ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

MICROPALEONTOLOGY AND FACIES ANALYSIS OF CARBONATE UNIT IN MUGHER AREA (SODOBLE STRATIGRAPHIC SECTION), NORTH WESTERN ETHIOPIA

MSc. THESIS

BY:

BERTUKAN GEBRE DETEBO

A thesis submitted to the school of Graduate Studies of Addis Ababa University in the partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences (Paleontology and Paleoenvironment)

May, 2018

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Approved by the Examining Committee

Dr. Balemwal Atnafu	------------	--------------
Head, School of Earth Sciences	Signature	Date
Dr. Balemwal Atnafu	--------------	--------------
Advisor	Signature	Date
Examiner	---------------	-------------
Dr. Mulugeta Fesseha	Signature	Date
Dr. Gilamichael Kidanemariam	----------------	--------------
Examiner	Signature	Date

May, 2018

Addis Ababa, Ethiopia

ABSTRACT

Thick layers of Jurassic carbonate unit (Antalo Formation) which were deposited in Mugher area (Sodoble section) were investigated in field and lab analysis. This study mainly aimed on exploring the micropaleontology, facies analysis, biostratigraphy and determination of the depositional environments of carbonate unit in sodoble section. Through field observation the detailed Lithostratigraphy of sodoble section carbonate successions of the area, was described and measured at three locally selected stratigraphic sections. At all these three local sections, the exposed carbonate layers are described based on their facies types and are sub-divided into three sub-units. Based on the petrographic study of 26 representative carbonate rock samples collected from the study area; the compositional and textural types of rocks were studied and grouped into seven microfacies types. Paleontological study of Sodoble section in Abay basin shows that the carbonate unit is rich in macro and microfossils. From those there are many benthic foraminifera like: Lenticulina subalata, Lenticulina quenstedti, Kurnubia palastiniensis, Nautiloculina olithica, Verneuilinoides minuta, Haplophragmoides bartensteini, Pseudocyclammina lituus and Alveosepta jaccardi are identified at species level as well as some bivalves, gastropods and brachiopods and ostracods are identified at genus level.

Based on the presence of index fossils of Pfenderina gracilis, Kurnubia palastiniensis and Alveosepta jaccardi, age of sodoble section carbonate rocks is assigned as Callovian to Kimmeridgian time. The general successive facies and facies belts of the carbonate units of Sodoble section from field investigations and microfacies analysis results shows entirely shallow marine water environment. It shows transgression from tidal environments of the inner ramp at the base with occasional interrupted episodes indicating a relatively high-energy environment to relatively low energy deep margin environments of the outer ramp at the top of the succession. The carbonate deposits of the section are correlated with some of equivalent deposits in Northwestern and other regional sedimentary basins of Ethiopia based on their Lithostratigraphy and chronostratigraphic relationship.

Key words:-Depositional Environment, Fossil, Microfacies, Facies, Paleontology, Sodoble section, Northwestern Ethiopia Plateau.

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List of Acronomy

ASS	Antalo super sequence
cf.	Compare with
FB	Facies belts
Sp.	Species
MFT	Microfacies type
SMFT	Standard Microfacies Types
USST	Upper sandstone
UTM	Universal Transverse Mercator

CHAPTER ONE

1. Background of the Study

The sedimentary regions of Ethiopia cover a significant portion of the country and comprise five distinct sedimentary basins; namely: the Ogaden, Abay (Blue Nile), Mekele, Gambela and Southern Rift Basins (see fig 1.1). The development of most of these basins is related to the extensional tectonic events that have taken place intermittently since the Late Paleozoic and continued up to Tertiary. The Ogaden, Abay and Mekele basins are presumed to be Intracontinental rift basins formed as a result of extensional stresses induced by the break-up of Gondwanaland in Upper Paleozoic era (Bosellini et al, 2001).

The Blue Nile Basin is situated in the Northwestern Ethiopian Plateau and is bounded to the E and SE by the tectonic escarpment of the uplifted western flank of the Main Ethiopian Rift and to the N and S by the Axum–Adigrat and Ambo lineaments, respectively (Gani, 2008), and contains a 1400m thick section of Mesozoic sedimentary rocks unconformably overlying Neoproterozoic basement rocks and unconformably overlain by Early–Late Oligocene and Quaternary volcanic rocks (Russo et al. 1994).

Carbonate rocks, such as limestone contain important and varied textures**,** structures and fossils that yield important information about ancient marine environments, paleoecological conditions and the evolution of life forms, particularly marine organisms, through time.

