ADDIS ABABA UNIVERSITY

SCHOOL OF EARTH SCIENCE

FACIES AND PALEOENVIRONMENT OF THE CARBONATE UNIT IN THE MERTULE MARIAM SECTION: EAST GOJJAM, CENTRAL ETHIOPIA

By Mahider Mulugeta

Thesis Submitted to the School of Earth Science, Addis Ababa University in partial fulfillment of the requirement for the Degree Master of Science (Paleontology and Paleoenvironment Stream)

September, 2020

Addis Ababa, Ethiopia

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BY

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September, 2020

Addis Ababa, Ethiopia

DECLARATION

I hereby declare that the thesis entitled as "**facies and paleoenvironment of the carbonate unit in the Mertule Mariam section: east Gojjam, central Ethiopia"** submitted to the School of Earth Science ,Addis Ababa university, is a record of an original work done by me under the guidance of Dr.Balemwal Atnafu. I further declare that the results embodied in this work have not been submitted in any other university or institute for the award of any degree. All sources and materials used for this thesis work have been well referenced.

ABSTRACT

A detailed study on the facies and paleoenvironment of the 330m thick carbonate unit of the Mertule Mariam section has been conducted. Field work and laboratory analysis were implemented inorder to accomplish the main objectives of this study. A total of 34 rocks and 17 dry marl samples are collected from the study area and have been examined under petrographic and binocular microscopes respectively.

Lithostratigraphically, the carbonate unit of the section is characterized by bedded and bioturbated limestone, fossiliferous limestone, mudstone, oolitic limestone and marl unit.

Based on field investigations and based on paleontological and petrographical studies, 11 microfacies types have been recognized and are grouped into four microfacies associations related to paleoenvironments of tidal flats, lagoon, high energy shoal and open marine. Consequently, the carbonate units of the study area represent a shallow marine setting depositional system.

Based on paleontological studies various macro and micro fossis are identified including foraminifera and ostracod microfossils; and Bivalve, Brachiopod and gastropod. Additionally algal fossils also recognized

The age of the carbonate unit is indicated as Callovian to early Kimmerdigian due to the presence of the following index fossils: *pfenderina sp*., Kurnubia *palastiniensis* and *Alveosepta jaccardi.*

The present carbonate unit is correlated with different measured sections in the Blue Nile basin and regionally with the Antalo limestone of the Mekele basin and Urandab Formation of the Ogaden basin depending on biostratigraphy and lithostratigraphy.

Key words: Carbonate unit, Paleoenvironment, Microfacies, Blue Nile basin, Microfacies association, Microfossil

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LIST OF ACRONYMS

A.S.L	above Sea Level
DEM	Digital Elevation Model
E	East
FZ	Facies Zone
FWWB	Fair Weather Wave Base
GPS	Global Positioning System
HCL	Hydrochloric Acid
H_2O_2	Hydrogen Peroxide
MFT	Microfacies type
M	Meter
ML	Mertule Mariam
PPL	Plane Polarized light
SMF	Standard Microfacies
W	West
XPL	Cross Polarized light

CHAPTER ONE

1. INTRODUCTION

1.1. BACKGROUND

Sedimentary basins are regions of depression due to prolonged crustal subsidence, in which Sediments are accumulated (Philip and John, 2005). The geology of Ethiopia ranges from oldest (Precambrian) to recent volcanic and sedimentary formation (Ministry of Mines and Energy, 2009, unpublished). Ethiopia's sedimentary regions occupy a large part of the country and consist of five distinct sedimentary basins: the Ogaden, Blue Nile, Mekele, Gambela, and Southern Rift Basins (Wolela Ahmed, 2008). The Mesozoic sediments of Ethiopia mainly occurs in: Blue Nile Basin (Getaneh Assefa, 1991 and Russo et al, 1994, Wolela Ahmed, 2007, 2009), Mekele Basin (Bosellini et al, 1997 and Beyth, 1971) and Ogaden Basin (Bosellini et al, 2001). This work focuses on the first region (Blue Nile Basin) especially on the area between Mertule Mariam and Mekane Selam towns (Fig.1).The Ogaden basin is the largest and deepest in terms of sediment thickness. The Ogaden Basin witnessed the first marine transgression and therefore exhibits the most expanded sedimentary sequence within Ethiopia. It is not only the reference section for the Ethiopian Jurassic, but also the most studied one, due to the possibility of hydrocarbon reservoirs. (Jain & Singh, 2019).According to Russo et al (1994), the sedimentary history of the Mesozoic succession is related to the formation of rift basins around the borders of mega continent as a result of Gondwana break up.

In addition to the initial breakup of Gondwana, the northeastern Horn of Africa was invaded by an Early Jurassic regional marine transgression (Abbate et al, 2015). According to (Abbate et al, 2015), carbonates are the common facies of the Jurassic transgression.

The Blue Nile Basin, situated in the Northwestern Ethiopian Plateau, contains 1200-1400 m thick Mesozoic sedimentary section; it is underlain by Neoproterozoic basement rocks and overlain by Early–Late Oligocene and Quaternary volcanic rocks (Gani et al., 2009).Additionally, Blue Nile Basin contains rare Paleozoic sediments (Getaneh Assefa, 1991, Merla, 1997).

Abay (Blue Nile) basin contains five major units from bottom to top; Adigrat Sandstone, Gohatsion Formation (Getaneh Assefa, 1981, Chernet et al, 2019), Antalo Limestone, Mugher Mudstone and Debre Libanos Sandstone (Getaneh Assefa,1991,Russo et al, 1994 ,Jain and Singh,2019).

The thickness of limestone in the Blue Nile basin ranges between 200-600m (Russo et al, 1994, Getaneh Assefa, 1991).

Paleoenvironmental interpretations derived from microfacies should be controlled by lithological criteria and sedimentary structures evaluated by the high information potential provided by fossils and biogenic structures. In the present studies the Microfacies types (MFT) were classified and compared with Standard Microfacies types (SMF) of Flügel, 1972 and Wilson, 1975.

The petrographic study of carbonates has been carried out for microfacies analysis on the basis of their textural, compositional and digenetic characteristics.

Carbonates are originated as skeletal grains or precipitates within the depositional environment. So that the fossil remains of animals and plants preserved in carbonate rock are used for the interpretation of depositional environment, geological record dating and biostratigraphy. The deep understanding of facies analysis and paleontology provides information in understanding the history of the earth; in terms of geological record, paleoenvironmental changes, and basis of correlation of strata through the identification of taxa‘s.

1.2. Description of the study area

1. 2.1 Location and accessibility

This project is conducted in northwestern Ethiopia plateau, particularly between 400030m and 480030m Easting and 20000m and 1140000m northing. The area is located 366 Km from Addis Ababa and can be accessed through the main Asphalt road that joins Addis Ababa and Dessie through Dejen-Bichena-Mertule Mariam-Mekane Selam. The section is located about 20 Km far from Mertule Mariam town, Between Mertule Mariam and Mekane Selam.

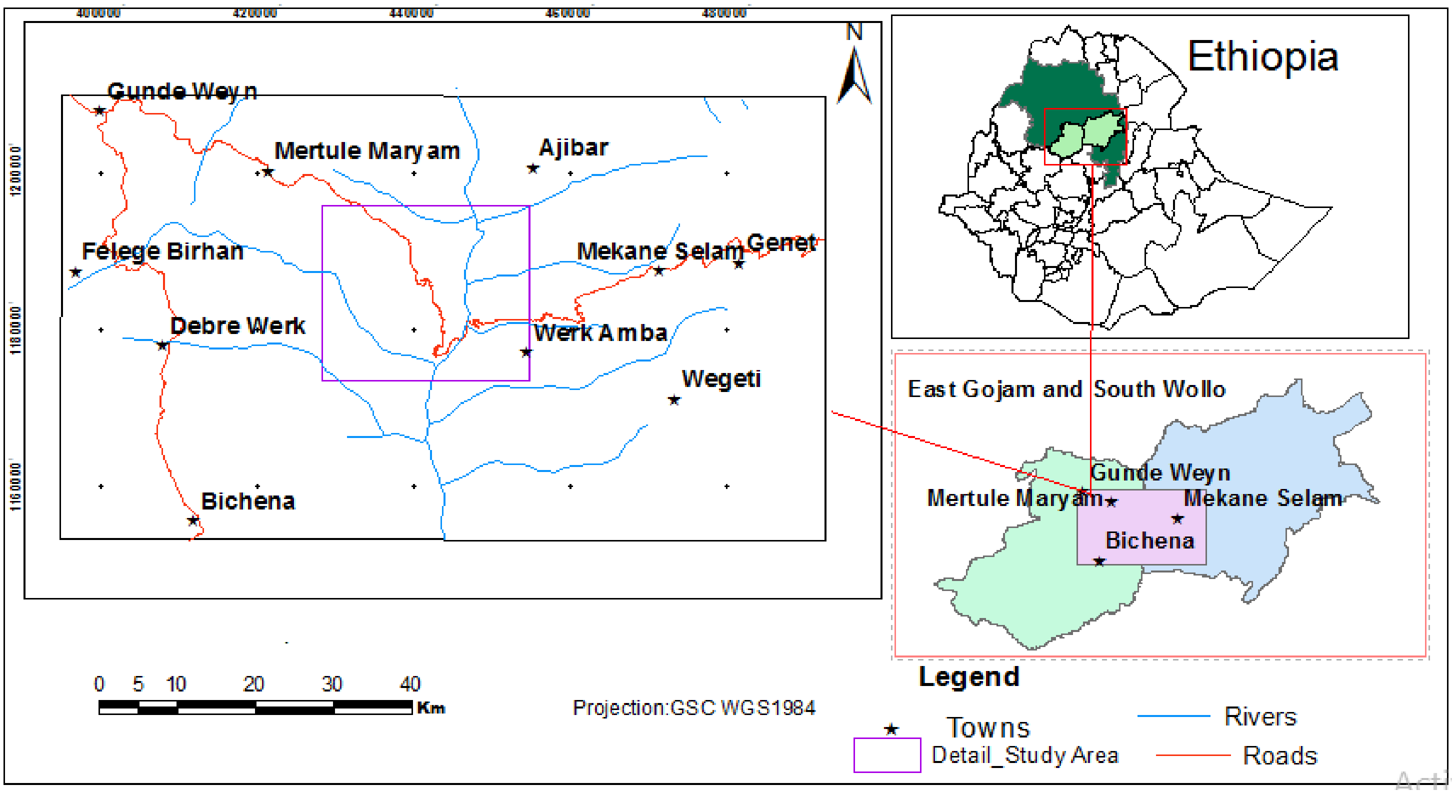


Figure 1.1. Location map of the study area

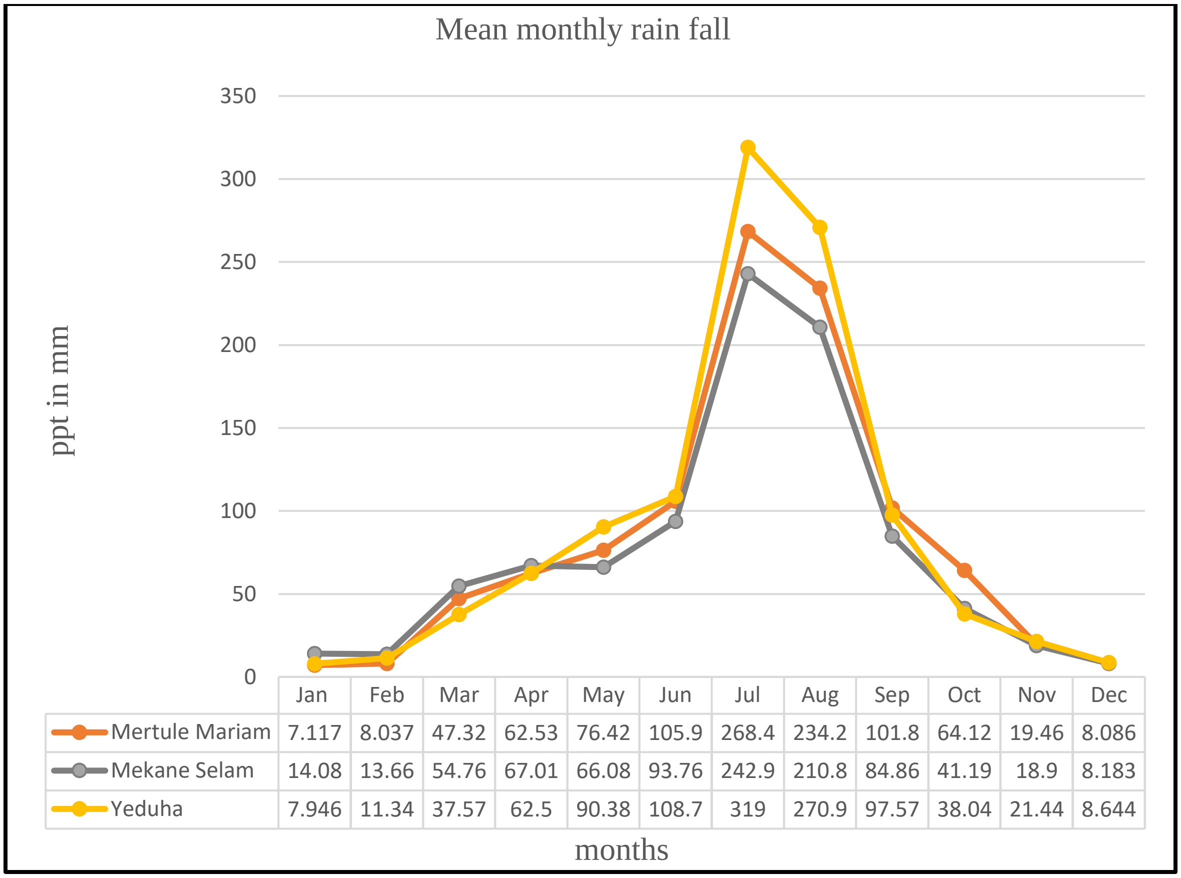
1.2.2. Climate

Weather is somewhat unpredictable and highly variable. Consequently, a longer-term view of the weather pattern of a particular locality is frequently more useful as an environmental tool (Habtamu Solomon, 2011).

1.2.2.1. Rainfall

In this study area, there are seven rainy months from March to September, where the small rains occur during March to May and the big rains are from June to September (Figure 1.2).

Monthly total rainfall records of three stations for the study area between year 1992 and 2018 is used to analyze monthly mean rainfall and annual mean rainfall. The mean monthly rainfall of National Meteorological Agency stations located at Mertule Mariam, Mekane Selam and Yeduha.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mertule Mariam	7.117	8.037	47.32	62.53	76.42	105.9	268.4	234.2	101.8	64.12	19.46	8.086
Mekane Selam	14.08	13.66	54.76	67.01	66.08	93.76	242.9	210.8	84.86	41.19	18.9	8.183
Yeduha	7.946	11.34	37.57	62.5	90.38	108.7	319	270.9	97.57	38.04	21.44	8.644

Figure 1.2.mean monthly rainfall from 1992-2018(data source: National Metrological Agency of Ethiopia, 2019).

The monthly mean records of rainfall for twenty-six years shows that the mean annual rainfall at Mekane Selam (at elevation of 2605m a.s.l), Mertule Mariam (at elevation of 2676m a.s.l) and Yeduha (at elevation of 2375m a.s.l) is 1831,1591,2267mm respectively. Thus, the study area receives average annual rainfall of about 1896 mm.The highest mean monthly rainfall recorded in July for the stations and the minimum mean monthly rainfall recorded in January for Mertule Mariam and Yeduha and in December for Mekane Selam.

1.2.2.2. Temperature

The monthly mean temperature records at Mekane Selam and Yeduha stations for the years between 1992 and 2018 have been used to calculate monthly mean temperatures. The computed average mean monthly temperature are given in Figure 1.3.

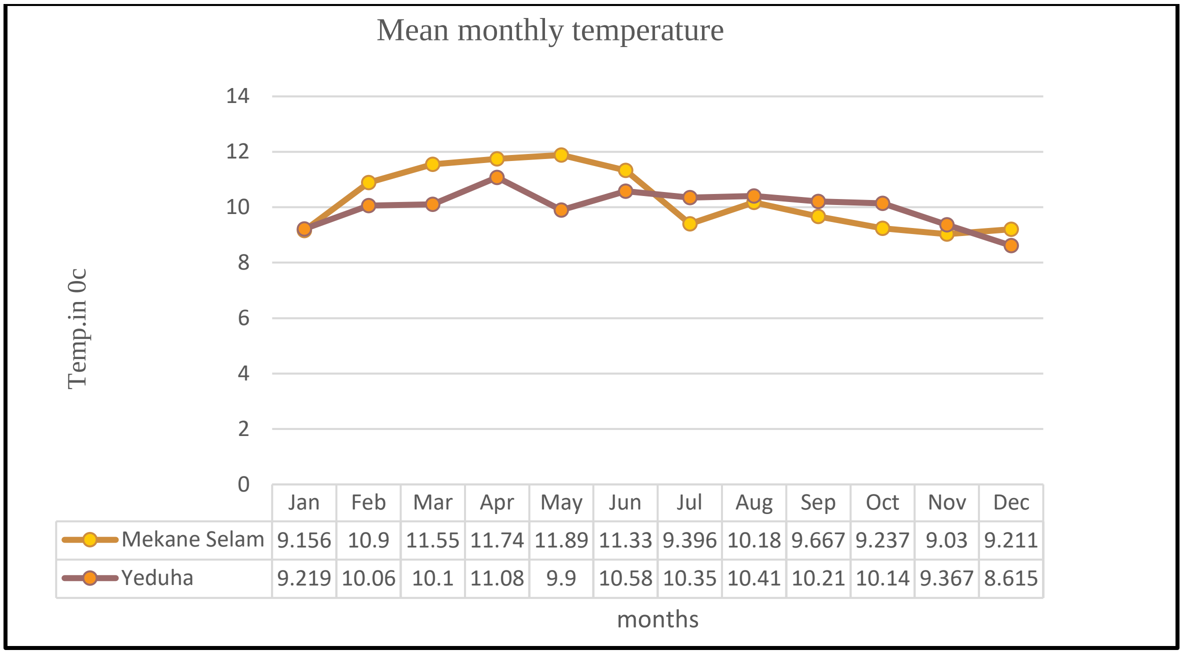


Figure 1.3.Mean monthly temperature from 1992-2018 (Data Source: National Metrological Agency of Ethiopia, 2019).

The highest mean monthly temperature in both stations (Mekane Selam and Yeduha) occurs in the months of April, which is 11.74 and 11.08 0c respectively. The lowest mean monthly temperature occurs in the month of December for Yeduha (8.6150c) and November for Mekane Selam (9.030c).

1.2.3. Physiography and Drainage

The topography of the Mertule Mariam section is characterized by flat and rugged around the Blue Nile River and have high to medium elevated areas at other localities (Fig.1.4). The elevation ranges between 1104m and 3500m above mean sea level as shown below from DEM with 90m x90m resolution. The study area drained with the Abay main river and Jema, Chemoga, Gula, Yeda, Bogena, Aleltu, Cheye and muga river small rivers which drained into Abay river.

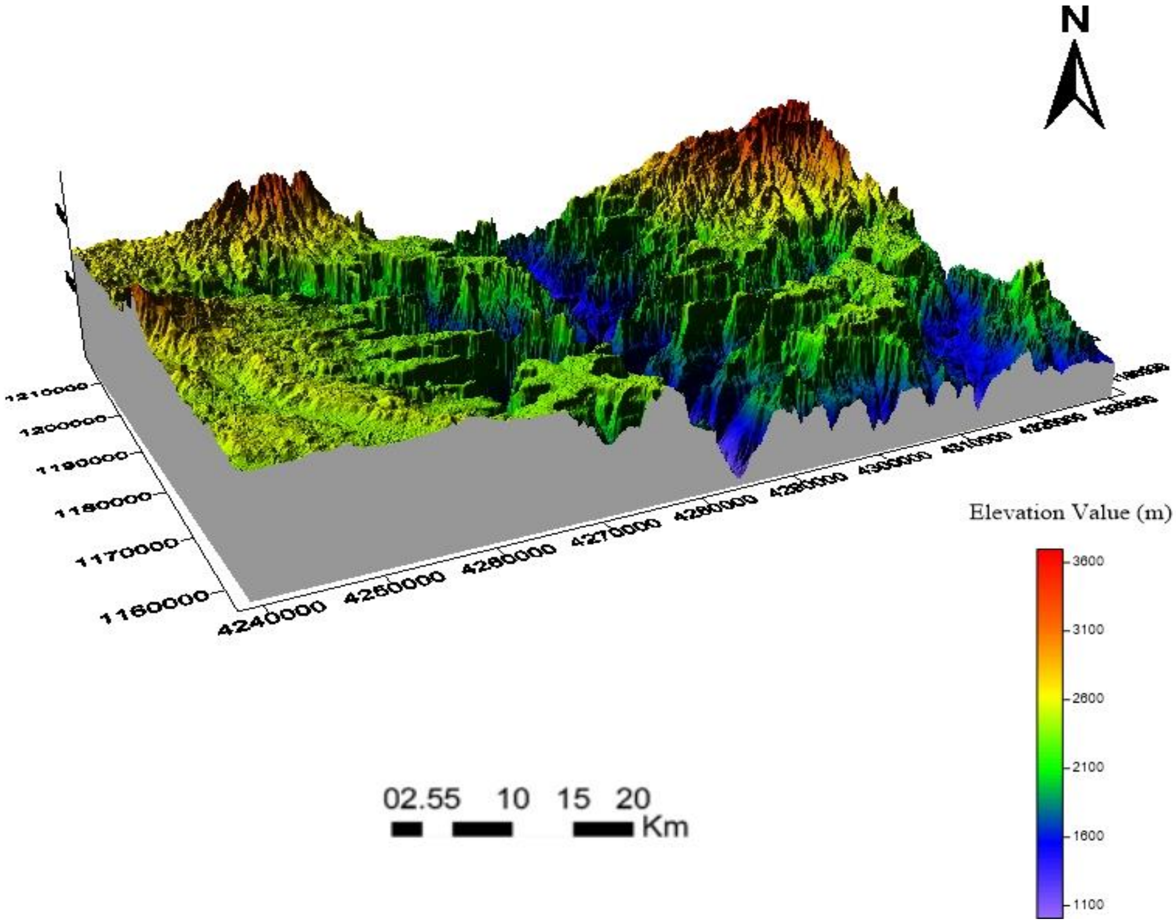


Figure 1.4.Physiography and Drainage map of the study Area

1.2.4. Vegetation coverage

The study area covered by brush type of vegetation, which has spine. The area densely cover by those brushes at the marl unit. The vegetation coverage in other localities is sparsely distributed.

1.2.5. Population settlement

The study area dominated by Amhara nation, who speak Amharic language. Most peoples live at the top of the gorge due to the suitability of the area for the farming activity and the weather condition. They participate in agricultural practices, cultivating different kinds of crops such as Wheat, maize, barley and teff and participate also in breeding of all domestic animals such as cattle, sheep, goat and donkeys commonly.

1.3. Previous Works

Since the mid-19th century, the study of sedimentary rocks in Ethiopia has begun (Kazmin, 1973 and his references Blandford, 1870 and Dainelli, 1943; Mohr, 1962). The sedimentary rock cover in Ethiopia accounts for more than 40% of the surface area of the country (Asrat, 2015). According to Asfawossen Asrat, 2015 in Ethiopia there are more than 100,000 square kilometers of carbonate rocks exposed. Most of Ethiopia's research on carbonate deposits was largely focused on regional level. Carbonate units in the stratigraphic record make up about one-fifth to one-quarter of all sedimentary rocks (Boggs, 2009). According to Boggs (2009) Carbonate rocks, such as Limestone contain important and varied textures, structures and fossils that provide important information about ancient Depositional environments, paleo ecological conditions and the evolution of life forms, especially marine ones. Paleontological study of Carbonate rocks of Harar was studied by various authors (Greitzer, 1970 and Kazmin, 1973). Many authors classify the carbonate units of Harrar into different groups based on different Criteria. E.g, Kazmin (1973) group Hammanlei series of marine succession into three units from bottom to top as: - oolitic, dolomitic limestone with intercalation of marl and sandstone (unit one), unit two contains grey oolitic limestone with subordinate beds of red and yellow limestone and finally limestone with concretions of chert and druses of quartz (unit three*)*. There are various researches which were conducted outside Ethiopia on microfacies and Paleoenvironment of carbonate units: in Yemen the depositional environment of the tertiary carbonate sequence of Socotra Island has been determined as it was shallow marine environment except Mughsayl formation which was deposited in deep marine environment(Al-aydrus, 2011).By doing the detailed microfacies analysis and the diagenetic settings of the Middle Jurassic samana suk formation exposed at the sheikh budin hill section, Nizami Rauf Abdur and Sheikh Ahmad Riaz, in 2009 conclude the formation was deposited in an environment of shallow shelf with open and restricted marine conditions as carbonate platform depositional product. According to general stratigraphical relationships between Africa, Madagascar, India and Arabia, the Antalo Super sequence was deposited on a homoclinal ramp (Bosellini et al., 1997***).*** The Mekele outlier has 700-800 m thickness Antalo limestone and four different facies types have been identified (Beyth, 1972 and Bosellini et al, 1997). According to Bosellini et al.1997, the age of the Antalo Limestone in Mekele outlier was assigned to Late Callovian (?)-Kimmeridgian. The important studies on the sedimentary succession within the Blue Nile basin include that of Aubry (1886), Dainelli (1943), Mohr (1963) and Beauchamp (1977). Later works on the Mesozoic succession of the basin include that of Getaneh Assefa (1980, 1981, 1991); Russo et al. (1994), Wolela (1997), Dawit & Bussert (2009). An excellent study, which focused on the age and depositional environment of the carbonate units in the Blue Nile Basin is that of Russo et al. (1994.) According to Russo, et al., (1994) the age of limestone in the Basin is determined by using index fossils as it range from Callovian to Kimmeriginan from bottom to top due to the presence of *Pfenderina sp.* and *Nautiloculina oolithica* at the *base Kurnubia palestiniensis, Parurgonina caelinensis, Conikurnubia sp.* and *Salpingoporella annulata* at the top of the unit.

Based on nannofossil record from the Blue Nile Basin the new age spanning from Early Callovian to Late Tithonian has been determined for the Antalo limestone (Jain and Singh, 2019).

1. 4. Problem Statement

Carbonate units contain fossils which are important to identify age and depositional environment of the unit (Boggs, 2009). To explore such important information detail study of the units by using different methods is needed. Among the methods facies analysis and paleontology are the most powerful methods for detail investigations of carbonate sedimentary rocks (Flugel, 2004).

Despite the presence of numerous sedimentary basins in Ethiopia, limited number of detail studies exist that address the sedimentary succession of such basins, especially on carbonate units. Many geological researches have been conducted on Blue Nile basin but very little amount of related researches on paleontological and environmental studies was conducted on carbonate units in the Blue Nile basin (e.g. Russo et al, 1994, Dawit ,2010, Jain and Singh,2019).

Since there was no accessibility from gunde weyn to Mekane Selam the facies, paleontology and depositional environment of Carbonate units of the Mertule Mariam section is not studied. Moreover, the correlation of the section with other sections of the country is not studied. This detail study Focus on such aspects is the first and it will help to identify the depositional environment, age and the lateral and vertical extent of carbonate units within the specific area and the Blue Nile basin**.**

1.5. Objectives

1.5.1 General objective

The principal objective of this research is to study and interpret facies, depositional environment and paleontology of the carbonate units found in the Mertule Mariam section.

