting. According to Kumon et al. (1992), passive margin sandstones from plate interiors or stable continental margins typically have high quartz content.

4.2.4 Porosity Evaluation and Quantification

Thin sections of the Calub-Y well and Hilala-X Well core samples were analyzed quantitatively using an optical microscope, and the results were reported (Table 4.5). According to the statistics, the Adigrat sandstone rock has a low to medium porosity. The Adigrat Sandstone is a medium reservoir rock as a result.

C3S8	2769	14	3	82	1
C3S9	2768	0	0	0	0
C3S10	2767	0	0	0	0
C3S11	2766	6	4	88	2
C3S12	2765	2	14	81	3
C3S13	2764	1	27	66	6

Table 4.6: Adigrat sandstone of Calub-Y well and identified amount of porosity from point counting

Sample code	Depth	Matrix	Cement	Grain	Average porosity
C3S1	2776	14	22	62	2
C3S2	2775	2	25	68	5
C3S3	2774	5	18	73	4
C3S4	2773	6	34	59	1
C3S5	2772	17	8	72	3
C3S6	2771	17	21	60	2
C3S7	2770	8	8	76	7

C3S14	2763	4	6	86	4
C3S15	2762	5	4	87	4

Table 4.7: Adigrat sandstone of Hilala-X and identified amount of porosity from point counting

Sample code	depth	Matrix	Cement	Grain	Average porosity
H4S1	3134.7	8	7	76	8
H4S2	3135	14	3	82	1
H4S3	3136.5	15	5	75	5
H4S4	3137	10	4	80	6
H4S5	3138.7	6	4	88	2
H4S6	3139.4	2	14	81	3
H4S7	3140.5	1	27	66	6
H4S8	3141.5	4	6	86	4
H4S9	3143	3	6	87	4
H4S9	3144.5	5	12	78	5

CHAPTER FIVE

5. Conclusion and Recommendation

5.1 Conclusion

The findings of this study on the Adigrat sandstone offer important new information about its mineralogy, texture, and ultimate provenance. Adigrat sandstone was extracted from the calub-Y and Hilala-X wells. The creation and history of sedimentary rocks can be better understood by identifying and quantifying these components. The study area's classified Adigrat sandstone is primarily Quartz arenite, with a small number of samples falling into subarkoses and sublithic arenite fields. Petrographic analysis of quartz grains revealed somewhat sutured and twisted grains as well as convex-concave contact between grains, indicating diagenesis, particularly compaction, had an impact on the Adigrat sandstone. The Adigrat sandstone exhibits low-medium porosity. The intense compaction leads to the general densification of sandstone during the early diagenesis stage. Different clay cementation and dissolution in a later stage leads to the differentiation of reservoir quality. The modal composition analysis of sandstone provenance is summarized as craton interior, recycled orogeny and continental block provenance. From Calub-Y and Hilala-X Adigrat sandstone similarity, interms of modal composition, and provenance, it is possible to infer that the reservoir properties anywhere between these localities (Calub & Hilala) can be the same.

5.2 Recommendations

The study suggests that Markov chain analysis be used to define and identify lithofacies trends or cycles in locations that expose this lithology. As soon as these cycles are formed, they can be used for local and regional correlation. Since the Ogaden basin is a suitable location for conducting a wide variety of scientific inquiries, researchers must focus on exploring the general provenance of the Adigrat sandstone in the region.

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