Facies analysis can guide us to know the environments of depositions, diagenetic features of sedimentary rocks, depositional conditions, fossil contents, porosity and permeability of the rocks, sedimentation processes undertaken by the rocks. Microfacies tells as the total of all sedimentological and paleontological data which can be described and classified from thin sections, peels, polished slabs or rock samples. Its studies aim for the recognition of overall patterns that reflect the history of carbonate rocks, by means of a thorough examination of their sedimentological and paleontological characteristics (Flugel, 2004). Particularly, microfacies analysis focuses on those compositional and textural constituents of carbonates that reflect the depositional and diagenetic history and determine the practical usefulness of carbonate rocks.

According to Haq (1978) micropaleontology is the study of microscopic fossils, cuts/scraches across/through many classificatory lines. Microfossil is any fossil, usually small, whose distinguishing characteristics are best studied by means of a microscope. Microfossils are small in size and large numerical abundance; relatively small sediment samples. Therefore it is used for the application of more rigorous quantitative methods of analysis. Particularly marine microfossils occur in sediments of Precambrian to Recent ages, and in every part of the stratigraphic column one or more groups can always be found useful for biostratigraphic, paleoenvironmental and paleoecological interpretations. For example, the benthic foraminifera group is more suitable for reconstructing depositional environments in addition to biostratigraphic indicators, as the occurrence is restricted to well-defined habitats (Bilal U. Haq, 1978).

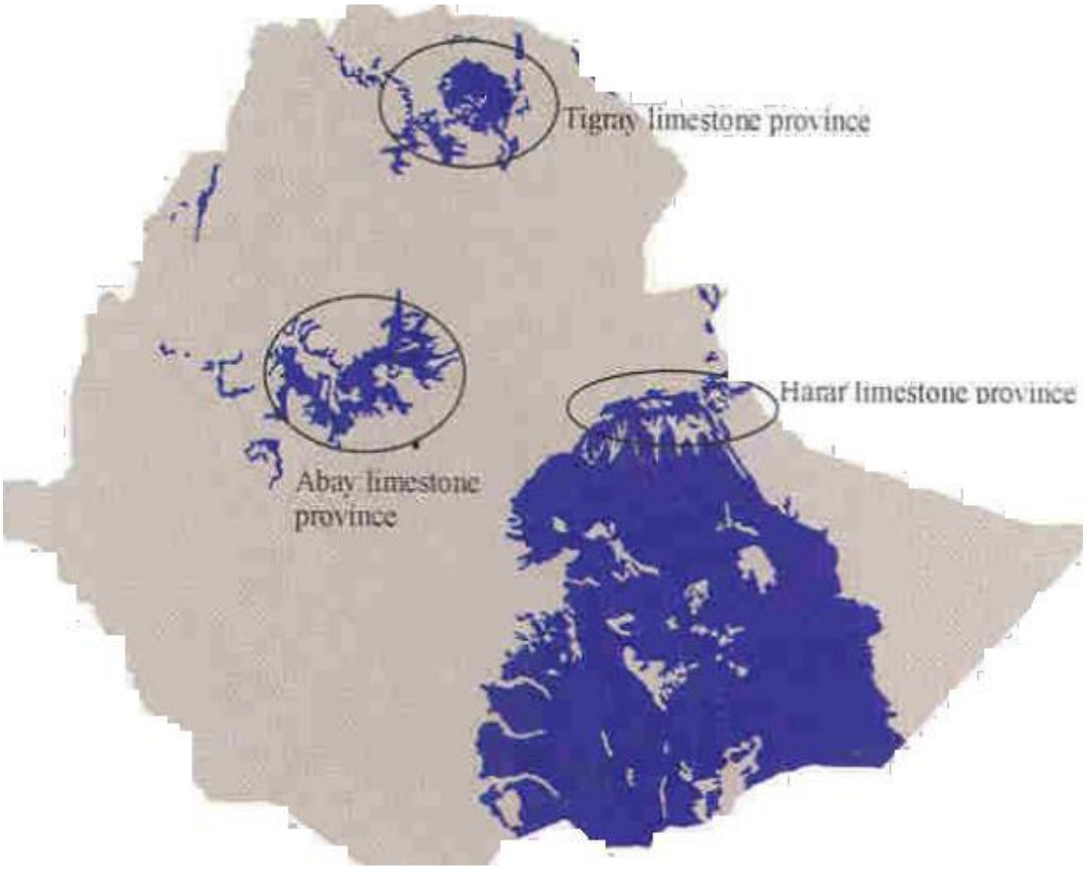


Figure 1.1: Locations of Mesozoic sediments of Ethiopia, source: from Wondafrash, et al. (2009)

1.1 Study Area Overview Description

1.1.1 Location of the Study Area

The study area is under investigation situated in Blue Nile basin, Oromiya region on the North western Ethiopia around Mugher area and it is 110km far from Addis Ababa the capital city of Ethiopia and 20 km from Inchin Town. It is geographically bounded between 0429000 to 0438000 m E and 1046000 to 1052000 m N in UTM (Universal Transverse Mercator) and it is found in Minare and Inchin Topho sheet. The map is presented only to show the area and the location of study. The study undertaken on one locally selected stratigraphic section in Sodoble section throughout the area which is located in Adaa Berga Woreda. The rectangles in the map show the present studied subsections area.