1.5.2. Specific objective

Specifically the study has the following objectives

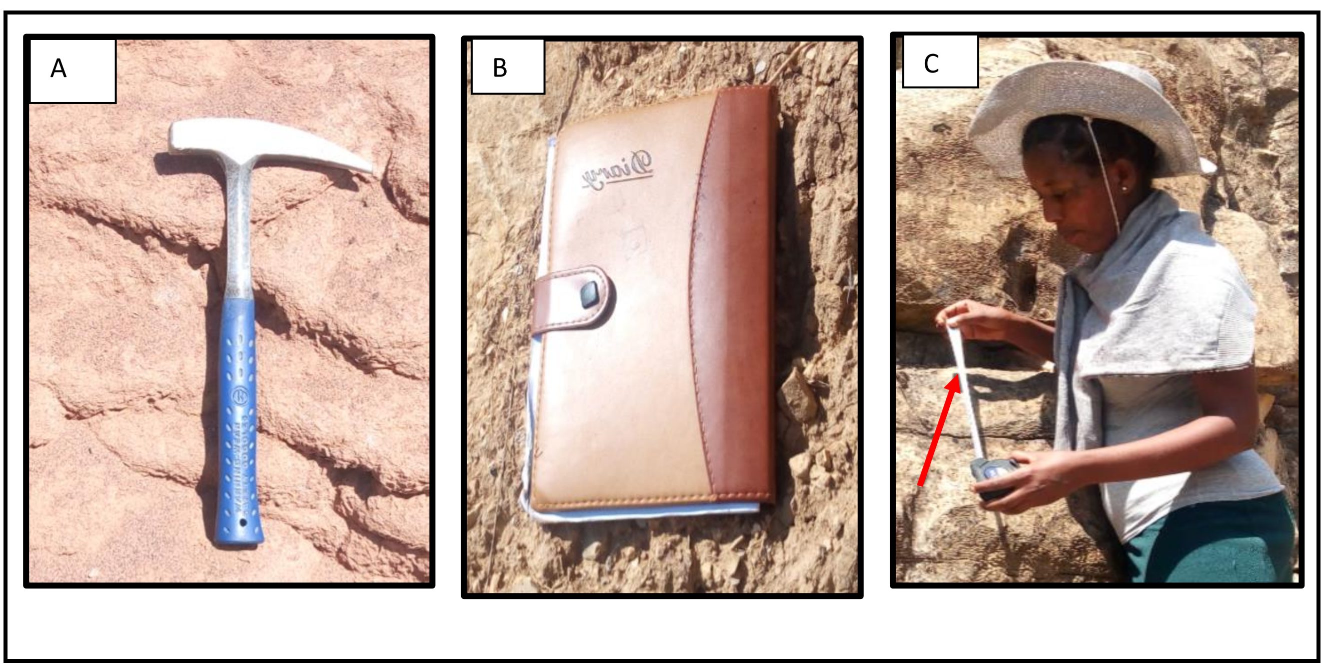
- To Produce a detailed stratigraphic log of the Carbonate unit
- To Identify and describe micro and macro fossils in the carbonate units of the study area
- To determine the relative age of the carbonate unit found in the area
- To describe petrographic properties of the carbonate rocks and to determine microfacies types
- To correlate rocks of the section intrabasinaly and regionally

1.6. MATERIALS AND METHODS

1.6.1. Materials

1.6.1.1. Field Instruments

In order to accomplish this research various materials were used for field data collection and laboratory analysis. Instruments that exist at Addis Ababa university school of earthscience were used to perform field data collection, rock sample and dry marl sediment collection (Figure 1.5). These are geological hammer, note book, meter stick, dilute 10% HCl, GPS, sample bag, plastic sample bag, marker, pen, standard scale and hand lenses**.**



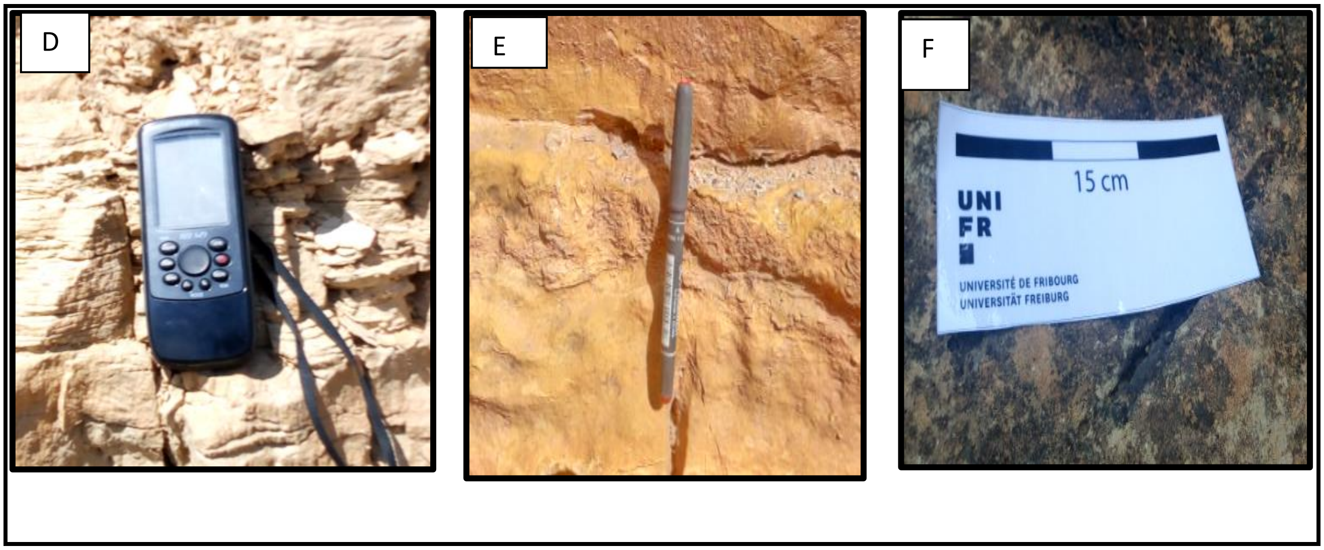
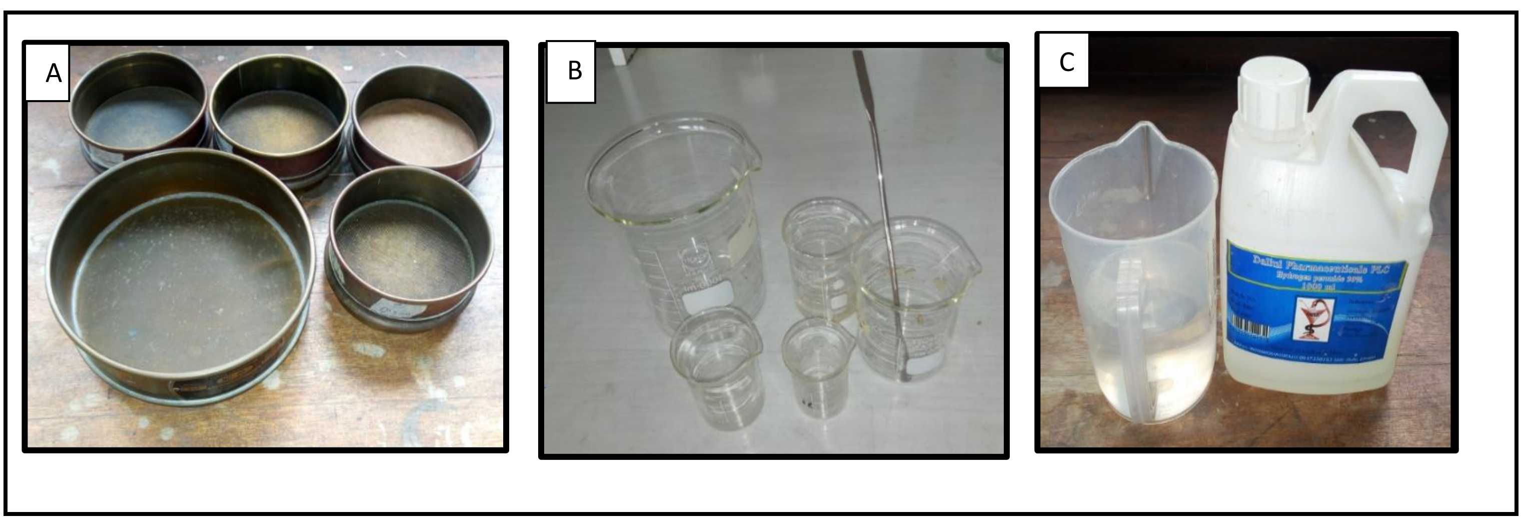


Figure 1.5.Photograph shows some of the instruments used during field work. A.Geologicalhammer B Note book C.meter stick D.Gps E.Marker F. standard scale.

1.6.1.2. Laboratory instruments

The instruments found in the sedimentology and paleontology laboratory of Addis Ababa University were used to extract and identify macro and microfossils and thin section analysis. These are, 100, 150 and 250 ml standard beaker, set of USA (United States of America) standard sieve number 35, 45, 60,120 and 450, which have 0.5 mm, 0.355 mm, 0.25 mm, 0.125 mm and 0.21 mm mesh sieves sizes, wash with water, 250 ml plastic containers, labels, petrographic microscope, light reflected binocular microscope, 30% H_2O_2, water, paint brush and different software including Arc GIS, Strater.



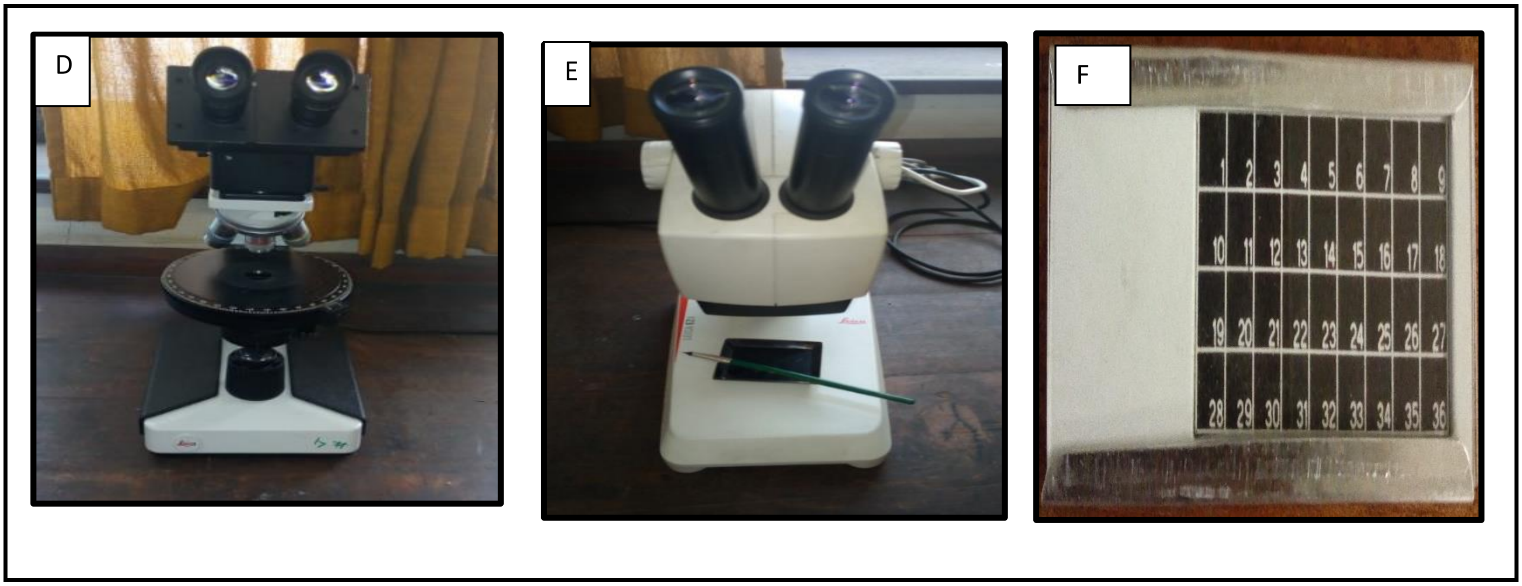


Figure 1.6.photograph shows laboratory instruments. A.standard sieve B.standard beaker C.H2O2 D. Petrographic microscope E.Binocular microscope, brush and black plate F.Picking plate

1.6.2. Methods

Various methods were implemented to determine the depositional environment, microfacies and age of the carbonate unit in the study area. Each method with detailed activities looks like as follows.

1.6.2.1. Field work and sample collection

Two Field trips were carried out to accomplish the research. The first trip was done at the end of 2011and some amount of samples were collected.

The second trip was conducted from mid of November to December first 2019 for a detailed Fieldwork and the third field was for data verification in March first. During this field work, the stratigraphic relationship of the carbonate unit with other rock units were identified, description of all the lithological variation in color, textures, sedimentary structures, macrofossils based on size and morphology, trace fossil identification, and degree of bioturbation identification

Many representative carbonate rock samples are collected for thin section preparation and further investigation and 17 marl samples are also collected for micro fossil identification.

The detailed stratigraphic sections were logged depending on the lithology variation to document thier microfacies architecture, paleontology and to see the lateral and vertical relationship of the carbonate unit in the sections, to construct their depositional model and finally to correlate with time equivalent carbonate rock unit.

1.6.2.2. Laboratory work and data analysis

Laboratory analyses were conducted on collected samples from the studied section to support the macroscopic analysis of field data. These include a petrographical, macrofossil and micropalaeontological description and analysis. The petrographic analysis were performed on 34 representative carbonate rock sample collected from the section for microfacies analyses and fossil identifications in Addis Ababa university department of earth science. For each sample the textures including mineralogical compositions, degree of bioturbations, varieties of skeletal and non-skeletal grains, various biogenic sedimentary structures, common diagenetic type, microcrystalline micrite, sparite identifications and descriptions were done. In order to identify the microfossil, the collected marl samples were prepared i.e. 100 grams of dry marl samples were placed in beaker, soaked in 100 ml of 30% concentrated H_2O_2 solution and were mixed with 200 ml of water. After minimum of 48hr the samples were then washed over USA Standard sieves with various size. Air and sun drying method was used to dry samples over 12 hr.

Figure 1.7.hotograph shows the microfossil separation method from sediments by using binocular microscope.

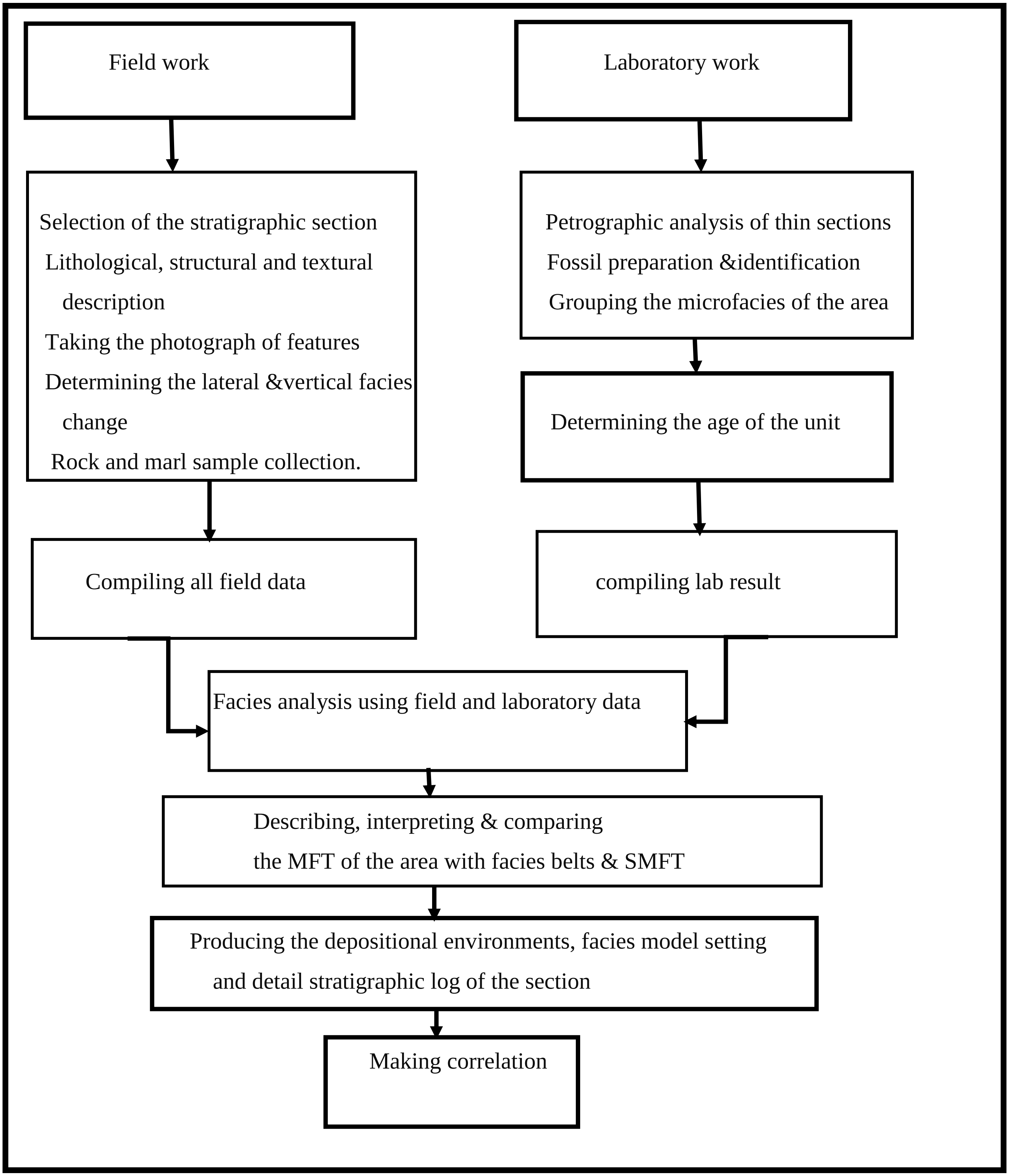


Figure 1.8. Methodology flow chart

1 .7. Significance of the study

This study helps to understand the detailed paleontology and facies characteristics of the carbonate unit in the selected stratigraphic section. This will be important to obtain a detailed picture of the depositional environment, age and the lateral and vertical relationship of the carbonate within the basin. Additionally, the result of this research will be an additional base for other studies to be conducted in the area.

1.8. Limitation of the study

The limitation of this thesis work is the absence of scanning electron microscope (SEM) to capture detailed photos of microfossils: foraminifera and ostracodes; identification of these microfossil species is a challenge. Attempts have been made by using camera and capture one sample photo many times and select the best.

1. 9. Structure of the thesis

This thesis contains seven chapters, which are organized as follows. Chapter one gives general information about the area of study. Second chapter provide a regional scale overview and basin evolution. In Chapter Three description of the lithology of the section. Chapter four gives information about the paleontology of the Mertule Mariam section obtained from macro and micro fossils and also fossils from thin section. In chapter five diagenesis and microfacies analysis is presented and the depositional environment of carbonate unit of the Mertule Mariam section is interpreted. In chapter six discussions on depositional environments of carbonate units of the section, their age and the correlation with other section perform. Finally in chapter seven the main conclusions and recommendations for the future study have been accomplished.

CHAPTER TWO

2. REGIONAL GEOLOGY AND BASIN EVOLUTION

2.1 Regional Geology

Depend on the work of many researchers, the Geology of Ethiopia is wide stratigraphically and were present in Southeastern and Northwestern Ethiopia which ranges from older Precambrian up to recent. From those, Blanford, 1869; Kazmin, 1973, Merla et al., 1979, Turi et al. (1980); Gebreyohannes Habtezeghi, 1984; Russo, et al. (1994); Abiyyu Hunegnaw et al., 1998; Bosellini et al., 2001); Asfawossen Asrat (2015); and Gani et al. (2008) have given some contribution to describe the stratigraphy of Blue Nile basin.

The lithological description of Blue Nile basin is as follows:

2.1.1. Basement Rocks

The basement of Ethiopia is a complex of metamorphic and igneous rocks of Precambrian and lower Paleozoic age (Getaneh Assefa, 1991).Rocks in the Blue Nile basin consist of Precambrian basic to acidic rocks (Kazmin, 1975).Tamrat and Tibebe (1997), are also describe that Precambrian crystalline basement is highly weathered coarse grained, acid plutonic consisting mainly quartz and alkali feldspars, different types of textures, faults and numerous dykes were observed. These rocks are made-up of variably metamorphosed quartzofeldspathic schists and gneisses, migmatites and plutonic rocks. In Blue Nile basin the basement rocks are unconformably overlain by Triassic - Early Jurassic Adigrat sandstone in most parts, but in some localities it is unconformably overlain by Paleozoic sediments.

2.1.2. Pre-Adigrat Sandstone

Prior to Dawit (2009), the pre-Adigrat has been simply considered as single unit. As assumed by Kazmin (1975) the age of pre-Adigrat I is a broad interval of Carboniferous-Mesozoic age and is made up of sandstone siltstone and shales filling north-south trending channels that are carved in to basement gneiss (Mohr, 1963, Jespen & Athearn, 1964). However, Dawit classified the pre-Adigrat unit in to three distinct units. From bottom to top, they are the Pre-Adigrat I, II and III.The Pre-Adigrat II is a 800m thick unit that unconformably overlies either the Precambrian basement or pre-Adigrat I. Lateral accretion deposit, floodplain fine and playa-lake mudstone characterizes its lower part (Dawit and Bussert, 2009).

The pre-Adigrat III reaches a thickness of 400m, and is composed of three successive cycles of stacked, multi-story sheet sandstone bodies. It is dominated by horizontal bedding and low angle cross-bedding (Dawit and Bussert, 2009).

2.1.3. Adigrat Sandstone Unit

The Adigrat Sandstones are widespread in Ethiopia and with correlative units in the whole of East Africa and Arabia (Fazzini et al., 2015). The unit generally overlies the basement unconformably, but in some places it overlies unconformably the Paleozoic continental sediments (Merla, 1979, Getaneh Assefa, 1991, Russo et al., 1994,Fazzini et al., 2015) but in the Ogaden basin the Adigrat sandstone overlies conformable with the Permo-Triassic Karoo deposits (Hunegnaw et al. 1998). According to Russo et al. (1994, Blanford, 1870) the thickness of this unit ranges from 100 to 700 m.It is considered to be Triassic–Early Jurassic in age based on some biostratigraphic data and comparison with adjacent areas providing fossil ages. The age of the Adigrat sandstone unit is Permian–Triassic age which is given from palynological evidence; Jepsen and Athearn 1961, 1964; Mohr 1962; Beauchamp and Lemoigne 1975; Russo et al. 1994). The formation is 450 m thick at Dejen-Gohatsion, 850 m thick at Amuru Jarty, 750 m thick at Fincha River, 200 m thick in the Getema (Arjo) area, and 150 m thick in Ejera area (Assefa and Wolela, 1986; Serawit and Tamrat, 1996; Tamrat and Tibebe, 1997). The upper part of this formation is composed of alternating carbonaceous mudstones, carbonaceous siltstones and sapropelic coals (Assefa and Wolela, 1986; Wolela, 1991). According to (Bosselini et al., 1989), large-scale down warping occurred in Triassic to Jurassic time, resulting in the deposition of the alluvial fan, fluviatile, lacustrine or swampy facies of this unit in the Blue Nile basin.

2.1.4. Gohatsion Formation

Ethiopia, being a gently subsiding, low–lying ramp was obviously more responsive to lowered sea–levels, resulting in the deposition of massive anhydrite–gypsum units or Gohatsion Formation (Jain & Singh, 2019). The age of this Formation is Liassic to Late Bathonian, as determined from micro and macrofossils studies by Assefa (1981). It has 450 m thickness and consists of an association of claystone, limestone, mudstone, dolostone, shale and Gypsum, variously alternating with beds of siltstone and sandstone. According to Getaneh Assefa (1981) the Gohatsion Formation has four informal members: the Mudstone member, the lower claystone member, the gypsum member and the upper claystone member in ascending stratigraphical order. The gypsum beds are characterized by mottled texture, and are inter-bedded with glauconitic mudstone beds and rare thin sandstone beds (Getaneh Assefa, 1991). The Gohatsion formation comprises complex of coastal fluvial, coastal lacustrine, restricted arid lagoonal ,supratidal, intertidal, shallow subtidal and silled lagoonal deposits (Getaneh Assefa,1981).The environment of deposition for the terrigenous clastic is interpreted as deltaic, and shallow lagoonal and supertidal for the gypsum, limestone, shales and dolomite (Getaneh Assefa, 1991).

2.1.5. Antalo Limestone Unit

The term Antalo Limestone, though originally assigned by Blanford (1870) to the limestone unit in northern Ethiopia, was subsequently extended to the limestone unit of the Blue Nile basin. The 420 m thick carbonate succession, as described by Russo et al. (1994), It conformably overlies the Gohatsion Formation and can be subdivided into three parts. The lower part (180 m thick) is composed of burrowed mudstones that grade upwards into oolitic and coquinoid limestones with or without intercalated marl beds, and then into massive limestones with scattered patches of corals, nerineids and stromatoporoids, for which a shallow water environment was inferred. The middle part (200 m thick) consists of coqinitic interbedding of marly limestones and marls. The presence of ammonite fauna (e.g., Lithacoceras sp. and Subplanites spathi), in association with brachiopods (e.g., Terebratula pelagica and Nanogyra) and other infaunal siphone feeders (Anisocardia, Venilicardia and Somalirhynchia somalica and Zeillleria latifrons) suggests a shelf to open marine environment (Russo et al. 1994, Glamichael et al., 2009). The upper part (50 m thick) comprises laminated oolitic and reefal limestones, which was interpreted to indicate the return of shallow water conditions.

2.1.6. Mugher Mudstone Unit

The Mugher Mudstone formation in the Blue Nile basin comprises marginal marine and continental sediments of late Jurassic to cretaceous age (D.Schmidt and C.Werner, 1998).This unit was previously known as the upper gypsum (Aubry 1886, Merla et al. 1979). The succession is 15 m in the Gohatsion area but thickens eastwards to reach up to 320 m in the Jema river valley. It conformably overlies the Antalo Limestone (Getaneh Assefa, 1991, Russo et al., 1994). According to Getaneh Assefa (1991) and Russo et al. (1994) the unit subdivided into two parts. The lower part (15 m thick) is composed of alternating beds of nodular and vein-filling gypsum, dolomites, and shales, for which Getehan Assefa (1991) assign as supratidal and lagoonal environment. The rest of the succession (244m) in thickness is characterised by interbedded sand- silt and mudstones with local occurrences of lignite layers and scattered plant fragments. This siliciclastic succession was interpreted by Getaneh Assefa (1991) to represent deposits of a meandering river system. Regarding the stratigraphic position of the Mugher Mudstone, Assefa (1991) assumed a broad interval of post-Kimmeridgian to pre-Middle Eocene age. According to the work of D.Schmidt and C.Werner, (1998), on Alem Ketema and Lemi sections the Mugher Mudstone layer which has Neocomian age has been identified by using ostracods and vertebrate fossil.

2.1.7. The Debre Libanose sandstone

This unit is unconformably overlain by tertiary basalts, is composed of sandstone interbeded by conglomerate and shale (Getaneh Assefa, 1991). It is widely exposed in the valley of the Zega Wodem River and its tributaries. It conformably overlies the Mugher mudstone formation and is, in turn overlain by trap volcanoes. The sandstone attains a thickness of 280m near Lemi; 200m in the Jema River; 230m in Debre Libanoes; 312m in the Mugher River section and pinch out towards the Abbay River Gorge (Wolela Ahmed, 2004). The main sedimentary structures of the sandstone are large and small-scale planar tabular and asymmetrical through cross-beds, convolute beds, flat beds, scoured and channel surface and massive beds. Some fining upward trends occur from medium- to fine grained sandstone up to laminated clay stones (Getaneh Assefa, 1991 and Russo et al., 1994). This unit is interpreted as a deposit of sandy-braided rivers on a broad alluvial plan (Getaneh Assefa, 1991, Wolela Ahmed, 2009).

2.1.8. Tertiary and Quaternary Volcanoes

Mohr (1962) divide the Cenozoic volcanic rock of Ethiopia into Trap Series and Aden Series and explained the trap series for the flood basalts of the Ethiopian plateau and Aden series for the volcanics of the rift valley. Then Getaneh Assefa (1991) describe there is thick massive flood lavas chiefly of basalt, unconformably overly the Mesozoic sediment. The early-late Oligocene flood basalts together with subordinate trachytes and rhyolites cover much of the northwestern Ethiopian plateau and ranges in thickness from 500 to 2000 m (Gani et al., 2009 and his reference Hofmann et al., 1997).

Age	Thickness(m)	Lithology	Formation
Paleocene-Pliocene	500-2000		Volcanic Rock
Barremian-Cenomanian	280		Debre Libanose Sandstone
Portlandian-Aptain	320		Mugher Mudstone
Callovian-Kimmeridgian	600-700		Antalo Limestone
Bthonian-Oxifordian	350		Gohatsion Formation
Ansian-Pliensbachian	700		Adigrat Sandstone
CarnianNorian-AsselianSakmarian	1300		Pre-Adigrat Sandstone
Pre-Cambrian	????		Basement Rock

Figure 2.1. Shows the general stratigraphy of the Blue Nile Basin with major lithologies, Age and maximum thickness (modified from Hofmann et, al.1997, Wolela, 2009 and Dawit and Bussert, 2009).