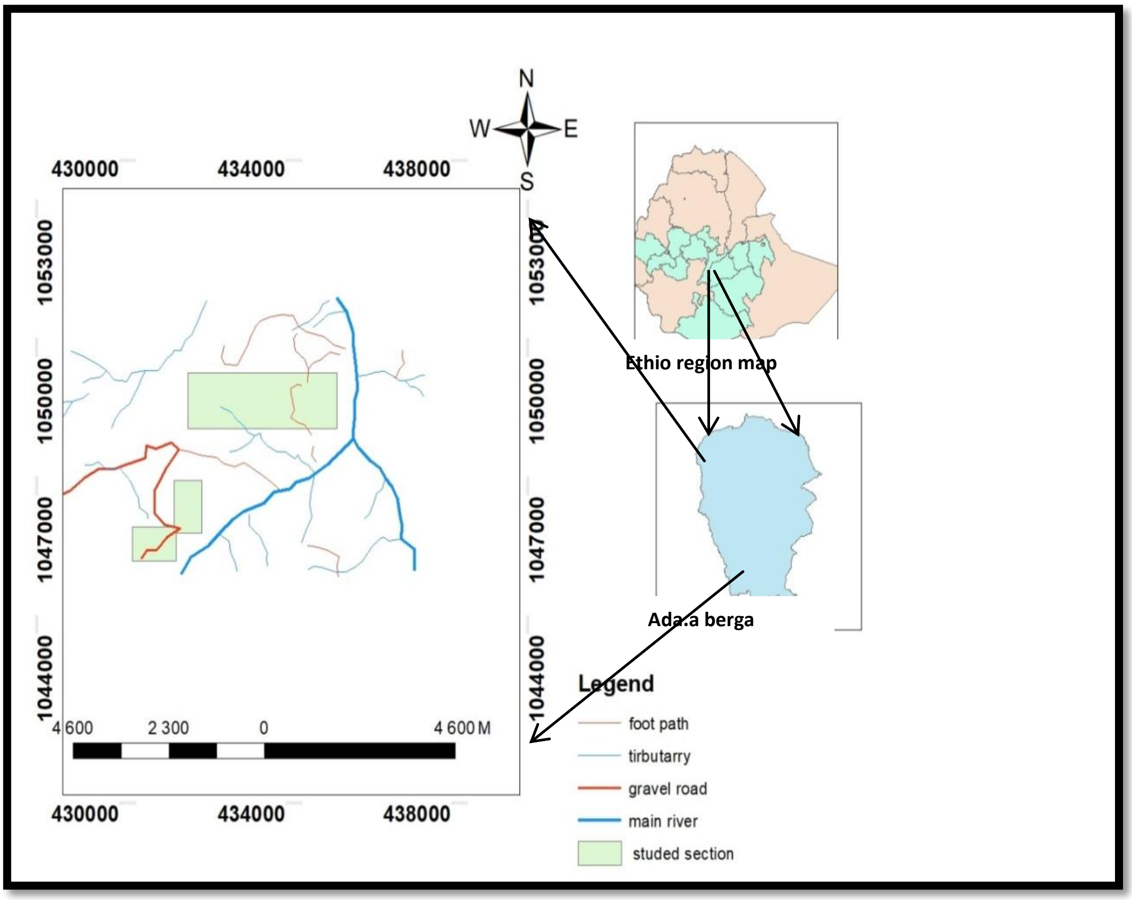


Fig 1.2 location map of the study area

1.1.2 Climatic Condition and Vegetation

According to Climate-Data.org in https://en.climate-data.org/location/762997/, Mugher area has at an average temperature of 14.9 °C, June is the hottest month of the year. The lowest average temperatures in the year occur in December, when it is around 18.2 °C. The summers are much rainier than the winters in Mugher area. The greatest amount of precipitation occurs in July, with an average of 281 mm and lowest in December, with an average of 8 mm. In terms of vegetation, it is covered by grasses and moderately vegetated by scattered patches of trees and scrubs.

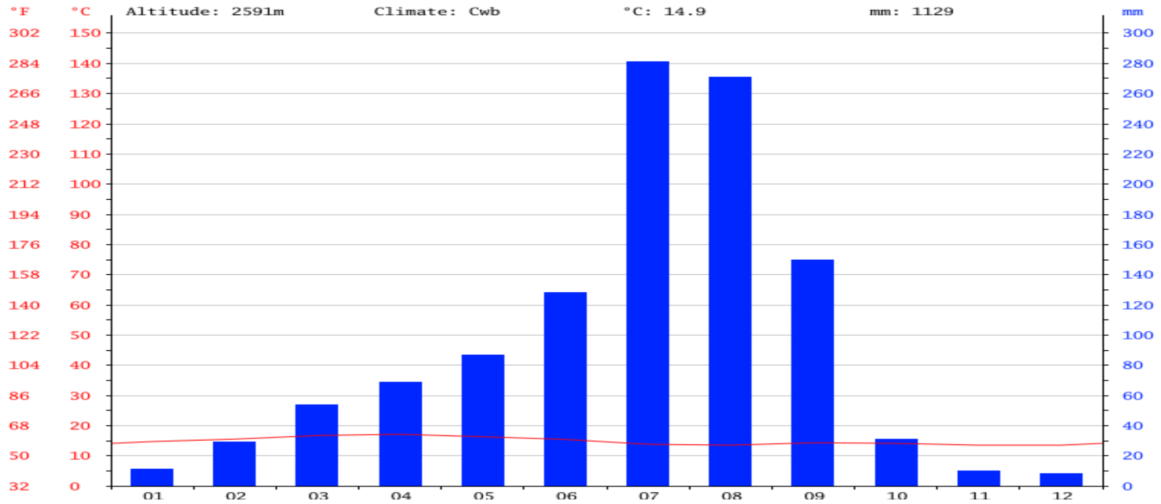


Figure 1.2: A bar chart that show climatic condition around Mugher area Source: from Climate Data.org in https://en.climate-data.org/location/762997/

1.1.3 Physiographic and Drainage Pattern of the Study Area

The study area is a part of Inchin and Minare topographic map sheet with the scale of 1:50,000 which part is of the central Northwestern Ethiopia plateau and most part of the

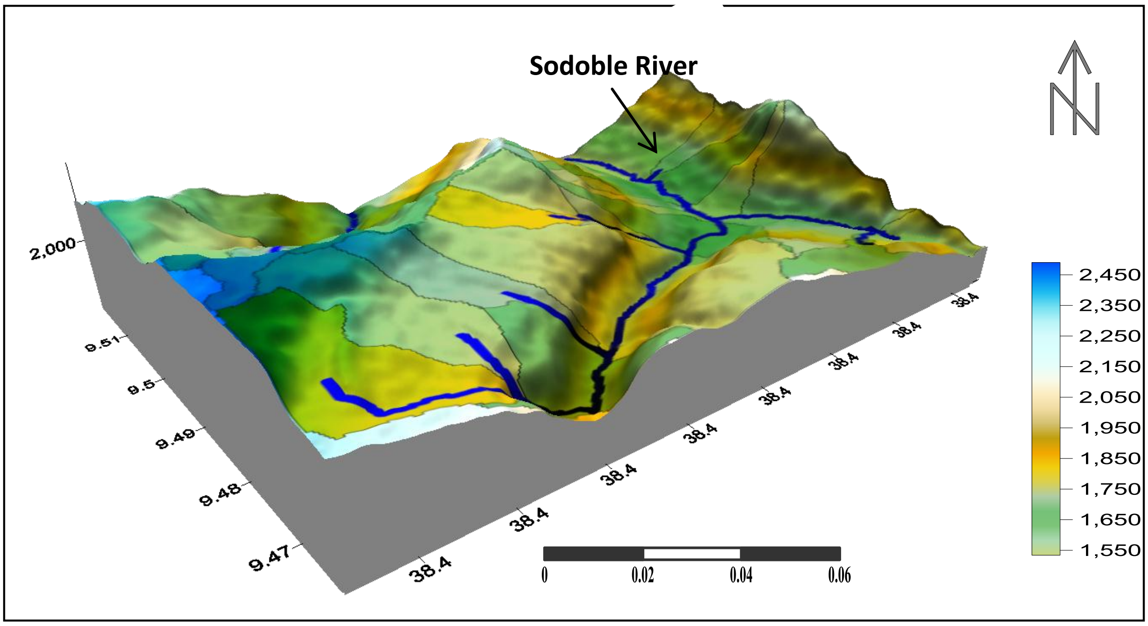


Figure 1.3: Physiographic and Drainage of the Study Area

main Ethiopian rift margin. The study area has a high rugged topography and characterized by steep slope to gentle terrains as observed during the field investigations. These physiographic features have been developed through tectonic activities which is associated rift-forming processes. The elevation ranges from 1550m to 2450m as visualized from DEM (Digital Elevation Model with 30m resolution, source: SRTM) of the study area. Sodoble and Kersa River are the main rivers in the study area and there are number of streams joining this river. These rivers are the tributaries of the Mugher River which is out of the study area. In general, as observed from the physiographic map of the study area as well from field observation, the drainage pattern of the area shows dendritic drainage pattern (fig1.3).