2.2. Basin Evolution

Tectonic evolutions throughout Northeastern Africa of the country and sea level fluctuations through geologic time in general have the great roles for the formation of basins and thick Mesozoic sedimentary sediments accumulation within them. In general the Late Paleozoic to Mesozoic sedimentary basins of Ethiopia are the result of a complex history of suturing and rifting during cyclical assembly and dispersal of Supercontinents (A.Mogessie et al, 2002, Dawit Lebenie, 2010).

The break-up of Gondwanaland, which began in the late Paleozoic and persisted up to Jurassic time, produced Aulacogen-like basins around the borders of the mega continent. The Blue Nile basin of Ethiopia is one of the northern most failed arms of these trough systems (Russo et al, 1994). According to A.Mogessie et al., (2002), Russo et al., 1994 , Gani et al,2009 the sedimentary evolution of the Blue Nile River succession appears to have been controlled by the following geodynamics stages.

1. Peneplain stage: represents the situation before any tensional effect and before the break up of Gondwanaland.
2. Intracontinental rift stage: the breaking up of Gondwanaland produce continental rift along the border of African as a result of NW-SE tensional stress with a corresponding thinning of a continental crust. Aulacogen-like Basins were formed and filled up with karro sediments.
3. Post rifting stage: this stages corresponds to the deposition of basal clastic sediments (Adigrat sandstone) over the entire east Africa.
4. Early flooding of craton: corresponds to rifting stage and subsidence of future African continental margin and to the eustatic sea level rise.
5. Drowning of the craton: this stage is related to a major Callovian-early Oxfordian transgression caused by the Gondwana break up and by the formation of the African continental margin. The deposition muddy sandstone and the upper sandstone units is a result of this event.

2.3. Jurassic Carbonate Unit of Ethiopian Sedimentary Basins

According to Beyth (1972b), Assefa (1988; 1991) and Asrat et al. (2008) thick carbonate Successions are found with different thickness and exposure mainly in three different regions of Ethiopia (Figure 2.2) in Northern Ethiopia, the Mekelle Outlier and Danakil Depression, in Central Ethiopia, the Blue Nile basin and in the Southeastern Ethiopia, the Ogaden basin including western Hararghe region.

Depending on geographical name of their deposit different name have given for the Upper Jurassic limestone. For example, Antalo Limestone Formation (in the Mekelle Outlier and Blue Nile) after a type section located first in the Antalo village, Hamanlei Formation and Urandab Formation in the Ogaden basin. In Ethiopia the largest volumes of Jurassic age limestone are located in the eastern part of the country also thick limestone sequences is present in the Blue Nile basin in central and the Mekele area in northern Ethiopia. They are the results of the wide spread transgressions and extensional deformation, which is related to the breakup of Gondwanaland that has taken place on the horn of Africa starting from early Mesozoic time (Bosellini, 1989).

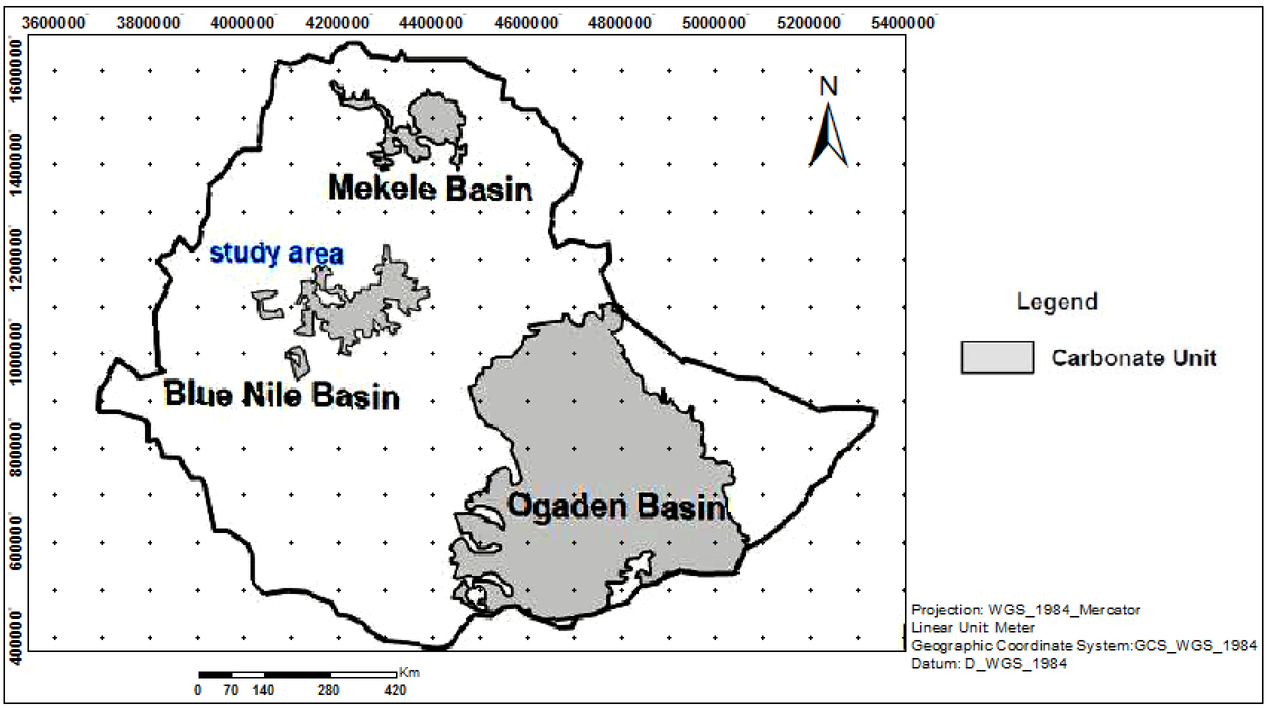


Figure 2.2.The thick carbonate units of Ethiopia in the Blue Nile, Ogaden and Mekele basin (modified from Ethiopia ministry of mine, 2011).

In Ethiopia the typical facies of the Jurassic transgression is represented by carbonates referred to as the Antalo Limestones as well as the Hammanlei and Urandab Formation (Russo et al., 1994). They conformably overlie the Adigrat Sandstones and their earliest occurrences (Pliensbachian/Aalenian) are found in the Ogaden (Beyth, 1971; 1972a; 1972b; Kazmin, 1973; Bosellini, 1999; Bosellini et al., 2001; Russo et al., 1994; Mengesha Tefera et al., 1996; Abiyyu Hunegnaw et al., 1998; Abbate et al., 2015).

2.4. Jurassic Fossils in Carbonate units of Ethiopia

Previous works such as Jaboli, 1959; Canuti and Radrizzani (1975), Russo, et al. (1994), Mansour (1975) and (Greitzer,1970) reported that many micro and macrofossils occur in the carbonates of Ethiopia. The genus Pfenderina foraminifera are also occurs in Ethiopia together with several other members of the so called "Middle Eastern Jurassic fauna" this includes *Pseudocylammina jaccardi*, *Everticyclammina virguliana*, *Kurnubia palastiniensis*, *Trocbolina palastiniensis*, *Rbapydinonina deserta-amiji*, *Orbitopesella praecursor* which have been recoginized in Ethiopia (Mansour A.T. (1975). Various species of ammonites have been identified from the carbonate unit of Diredawa area by Greitzer,1970. Jurassic invertebrate fossils like corals, brachiopods and bivalves have been identified by Keissling et al, 2011 from the Antalo limestone unit of the Mekele basin. From the study of Russo et al. (1994), various micro and macro invertebrate fossils have been identified from the carbonate unit of the Blue Nile basin. From those *Pholadomya somaliensi*, *Mactromya daghaniensis*, *Homanya inornata*, *Musculus somaliensis*, *Daghanirhynchia daghaniensis* and some gastropods like *Ampullina sp.* and *Gryphea costellata* macrofossils.

CHAPTER THREE

3. STRATIGRAPHY /THE STRATIGRAPHIC LOG

3.1. Introduction

The carbonate unit of the Mertule Mariam section has a 330 m thickness. The carbonate unit of the area is conformably overlain by a clastic unit made up of sandstone and mudrocks. At the base of the carbonate unit limited gypsum layers are observable apparently indicating the start of the underling Gohatsion Formation. The sedimentary units are exposed mainly by road cuts and along stream and river cuts.

In order to determine the lithofacies analysis, the lateral and vertical extent of the carbonate unit and to make correlations with other sections in the basin and other similar basins, a detailed facies analysis of the carbonate unit is investigated on the measured stratigraphic section.

Each lithologies was investigated and described, the name of lithology is given and the facies analysis was determined based on the textural, paleontological, sedimentary structures and the component of the carbonate unit observed during field investigation and petrographic analysis. The Limestone lithologies of the Mertule Mariam section ranges from Dunham (1962) Mudstones to Grainstones.

The carbonate rock unit of the study area is characterized by various lithologies, fossil content, trace fossil, textures and sedimentary structures. The field investigation has helped to identify nine different lithofacies from the measured carbonate unit that is overlain by a clastic unit. The identified carbonate lithofacies are; gypsum, fossiliferous Limestone, bioturbated micritic limestone, marly limestone, black limestone, oolitic limestone, bedded and bioturbated micritic limestone and shale. Let us see the completion of the log first on what to characterize.

3.2. The stratigraphic log

The stratigraphic log of the Mertule Mariam section has been done (see next page).

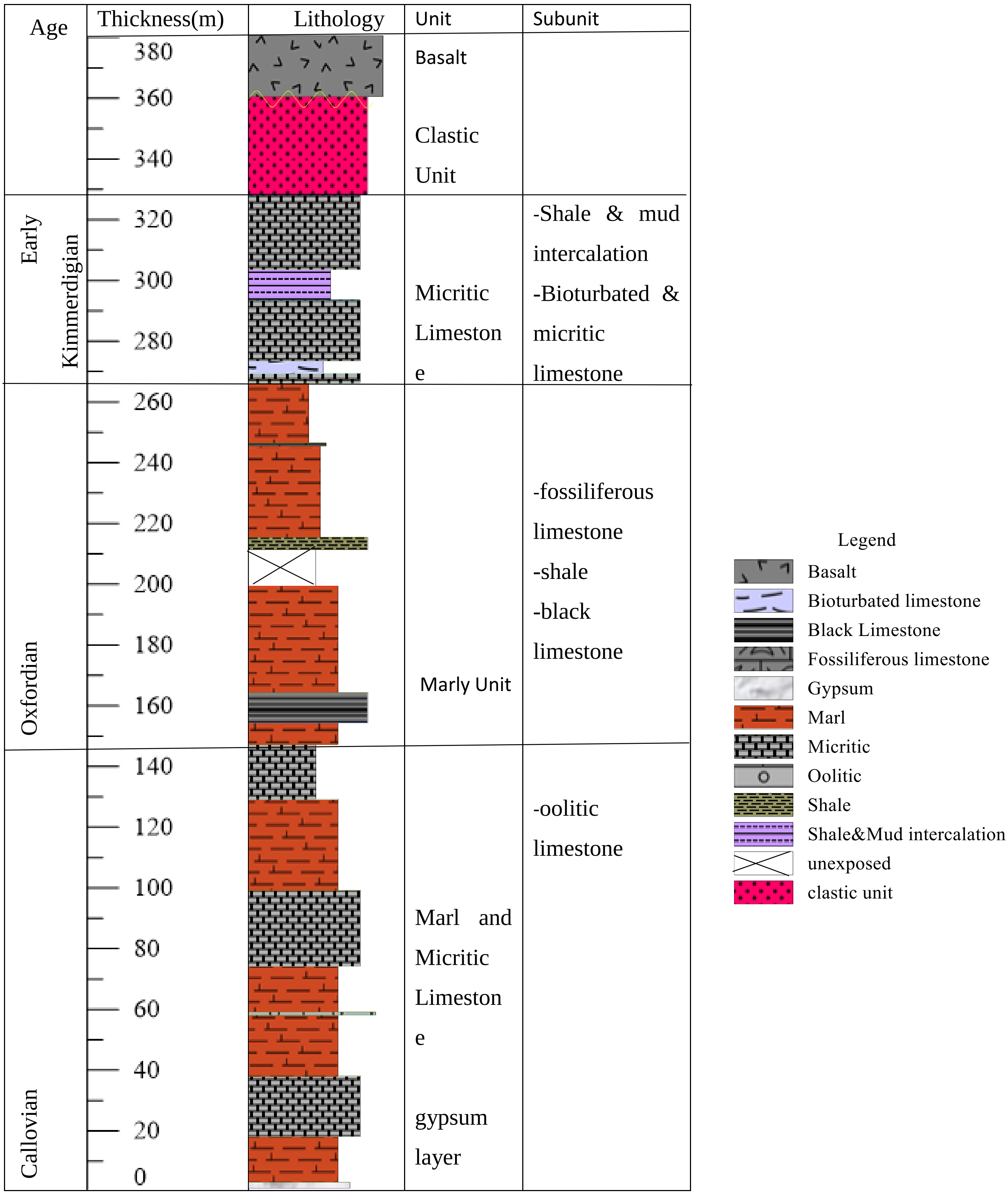


Figure 3.1.the stratigraphic log of the Mertule Mariam section.

3.3. Description of the lithologic units and subunits

3.3.1. The gypsum layers

At the base of the carbonate unit limited gypsum layers are observable apparently indicating the start of the underling Gohatsion Formation. In the study area the gypsum unit is overlien by the 15 m thick marl and has 2m thickness. It has whitish to grayish color and exposed by quarrying around the asphalt road.

3.3.2 .The carbonate units

3.3.2.1 .Marl and Micritic limestone unit

This unit found at the base of the logged section above the gypsum layers, which has 140 m thickness. This unit contains marl and micritic limestone dominantly and thin oolitic limestone layer subunits at some localities.

Figure 3.2. The oolitic limestone from ML-F8 at the middle part of the section.

3.3.2.2. Marl Unit

This unit is found at the middle part of the stratigraphic log dominantly and has 125m thickness. The unit contains various types of sub units: marl, black limestone, shale and fossiliferous limestone subunits.

3.3.2.2. A.marl

Marl occurs dominantly at the middle part of the stratigraphic log. Additionally marl has been observed with in gentle slope throughout the section, between cliff forming micritic limestones with yellow, gray, light color. The marly limestone unit is fine grain, contains micro fossils and macro invertebrate fossils like brachiopod, bivalve and gastropod at the bottom and middle part of the section. This rock unit varies from place to place in terms of fossil content, which consist high amount of foraminifera and ostracod fossis in some locality and lack of those fossils in other places.

Figure 3.3.marly limestone from ML-E0 (X -442868 Y-1176848 Z-1427).where X is Easting,Y is Northing and Z-is Elevation in meter throughout the chapter.

3.3.2.2. B.Black limestone

It occurs at the middle part of the studied section and exposed by road cut. The unit characterized by black color, small fragmental material and has 3m maximum thickness, which underline and overlien by marl. It is highly weathered and fractured. The out crop of this unit looks like basalt since it has very black color. This sub unit has been occurred *at X-442868 Y-1176848 Z-1427.*

3.3.2.2. C.Shale

The shale occurs at the middle part of the Mertule Mariam section. It also intercalates with micritic limestone and marl unit at the upper part. It shows fissility nature and has grayish color. The shale has 4m thickness, exposed by road cut. It overlien by marl and it overlies the unexposed area at the middle part of the studied section.

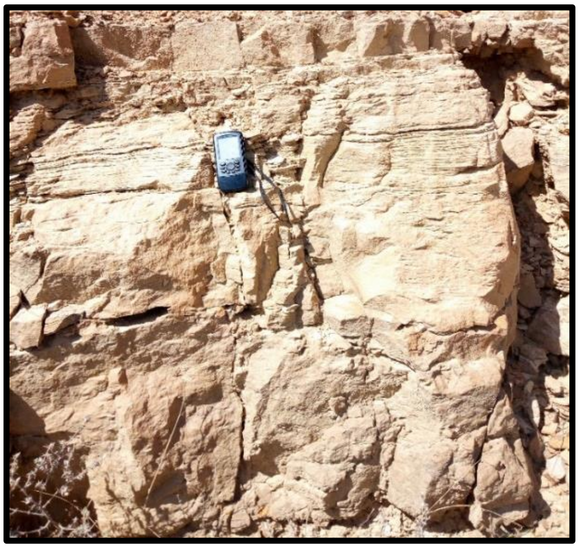


Figure 3.4. The shale unit from ML-F7 (X- 1442581 Y-1177060 Z-1450).

3.3.2.2. D.Fossiliferous Limestone

In the studied section the fossiliferous limestone unit is found in the middle part, which is exposed by road cut with maximum thickness variation between 50cm and 1m. It is characterized by yellow to brown color in fresh sample. It is overlien and underline by the marl and contains various shell fragments. Fossils including brachiopods and bivalve are common in this rock unit.

Figure 3.5. The fossiliferous limestone unit in the studied section from sample ML-F8 (X-442713 Y-1177075 Z-1437).

3.3.2.3. Micritic limestone Unit

This unit occurs dominantly at the upper part of the logged section, overlain by the Clastic Unit and has 65 m thickness. The micritic limestone unit occurs as a cliff former throughout the section intercalate with the marl unit. It contains bioturbated micritic limestone and bedded and bioturbated micritic limestone subunits.

3.3.2.3. A.Bioturbated Micritic limestone

It is found at the upper part of the stratigraphic log. It exposed by road cut. Which has up to 30 m thickness and yellow, whit to gray color. At the upper part of the section the unit intercalated with thin beds of shale, mud and marl the thickness of the intercalated unit varies between 50cm and 2m thickness variation. In the studied section this unit mainly occur as cliff former. The micritic limestone contains bioturbation (Figure 3.6).

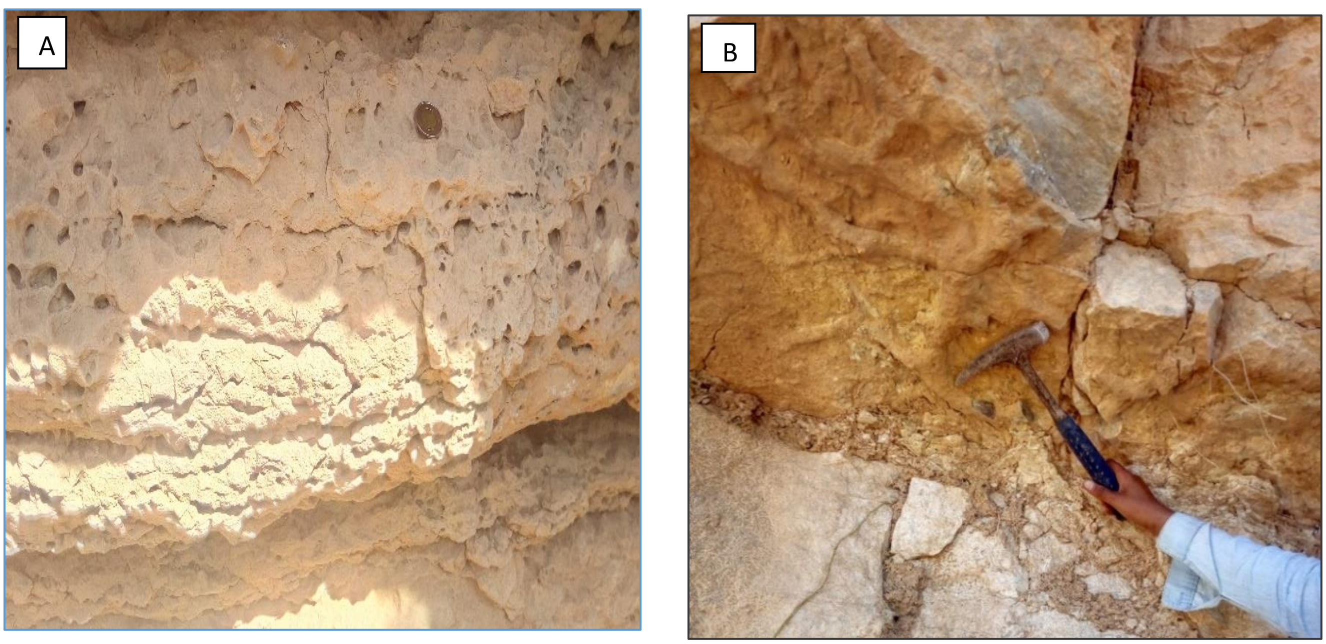


Figure 3.6.Field out crop of the bioturbated micritic limestone from upper part of the section (X-442718 Y-1177340 Z-1528).

3.3.2.3. B. Bedded and bioturbated micritic limestone

This unit occurs at the top part of the studied section and exposed by road cut. It has whitish to grayish color with the bed thickness variation between 20cm and 50cm and it is bioturbated at the base. It overlien by micritic limestone and shale and micritic limestone intercalation.

Figure 3.7.The bedded and bioturbated limestone from the upper part of the studied section.

3.3.3. The Clastic unit

This unit is sandwiched between the carbonate unit and the volcanic rocks in the study area and it’s observation in the stratigraphic log is as a road cut exposure. The unit is composed of sandstone and also with mudstone beds. It is characterised by lithologies with reddish and grayish color. during this work no detail study has been done on this clastic unit to make a differentiation whether the unit is part of Mugher Mudstone or Debre Libanose Sandstone But in 2020 Worash Getaneh and Balemwal Atnafu assigned this unit as Mugher Mudstone.

3.3.4. Basalt

The basalt unit overlies unconformably on the clastic unit of the Mertule Mariam Section. It is exposed by a road cut for this studied section. This unit is characterized by well-developed columnar joining. This unit covers wide area over the Mesozoic sediments.

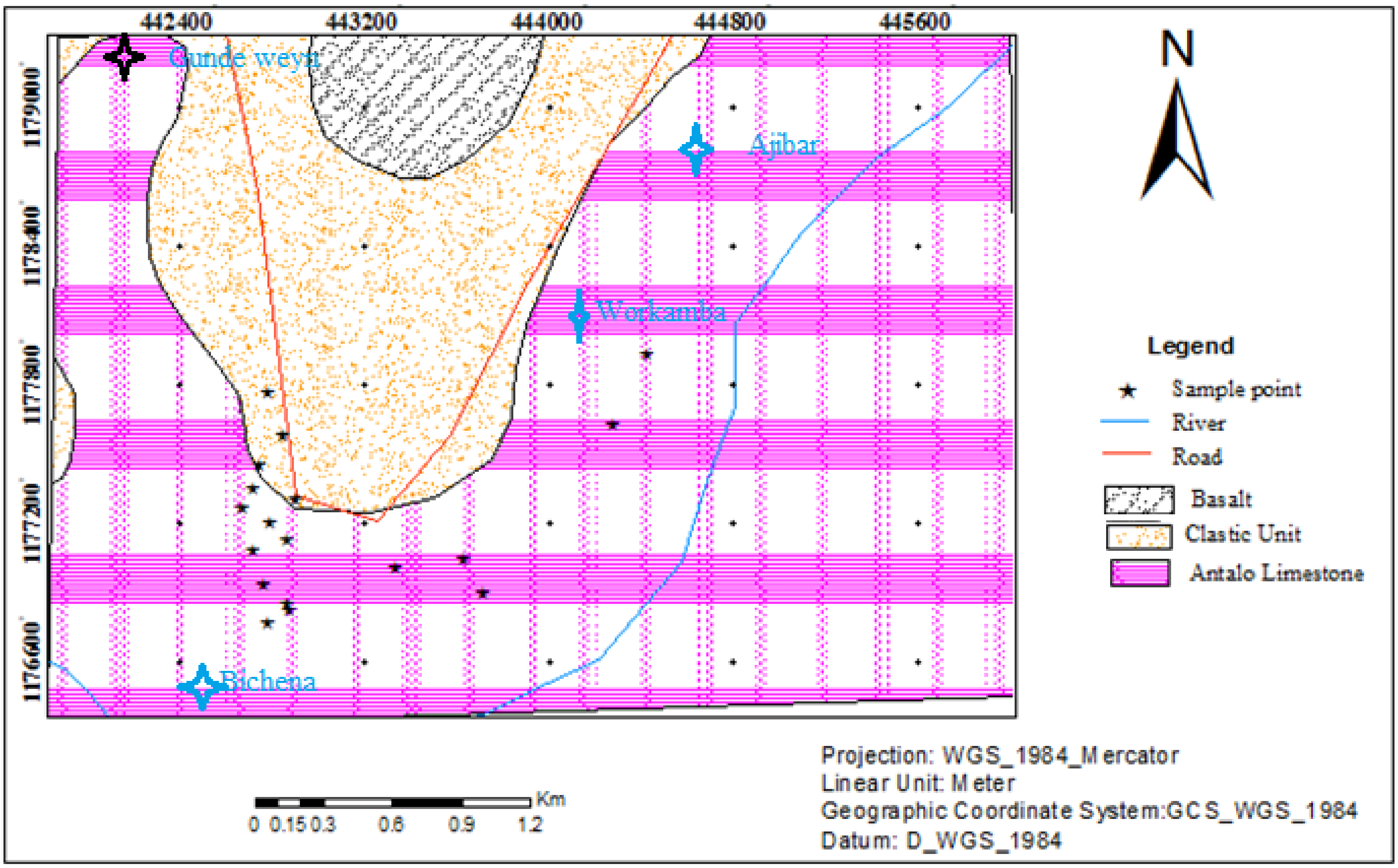


Figure 3.8.The geological map of the study area at the scale of 1:1500 which shows the lithologic units and the samples (Adopted from Ferede Chumburo, July 2015).

CHAPTER FOUR

4. PALEONTOLOGY

4.1. Introduction

Paleontology is the scientific study of the past life through the analysis of plant and animal fossils, including those of microscopic size, preserved in rocks. It is concerned with all aspects of the biology of ancient life forms: their shape and structure, evolutionary patterns, taxonomic relationships with each other and with modern living species, geographic distribution, and interrelationships with the environment. Paleontology is mutually interdependent with stratigraphy and historical geology because fossils constitute a major means by which sedimentary strata are identified and correlated with one another.

In the carbonate rocks of the Mertule Mariam section small amount of macro invertebrate fossils and high amount of microfossils are present. These macro and microfossils are washed and prepared well in sedimentology lab. Finally their taxonomy is identified into genus and species level. For the classification of macro invertebrate fossils the identification and description of observable fossil morphology and comparison with previous works in the country is applied. Since the gastropod and bivalve fossils preserved as mold, their morphological description and taxonomic classification is a little bit difficult than brachiopod fossils. More than 280 micro and macro fossils have been identified from the carbonate unit of the Mertule Mariam section.

Totally 6 macro fossils species have been identified from the section. From these species; Bivalve (*Pholadomya somaliness* and *Nanogyra nana),* Brachiopod *(Terebratula ventricosa***,** *Somalirhynchia africana* and *Bihenithyris mediocostata*).and gastropod (*Pseudomelania Sp*) have been identified.

The Microfossils morphological description was done using binocular reflecting microscope and comparison of published micropaleontological data done in other countries for classification.

Additionally, Identification of foraminifera fossils under thin section like *Nautiloculina oolithica*, *Alveosepta Jaccardi, Kurnubia Plastinessis* has been also carried out.

4.2. Foraminifera

Foraminifera are small, predominantly marine heterotrophic protists that construct chambered shells (Brazier, Flugel, 2010). According to Flugel (2010) Foraminifera provide time markers for biozonations of shallow and deep marine carbonates, are excellent environmental proxies and permit ancient depositional systems to be reconstructed (Lei et al., 2017).

Foraminifera are covered with an organic test that varies from a simple single chamber with an aperture to a complex, multichambered perforate, calcitic wall, to an agglomeration of mineral grains embedded in the organic test (Ishmal et al., 1981). Benthic foraminifera have been successfully used as facies indicators in modern and ancient carbonates due to the fact that the composition of foraminiferal assemblages varies in different parts of carbonate platforms and ramp.