1.1.4 Population and Settlement

The population density in the study area is very low. The closest big town to the study area is Reji and there are small villages like wayu biyo, Reji mokda and wayu wegidi are found within the study area. The two largest ethnic groups in the area were the Oromo and Amhara. Oromic language is spoken as a first language and the dominant one but some people spoke Amharic language. The majority of the inhabitant religions are protestant and Orthodox. There is also some Muslims are live in the study area. Some cultivated land, bush land, shrub land, salt flats and rock exposures are the land cover types in the study area.

1.2 Previous Works

Concerning the present thesis work no research has been well done on the specific study area especially in terms of micropaleontology. But a number of other reports have been done in geological work at regional wise, in central north western part of Ethiopia by different authors. The study area has been investigated by several researchers; from those, Kernkel (1926), Stefanini (1933), Merla, G., and Minucci, E. (1938), Jepsen and Athearn (1961 a, b), Meral (1973) and Mohr (1962 and 1974) has been carried out a concise account of Geological work prior to 1975.

Kovaiac, J. (1975), Getaneh Assefa (1987 and 1991), Zanettin et. al (1973, 1974, 1976 and 1978), Peccerillo and Bekele Megerssa (1992), Russo et al. (1994), Serawit and Tamrat (1999, 1996 and 1995), Tamrat and Tibebe (1997), Balemwal Atnafu (2003) Wolela Ahmed (1997 and 2004), were made a valuable contributions to understanding the geology of the area.

According to Asfawossen Asrat (2015) more than 100,000 sq. km of carbonate rocks are exposed in Ethiopia and these are widely exposed in the Mekele, in the Blue Nile basin and in the Ogaden Basin (including the Bale and Western Harrarghe areas). Jurassic limestones in Ethiopia have various names according to its type locality throughout the country, example: Antalo Limestone Formation (in Abay, Mekele and Dire Dawa area), Hammanlei Formation, Urandab and Gabredarre Formation (in

Ogaden basin and Harrar) (Kazmin, 1973; Blanford, 1869; Beyth 1972a;1972b; Bosellini et al,1997; Getaneh Assefa 1991; Russo et al, 1994).

The age and stratigraphy of carbonate rocks of Blue Nile basin is conducted by some authors. These are: - Based on the work of Russo et al. (1994) and Balemwal Atnafu (2003), the carbonate succession of Blue Nile basin which is 420 m thick, described by, 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 highly fossiliferous 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, Belmwal Atnafu 2003). The upper part (50 m thick) comprises planar laminated oolitic and reefal limestones, which was interpreted to indicate the return of shallow water conditions.

According to Turi et al. (1990), Belmwal Atnafu (1991, 2003) and Russo, et al., (1994) the age of limestone is described as the following. The presence of *Pfenderina sp*. and *Nautiloculina oolithica* at the base of the limestone unit points to a Callovian age. *Kurnubia palestiniensis*, *Parurgonina caelinensis*, *Conikurnubia sp*. and *Salpingoporella annulata* at the top of the unit indicates a Kimmeridgian age.

Mostly, the Abay canyon carbonate succession of has also been investigated from a stratigraphic point of view by Canuti P.et al. (1975), Gilamichael Kidanemariam et al.,(2009) and Balemwal Atnafu (2003) on facies and microfacies of Jurassic carbonates. However the Sodoble section is not detail studied in terms of micropaleontology and facies analysis (mainly Microfacies analysis) of the rocks. Therefore, in this paper, the study has been present on micropaleontology and facies analysis of carbonate unit and is used to interpret the environment of deposition and to give the age of the carbonate unit of the specific area.

1.3 Problem Identification

Sedimentary 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). In our country Ethiopia there are many sedimentary basins those are predicted by many authors' in terms of micropaleontology, facies analysis, stratigraphy and other aspects in regional level, however with scarcities of detail work. Related works are done by Belmwal Atnafu (2003) and Canuti p. et al. (1975) in abay basin on Facies, microfacies and diagenetic development of Jurassic carbonates.

The study area (Sodoble section) has not been studied in aspect of micropaleontology and facies analysis in detail. Therefore such detail studies can give chance for the first to identify the carbonate unit of the specific area. And the present study aimed on the detail work of micropaleontology, especially on foraminifers and ostracods and facies analysis of the carbonate unit of study area (Sodoble section) in order to identifications and interpretations of the environments of depositions, to see lateral and vertical relationship of carbonate unit of the Sodoble section with previous studied section in the basin and age estimation based on index microfossils which found in the section.

1.4 Objectives

1.4.1 General Objective

The main objective of this search thesis is detail study of the micropaleontology and facies analysis of carbonate unit which is found in Mugher area (Sodoble section).

1.4.2 Specific Objective

- To identify and describe microfossils of carbonate rocks of the study area.
- To describe detail microfacies properties of carbonate units and to classify the limestone unit according to Folk and Dunham classification.
- To interpret the depositional environment of carbonate unit of the study area.
- To determine the age of carbonate units of the study area.
- To construct detail stratigraphic log of the unit.
- To correlate the carbonate units of the area with regional units of the country and within basin.

1.5 Methods and Materials

In order to accomplish this thesis, different materials have been used and different methods have been applied. Detailed field studies following exposures on road-cuts and quarry side, lithofacies analyses, macrofossil collection and identification of them were carried out in the field.

During field investigation of Mugher area (Sodoble section) carbonate unit, 33 rock samples and 9 marl samples were collected. The microfacies analysis was carried out from 26 hard limestone samples and thin sections were studied with petrographic plane polarizing microscope. Photographs of outcrops, thin section and fossils were taken using digital camera. The classification scheme of Dunham (1962) and Folk (1962) have been applied for the carbonate rock naming. Facies belts and microfacies types are recognized based on standard microfacies types (SMFT) and Facies belt (FB) of Wilson (1975). The general works of the research are mainly divided into three phases; pre-field work, field work and post-field work. In the pre-field work assessment, it began with reviewing literatures and followed by identification of the problem; setting objectives and identification of methodology were done. Field and post-field works generally elaborated sample collection, stratigraphic logging, sample preparations (microfossils and thin section), sample analyses, fossil description and interpretations of field and laboratory data were done. In the following subdivision of the methods that applied in this research thesis is presented.

1.5.1 Field Work

Field work were accompanied with the collection of approximately 33 rock samples, 9 marl samples and macro invertebrate fossils. The sedimentological data such as lithology, texture and sedimentary structures were described and lithologic log of compositional and textural data was produced. During the field work the following materials were used: Topographic map (1:50,000 scale), regional geological map (1:250,000 scale), GPS, compass, hammer, hand lenses etc. Detail description for each of field activity is given as follows:-

1.5.1.1 Sample Collection

A collection of samples in the selected study area was done at three stratigraphic sections to measure complete stratigraphic section of Mugher area on November 2017. Representative samples of the unit in the study area were collected from surface following the river cut, road and quarry site of carbonate exposure. Both rock samples and marl samples were collected for petrographical analysis and microfossil extraction respectvly.

Collections of invertebrate macrofossil were also conducted in the selected stratigraphic sections. Fossil samples collected from the carbonate unit of the study area were mostly found as a mold or a cast. Some of the fossils collected in the field have already been removed from the rock those can be easily collected and some fossils remain embedded in the rocks, then their photograph was taken. Description and identification of macro fossils based on shape and size was made in the field.

In this study, description and the sampling of rock were vertical variations given more attentions. The description is based on lithology, texture, rock color, bedding, sedimentary structures, fossils and biogenic structures of the bed. Simple random sampling techniques are used.

1.5.2 Laboratory and Data Analysis

Detailed microfacies analysis of carbonate units through thin section study, fossil description and microfossil sample preparation were made in laboratory. Attempts made in laboratory are discussed below:-

1.5.2.1 Petrographic Analysis

For microfacies analysis and to investigate the compositional variation of limestones in the area about twenty-six (26) thin-section samples were and prepared. Each sample was viewed under a petrographic plane polarizing microscope. Thin sections are prepared for study of the relative abundance of the main carbonate constituents like: - carbonate allochems, matrix and cements, fossils and diagenetic features.

The standard microfacies types of Wilson (1975) based on Dunham's (1962) and Folk's (1962) classification of carbonate rocks were used in description and analysis of the observed carbonate microfacies. Depositional settings and Paleoenvironmental interpretation of most carbonate unit were identified based on compositional, textural and sedimentary data and by comparison with Standard microfacies types (SMFT) and Facies belts (FB) of (Wilson, 1975).

1.5.2.2 Microfossil Preparation and Description

Nine unconsolidated sediment (marl) samples were collected in order to isolate and identify microfossils of the study area. Those sediment samples are prepared in Addis

Ababa university stratigraphy and sedimentology lab. In order to extract and study microfossils 50 grams of dry marl sediment were placed in beaker, soaked in 50 to 75 ml of 30% concentrated H_2O_2 solution and 100 to 200 ml of distilled water. Samples are then gently stirred and low boiled. After minimum of 24hr the samples are then washed over by USA Standard Sieve No. 35,45,60,120 and 450 which have 0.5mm 0.375mm, 0.25mm, 0.123 mm and 0.032mm sieves sizes respectively. And then air drying method was used to dry samples over 6-12 hr. The dried samples were then carefully scattered on the black picking tray and scanned under binocular reflecting microscope (x35 magnifications) for picking and analysis of the recovered microfossils. Recognizable microfossils were picked with a fine paint brush and dropped into cavity slide microfossil card. All the representative microfossil specimens were mounted on micro slides for identification and selected microfossil were photographed for further morphological description.