Among numerous diverse groups of fossil, benthic foraminifera are particularly abundant and well protected, so they, alongside calcareous greengrowth (Dasycladales),are the foremost imperative fossils utilized for age assurance and stratigraphic subdivision of shallow marine carbonate deposite.The distinction for the major groups of foraminifera is based on the composition and structure of the test wall (Loeblich & Tappan 1988) and takes the wall structure and composition, chamber shape and arrangement, aperture and ornament into account, in order of importance for classification. Major foraminifera wall structures seen in thin sections and studied in SEM are agglutinated, microgranular calcareous, porcelaneous calcareous and hyaline calcareous.

Lenticulina quenstedti species

Family Lenticulinidae, Chapman, Parr and Collins, 1934

Genus Lenticulina, Lamarck, 1804

Type Species: - *Lenticulina quenstedti* Gümbel, 1862

Material: one test (plate 1:2)

Description: Test is involute, planispiral and elongate in outline. Peripheral margin are sharply angular, well-developed keel; chambers with strongly elevated sutures. Last chambers distinctly increasing in width; Aperture is terminal but not clearly visible. Chamber walls are smooth, finely perforate and optically hyaline. Umbliculus are circle ring like. It has been obtained from marl sample ML-E0, which is from the middle section.

Remark: it also reported from Urandab carbonate formation of Ogaden South Eastern Ethiopia by (Shigut Geleta, 1998) which is similar with this species.

Lenticulina subalata species

Family: Lenticulinidae Chapman, Parr and Collins, 1934

Subfamily: Lenticulininae Chapman, Parr and Collins, 1934

Genus Lenticulina Lamarck, 1804

Type Species: *Lenticulina subalata* Reuss, 1854

Material: 3 tests (plate 1:1)

Description: this species has simple nearly round Test; slightly elongated; involute. Chambers has smooth surface; sutures are relatively broad and strongly elevated, curved backward. Last chambers vary in size, become large (width) as they are added. Aperture is terminal but not clearly visible. Wall is finely perforate and optically hyaline. It has been obtained from Marl sample ML-S-A1 which is the lower part of the Mertule Mariam section.

Remark: Lenticulina subalata (Reuss, 1854), are also known from Jurassic's of India, Alhussein (2014) and from Jurassic rocks of Khashm Al-Qaddiyah, central Saudi Arabia, (Youssef and El-Sorogy, 2014).

Verneuilinoides minuta Species

Family Verneuilinidae, d'Orbigny, 1840

Genus Verneuilinoides, Loeblich and Tappan, 1949

Type Species:-*Verneuilinoides minuta,* Said and Barakat, 1958

Material: 17 tests (Plate 1:4)

Description: Test subtriangular and small in section, periphery rounded; successive sub globular chambers slowly increasing in size and regularly arranged. Wall surface smooth with no indication of surface ornamentation; aperture is small and present at the base of the last chamber.

Remarks: *Verneuilinoides minuta* are also known from Kimmeridgian of Syria, (Youssef and El-Sorogy, 2014); from Jurassic sedimentary rocks of Khashm Al-Qaddiyah central Saudi Arabia and Oxfordian and Kimmeridgian of Sinai (Egypt), Said and Barakat (2014).

Order: Foraminiferida

Sub Order**:** Textulariina

Super Family**:** Ataxophragmiacea

Family: Pfenderinidae

Sub Family**:** Kurnubiinae

Genu**s:** *Kurnubia*

Type species: Kurnubia palastiniensis Henson, 1948

Material: 6 (plate 3:5-7)

Description: Test elongate, early chambers trochospiral about a central column with chambers some-what inclined to the axis of coiling, later uncoiled, uniserial, and rectilinear, outer part of chambers has a characteristic subepidermal network, central part with endoskeletal pillars that are continuous from chamber to chamber, spaces between pillars later filled secondarily to produce a central column; apertural face consists of a plate over the umbilical region with many small apertures interspersed between pillars, where apertures are secondarily filled to produce a column, the septum adjacent to the column is resorbed to form a secondary foramen.it has been obtained from thin section of sample ML-1-7.

Stratigraphic range & distribution: L. Jurassic (Lias) to U. Jurassic (Kimmeridgian);

Remark: this species is similar with *Valvulinella jurassica* Henson, 1948.

Order: Foraminiferida

Sub Order: Textulariina

Super Family: Lituolacea

Family: Nautiloculinidae

Genus: *Nautiloculina*

Type species: Nautiloculina oolithica Mohler. 1938

Material: 8 samples (plate 3:1-2)

Description: Test free, lenticular in form, planispirally enrolled and involute, globular proloculus followed by numerous small chambers per whorl that increase gradually in size, interior simple, sutures radial to very slightly arched; wall microgranular calcareous. Agglutinated commonly diagenetically altered, foreign material more abundant in outer whorls of some species, structure simple, no. subepidermal network or other exoskeletal or endoskeletal structures present, wall single layered, but septa secondarily doubled by addition of a second wall layer over the previous apertural face as a new chamber is added, umbonal region also progressively thickened as chambers are added; aperture equatorial, a low interiomarginal.

Stratigraphic range: U. Jurassic to L. Cretaceous.

Remark: this species also occurs in Egypt, Israel, Switzerland and Saudi Arabia.

Family Vaginulinidae Reuss, 1860

Subfamilly Lenticulininae Chapman, Parr and Collins, 1934

Genus *Lenticulina* Lamarck, 1804

Type species *Lenticulina varians* Bornemann (1854)

Lenticulina varians Bornemann (1854) Plate 2, Fig. 17

1854. *Cristellaria varians* n. sp. – Bornemann, p. 41, Pl. 4, Figs. 32–34.

1991. *Lenticulina varians* (Bornemann) – Bhalla and Talib,

p. 100, Pl. 3, Fig. 8, *et syn.*

2002. *Lenticulina varians* (Bornemann) – Kottachchi et al.

Fig. 23(8).

Material: 2 samples (plate 1:7)

Description: the shell has circular outline.

Remarks: A single specimen of *Lenticulina varians* was recovered from the Jumara material that is similar to those described by Bhalla and Talib (1991) and Kalantari (1969) from the Jurassic sediments of India and Iran respectively. However, our specimen possesses slightly depressed sutures as compared to the flush sutures of the Iranian forms.

Family Elphidiidae Galloway 1933

Subfamily Elphidiinae Galloway 1933

Genus Elphidium de Montfort 1808

Type species *Elphidium sp.*

Material: 13 samples (plate1:8)

Description: Test planispirally coiled, involute and bilaterally symmetrical, hyaline. The last whorl shows several chambers almost equal in size. Sutures are distinctly depressed.

Family: Pfenderinidae

Subfamily: Pfenderininae

Genus Pfenderina Henson 1948

Type species *Pfenderina salernitana* Sarton et Crescenti, 1962

4.3. Ostracodes

Ostracodes are diminutive crustaceans, generally between 0.4 and 1.0 mm long, characterized by their calcareous bivalve carapace (Batista Dos Santos Filho et al., 2015). The body of ostracod is contained within a carapace of two valves which is often composed of calcite and has a high preservation potential. Ostracods are known from the Early Cambrian, and they are very common today (Paleontology, 2006). Ostracod species tend to have rather long stratigraphic ranges and so are of limited use in biostratigraphy. However, they are environmentally very sensitive and so are excellent paleoenvironmental indicators.

Subclass podocopida G.W. Muller, 1806 ¨

Order Platycopa Sars, 1866

Family Cytherellidae Sars, 1866

Genus Cytherella Jones, 1849

Type species: Cytherella sp.

Material: 5 carapace (plate 2:3)

Description: The carapace has a more regular oval outline showing a less sharp postero-ventral truncation. In addition, the surface is weakly reticulated.

Subclass Ostracoda Latreille, 1806

Order Podocopida Muller, 1894 ¨

Suborder Platycopa Sars, 1866

Family Cytherellidae Sars, 1866

Genus Cytherella Jones, 1849

Type species: *Cytherella cf. ventroconcava* Neale and Singh, 1985

Material: 3 carapaces (plate 2:4)

Description: it has straight, perfectly parallel longitudinal margins, symmetrically rounded end margins. The overall shape of the species is rectangular.

Remark: The present species is similar to Cytherella ventroconcava Neale and Singh, 1985 from the Middle Eocene of Assam, India.

Family Macrocyprididae Muller, 1912

Genus Macrocypris Brady, 1867

Type species: Macrocypris sp.

Barker, p. 484, Pl. 9, Figs. 3, 4.

Description: Dorsal margin high and evenly arched. Ventral margin sinuous with a marked mid-ventral concavity. Anterior margin broadly rounded. Posterior margin acutely rounded. Posterior and ventral margins appear to be obliquely down-turned due to the curvature of the carapace. Surface smooth. Highest and widest at mid length, maximum length immediately above the ventral margin. Hinge apparently as for the genus: that of the left valve comprises a smooth median ridge becoming denticulate each end.

Material: 2 carapace (plate 2:6)

Remarks: M. horatiana Jones and Sherborn (1888) from the Bathonian is considerably smaller than the present species and has a more tapered shape and its highest point is anterior of mid-length. The present species appears to be closely related to M. horatiana in the sense of Witte and Lissenberg (1994), but their figured specimens differ in being acutely pointed posteriorly and in having weak cardinal angles that give a slightly more angular appearance. The present species is rarely found as individual valves so that the internal details are not fully known.

Superfamily Cypridoidea Baird, 1845

Family Candonidae Kaufmann, 1900

Subfamily Paracypridinae Sars, 1923

Genus Paracypris Sars, 1866

Type species: *paracypris sp.*

2000 Paracypris sp. P3 Viviers et al., p. 419e420, Fig. 10, n. 10-11

2013 Paracypris eniotmetos Piovesan et al., p. 243, Figs. 3 and 10b

Material; 5 carapace (plate 2:1)

Description: shell small, elongate, dorsum convex; venter concave; anterior rounded; posterior acuminate.hing consists of simple contact of right valve in slight furrow on left valve.

Remarks: Differs from Paracypris cf. P. gracilis (Bosquet, 1854) Jones and Hinde, 1890 in its whole outline and the lack of any ornamentation. The size differences are attributed to different ontogenetic states. It is similar to Paracypris sp. described by Delicio (1994), but differs regarding height and valve overlap, which are, respectively, lower and less visible in the studied species.

Superfamily Darwinulacea, Brady and Norman, 1889

Family Darwinulidae Brady and Norman, 1889

Genus Darwinula Brady and Robertson 1885

Darwinula Brady and Norman, 1889, Trans.Royal Dublin Soc., ser.2, v 4, p.121.

Type species *Darwinula sp.*

Material: 4 carapaces (plate 2:5)

Description: shell elongate and straight, valve surface moderately convex; surface smooth.

Suboorder podocopina sars, 1866

Superfamily cypridacea Baird, 1845

Familiy Ilyocyprididae Kaufmann, 1900

Subamily cyprideinae Martin, 1940

Genus Cypridea Bosquet, 1852

Cypridea Bosquet, 1852, Acad.royale Belgique Mem.cour. et sav.etrang, v.24, p.47

Type species Cypridea *sp.*Bosquet, 1852

Material: 12 carapace (plate 2:2)

Description: shell subquadrate, medium sized in side view. Surface smooth, biconvex, pitted, nodose and weakly sulcate.

4.4. Bivalves

Bivalves are class of phylum Mollusca characterized by a shell that is divided into left and right valves. The valves are connected to one another at a hinge. Most bivalves articulate along a hinge line by means of teeth and sockets. The plane of symmetry passes between the two valves parallel to the hinge line. Bivalve differ from brachiopods in having equal left and right valve.

Main characteristics used for classification of bivalves are, nature of dentition (number, size and shape of the teeth), position the ligament, muscular scar, pallial line, shape and microstructure, concentric and radiating growth lines etc. The bivalve fossils collected from the studied section are preserved as a mold and which makes it difficult for taxonomy. For identification of bivalves, gastropods and brachiopod the description for each with figure is given. Then comparison with Jaboli (1943) and Keissling (2011) has been made. The systematic classifications of invertebrate taxa follow more recent published works done on the respective taxa.

Superfamily Pholodomyacea Gray, 1847

Family Pholadomyidae Gray, 1847

Genus Pholadomya G B Sowerby, 1823

Type species: *Pholadomya (Bucardiomya) somaliness* Sowerby, 1823

Material: one bivalved specimen (plate 5:1))

Description: This *Pholadomya (Bucardiomya) somaliness* species has equally spaced growth lines and style of ribbing is both radiating and concentric, umbo is small with very short hinge line. Length from anterior to posterior is 22 mm and from dorsal to ventral is16 mm.

Family Gryphaeidae Vialov, 193

Genus Nanogyra Beurlen, 1928

Type species: *Nanogyra nana* Sowrbey, 1822

Material: one right valve sample (plate 5:2-3)

Description: Shell small in size, shape ovate to semicircular. Umbones small, recurved and opisthogyrate. Strightposterior margin, ventral margin slightly convex. Left valve convex, more capacious than right valve. The muscle scar and palial line are not preserved in the sample Attachment area small. Ornamentation of the valves consist of well-developed growth laminations.

Remarks: *Nanogyra nana* species is similar with the species *Nanogyra fourtau* Stefaini, 1939.

4.5. Brachiopods

Brachiopods have a pair of conjugated valves or bilaterally symmetrical with an external shell consisting of two dissimilar but equilateral valves. Based on the presence or absence of articulation they have been divided into two major groups as inarticulate and the articulate (Palaeontology, 1979). The inarticulate have not an articulating hinge and are united by muscles. Their shells are composed of alternating layers of calcium phosphate and chitin. Articulate brachiopods have articulating hinges and calcitic shells. Brachiopods are an important part of most Early Jurassic faunas, with rhynchonellides the dominant group (Emig et al., 2013).

Order Terebratulida Waagen

Suborder Terebratulidina Waagen

Family Lissajousithyrididae Cooper

Genus Monsardithyris Alméras

Type species: *Terebratula ventricosa* Hartmann

Material: 2 articulated specimens (plate 5:4)

Description: Shells subcircular in outline or elongated. Surface smooth. Anterior margin gently rectimarginate to uniplicate but sulcus and fold not recognizable on shell surface. Growth lines gently visible at anterior margin. Beak short with large foramen.

Order Rhynchonellida Kuhn

Family Tetrarhynchiidae Ager

Genus Somalirhynchia Weir, 1925

Type species: *Somalirhynchia africana* Weir, 1925

Material: two articulated specimen (plate 5:6-7)

Description. *Somalirhynchia africana* has medium sized shells subtriangular in outline, strongly dorsibiconvex with maximum width attained past midlength; beak erect and massive with small hypothyrid pedicle foramen; deltidial plates disjunct. Anterior commissure strongly uniplicate; lateral commissure deflected ventrally; interareas large, somewhat concave. Ventral sulcus originates just past midlength, widening anteriorly into a long tongue with six costae. Dorsal valve high, domelike, with strong median fold with seven costae that begins near midlength and becomes strongly elevated anterior.

Remarks. This is one of the most morphologically variable rhynchonellid species so far encountered within the Jurassic of Israel, Saudi Arabia, Israel, Yemen and Somalia.

Genus Bihenithyris Muir-Wood, 1935

Type specie *Bihenithyris mediocostata* Cooper, 1989

Material: 2 articulated specimens (plate 5:9)

Description. Medium sized, biconvex shell. Umbo massive, suberect, truncated by large circular labiate foramen with distinct mesothyrid beak ridges. Dorsal valve with two well-developed folds flanking a deep median sulcus that forms a marked episulcation with the corresponding ventral fold at the anterior margin.

4.6. Gastropods

Gastropods are a large, univalved, coiled and highly diversified class within the phylum Mollusca. Some of these gastropods are terrestrial while other gastropods live in marine or freshwater habitat (Venkatesan & Mohamed, 2015). In Mertule Mariam section the gastropod fossil is preserved as mold and the taxonomic classification is a little bit difficult.

Subclass Prosobranchia Milne-Edwards, 1848

Order neogastropoda Thiele, 1928

Family Pseudomelaniidae Cossmann, 1909

Genus pseudomelania pictet and campiche, 1862

Material: 2 samples (plate 5:8)

Description: medium sized planispiral shell. The Genus contains three whorls and Two sutures. This specimen is collected from the middle part of the Mertule mariam section

PLATE 1

FORAMINIFERAN FOSSILS

1. *Lenticular subalata (*Reuss), (35x), sample ML-S-A

2-3. Lenticular quenstedti (Gumbel), (35x), axial view, sample ML-E0

4. Verneuilinoides minuta Said & Barakat, (35x), Axial section, sample ML-1-1

5-6. Kurnubia palastiniensis, (35x, sample ML-2-1

7. Lenticulina varians, (35x) from sample ML-2-1,35X

8. Elphidium sp. (35x)

9. Pfenderina neocomiensis, 35x from sample ML-4,35X

10. Pfenderella arabica Redmond, 35X, sample ML-2-1

PLATE 1

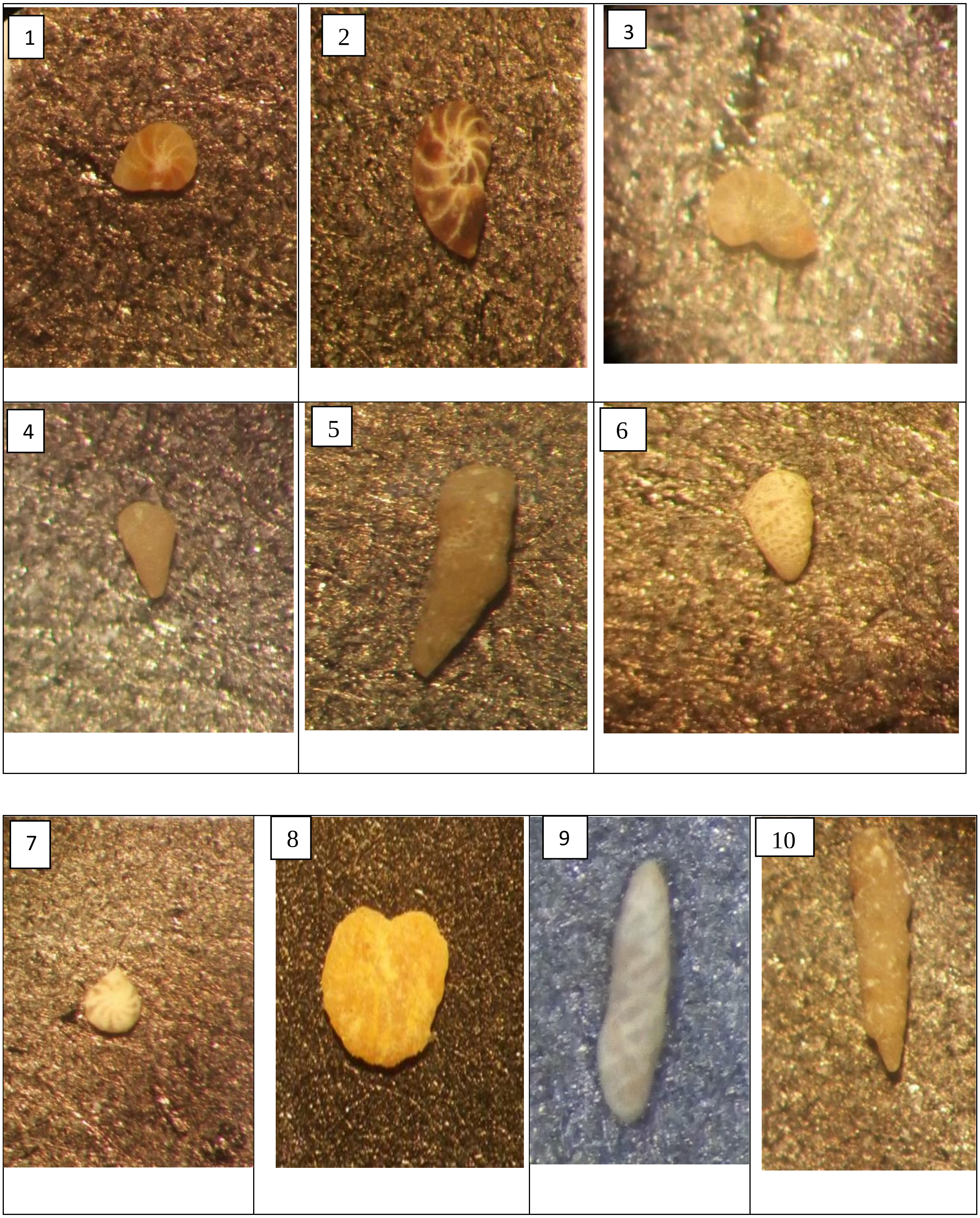


PLATE 2

OSTRACODE FOSSILS

1. *Paracypris sp*., from sample ML-1-4, 35X

2. *Cyprideis sp.*, from sample ML-4B, 35X

3. *Cytherella sp.*, from sample ML-1-4, 35X

4. *Cytherella cf.*, *ventroconcava*, from sample ML-1-4,35X

5. *Darwinula sp.*, from sample ML-1-1,35X

6. *Macrocypris sp.***,** from sample ML-5E, 35X

PLATE 2

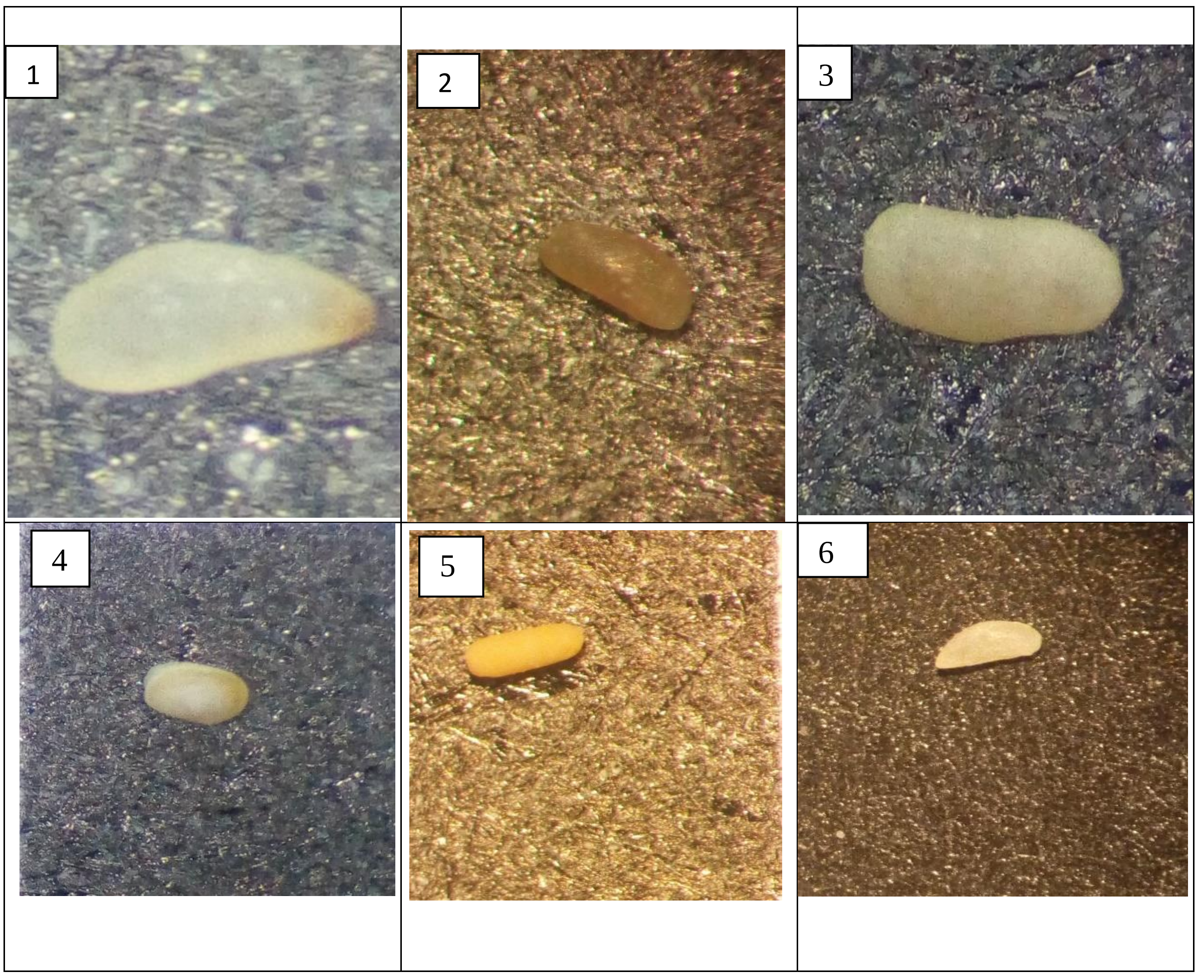


PLATE 3

Foraminifers' fossils identified from thin section

Figure 1-2 photomicrograph of Nautiloculina oolithica Mohler. 1938 (4x)

Figure 3-4 photomicrograph of Alveosepta jaccardi ML-SC—5&ML-1-7 (4x)

Figure 5-7 photomicrograph of Kurnubia palastiniensis Henson, 1948, oblique subaxial vertical section, ML-1-7 *(4x)*

Figure 8 Verneuilinoides sp., axial section

Figure 9 photomicrograph of Cerithid gastropod transverse section, ML-2-3 (4x)