1.6 Significance of the Study

As mentioned in the problem of the statement the micropaleontology and facies analysis of carbonate unit of Sodoble section is not detail studied and this is the first detail work for the studied area. Therefore, this study helps to understand the detailed micropaleontology and facies characteristics of the carbonate rock in the selected stratigraphic sections which is important to obtained detailed picture of depositional environment, age of the rock and to see lateral and vertical relationship of the carbonate succession among the studied area and other section with in basin.

1.7 Thesis Structure

The thesis is structured in seven chapters. It starts general information about the study area, background and literature review of regional geological setting and general sedimentary basin evolution. It includes detail Lithostratigraphy description, Petrographic description and description on paleontology of the study area. At the end the discussions on depositional environments of carbonate units of the area, their age and the correlation with local section and regional basin was made before concluding the study.

CHAPTER TWO

2. Regional Geology

Geology of Ethiopia is characterized by the occurrence of a very wide variety of rocks, differing in their age, origin and evolution. The rocks in the country classified into three broad categories; Tertiary and Quaternary volcanic rocks which occupy large parts of the country along the rift valley and plateau, continental and marine of late Paleozoic to Mesozoic sedimentary rocks and Precambrian basement complexes (Tefera et al. (1996). The East African region has been affected by two major phases of rifting. The first phase was the widespread rifting in Karoo times (Late Carboniferous to Early Jurassic) which stretches from Ethiopia to South Africa corresponds to the initiation of the break-up of Gondwanaland in that further subsidence took place. This subsidence combined with sea-level fluctuation produce cyclic patterns of shallow- marine carbonates, shales, evaporites and minor clastic deposits. The second rifting relates to the formation of the East African rift system from Cenozoic to Recent (Bosellini, 1989).

According to Beyth (1972a; 1972b), Sedimentary regions of Ethiopia cover a significant portion of the country. They classify into five distinct basins, namely: The Ogaden, Abbay, Gambela, Southern rift and Mekele basin. Paleozoic and Mesozoic sedimentary successions of Ethiopia are unconfarmably overly Precambrian basements. Most of sedimentary succession of the country is part of the vast sedimentary succession of East Africa which was deposited during the Mesozoic transgression. But also there are some late Paleozoic to early Mesozoic sedimentary rocks mainly sandstones and minor tillite, shale, siltstone and conglomerate present in some parts of the country. The Mesozoic succession of Ethiopia is present in the Mekele outlier, Blue Nile Basin and Southeastern Ethiopia with adjacent in the Ogaden Basin (Kazmin, 1973; Merla et al., 1979; Bosellini et al., 2001; Beyth 1972a; 1972b; Getaneh Assefa; 1991; Russo et al., 1994).

2.1 Jurassic Carbonate Unit of Ethiopian Sedimentary Basins

Based on Ronov (1983), carbonate rocks make up about one-fifth to one-quarter of all sedimentary rocks in the stratigraphic record of the world. This carbonate deposit is occurring in many Precambrian assemblages and in all geologic systems from the Cambrian to the Quaternary. Both limestone and dolomite are well represented in all stratigraphic record. Dolomite is dominant carbonate rock in Precambrian and Paleozoic sequences, whereas limestone is dominant in carbonate units of Mesozoic and Cenozoic age. Because of their content, Carbonate rocks are important group of rocks for other reasons they contain much of the fossil record which is important to studyearth history. In addition, most of the time they are complete with structures and textures that provide invaluable insight into depositional environment conditions of the past. Aside from their basic value as indicators of earth history they also have considerable economic significance.