PLATE 3

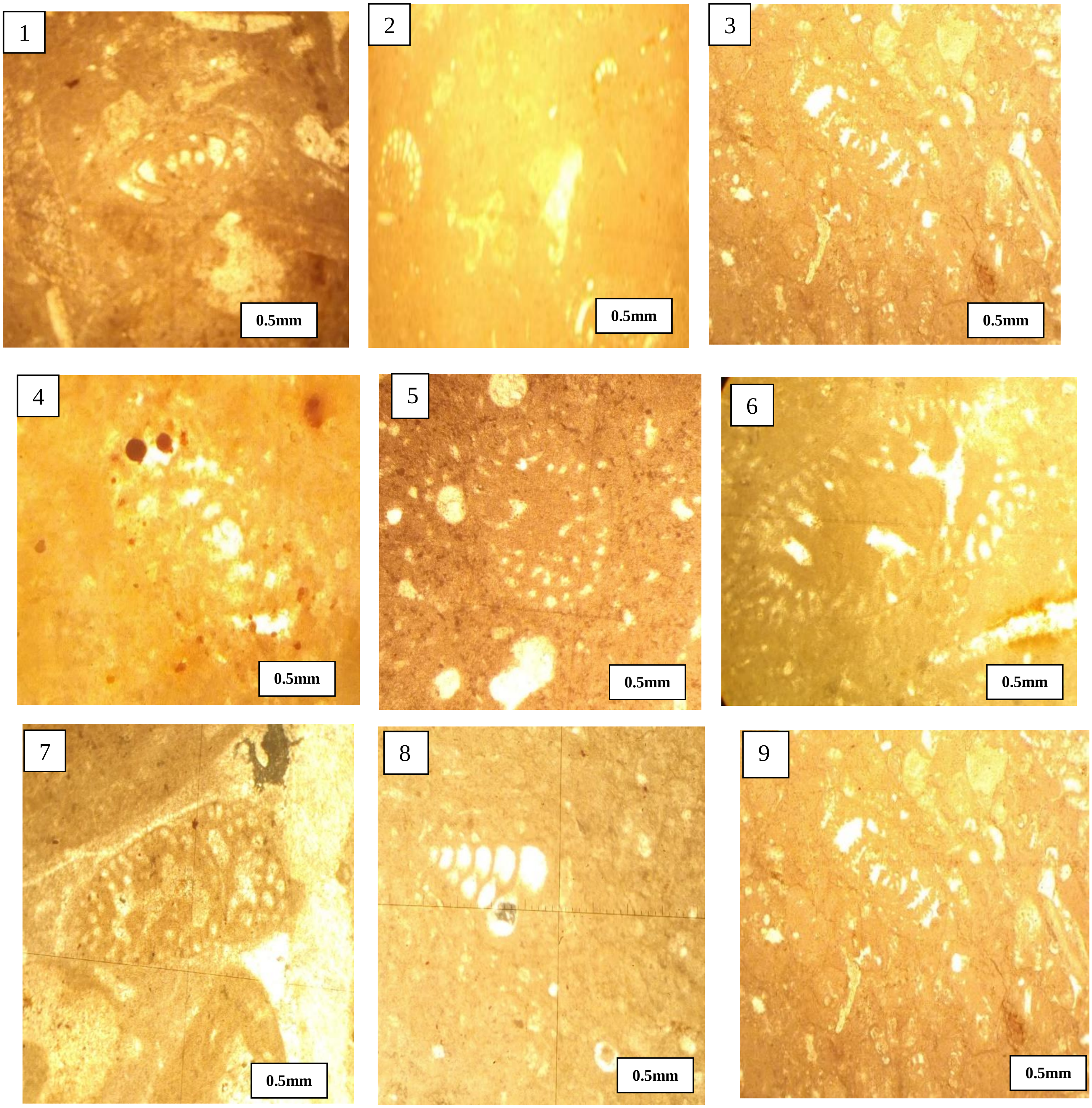


PLATE 4

Calcareous Algaes identified from thin section

1. *Salpingoporella melitae*, Barremian; *transverse section*

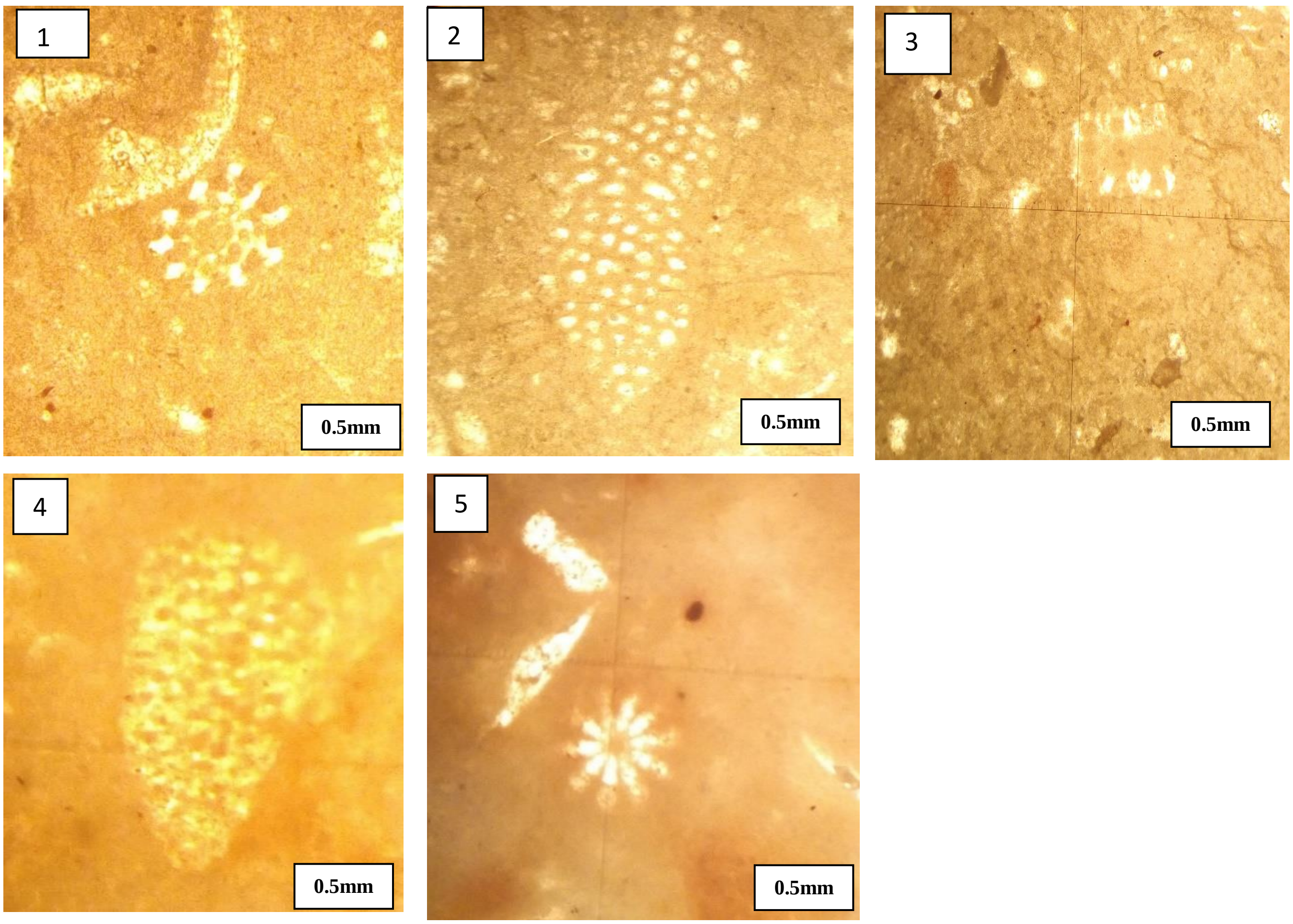
2. *Clypeina parasolkani*, Berriasiane, *transverse section*, ML-2-3

3. *Neoiraqia insolita*, ML-1-7, oblique longitudinal

4. *Permocalculus inopinatus* Elliott

5. *Acicularia elongata* Carozzi

PLATE 4



Macro invertebrate fossils

Figure .1. *Pholadomya (Bucardiomya) somaliness* Sowerby, 1823

Figure 2&3**.***Nanogyra nana* Sowrbey, 1822, right and left valve respectively

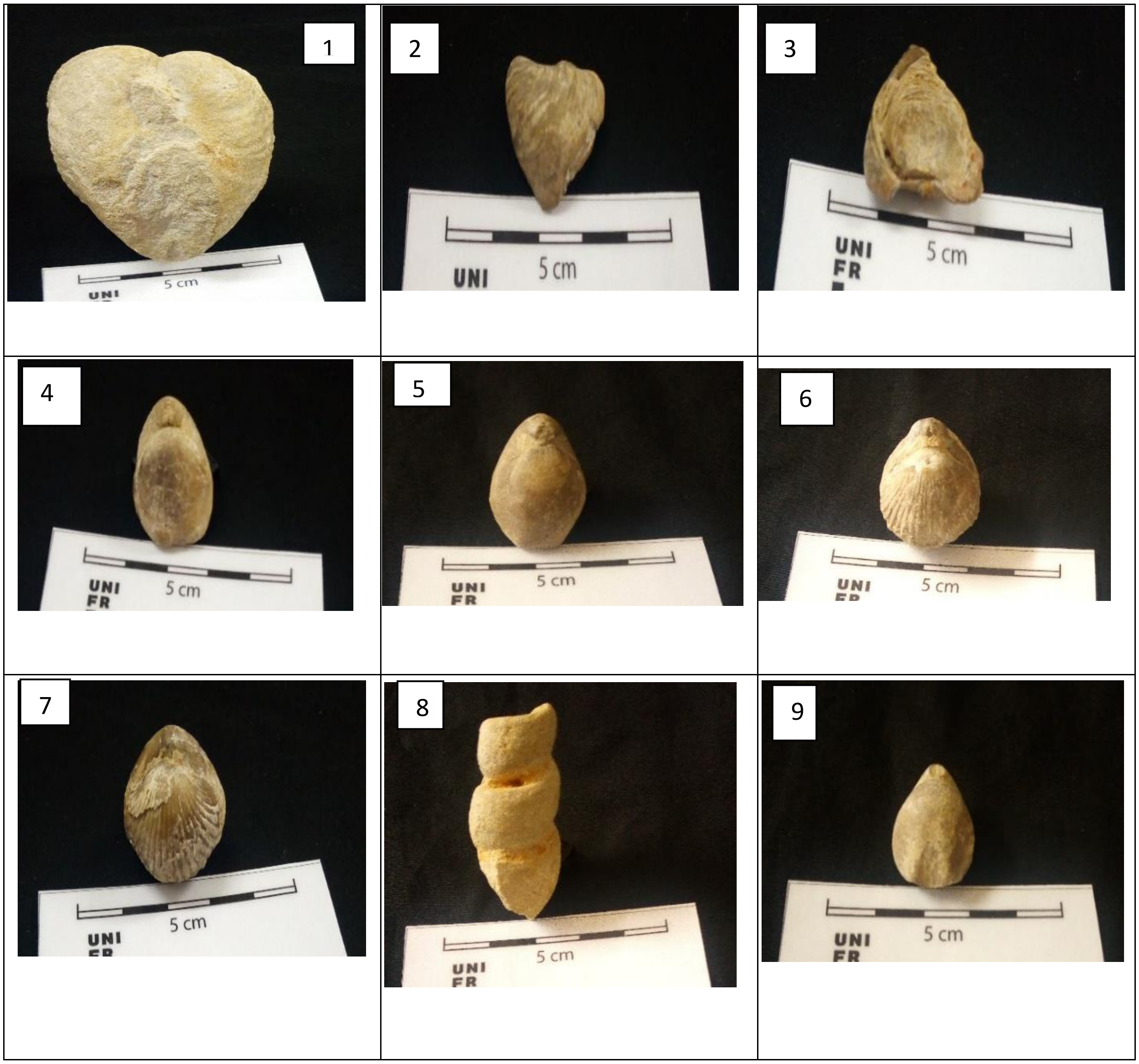
Figure 4&5.*Terebratula ventricosa* Hartmann, Brachial valve view

Figure 6&7**.***Somalirhynchia africana* Weir, 1925

Figure 8**.** *Pseudomelania Sp.* pictet and campiche, 1862

Figure 9**.** *Bihenithyris mediocostata* Cooper, 1984

PLATE 5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CHAPTER FIVE

5. MICROFACIES ANALYSIS AND DIAGENESIS

The facies analysis, age determination and depositional environment interpretation of carbonate units can be understood well through microscopic study. It is difficult to describe all the properties of carbonate rocks using field observation alone. Hence, detailed studies were carried out through studies of thin-sections. Due to the limited macroscopic data in the carbonate unit of the Mertule Mariam section, this study concerns mostly on microfacies analysis of carbonate units in the section. These detailed thin section descriptions and identifications were undertaken on the base of Dunham (1962) and modified Embry and Klovan (1971) carbonate rock classification scheme. Fossil content and constituent composition of each sample were identified and by using the obtained data, microfacies types and depositional environments were determined.

5.1. Microfacies Analysis

Microfacies refer to the total of all the paleontological and sedimentological criteria described and analyzed from thin sections (Flugel, 2004). It provides the basic microfacies data analysis of the carbonate rocks using the hand lens in the field were combined with a detailed microfacies study of the thin sections in the laboratory in order to obtain a complete picture of the measured section. The microfacies of the carbonate unit in the Mertule Mariam section were investigated through 34 thin-sections analysis. Each sample was studied under a petrographic microscope and the description and proportion of each thin section has been done. For the microfacies analysis of the carbonate unit of the studied section, the standard microfacies classification schemes of Wilson (1975) and Flugel (1982; 2004) and ramp microfacies type of Flugel (2004) has been followed. Paleoenvironmental reconstructions of carbonate unit were interpreted based on compositional, textural, fabrics, sedimentary data and by comparison with modern carbonate environments.

The following microfacies types have been identified and described from the studied section.

5.1.1. Oolitic –Packstone/Grainstone Microfacies Type (MFT 1)

Description: This micro facies occurs at the middle and the upper part of the studied section from sample ML-II, ML-III and ML-A2.The allochems in this microfacies characterized by moderately to well sorted ooid grains and bioclast of bivalve, echinoid and dominantly miliolid group foraminiferas (Fig.5.1).The ooid and bioclastic grains are cemented by coarse sparite cement. The ooid allochems have been micritized and the nuclei have been formed by miliolid and other group of foraminiferan fossils.

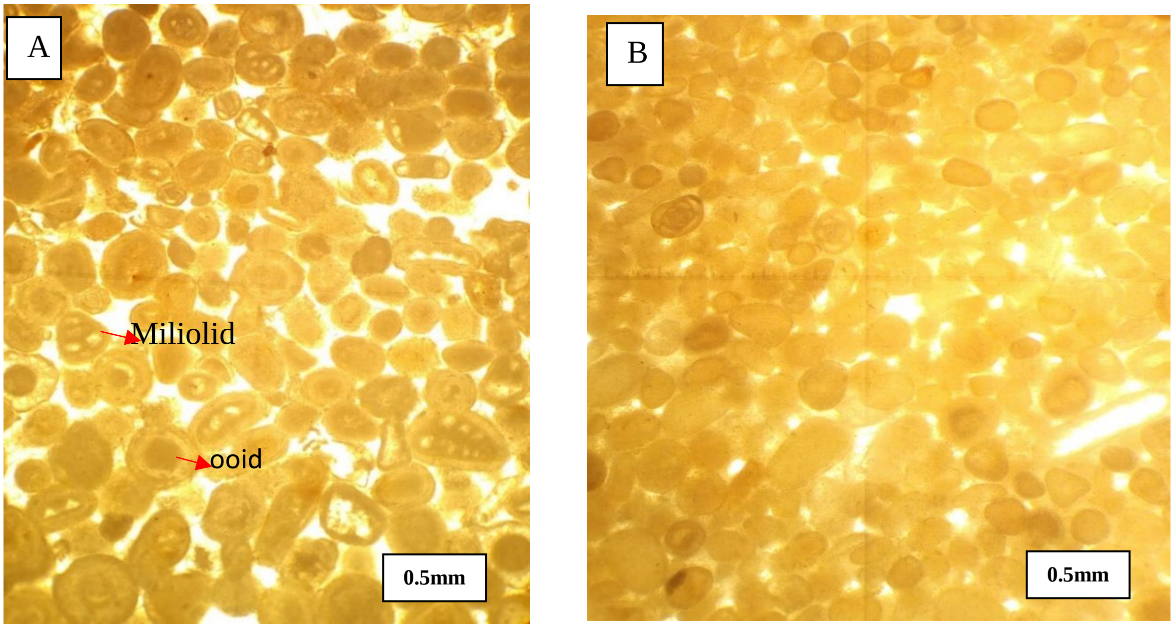


Figure 5.1.The microphotograph shows the oolitic-bioclastic Packstone/Grainstone type microfacies. A.under ppl, 4X magnification A.from sample ML-III and B from ML-II.

Interpretation: The presence of fossils within ooids indicates short-term stable conditions in the time of ooids growth (Flugel 2004). The bioclasts and thin-rim ooids with sparry calcite indicate comparatively high-energy conditions of a shoal at the platform margin (Flügel, 2010).this microfacies is similar with SMF 15&FZ 6 of Flugel,2010.

5.1.2. Bioclastic Mudstone Microfacies Type (MFT 2)

Description: This microfacies occurs at the upper part of the section with sample ML-1-2, ML-2-4, ML-2-12, ML-2-14, and ML-2-15, ML-SC-3, ML-I. It occurs dominantly in the studied section. Bioclast are composed of diverse types of fossils. However, it is dominated by unidentified foraminifera, echinoids, brachiopod and bivalve shells. This microfacies has a high amount of micrite (90%-92%) and are dominated by stylolitic structures and is moderately fractured and bioturbated.

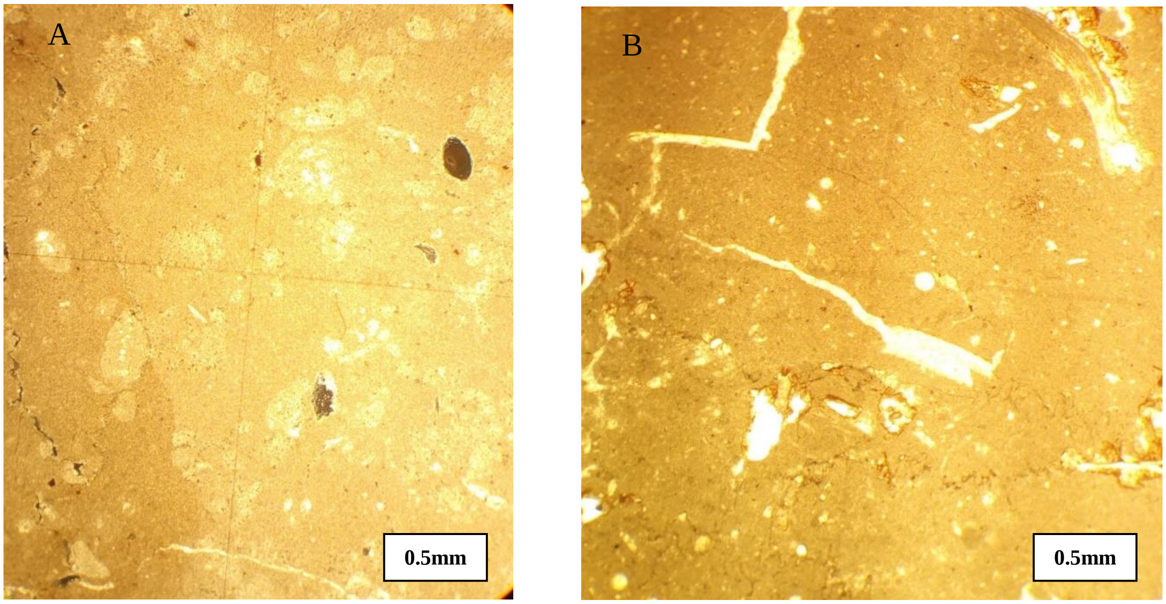


Figure 5.2.Photomicrograph of Bioclastic Mudstone type microfacies A. under XPL, from sample ML-2-15 and B under ppl, from sample ML-1-2.

Interpretation: Calcareous mud in warm water setting comes from the breakdown of calcareous algae, in organic precipitations from sea water and from disintegration of large skeletal particles into their smallest unit. These mudstones accumulated in quite water areas that are not affected by tidal or strong oceanic currents (Tucker & Wright, 1990). This microfacies is similar with the SMF 8 of Flügel (2010)

5.1.3. Bioclastic Packstone/Grainstone Microfacies Type (MFT 3)

Description: This microfacies occurs at the lower to middle part of the studied section with sample ML-1-9, ML-2-2, ML-2-5, ML-2-7, ML-F8, ML-1-3 and ML-SC-4. This microfacies composed of large bivalve shells and echinoid plate allochems. Those allochems are cemented by micrite cement and most of them have been micritized marginally to completely (Figure 5.3).

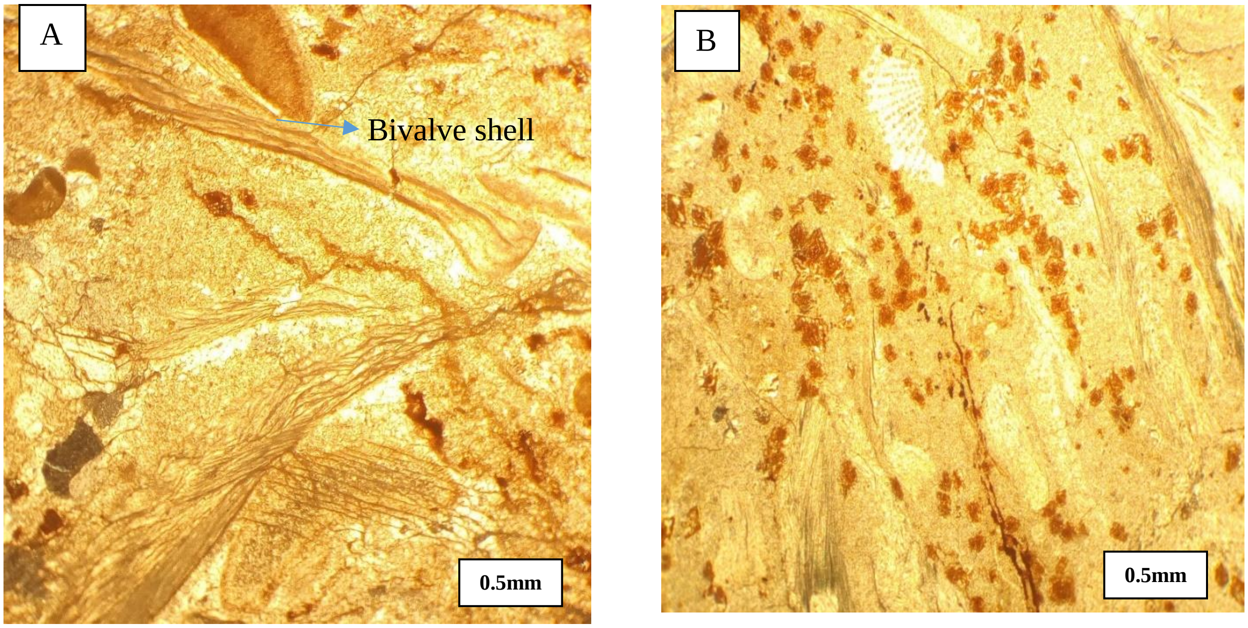


Figure 5.3. Photomicrograph showing bioclastic Packstone/Grainstone type microfacies, which includes brachiopod, echinoid and bivalve shells. Those bioclasts are moderately-highly micritized. A from sample F8 and B.from sample ML-2-2, under ppl.

Interpretation: These deposits showing evidence of intense reworking and containing a predominantly open marine fauna imply a formation in a marine environment with high hydrodynamic energy; they represent bioclastic shoals on the platform margin or on highs in the platform interior (corresponding to FZ 6 of Flugel, 2004). The coarse bioclasts indicate comparatively high-energy conditions of a shoal at the platform margin (Flügel, 2010).

5.1.4. Peloidal-Bioclastic Wackstone/Packstone Type Microfacies (MFT 4)

Description: Obtained at the middle part of the studied section from sample ML-3. It also contains the bivalve bioclast and small amounts of intraclast.

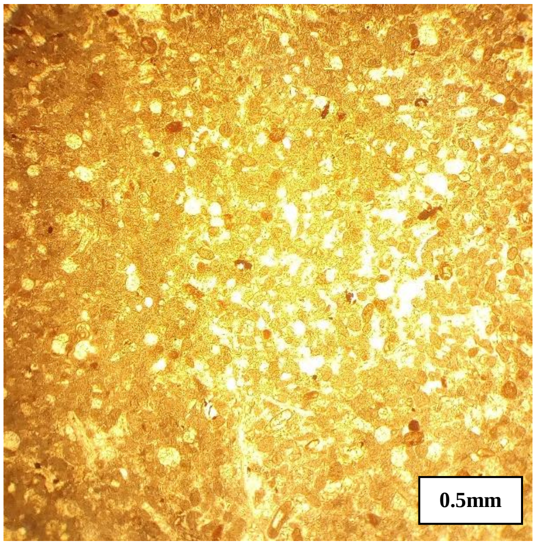


Figure 5.4.the photomicrograph of bioclastic-Peloidal grainstone type microfacies from sample ML-3, under ppl.

Interpretation: Many peloid rich carbonates indicate low energy lagoon environment and have a carbonate mud (micrite) type of cement. It is difficult to distinguish the grains since the grains are compacted.

5.1.5. Bioclastic Dolomudstone (MFT 5)

Description: This microfacies is rare in the studied section, which is recorded only in the upper part of the section. Fine grained crystalline dolomitized micrite is dominant. Sample ML-02.contains a shell fragment of bivalve (red arrow), which is affected by neomorphism (the aragonitic bivalve shell replaced by calcite).

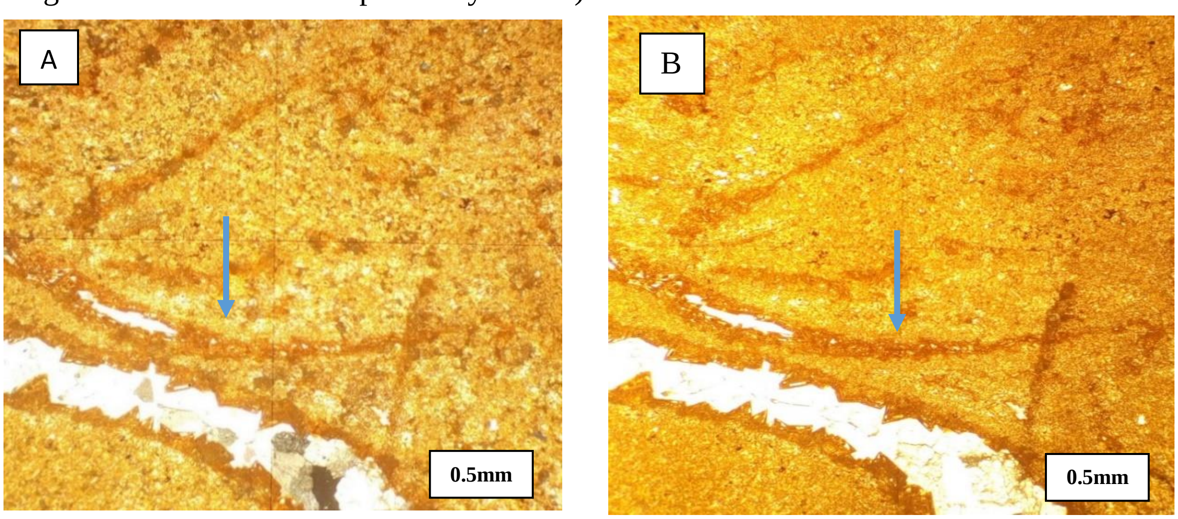


Figure 5.5. The photomicrograph of bioclastic fine grained crystalline Mudstone type microfacies. A. from sample ML-2, under xpl, and B under ppl.

Interpretation: According to Amthor&Friedman, 1991**,** the very fine crystalline dolomite crystal restricts to peritidal depositional environment. The fine crystal size represents a result of early dolomitization of precursor on peritidal lime mudstone or neomorphism of a pen contemporaneous or early diagenetic dolomite (Zenger, 1983; Amthor&Friedman, 1991). However, the dolomite is not indicating their depositional facies, which indicate diagenetic facies. But, due to presence of the fine grain size, presence of quartz grains, lack of fauna, fenestral fabric & vertical changes suggest that deposition occurred in a low-energy, restricted intertidal & supratidal environment (Wilson & Evans, 2002). Therefore, this microfacies is deposited in shallow subtidal to lower intertidal environments, which is corresponding to SMF-23 of Wilson (1975) and Flugel (2010) of facies belt 8.

5.1.6. Un fossiliferous Mudstone type Microfacies (MFT 6)

Description: This type of microfacies occur at the upper part of the section from sample ML-2-13 and ML-2-8. It contains high micrite content (99%-100%) and it is porous, fractured and bioturbated.

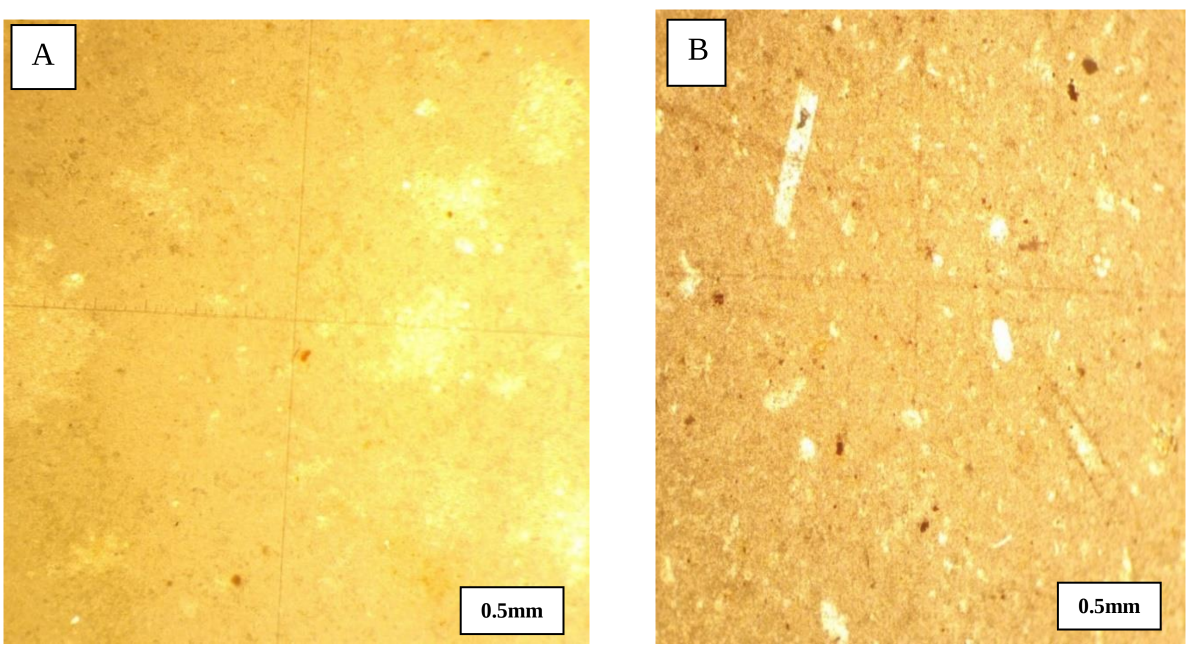


Figure 5.6. The photomicrograph of un fossiliferous Mudstone type microfacies. A from sample ML-2-13, under ppl, and B from ML-2-8, 4X, under xpl.

Interpretation: The un fossiliferous Mudstone Microfacies has been deposited in a low-energy, poorly fossiliferous environments, which are common in shallow restricted intertidal areas of calm conditions which have no water circulation (Flugel,1982) that reduce the normal wave or current energy on shallow marine carbonate shelf. The relative absence of microfauna strongly advocates deposition in nearshore domain at water depth less than 5m, where a nearshore and tide condition is common. This microfacies correspond to facies SMF-23 of Wilson (1975) and Flugel (2010).

5.1.7. Bioclastic-Intraclastic-Wackstone /Packstone Microfacies (MFT 7)

Description: This microfacies is composed of bioclasts including fragments of echinoid plate, bivalve and foraminifera (miliolid group).it is porous, bioturbated and contain intraclast and bioclast allochems with micrite and very small amount of sparite cement (see the proportion from the Appendix I). From sample ML-1, ML-E1, ML-1-1, ML-2-9, ML-2-11 and ML-A3.

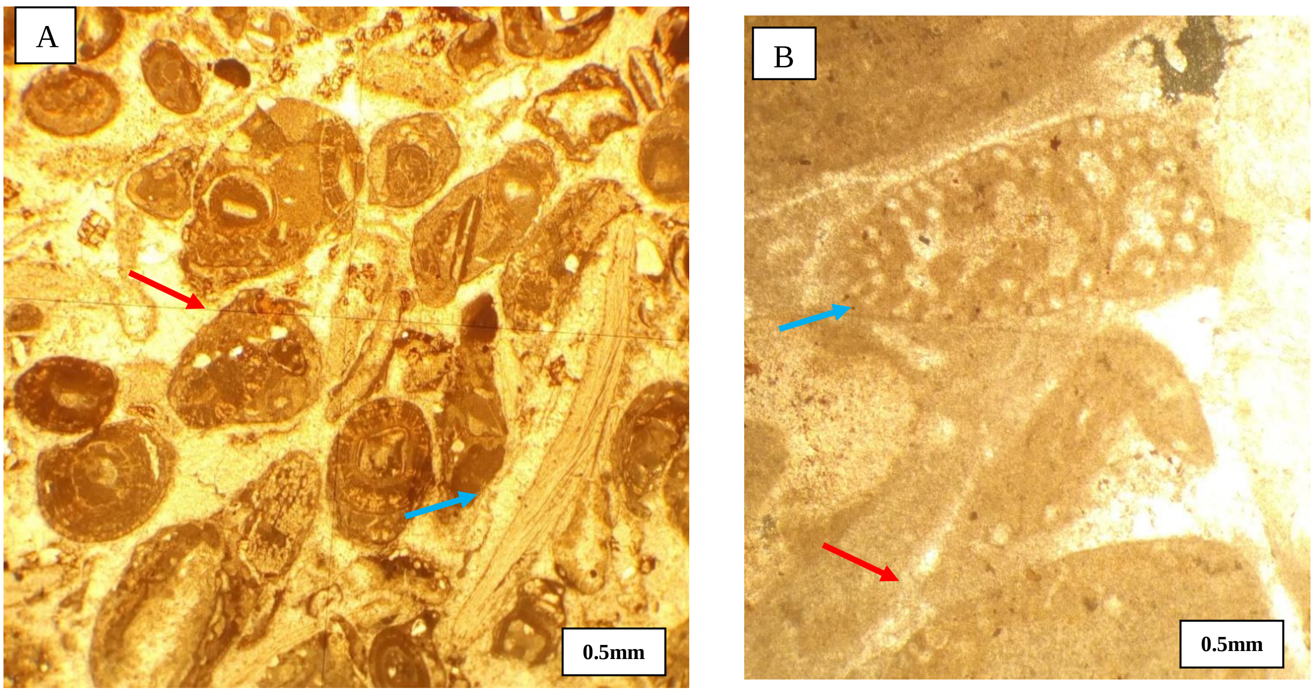


Figure 5.7. A bioclastic-intraclastic Wackstone/Packstone type microfacies. A.from sample ML-2-11, which contains intraclasts (red arrow) and a molluscan shell fragment (blue arrow), B.from sample ML-2-9, which contains intraclast (red arrow) and foraminifera fossil (blue arrow) both A&B have been taken under ppl.

Interpretation: Intraclastic grainstones are interpreted as having been deposited by storm-wave erosion and reworking of various sediment types in shallow-marine environments (Flügel, 2004).The presence of intraclasts and the grain-supported fabric indicates high energy condition. Thus, this facies was deposited in high energy shoal environment with open circulation in the presence of benthic foraminifera and other bivalve shell fragments.

5.1.8. Bioclastic Mudstone/Wackstone Microfacies (MFT 8)

Description: This microfacies recorded from sample ML-1-7, ML-1-5, ML-E1, and ML-2-3.This microfacies is composed of variable amounts of microbioclasts including bivalves, and miliolid fragments.

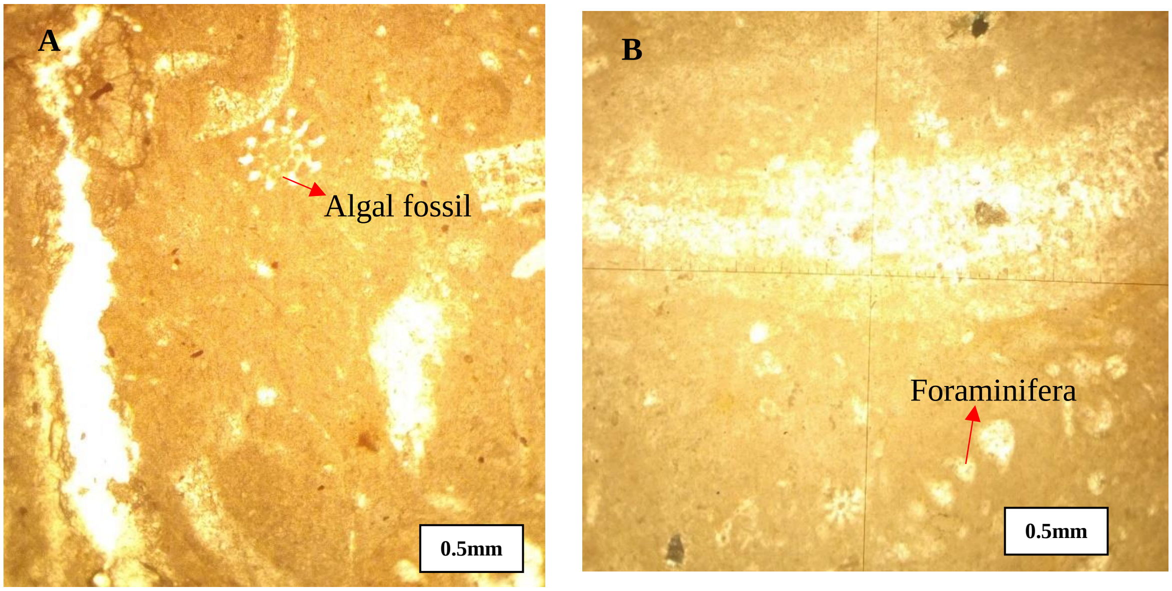


Figure 5.8. A photomicrograph which shows the bioclastic Mudstone/Wackstone microfacies type. A: .from sample ML-2-3, under ppl. B:.from sample ML-1-5,4X magnification, under ppl.

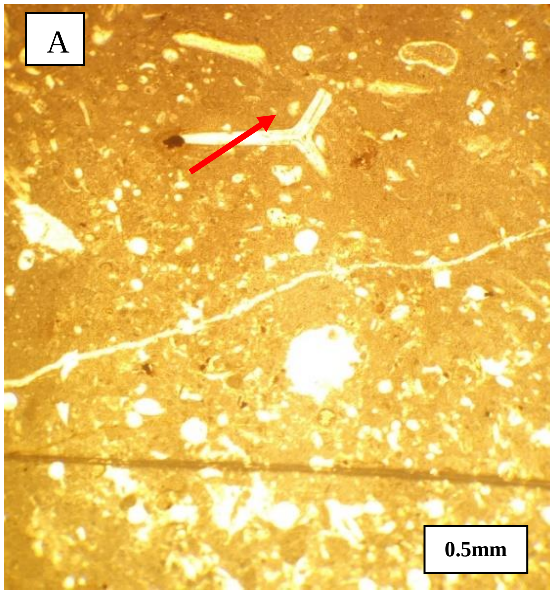
Interpretation: It is characterized by bioclast fragments and a mud dominate fabric indicating that this facies was deposited in low-energy conditions of platform interior setting.

abundant, high-diversity, and well-preserved fossils set in micrite indicate relatively low-energy open platform environments with efficient current circulation (Flügel, 2010).

The most similar standard microfacies type of Flügel (2010) for this facies is the SMF 9.

5.1.9. Bioclastic Spiculite-Wackstone /Packstone Microfacies (MFT 9)

Description: This microfacies recorded at the middle part of the section from sample ML-2-6 and ML-SC-5. The main distinctive feature of this facies is the abundance of sponge spicules in a micrite-dominated matrix with some gastropod shell, brachiopod, echinoid plate, bivalve, and miliolid bioclasts. Diagenetically stylolite structures and fracture have been observed.



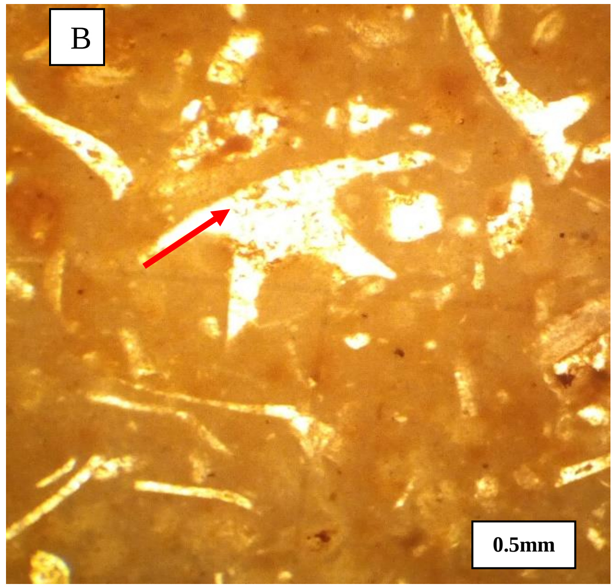


Figure 5.9. The photomicrographaph shows the spiculite-Wackstone/Packstone microfacies, which contains mainly sponge spicules (red arrow) A from ML-2-6 and B from Ml-SC-5 , under ppl.

Interpretation: Presence of abundant sponge spicule and milioid foraminifera with abundant homogenous micrite and overlain by skeletal sandy limestone and underlain by coral framestone indicates the bioclastic spiculite wackstone is interpreted to have deposited in the proximal open marine environment below fair weather wave base near to normal storm wave with normal circulation. This microfacies is corresponding with FZ3 facies zone of Flugel (1982) and Wilson (1975), which indicate proximal open marine environment with open circulation. This microfacies is comparable to SMF 8 of Flügel (2010).

5.1.10. Coral Framestone Microfacies (MFT 10)

Description: This microfacies recorded at the middle part of the studied section from sample ML-F20.It contains bivalve and coral bioclast. However, dominated by coral fossils and the remaining part is micrite (70%).

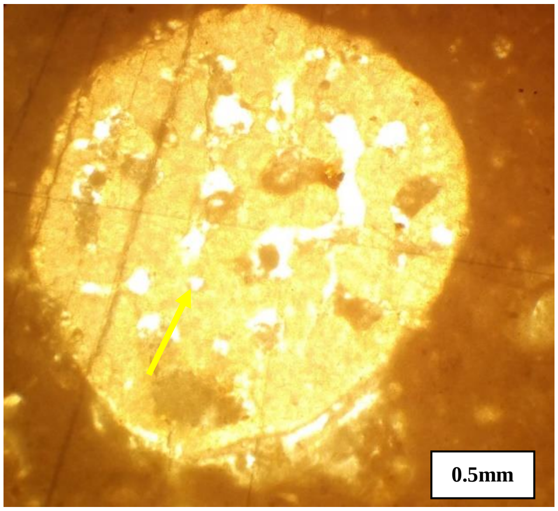


Figure 5.10. A photomicrograph which shows the coral bioclast (Yellow arrow) with in the micrite, under ppl.

Interpretation: This facies is comparable to SMF7 and RMF12 (Wilson 1975; Flugel 2004).

5.1.11. Bioclastic-Peloidal –Oolitic -Grainstone type microfacies (MFT 11)

This microfacies is characterized by a high abundance of micritized small peloids (71%), which has good sorting and ooids (20%). Obtained from sample ML-E2.Subordinate intraclasts and bioclasts are also present in this microfacies. Bioclasts of this microfacies composed of foraminifera but dominated by miliolid group and molluscans.

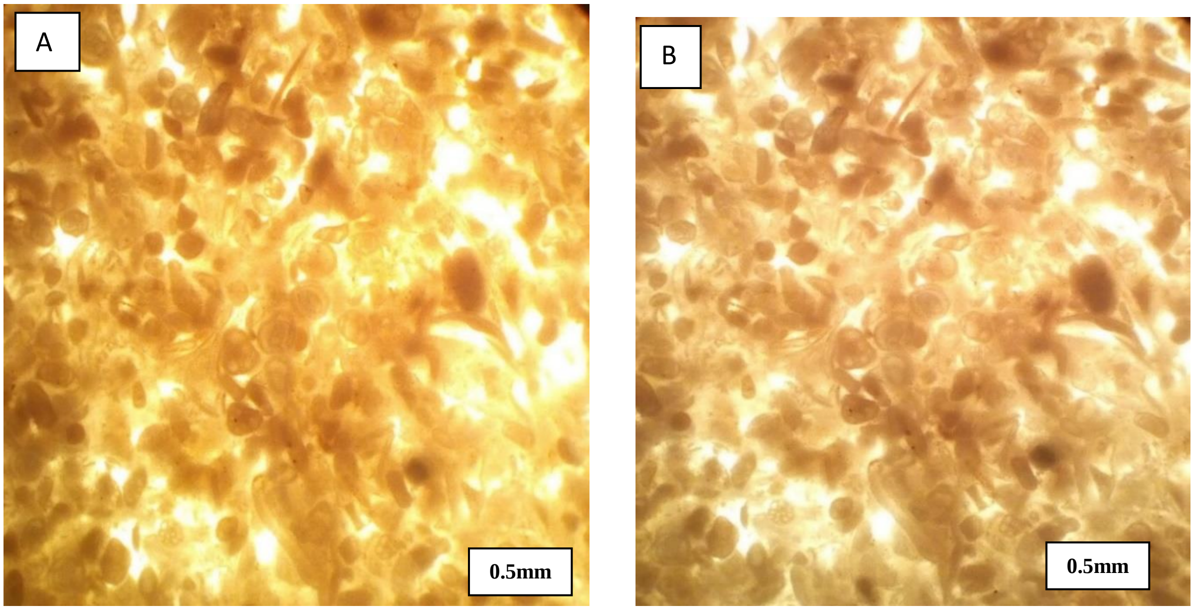


Figure 5.11.A photomicrograph shows the Peloidal-ooid grainstone. A under ppl and B under Xpl, from sample ML-E2.

Interpretation: The high degree of sorting and rounding suggests constant, high energy conditions above fair-weather wave base, for the upper shoreface environment. This microfacies is compared with SMF Type 15 of Wilson (1975), correspond to facies belt 6, which is deposited in moderate circulation conditions and efficiency of winnowing by wave current.

5.2. Diagenetic features of the carbonate unit

5.2.1. Introduction

Diagenesis refers to all the processes which occur to a sediment after deposition, during burial or any subsequent uplift. Major controls on carbonate diagenesis are mineralogy and crystal chemistry, the chemistry of pore waters, water movement, dissolution and precipitation rates, grain size, and the interaction with organic substances. The diagenetic processes affecting carbonate sediments and rocks are micritization dissolution and cementation, compaction, neomorphism, dolomitization, and the replacement of carbonate grains and matrix by non-carbonate mineralogies like silicification and chertification (Flugel, 2010). The diagenesis of carbonate rocks occur in the three main environments: the marine, near surface meteorite and burial environment (Moore & Wade, 2013). Diagenesis in the marine environment is a common process in many shallow-marine carbonate depositional environments (Cantrell & Hagerty, 1999). The petrographic investigation of the Mertule Mariam section resulted in the identification of such diagenetic processes.

5.2.2. Compaction and pressure solution (stylolitization)

Stylolitization refer to mechanical and chemical processes, triggered by the increasing overburden of sediments during burial and increasing temperature and pressure conditions. Stylolites are irregular dissolution surfaces with multiscale roughness created by intergranular pressure solution. High solubility and fast reaction kinetics make carbonate rocks the predominant lithology susceptible to pressure-solution (Humphrey et al., 2020 and their references: Koehn et al. 2007 and Ebner et al. 2010). Chemical compaction involves pressure solution at grain to grain contacts resulting in interpenetrating and/or sutured contacts between grains. In addition to grain to grain suturing, pressure-solution seams commonly develop approximately parallel to bedding. Presumably, the reason stylolite are usually parallel overall to bedding is that bedding surfaces are usually the paths of easiest flow of pore solutions (Adams and Mackenzie, 1998).Stylolite occurs mainly at the middle and upper part of the studied section (Fig.A&B) from sample ML-28 and ML-2-13 respectively.

5.2.3. Dolomitization

Dolomitization is a process whereby limestone or its precursor sediment is completely or partly converted to dolomite by the replacement of the original CaCO3 by magnesium carbonate, through the action of Mg bearing water (Flugel, 2010).Dolomite crystals are small euhedral to subhedral rhombic which range from 1-5 micrometer in size (Rameil, 2005 and reference Budd,1997).dolomitization has been observed from the middle to upper part of the area (Fig.C) from ML-E1.

5.2.4. Fracture

Fractures are the results of compaction processes and commonly found at various levels in the measured sections. It is particularly effective and common in carbonate rocks because, of their brittle nature of carbonates relative to the more ductile fine-grained siliciclastic, which they are often interbedded (Longman, 1980). Fracturing can take place at practically any time during the burial history of a carbonate sequence starting with shallow burial because of common early lithification.it occurs at the upper part of the studied section (Figure E) from sample ML-2-12.

5.2.5. Cementation

Cementation is the processes of the precipitation of mineral (mostly calcite) in primary or secondary pores and requires the supersaturation of pore fluids with respect to the mineral (Flugel, 2010).The source of calcite cement varies depend on diagenetic environment, in the marine realm it is sea water where as in the meteoric and burial environment it generated from the dissolution of carbonate grains and finer sediments (Moore & Wade, 2013).In the studied section the sparite cement observed between ooid grains (Figure C).The micrite cement occurred dominantly in the area.

5.2.6. Neomorphism

Neomorphism is the term which tells combined processes of replacement and recrystallization. replacement refers to the change of one mineral to another mineral , whereas, recrystallization indicates a change in size or shape of a crystal, with little or no change in chemical composition or mineralogy (Moore & Wade, 2013). Mollusca shell in the study area show inversion means changing aragonite, which forms the skeletal materials and cement into equant blocky calcite crystal. The term neomorphism has been introduced by Folk (1965), which includes aggrading and degrading recrystallization. Aragonite and high magnesium calcite are the most soluble carbonate polymorphs. The aragonite forming skeletons of the fossils becomes dissolved and replaced by calcite (Figure H) from sample ML-1-7**.**

5.2.7. Dissolution

The movement of carbonate saturated water through the cavities of the carbonate rocks caused the partial dissolution of the unstable minerals. This process usually takes place in diagenetic (Erfani et al., 2016). Since aragonite is less stable than calcite, it dissolves easily and rapidly. Dissolution is particularly important in near surface meteoric environment and through small vugs extensive cave systems may develop in limestone through karstification (Moore & Wade, 2013).In the studied section dissolution has been observed dominantly with in the shell of gastropod fossil (Figure F) from sample ML-2-6.

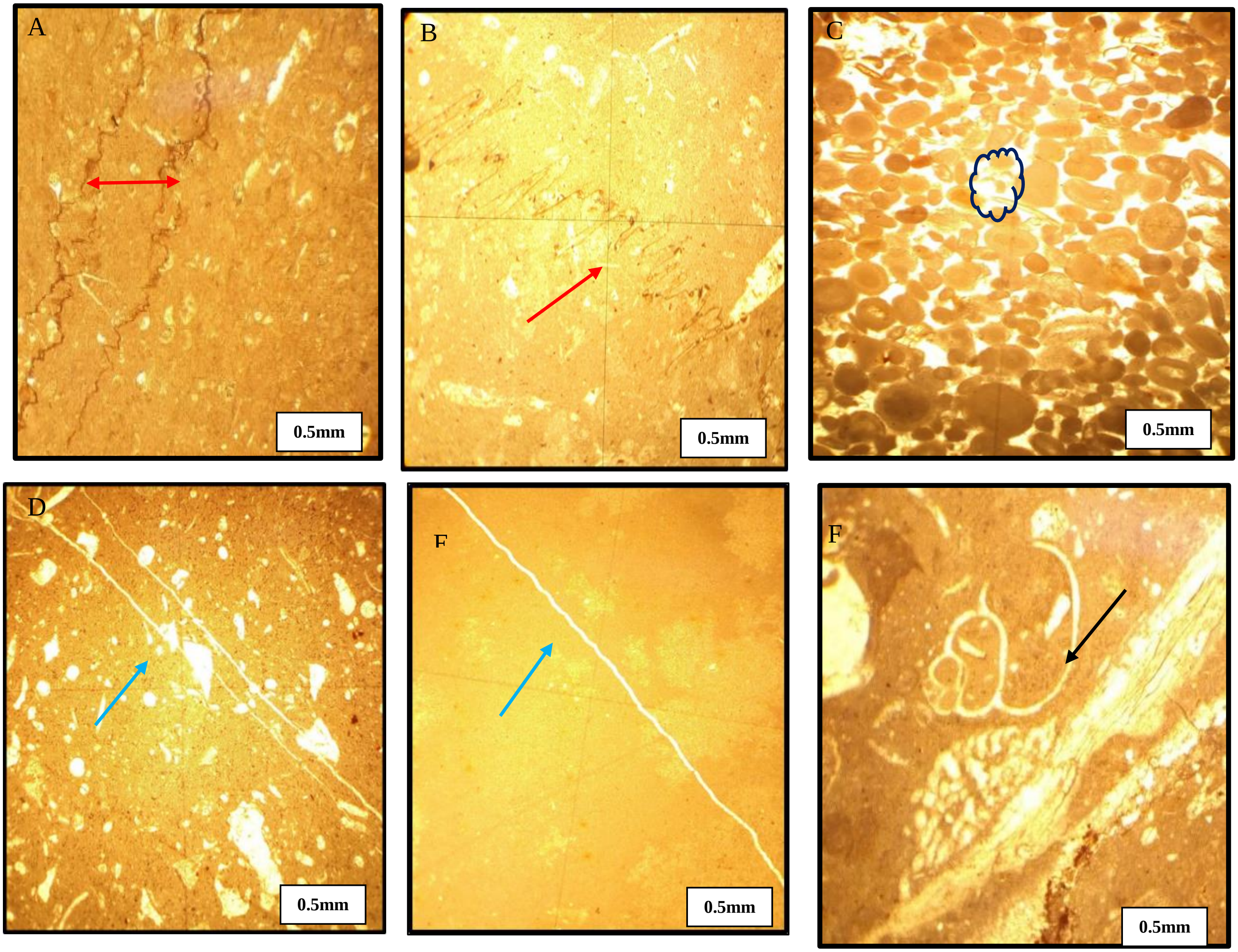
5.2.8. Micritization

The term micritization refers to conversion of allochemical constituents of the carbonate rocks into micrite or lime mud through boring activity of endolithic algae (Flugel, 1982). Reworking of carbonate sediments by boring, burrowing and sediment-ingesting activities of organisms, just as they do in siliciclastic environments are common in the study area. These activities may destroy primary sedimentary structures in carbonate sediment and leave behind mottled bedding and various kinds of organic traces (Tucker 1981; Tucker and Wright, 1990). Additionally, many kinds of small organisms, such as fungi, bacteria and algae create microborings in skeletal fragments and other carbonate grains. Fine-grained (micritic) aragonite or high-magnesian calcite may then precipitate into these holes (pore space). These boring and micrite-precipitation process may be so intensive in some warm-water environments that carbonate grains are reduced almost completely to micrite, with a process called micritization. If boring is less intensive, only a thin micrite rim or micrite envelope, may be produced around the grain. Micritized carbonate grains and bioclasts are common throughout the study area (Figure C&I), the ooid grains in Fig C and the margin of bivalve shell in Fig I have been micritized.

5.2.9. Silicification

Silicification of carbonate rocks involves replacement of carbonate by silica as well as precipitation of pore-filling silica cement (Flugel, 2004).

This type of diagenesis is rare in the studied section, which only recorded from the upper part of the section with sample ML-2-9. The shell of bivalve has been dissolved and moderately replaced by silica (Figure I).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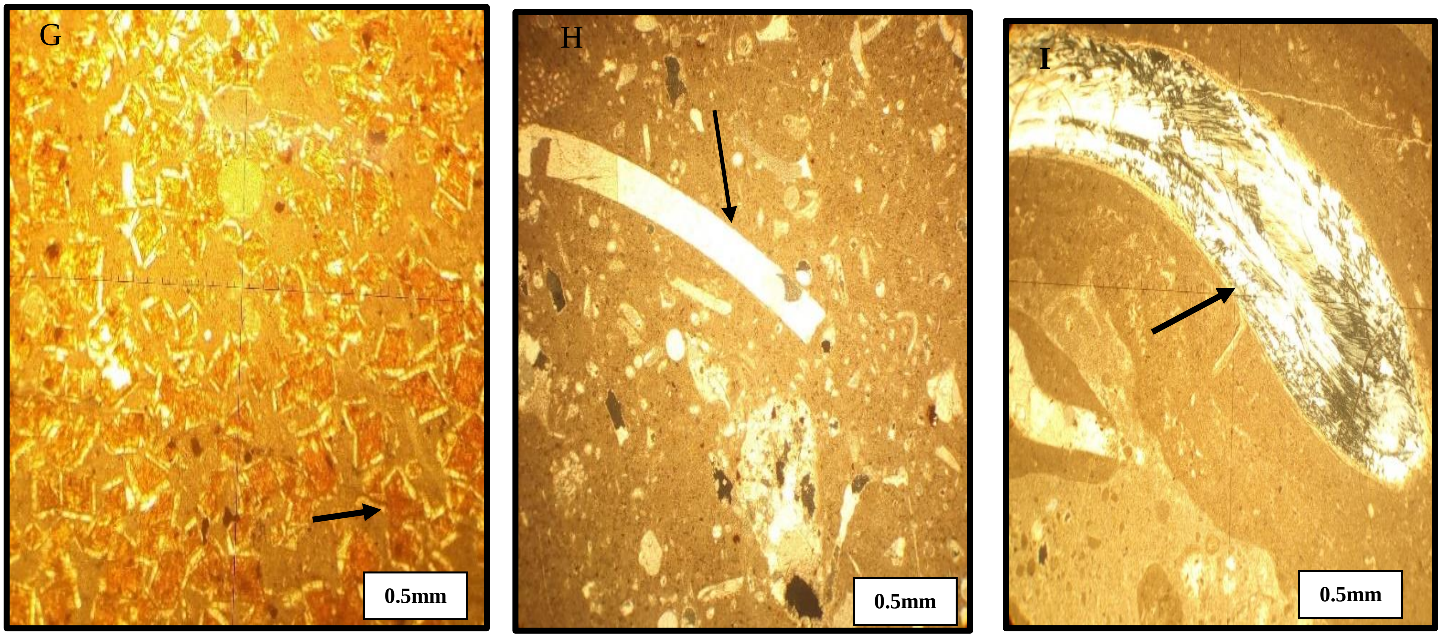

Figure.5.12. A Microphotograph showing diagenetic features of the carbonate unit in the Mertule Mariam Section*:* A-B shows (chemical compaction) stylolite structure from ML-1-7 &ML-2-15 respectively (red arrow). C.sparite cement between ooid grains from sample ML-03 (the circle).D.Fracture from sample ML-2-6 &ML-2-12 respectively (yellow arrow).F.Dissolutionof of gastropod fossil from sample Ml-1-3 (arrow). G .Dolomitization (the arrow). H.Neomorphism, the aragonitic shell of bivalve dissolved and replaced by calcite from sample ML-1-7 (the arrow) and I.silcification of the bivalve shell from ML-2 (the arrow).

CHAPTER SIX

6. DISCUSSION

6.1. Introduction

Based on the detailed outcrop investigations, petrographic analysis of 34 thin sections and the analysis of 17 dry marl sediments, the Mertule Mariam section, the Upper Jurassic (Callovian-early Kimmeridgian) Carbonate deposits are characterized by thick layers of carbonate rock, mainly limestone rock unit with small dolomite rock unit. These carbonate successions have various distribution of skeletal and non-skeletal allochems which are embedded by microcrystalline (micrite) and/or sparry calcite cement, which ranges from mudstone to grainstone microfacies of the carbonate succession.

The studied Carbonate rock units consist of various textures and depositional environment with different paleontological distribution. Based on these varying sedimentological and paleontological information collected from the measured section and laboratory data description and analyses, depositional environment interpretation, age determination and intrabasinal and regional correlation are discussed as follows:

6.2. Facies associations and depositional environments

Depositional environment is a geomorphic unit in which deposition takes places. Depositional environments can be interpreted and classified through facies analysis, which is body of rock characterized by a particular combination of lithology, texture, group of sedimentary structures, fossil content, color, geometry etc., (Flugel, 1982).

The upper part of the section (20m thick), around the contact the limestone is well-exposed and contains 15-20cm marl and dolomite intercalation b/n the limestone layer.at the base it contains 10m shale and mud intercalation. From this area various marl and limestone unit samples (Figure 3.8) have been collected for thin section preparation and microfossil identification. From outcrop description and thin section analysis the limestone in this part is micritic (Folk, 1962) or mudstone (Dunham, 1962).the marl from this part contains very small no of foraminifera and ostracod fossils. when we see the amount of micro fossils contained within the mar unit from bottom to top in the logged section it becomes smallest to the top.20 m thick bedded micritic limestone and it is bioturbated at the base is also observed below the contact at the right when we go to Mekane Selam.

The middle part of the studied section dominantly covered by marl unit and it also contains 4m thick shale, 1m fossiliferous limestone, 2m dolomitized limestone and 2.5 cm variegated colored clastic mudstone at various places from bottom to top. Many marl samples have been collected for foraminifera fossil identification. Black limestone unit with sandy fragments, 10m thick around the asphalt road (at 442764 easting and 1176924 northing) also observed. The main difficulty in this area is around 12m thick area is highly covered by plants and there is no exposure to take sample. Generally the middle section is covered by marly unit.

At the base of the logged section, above gypsum the area covered by 15m mar unit which is rich in macrofossils dominantly Brachiopod fossils.additionaly, it contains many foraminiferan fossils but it hasn't ostracod fossils. When we go up to the middle of the section there is 20m thick micritic limestone and various samples collected and leveled (Figure 3.8).between the first and the second cliff forming limestone the area is covered by 35m marl unit (sample ML-2 &ML-4) with 2m oolitic limestone (sample ML-A2 & A3) at the middle. The second cliff is micritic 25m thick micritic limestone unit with 10m oolitic limestone at the middle part. From the above, the deepening upward trend can be observed going from Packstone/grainstone to mudstone at the top.

Facies association is a groups of facies genetically related to one another, which have the same depositional environment. On the basis of lithology, sedimentary structures, trace fossil association, textures, presence and proportion of non-skeletal (ooids, Peloids, oncoids, aggregate, and intraclast) and skeletal (bivalve, brachiopods, gastropods, corals, echinoids, crinoids and other benthic foraminiferal) grains, and field relationship with overlain and underlain rock unit, 11 different microfacies type have been recognized and grouped into shallow marine carbonate deposits of (I) tidal flat, (II) lagoon, (III) High energy shoals and (IV) open marine environment and discussed as follows.

6.2.1. Facies Association I (Tidal Flat system)

Carbonate tidal flat occur in settings, which are protected from open ocean waves by wide shelf lagoons, which dampening the incoming waves by its position behind barrier land that separate back shoal lagoons from open ocean (Walker, 1992; Reading, 1996). These tidal flat are partly sea and partly land, which are flooded during high tides and are exposed during low tides that is why they contains clastic and carbonate layers alternatively as observed in the study carbonate rock unit. This facies association contains two microfacies as follows:

6.2.1.1. Bioclastic Dolomudstone (MFT 5)

This microfacies is rare in the studied section, which recorded only at the upper part of the section from sample ML-02.It contains the shell fragment of bivalve, which affected by neomorphism (the aragonitic bivalve shell replaced by calcite).

According to Amthor&Friedman, 1991, the very fine crystalline dolomite crystal restricts to peritidal depositional environment. The fine crystal size represents a result of early dolomitization of precursor on peritidal lime mudstone or neomorphism of a pen contemporaneous or early diagenetic dolomite (Zenger, 1983; Amthor&Friedman, 1991). However, the dolomite is not indicating their depositional facies, which indicate diagenetic facies. But, due to presence of the fine grain size, presence of quartz grains, fenestral fabric & vertical changes suggest that deposition occurred in a low-energy, restricted intertidal & supratidal environment (Wilson & Evans, 2002). Therefore, this microfacies is deposited in shallow subtidal to lower intertidal environments, which is corresponding to SMF-23 of Wilson (1975) and Flugel (2010) of facies belt 8.

6.1.1.2. Un fossiliferous Mudstone (MFT 6)

This type of microfacies occur at the upper part of the section from sample ML-2-13 and ML-2-8. The micrite content is high (98%-99%), which is porous, fractured and bioturbated.

The un fossiliferous Mudstone microfacies has been deposited in a low-energy, poorly fossiliferous environments, which are common in shallow restricted intertidal areas of clam conditions which have no water circulation (Flugel,1982) that reduce the normal wave or current energy on shallow marine carbonate shelf. The relative absence of microfauna strongly advocates deposition in nearshore domain at water depth less than 5m, where a nearshore ebb and tide condition is common. This microfacies correspond to facies SMF-23 of Wilson (1975) and Flugel (2010).

6.2.2. Facies Association II (Lagoonal facies)

Lagoons form along carbonate coastlines, where a beach barrier wholly or partly encloses an area of shallow water, which have very limited connection to the open ocean. Seawater reaches a lagoon directly through a channel to the sea or via seepage through a barrier (Nichols, 2009).

6.2.2.1. Peloidal –Bioclastic Wackestone/Packstone (MFT 4)

Obtained at the middle part of the studied section from sample ML-3. Which also contains the bivalve bioclast and small amount of intraclast.

Abundance of peloids and green algae in micrite with low diversity of fossils indicates deposition in restricted shallow subtidal (lagoonal) water as well as a slow sedimentation rate (Wilson, 1975; Flügel, 2010). The facies is compatible with the SMF 12 and RMF20 of Flügel (2010).

Well-rounded and show weak to moderate sorting. This facies is ascribed to a restricted environment of platform interior on the basis of these characteristics.

6.2.2.2. Facies Association III (high energy shoal)

The high energy shoal environment represents the platform margin that separates the open marine from a restricted lagoon (Burchette and Wright, 1992). In the studied section this facies association includes **five** microfacies types; Bioclast-intraclast-Wackstone /Packstone microfacies (MFT 7), Bioclastic Packstone/Grainstone (MFT 3), Oolitic –Packstone/grainstone (MFT 1), Bioclastic-Peloidal –oolitic -grainstone (MFT 11) and Coral framestone microfacies (MFT 10).

6.2.2.3. Bioclastic-Intraclast-Wackstone /Packstone Microfacies (MFT 7)

This Microfacies is composed mainly of micritic intraclasts. Obtained From sample ML-1, ML-E1, ML-1-1, ML-2-9, ML-2-11 and ML-A3. The skeletal components of this microfacies are mostly benthic foraminifera and reworked bivalve shell fragments. The binding material is sparry calcite cement.

Intraclastic grainstones are interpreted as having been deposited by storm-wave erosion and reworking of various sediment types in shallow-marine environments (Flügel, 2004).

The presence of intraclasts and the grain-supported fabric indicates high energy condition. Thus, this facies was deposited in high energy shoal environment with open circulation in the presence of benthic foraminifera and other bivalve shell fragments.

6.2.2.4. Bioclastic Packstone/Grainstone (MFT 3)

This microfacies occurs at the middle part of the studied section with sample ML-1-9, ML-2-2, ML-2-5, ML-2-7, ML-F8, ML-1-3 and ML-SC-4. This microfacies composed of large Bivalve shell, and echinoid plate allochems. Those allochems are cemented by micrite cement and most of them have been micritized marginally to completely (Figure 5.3).

The coarse bioclasts indicate comparatively high-energy conditions of a shoal at the platform margin (Flügel, 2010).

6.2.2.5. Oolitic –Packstone/Grainstone (MFT 1)

This micro facies occurs at the middle and the upper part of the studied section from sample ML-II, ML-III and ML-A2.The allochems in this microfacies characterized by moderately to well sorted ooid grains and bioclast of bivalve, echinoid and dominantly miliolid group foraminiferas (Figure 5.1) the ooid and bioclastic grain cemented by coarse sparite cement. The ooid allochems have been micritized and the nucleus have been filled by miliolid and other group of foraminifera fossil.

The presence of fossils within ooids indicates short-term stable conditions in the time of ooids growth (Flugel, 2004).Good sorting and roundness indicate that the depositional setting of this facies was the center of high-energy shoal of the platform interior. The abundance of ooids, lack of micrite and presence of well-sorted allochems are indicative of a high-energy shoal environment above fair weather wave base (FWWB) (Burchette and Wright, 1992).This Facies is similar to the SMF 15 (carbonate sand shoals and banks) of Flügel (2010).

6.2.2.6. Bioclastic-Peloidal –Oolitic -Grainstone (MFT 11)

This microfacies is characterized by a high abundance of micritized small Peloids (71%), which has good sorting and ooids (20%). From sample ML-E2.Subordinate intraclasts and bioclasts are also present in this microfacies. Bioclasts of this microfacies composed of foraminifera but dominated by miliolid group and Mollusca.

The high degree of sorting and rounding suggests constant, high energy conditions above fair-weather wave base, for the upper shoreface environment. This microfacies is compared with SMF Type 15 of Wilson (1975), correspond to facies belt 6, which is deposited in moderate circulation conditions and efficiency of winnowing by wave current.

6.2.2.7. Coral Framestone Microfacies (MFT 10)

This microfacies recorded at the middle part of the studied section from sample ML-F20.It contains bivalve and coral bioclast. However, dominated by coral fossils and the remaining part is micrite (70%).

6.2.4. Facies Association IV (open marine system)

6.2.4.1 Bioclastic Mudstone/Wackstone (MFT 8)

This microfacies recorded from sample ML-1-7, ML-1-5, ML-E1, and ML-2-3.This micro facies is composed of variable amounts of microbioclasts including bivalves, and miliolid fragments.

It is characterized by bioclast fragments and a mud dominate fabric indicating that this facies was deposited in low-energy conditions of platform interior setting. Abundant, high-diversity, and well-preserved fossils set in micrite indicate relatively deep and low-energy open platform environments with efficient current circulation (Flügel, 2010).

The fragmented bivalve and micritized bioclast indicate SMF type 9 of shallow water with open circulation close to wave base. Therefore, this facies is comparable with the FZ-3 facies of Wilson (1975), which is deposited in open platform or open sea shelf.

6.2.4.2. Bioclastic Spiculite-Wackstone /Packstone (MFT 9)

This microfacies recorded from the middle part of the section from sample ML-2-6 and ML-SC-5. The main distinctive feature of this facies is the abundance of sponge spicules in a micrite-dominated matrix with some gastropod shell, brachiopod, echinoid plate, bivalve, miliolid Bioclasts. Diagenetically Stylolite structure and fracture have been observed.

The Presence of abundant sponge spicule and Miliolid foraminifera with abundant homogenous micrite and overlain by skeletal sandy limestone and underlain by coral framestone indicates the Bioclastic Spiculite Wackstone is interpreted to have deposited in the proximal open marine environment below fair weather wave base near to normal storm wave with normal circulation. This microfacies is corresponding with FZ3 facies zone of Flugel (1982) and Wilson (1975), which indicate proximal open marine environment with open circulation.

6.2.4.3. Bioclastic Mudstone (MFT 2)

This microfacies occurs at the upper part of the section with sample ML-1-2, ML-2-4, ML-2-12, ML-2-14, and ML-2-15, ML-SC-3, ML-I. It occurs dominantly in the studied section. Bioclast is composed of diverse types of fossils. However, it is dominated by unidentified foraminifera, echinoid, Brachiopod and bivalve shell. This microfacies has high amount of micrite (90%-92%) and dominated by stylolite structure and moderately it has been fractured and bioturbated.

Calcareous mud in warm water setting comes from the breakdown of calcareous algae, in organic precipitations from sea water and from disintegration of large skeletal particles into their smallest unit. These mudstones accumulated in quite water areas that are not affected by tidal or strong oceanic currents (Tucker & Wright, 1990). This facies is compared with SMF type 8 of facies belt 3 of Wilson (1975), which is deposited in open marine shelf, with open circulation and low energy water below normal wave base.

6.7. Facies model for the Carbonate Unit of the Mertule Mariam Section

From the work of Ahr (1973) ramp environment was recognized as a major type of depositional setting for carbonate rock unit and was used as an alternative to the carbonate shelf. A carbonate ramp is a gently sloping surface with a slope of less than 1degree from near costal land extends up to basin. Ramp slope gently range from intertidal to basinal depths, with no major change in gradient. On a ramp environment, the shallow water carbonate units pass gradually to offshore into deeper and deeper water then into basinal sediments. Therefore, on the basis of detailed sedimentological and paleontological information, the vertical and lateral distribution of the facies types, and comparison with similar modern facies, the carbonate successions indicate deposition in a shallow marine setting.

Depositional models are summaries of sedimentary environments or systems. Depositional models provide a guide for future observations, evaluate the validity of existing concepts (Walker, 1979; Miall, 1999). The Model created from simulation, theory, and the simplification of multiple observations from the study area. Wave base and storm wave base, high and low tide are used as basic boundaries in the classification of the major shallow-marine environments (Flugel, 2010).

6.7.1. Inner ramp

It is the zone above FWWB dominated by sand shoals or organic barriers and shoreface deposits and back barrier peritidal areas (Burchett and wright, 1990). Ramps with mesotidal regimes will show a mixture of beach barrier, tidal inlet, lagoon and tidal flat deposition. Hence, agitation of carbonate sediment in shallow nearshore water results in a shoreface facies of carbonate sand bodies with skeletal debris and ooids formed in the shallow water forms bioclast and oolitic carbonate sand shoals is characteristics of this inner ramp environment. From the Mertule Mariam section carbonate unit, the oolitic Packstone/Grainstone, Bioclastic-Peloidal –Oolitic –Grainstone, Bioclastic-Intraclast-Wackstone /Packstone, Bioclastic Dolomudstone have been deposited in this environment.

6.7.2. Mid ramp

It is the zone between FWWB and SWB where the sea floor is affected by storm wave but not by fair weather wave. Sediments show evidence of frequent storm reworking (Burchett and wright, 1990). The bioclastic Wackstone and Bioclastic spiculite-Wackstone /Packstone have been deposited in this environment.

6.7.3. Outer ramp

This zone extends from the depth limit to which the most storm influence the seafloor to the basin plain (Burchett and wright, 1990). Deeper parts of the ramps characterized predominantly by low energy setting. The bioclastic mudstone and some marl unit are the main facies type of outer ramp environment. Generally the overall facies associations of carbonate deposits of the area are showing a low gradient of depositional dip from inner-ramp domains (tidal flat, lagoon and shoreline high-energy shoals deposits) to mid-outer ramp areas of fore shoal to offshore low energy deposits. From this the vertical nature of these microfacies suggests cyclic deposition.

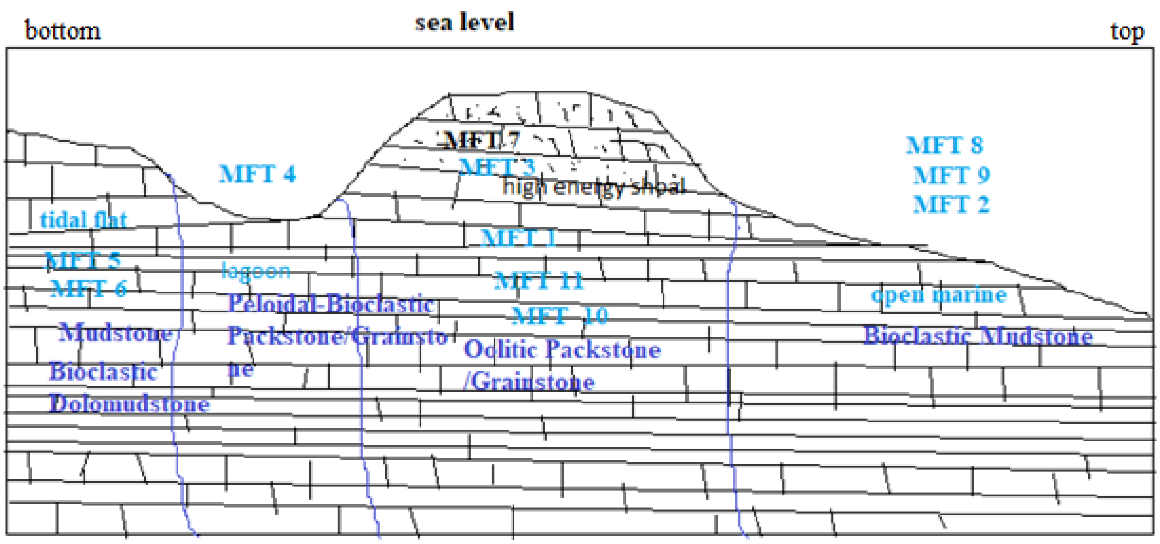

Figure 6.1.Schematic diagram showing the depositional model of the Mertule Mariam Section

6.8. Biostratigraphy and The Age of the Mertule Mariam Section Carbonate Unit

One of the most important practical applications of micropaleontology is the use of microfossils in biostratigraphy. Furthermore, because the same species will never re-evolve at a later time, all rocks containing a given species can be assumed to have been deposited during the time that species was extant (alive), no matter where those rocks are found. . A species evolves once, survives for a time, and then becomes extinct. A rock containing that fossil species is assumed to have been deposited during the interval of geologic time between the origination and extinction of that species. By ranking the order of appearance of different species through time, it is possible to subdivide geologic time biostratigraphically. Microfossils are excellent for biostratigraphy and correlation. This is because microfossils are very abundant (being so small, there are many specimens per rock sample), they had a high rate of evolution (many speciation events, so many potential biostratigraphic zones), and they often had very wide geographic distributions.

The biostratigraphy of the studied section is mainly based on microfossils (foraminifers' fossils). Due to the presence of index foraminifera fossils like Pfenderina sp., Kurnubia palastiniensis, Alveosepta jaccardi the age of the carbonate unit in the Mertule Mariam section ranges from Callovian to Early kimmerdigian.

Pfenderina sp. found in the lower part of the section from sample ML-2-1.

The foraminifers *Nautiloculina oolithica* and *Kurnubia palastiniensis* suggests a late Callovian/early Oxfordian age (Keissling et al., 2011), both Kurnubia palastiniensis and Nautiloculina oolithica obtained from sample ML-1-5. *Alveosepta jaccardi*, index foraminifera fossil occurs at the upper part of the Mertule Mariam section from sample ML-SC-5 and ML-1-7 and based on the work of Bassoullet, 1997; Bucur and Sasaran, 2005 *Alveosepta jaccardi indicates* an age of Late Oxfordian to Early Kimmeridgian. According to Russo et al., 1994, the carbonate unit in the Blue Nile basin dated as Callovian to Kimmerdigian which is equivalent to the Mertule mariam section on Lithostratigraphy and chronostratigraphy.

6. 9.Correlation of the Mertule Mariam section Carbonate Unit

6.9.1. Intrabasinal Correlation

Callovian to early kimmerdigian carbonate units which have 330m thickness has been studied in the Mertule Mariam section. It is grouped into eleven microfacies types based on petrographical and paleontological study.

The 550m thick limestone unit is exposed in both Gundo Meskel and Ejere sections. Lithologicaly the bottom part is clean, white, sometimes dull-white to light yellow, detrital, occasionally oolitic, fine grained, dense, rarely fractured, thickly bedded (up to 3 meters), rarely stylolitic, becoming more yellowish with thin fossiliferous and calcareous shale beds near its top. Its age is assumed to be upper Jurassic. These two sections are also correlable with middle-upper part of the Mertule Mariam section based on the facies type.

The Jema section is dominated with light gray micritic limestone in color and fine grained texture at the middle part. The upper part of the micritic unit is dominated by bioclast .Consequently, the carbonate unit of the Jema section is correlable with the lower-middle part of the Mertule Mariam section. The carbonate unit of the Mugher is also correlable with the studied section.

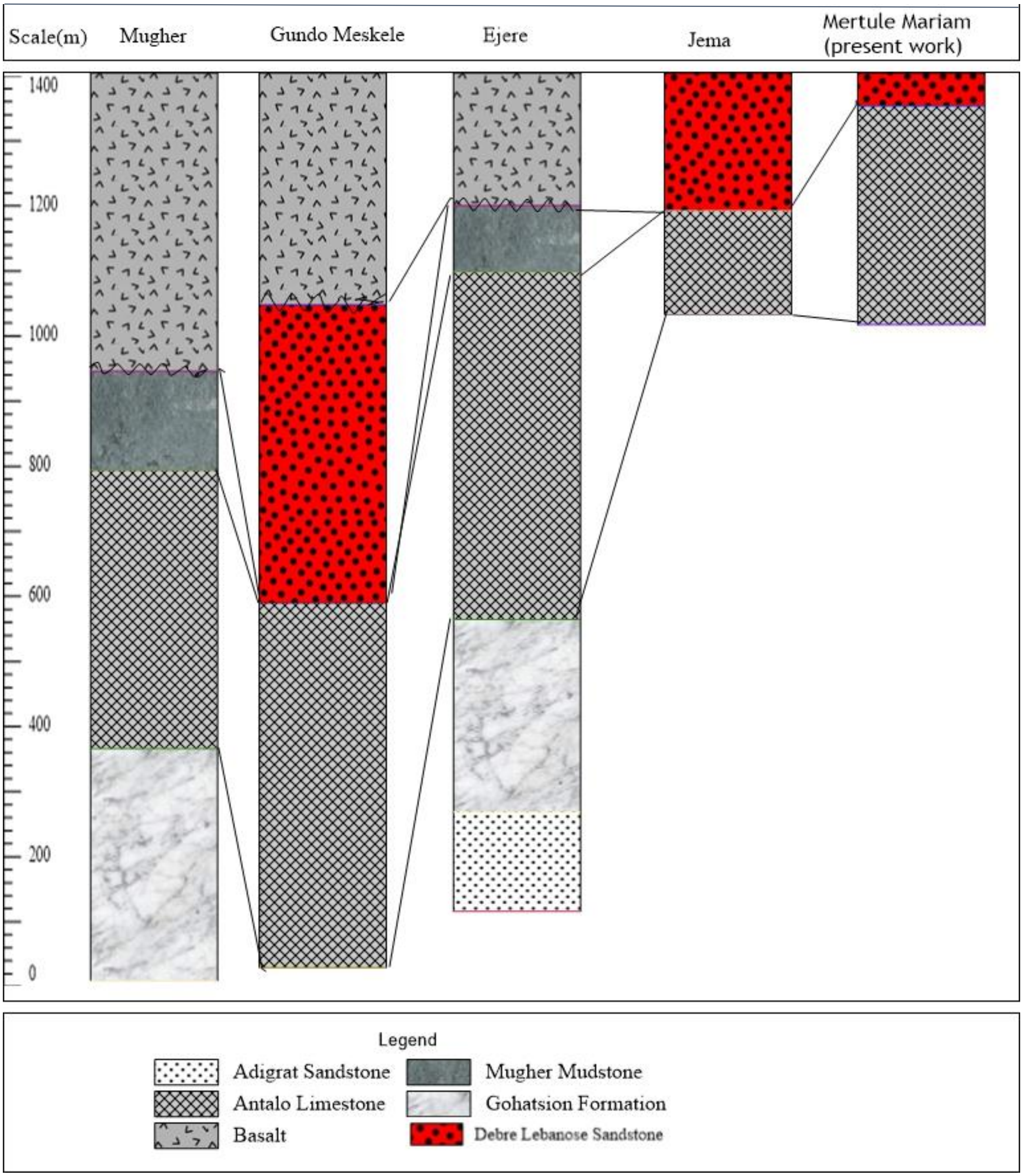

Figure 6.2. Intrabasinal correlation of the limestone at different sections.(Mugher, Gundo Meskel, Ejere and Jema) with the studied section within the Blue Nile Basin. Source: Mugher (Getaneh, 1981), Gundo Meskel, Ejere (Ministry of mine and energy, 1996), Jema section (Geremu Gecho, 2018, un published) and Mertule Mariam section (present work).

6.9.2. Regional correlation of the Carbonate Unit

Early Jurassic-Oxfordian time is a major transgression, probably related to the subsidence phase and a major sea level high stand occurred all over East Africa with the drowning of the craton and documented by the carbonate deposits in different basins (Bosellini, 1989; Russo et al. 1994). Hence, the Upper Jurassic (Oxfordian-Kimmeridgian) carbonate succession throughout the East African margin and the Arabian platform is characterized by the development of numerous carbonate and evaporate unit with boundaries reflecting regional shift in tectonic regions. Among these, carbonate deposits in Ethiopia can be best examples.

Extensive carbonate deposits are exposed in Ethiopia particularly in three regions: the Mekele outlier in northern Ethiopia, the Blue Nile basin in central Ethiopia and the Ogaden Basin in the southeast Ethiopia and the carbonate unit in those areas are correlated.

The carbonate unit of the **Blue Nile Basin** , up to 420 m thick carbonate successions of shallow marine origin, also named 'Antalo Limestone Formation' are described by Russo et al. (1994) ,which conformably overlying the Gohatsion Formation and can be divided into three parts (lower, middle and upper limestone).

The lower part (180 m thick) is composed of burrowed mudstones that grade upwards into oolitic and coquinoid limestone rich in corals, stromatoporoids, bivalve, gastropods, benthic foraminifera with or without intercalated marl beds and then into massive shallow water environment (Russo et al., 1994).

The middle part (200 m thick) consists of highly fossiliferous interbedding of marly limestone and marls. Presence of ammonite fauna (e.g., *Lithacoceras* sp. and *Subplanites spathi*) in association with brachiopods (e.g., *Terebratula pelagica and Nanogyra*) and other infaunal siphone feeders (*Anisocardia*, *Venilicardia*, *Somalirhynchia somalica*, *and Zeillleria latifrons*) suggests a shelf to open marine environment (Russo et al., 1994).

The upper part (50 m thick) comprises planar laminated oolitic and reefal limestone, which was interpreted to indicate the return of shallow water conditions. Based on presence of oolitic bars, coral patches, offshore and more protected facies inshore, this unit is interpreted to represent a shallow water environment similar to the lower unit. Presence of *Pfenderina* sp. and *Nautiloculina oolithica* at the base of the limestone unit used to assign a Callovian age (Russo et al., 1994) and presence of *Kurnubia palestiniensis*, *Parurgonina caelinensis*, *Conikurnubia* sp. and

Salpingoporella annulata at the top of the unit indicates a Kimmeridgian age (Turi et al., 1990, Atnafu, 1991, 2003, Russo et al., 1994).

Therefore, due to the presence of oolitic and coquinoid limestone rich in corals, stromatoporoids, gastropods, bivalve and benthic foraminifera of *Nautiloculina oolithica* the lower part of the Blue Nile carbonate rock unit is considered to be correlative with the lower part of the study section of the Mertule Mariam section carbonate unit. Additionally, due to the presence of predominant index fossil of benthic foraminifera of the *Nautiloculina oolithica* and *Kurnubia palestiniensis* the carbonate unit of the Blue Nile basin is correlative with the middle-upper part of the study area.

The Carbonate unit of the **Mekele Basin**, 700m thick Antalo super sequence which overlies the transitional unit, is a carbonate-marly succession of Late Oxfordian–Early Kimmeridgian age (based on foraminiferal fauna) and is equivalent to the Upper Limestone unit of the Blue Nile Basin (Bosellini et al. 1997). Based on the work of Beyth (1972a, b) the carbonate unit of the Mekele basin contains four facies types. Those are (i) a cross-bedded sandy oolitic and coquina with minor amount of marl and a few chert beds, with microfauna including mainly corals, gastropods, and echinoids, (ii) interbedding of marl and lithographic limestone with abundant brachiopods and some algal and chert beds, (iii) cliffs of coral and algal reef limestone‘s interbedded with marl and biostromes, and (iv) black to grey microcrystalline limestone interbedded with marl.

Bosellini et al. (1997) attempted to subdivided the same limestone unit into four depositional sequences, which are composed of thickening and shallowing up cycles and also he noted that the limestone succession was deposited in a homoclinal ramp or on a wide cratonic margin gently dipping to the southeast and they assigned the age of the Antalo limestone to be Late Callovian to Kimmeridgian age.

In the **Ogaden basin**, southeastern Ethiopia from the works of (Abbate et al., 1974; Worku and Astin, 1992; Hunegnaw, 1998), the Urandab Formation corresponds to the maximum flooding sequence deposited during the break-up Gondwanaland (Callovian- Oxfordian) and is composed of dark, laminated marls and limestone containing a pelagic marine fauna.

Therefore, the Urandab Formation of the Ogaden basin is correlable with the carbonate rock unit of the study area biostratigraphically and lithostratigraphically.

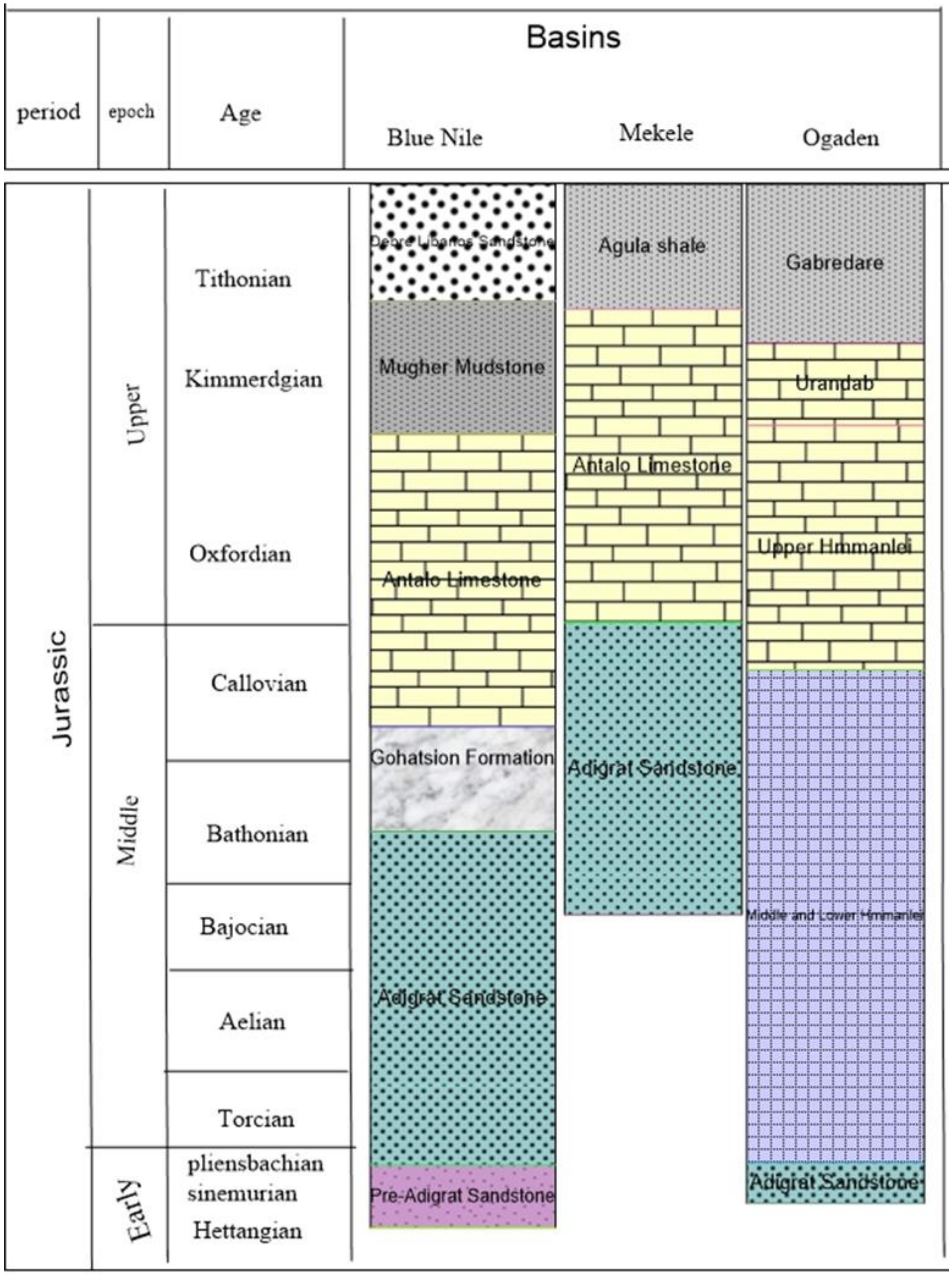

Figure 6.3. Regional correlation of the Carbonate unit throughout Ethiopian basins (Blue Nile, Mekele and Ogaden).source Blue Nile Basin (the present study and Russo et al., 1994), Mekele Basin (Levitte, 1970 and Bosselini et al., 1997) and Ogaden Basin (Abate et al, 1974 and Hunegnaw, 1998).

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The study area is situated in central Ethiopia, Blue Nile basin locally in the Mertule Mariam section. The facies and paleoenvironmental study on the study section provides the first detail understanding of the carbonate units in the Mertule Mariam Section. The most important results achieved from this study are the following:

-Based on a detailed field investigation and laboratory description and analysis of 34 thin sections and 17 productive dry marl sediments, 11 microfacies types have been recognized. These microfacies are grouped in four facies associations including tidal flat facies, high energy shoal facies, lagoonal facies, and open marine facies.

-Various macro and microfossils have been identified from the carbonate unit of the Mertule Mariam section. From these foraminifera fossils including *Lenticulina quenstedti* Gümbel, 1862, *Lenticulina subalata* Reuss, 1854, *Verneuilinoides minuta*, Said and Barakat, 1958, *Kurnubia palastiniensis* Henson, 1948, Nautiloculina oolithica Mohler. 1938, *Lenticulina varians* Bornemann (1854), and *Elphidium sp.*and ostracodes of *Cytherella sp., Cytherella cf. ventroconcava* Neale and Singh, 1985 *paracypris sp. ,Darwinula sp., and Cypridea sp.*Bosquet, 1852 and invertebrate macrofossils of Bivalve including *Pholadomya (Bucardiomya) somaliness* Sowerby, 1823 and *Nanogyra nana* Sowrbey, 1822,Brachiopod *Terebratula ventricosa* Hartmann, Somalirhynchia africana Weir, 1925 and *Bihenithyris mediocostata* Cooper, 1989 and Gastropod Genus pseudomelania pictet and campiche, 1862 is recognized.

-The age of the carbonate unit in the Mertule Mariam section is determined and dated to be Jurassic. Particularly Callovian to early kimmerdigian due to the presence of the following index fossils; *pfenderina sp*., Kurnubia *palastiniensis* and *Alveosepta jaccardi.*

-based on the data generated from field and petrographic studies, indicates that the carbonate units were deposited in shallow marine environment, which includes the shallow inner ramp of near coast tidal environment, restricted lagoonal , high energy shoal, and proximal mid to outer ramp open marine environment.

-The carbonate unit of the studied section is correlative with previously studied units in the Blue Nile Basin and regionally equivalent with units in the Ogaden Basin and the Mekele Basin biostratigraphically and lithostratigraphically.

7.2. Recommendation

Better understanding of the microfacies analysis and Paleoenvironment of the carbonate units could be achieved with:

-More detailed micropaleontology and biostratigraphy studies inorder to better understanding of stratigraphy and Paleoenvironment.

-More detailed sampling (higher number of samples) for petrographic study and microfossil identification.

-Sampling and analysis of more sections inorder to know the lateral continuity of the carbonate unit.

-Strengthen this study in the Mekane Selam section inorder to obtain complete picture of the depositional model.

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Appendix I petrographic description of Carbonate rock sample collected from Mertule Mariam section

Sample code	Major components (%)						Rock Name		SMFTs
	Allochems				cements		Dunham	Folk	
	ooid	peloid	Bioclast	intraclast	Sparite	micrite			
ML-1			67	25	8		Packstone	Biosparite	SMFT 10
ML-3	-	80	5	-	15	-	Packstone	Biopelsparite	SMFT 12
ML-A2	84	-	4	-	12	-	grainstone	Biooosparite	SMFT 15
ML-A3	75	-	3	10	12	-	Packstone	Biooosparite	SMFT 10
ML-I	-	-	5	-	-	95	Mudstone	Biomicrite	SMFT 3
ML-II	96	-	-	-	4	-	Grainstone	oosprite	SMFT 15
ML-III	83	-	15	-	12	-	Packstone	Biooosparite	SMFT 15
ML-E1	-	-	20	-		80	Wackstone	Biomicrite	SMFT 10
ML-E2	-	91	4	-		5	grainstone	Biopelsparite	SMFT 15
ML-F20	-	-	30	-	-	70	Packstone	Biomicrite	SMF 7
ML-F8	-	-	85	10	-	5	Packstone	Biomicrite	SMFT 5
ML-SC-5	-	-	25	-	-	75	Packstone	Biomicrite	SMFT 8
ML-SC-4	-	-	15	-	-	80	Wackstone	Biomicrite	SMFT 5

ML-SC-3			10		5	85	Mudstone/ Wackstone	Biomicrite	SMFT 8
ML-1-1			10	10		85	Wackstone	Biomicrite	SMFT 10
ML-1-2			8			92	Mudstone	Biomicrite	SMFT 8
ML-1-3			55			45	Bioclastic Packstone	Biomicrite	SMFT 5
ML-1-5			15			85	Mudstone/ Wackstone	Biomicrite	SMF 9
ML-1-7			12			88	Mudstone Wackstone	Biomicrite	SMF 9
ML-1-9	55		20	15	10		Packstone/ grainstone	Biooosparite	SMFT 5
ML-2-2	-	-	80	-	-	20	Packstone	micritic	SMFT 5
ML-2-3			15			85	Mudstone/ Wackstone	Biomicrite	SMFT 9
ML-2-4			10	-	-	90	Mudstone	Biomicrite	SMFT 8
ML-2-5			60	30	10	-	Packstone/ grainstone	Biosparite	SMFT 5
ML-2-6			64			34	Bioclastic Packstone	Biomicrite	SMFT 8
ML-2-7			60		40		Packstone	Biomicrite	SMFT 5
ML-2-8			2			98	Mudstone	Micritic	SMFT 23
ML-2-9			40	10	-	50	Packstone	Biomicrite	SMFT 10
Ml-2-11	20		10	65	5		Packstone	Biooosparite	SMFT 10

ML-2-12	-	-	1	-	-	99	Mudstone	Biomicrite	SMFT 8
ML-2-13						100	Mudstone	Micritic	SMFT 23
ML-2-14			5			95	Mudstone	Biomicrite	SMFT 8
ML-2-15	-	-	10	-	-	90	Mudstone	Biomicrite	SMFT 8
ML-02	-	-	4	-	-	96	Mudstone	Biomicrite	SMFT 23

years	Months												Average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	0			49.4	25.9								25.1
1993			35.1	205.3	53.3	98.3	192.2	97.5			10.4	0	86.5125
1994		21.9		44.5	43.9	69.4	276.4	238.1	74.2	8.1	19	0	79.55
1995	0	26.4	58	108.7	98.6	18.7	320.1	226.1	55.4	0.4	0	24.5	78.075
1996	32.8	1.6	63.8	102.6	83.1	135	243.6	194.5	78.2	0.2	23.3	6.5	80.4333333
1997	48.9	2.2	62.5	73.9	49.4	94.7	164.7	137.9	43	110.2	100.2	17	75.3833333
1998	23.2	3.7	102.8	48	70.2	70.9	319	264.7	123.7	118.1	19.3	0	96.9666667
1999		0	2.4	63.9	24	33.1	265.1	220.2	80.7	90.1		9.8	78.93
2000	0	0	12.5	127.8	43.8	84.1	286.1	185	111.3	74.7	36.5	9	80.9
2001	0.4	27.3	133.9	55.1	58.4	104.8	319.2	168.7	45.2	62.2	0.9	20.8	83.075
2002	55.3	14.8	60.3	38.6	41.5	57.1	276.6	212.5	91	0	7.1	28.1	73.575
2003	15.2	47.1	77.8	55	8.8	80.2	245.1	150.6		0	4	9.3	63.0090909
2004	0.8	0.9	29.4	44.6	21.3	95.9	184.2	181.5	51.7	41	3.4	0	54.5583333
2005	12.2	0	61	55.2	86.3	60.2	207.1	150.9	122.4	32.9	5	0	66.1
2006	3	0	60.5	67.5	86.7	221.6	230.8	251.5	115	40.6	21.1	18.1	93.0333333
2007	4.4	66.9	71.2	58.1	79.8	223.8	241.4	151.6	108.5	14.1	0	0	84.9833333
2008	19.6	0	0.4	32.5	62.6	100.6	278.4	210.3	90.9	147.7	80.3	0.4	85.3083333
2009	7	7.1	71.8	21.6	11.1	32.4	266.2	203.8	26.2	71	10	38	63.85
2010	14.3	9.7	35.8	111.9	54.3	56.8		253.7	85.9	1.5	10.5	4.6	58.0909091
2011	40.7	0	177	51.8	60	104.3	200.1	216.7	114.8	0	37.7	0	83.5916667
2012	0	0	74.1					224.6	95	6.2	0	2.1	50.25
2013	20.9	2.8	26.9	36.9	33.8	123.7	452.9	418.4	102.5	84.4	17.4	0	110.05
2014		54.6	35.3	72	121.6	60.6	186.6	230.2	143.6	19.5	9.8	0	84.8909091

2015	0.2	4.1	37.1	12.7	138.9	48.9	0.2	240.7	79.6	16			57.84
2016	10.8	6.2	0	101	154.5	122.7	176.3	228.8	80.7	8.5	0	0	74.125
2017	0	23.6	71.8	33.7	165.8	37.2							55.35
2018	0	20.5	7.6	69.9	40.6	209.1	254		32.3				79.25
Average	13.46522	13.656	54.76	67.00769	66.08462	93.764	242.8826	210.7708	84.86087	41.1913	18.90455	8.182609	

Appendix II mean monthly rainfall (mm) at Mekane Selam station

Appendix III Mean monthly temperature (o_c) of Mekane Selam station

year	Months												Average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	0	0	0	12.8	13.8	13.7	10.8	10.2	10.5	10.2	9.7	10.4	8.50833333
1993	0	0	11.9	11	10	9	9.7	10.1	0	0	10.4	9.8	6.825
1994	0	8.4	8.2	8.6	8.1	9	10.1	9.9	10.1	10.1	0	0	6.875
1995	0	8.3	7.9	8.1	8.5	9.1	7.4	7.5	8.1	8.3	8.7	8.7	7.55
1996	0	9.9	8.8	8.8	8.8	9.7	9.2	9.1	9.6	9	8.8	9.4	8.425
1997	10	9.8	10.7	10.7	11.1	11.3	10.9	11	12.1	11.2	11	11.2	10.9166667
1998	12	12.7	13.1	13.9	14	12.6	10.9	11.4	11.2	10.9	9.3	9.9	11.825
1999	10.6	12	12.6	13	12.7	12.4	10.2	10.5	11.3	10.6	9.2	10.2	11.275

2000	10.6	11.6	12.7	11.5	13	11.8	10.4	10.5	11	10.5	10.1	10.5	11.1833333
2001	10.8	12.1	11.8	12.8	13	11.4	10.5	11.2	11.1	10.9	10.1	10.8	11.375
2002	11	12.5	12.6	12.6	14.2	12.6	11.5	10.9	11.2	11	10.8	11.2	11.8416667
2003	11.7	12.9	12.4	12.8	14.3	12.3	11	11.3	0	10.5	10.9	10.7	10.9
2004	12.6	11.7	12.1	12.8	13.8	12.1	10.7	10.9	11.2	10.1	10.6	11.5	11.675
2005	11.1	13.4	13	13.4	12.5	12.5	10.9	11.1	10.9	10.4	9.9	10.1	11.6
2006	11.8	12.6	12.5	12.4	13	12.2	10.9	11	11.3	11.4	10.9	11	11.75
2007	11.7	12.4	12.7	12.6	13.4	11.7	11	10.9	10.8	10	10.2	9.8	11.4333333
2008	11.3	11.5	12.9	12.3	12.7	11.7	10.6	10.9	11.1	10.7	10.3	10.9	11.4083333
2009	11.7	12.4	12.8	12.7	11.3	11.3	8.4	8.7	9.2	8.3	8	8.8	10.3
2010	8.8	10.5	9.8	9.8	10.7	10.7	0	9.3	9.8	10	9.8	10.4	9.13333333
2011	10.9	11.2	11.7	12.4	12.4	12.2	10.9	11.3	11.2	10.8	11	10.5	11.375
2012	11.3	11.9	12.5	0	0	0	0	10.8	11	10.4	11.4	11	7.525
2013	12	13.1	13.7	13.5	13.9	12.4	10.8	11.1	11.6	10.7	10.9	10.3	12
2014	12.2	12.5	12.9	13	13	13.1	11.9	10.9	11.4	11	10.7	10.5	11.925

2015	10.9	12.9	12.6	13.5	13.5	13	12.1	11.6	11.7	0	0	0	9.31666667
2016	12.6	13.2	14.6	15.8	12.9	13	11.7	11.5	12	11.3	10.5	9.9	12.4166667
2017	10.3	12.3	12.8	13.2	12.8	13.2	0	0	0	0	0	0	6.21666667
2018	11.3	12.4	12.5	13.1	13.5	12	11.2	11.2	11.6	11.1	10.6	11.2	11.8083333
average	9.155556	10.8963	11.54815	11.74444	11.88519	11.33333	9.396296	10.17778	9.666667	9.237037	9.02963	9.211111	

Appendix IV Mean monthly rainfall (mm) of Mertule Mariam station

years	Months											Average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992							**429.5**	**581.5**	**226**	**426.5**	**12**	**0**	**279.25**
1993	0	20.5	161	197									94.625
1994						182.4	460	207.5	114.9			0	192.96
1995	0	2.3	60	111.9	58.9	97.2	269.6	234.2	43.2	13.1	3.8	26.9	76.75833
1996					137.3	51		233.5	70.9	4	40.6		89.55
1997		0	62.9	65.3	33.9	201.3		205.6	78.5	136.8	37	0	82.13
1998		0	4.1	9.5	93.8	148.8	447.3	216.2	67.3	60.4	0	0	95.21818
1999	27.7												27.7
2000	0	0	0	118		62.1	189.9	183.4	53.6	77.9	14.8	11.1	64.61818
2001	0	27.5	78.3	18.5	51.8	181.3	267.6	224	89.6	50.5	0	0	82.425
2002	17.5	0	36.7	73.1	0	59.4	43.8	157	44.6	0	0	0	36.00833

2003	0	0	17.2	15.6	16.9	85	294.4	229.2	115.4	9.5	20	32.7	69.65833
2004	0	3.3	16.3	51.4	40.6	150.1	236.7	152.7	78.2	79.8	1.7	0.4	67.6
2005	36.5				64.7	73.6	297.1	172	130.6	52.9	14.8	0	93.57778
2006	6.5	5.9	76.4	112.8	39	97.3	235.9	378.3	89.4	35.4	40.9	31.1	95.74167
2007	13.4	37.1	29.1	64.8	75.1	132.3	335.6	141.1	181.9	18.2	0	0	85.71667
2008		0	1.5	8.5	115.5	107.2	332	176.2	58.1	65.3	8.8	3.7	79.70909
2009	4.1	14.3	70.1	42.1	40.4	58.8	234.6	269.9	52.4	150.2	11.6	6.3	79.56667
2010	18.6	3.4	54.4	79.3	62	64.6	269.6	293.5	102.2	22.4	26.1	16.7	84.4
2011		0	66.6	48.5	96.2	119	249.9	209.9	176.4	7.7	65.7	0	94.53636
2012	0	0	67.6	36.5	13.7								23.56
2014				62.2	184.9	54.5	169.1	255.8	149.7	26.4	32.4	14.1	105.4556
2015	1.1	1.4	33	3.7	136	139.9	100.1	114.4	102.9	31.6	56.1	26.8	62.25
2016	2.7	6.8	41.8	78.4	177.3	85.4	290	299	109.2	54.9	0	0	95.45833
2017	0	30.2	22	53.4	90.3	71.8	215.1	196.4	104.6	23.1	22.4	0	69.10833
2018	0							254.7					127.35
average	7.11666667	8.03684211	47.3157895	62.525	76.415	105.857143	259.9105	218.3864	95.88571	46.005	19.835	8.49	

Appendix V mean monthly rainfall (mm) of (Yeduha) station

years	Months												Average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	9	47.1	18.8	96		53.7	228.6	313.8	176.2	131.4	0	23.5	99.82727273
1993		23	31.7	83.9		85.5	367.5	79.2	140.9	33.3	0	0	84.5
1994	1.4	2.4	27.3	40.6	25.2	100.3	416.5	253.6	104.7	0	4.2	0	81.35
1995	0	9.7	15.4	81.5	79.2	20.2	262.5	244.3	34.9	0.8	0	34.4	65.24166667
1996	15.2	0.4	94.4	100.4	95.5	157.5	215.2	202.3	46.2	3.6	21.5	1.4	79.46666667
1997	36.8	0		154.4	49	90.5	228	180.2	43.9	136.3	45.6		96.47
1998	1.2	12	33.4	15.8	134.5	80.2	271.5	261	122.8		2.1	0	84.95454545
1999	13.1	0	1.5	34.7		47.9	314.1	313.9	40.5	144.3	1.5	2.2	83.06363636
2000	0	0	0.9	111.5		65.2	302.8	250.1	151.9	55.2	81.1	11.2	93.62727273
2001	0	11.3	96.6	46.3	86.5	147	419	224.8	44.1	5.9	1.7	3	90.51666667
2002	23.8	21.2	17.9	23.5	6.4	71.4	270.5	168.5	67.4		0	38.4	64.45454545
2003	7.8	18.1	74.9	33.1	0		242.4	249.9	122.3	16.7	27.5	29.5	74.74545455
2004	10.5	6.8	42	52.7	41.6	113.6	175.6	189.4	65.5	32.2	0.2	4.8	61.24166667
2005	7.7	0	70.8	40.3	70.2	57.9	402.9	208.5	232.9	37	18.8	0	95.58333333
2006	2.8	2.5	59.9	84.6	56.8	103.6	397.3	330.5	101	18.7	3.4	6.3	97.28333333
2007	21.9	11.8	21.9	60.8	106	252.3	340	253.9	124.9	28.4	0.1	0	101.8333333
2008	0	0	0	43.8	69.4	132.1	287.8	269.1	103	61.7	151.2	0	93.175
2009	1.7	3.6	25.2	61.9	75.6	37.6	408.6	401.9	65.3	69.6	9.5	19.3	98.31666667

2010	13.5	28.1	38.3	125.7	168.8	42.3	326.4	346.4	49.3	0	28.5	21.1	99.03333333
2011	11.7	0	125.7	60.7	163	47.3	212.6	237.9	88.3	1.3	107.5	0	88
2012	0	0	64.1	62.1	24.8	138.1	346.9	278	141	15.1	0	4.5	89.55
2013	3.5	0	0.8	30.4	48.4	147.6	353.4	361	84.8	40.1	15	0	90.41666667
2014	0	8.2	17.5	29.7		88.6	335.6	300.2	129.9	29.8	16.7	0	86.92727273
2015	0	71.7	13.3	0	170.7	202.8	171.1	272.4	90.9	0	0	16.5	84.11666667
2016	25		16.5	73.1	205.5	131.1	510.2	333.8	48.6	36.2	0	0	125.4545455
2017	0	5.6	30.5	77.5	220.9	302	486.6	519.8	115.6	15.4		0	161.2636364
2018	0												0
average	7.94615385	11.34	37.572	62.5	90.3809524	108.652	318.984615	270.938462	97.56923077	38.04166667	21.444	8.644	

Appendix VI mean monthly temperature (oc) of shebelberenta (Yeduha) station

													average
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1992	8.8	10.3	9.5	11.2	11.4	10	7.8	8.3	9.52	8.7	7.9	10.9	9.525
1993	7.9	10.2	10.6	11.1	11.5	10.7	10	10.9	10.6	10.6	8.3	7.5	9.991667
1994	8.5	10.6	10.6	11	12	10.2	10.3	10.6	9.9	9.4	9.2	7.2	9.958333
1995	8.9	12.3	10.5	11.8	11.5	11.4	11.2	11.2	10.8	10.5	9.5	9.6	10.76667
1996	0	10.4	11.4	11.7	11.2	10.5	10.6	11.1	9.8	8.6	7.9	8	9.266667
1997	9.2	9	0	11.6	11.9	11.4	11.4	11.3	10.2	10.5	10.2	0	8.891667
1998	9.4	11	10.6	13.6	13.3	11.7	11.6	11.8	11.1	11.1	7.7	4.7	10.63333

1999	8	9.4	11	11.3	0	10.8	10.8	10.9	9.7	9.7	6.5	7.8	8.825
2000	8.7	10.2	11.8	11.2	0	10.1	11	10.2	10.4	9.8	8	6.6	9
2001	6.4	10	10.3	11.4	11.8	10.8	10.7	10.9	10.6	10.6	9	9.4	10.15833
2002	10.1	9.7	10.1	10	10.5	11.2	11.7	10.4	10.9	11.3	9.4	8.3	10.3
2003	6.7	8.5	7.1	7.7	8.1	0	0	0	0	0	0	0	3.175
2004	0	0	3.7	5.4	5.1	12.4	11.7	11.7	11.3	9.9	10.1	9.8	7.591667
2005	10.7	11.7	11.9	13.2	12.5	12	11.8	12	12	13.2	10.3	8	11.60833
2006	8.8	10	11	11.5	12.5	11.7	12.1	12	11.2	12.7	12.1	12.1	11.475
2007	12.6	12.1	12.4	12.8	13.1	11.9	12.3	12.1	12.2	12.9	12.6	11	12.33333
2008	10.8	12.3	12.3	13	13	13	11.8	11.9	12.8	12.1	12.2	11.3	12.20833
2009	11.4	11.5	12.2	12.2	12.5	12.4	11.8	12	11.7	12.1	12.2	11.8	11.98333
2010	10.9	12	13	12.9	12.9	12.1	11.2	11.7	11.2	11.5	11.2	11.1	11.80833
2011	11.2	11.5	11	12.2	12.2	11.6	11.4	11.9	11.2	11.2	10.9	9.3	11.3
2012	9.6	10.5	11.4	12	12.5	12.2	11.8	11.8	11.3	10.3	10.3	10.4	11.175
2013	11.2	11.7	13.3	12.9	12.9	12.4	12.1	11.9	11.6	11.6	11.7	11.1	12.03333
2014	12.1	12.1	11.7	12.2	0	11.1	11.4	11.3	11.5	11.1	11.9	11.8	10.68333
2015	12.3	11.8	12.1	12.1	12.1	11.6	11.1	11.2	11.2	11.7	11.5	11.6	11.69167
2016	11.4	11.5	11.7	11.5	11.4	11.4	10.8	11	11.4	11.2	10.9	11.4	11.3
2017	11.4	11.4	11.6	11.6	11.4	11	11.1	11	11.5	11.6	11.4	11.9	11.40833
2018	11.9	0	0	0	0	0	0	0	0	0	0	0	0.991667
average	9.234615	10.05385	10.12692	11.07308	9.842308	10.6	10.45	10.49231	10.23462	10.2	9.423077	8.526923	