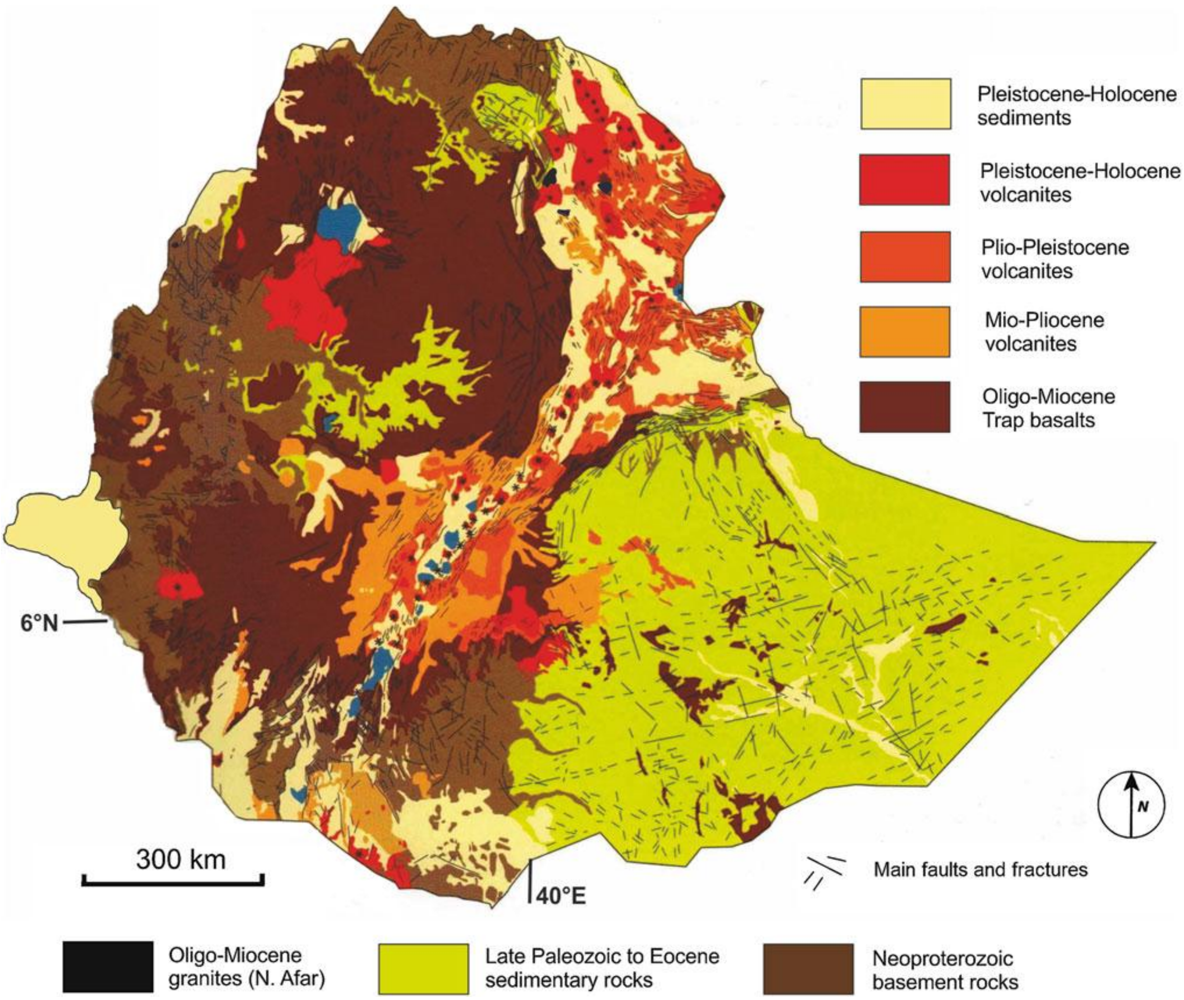


Figure 2.1: Regional geological map of Ethiopia adopted from Tefera et al. (1996)

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 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).

In Ethiopia the typical facies of the Jurassic transgression is represented by shallow-water carbonates referred to as the Antalo Limestones as well as the Hammanlei and UrandabFormation (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). However, in the Blue Nile basin the Adigrat Sandstones are followed by the Gohatsion formation which contain interbedded gypsum unit with glauconitic sandy mudstone and dolomite of Liassic to Callovian age (Russo et al., 1994).

2.2 General Stratigraphic Succession of Northwestern Ethiopia Plateau

Different studies have confirmed that stratigraphically wide rock units 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; Bosellini et al., 2001; Mengesha Tefera et al., 1996; Abiyyu Hunegnaw et al., 1998; Balemwal Atnafu (2003); Asfawossen Asrat 2015; Gebreyohannes Habtezeghi, 1984; Workineh Haro, 2010; Russo, et al. (1994); Gilamechael Kidanemariam et al.,(2009) Turi et al. (1980) ; Gani et al. (2008) and Wondafrash et al. (1993) are given some contribution to describe the stratigraphy of Blue Nile basin.

As it is stated by Wolela Ahmed (2007), the Blue Nile basin part of Northwestern Ethiopian Plateau contains thick Mesozoic sedimentary section and this thick Mesozoic deposit is underlain by Neoproterozoic basement rocks and overlain by early–late Oligocene volcanic rocks. Rabben et al., (1979), Beicip (1985) and Balemwal Atnafu (2012) also elaborately discuss the stratigraphy and history of sedimentation in the Abay basin.

Based on this study and the data reported by Mohr (1963), Assefa (1991) and Russo et al. (1994), the complete succession in the Blue Nile Basin consists of a crystalline basement (precamberia) rocks, Paleozoic sediments (pre-Adigrat sandstone), Adigrat Sandstone, Gohatsion Formation, Antalo Limestone, Mugher Mudstone, Ambaradom Sandstone (Debrelibanose) and Tertiary Volcanic rock in ascending order . Its lithological description is as follows:-

2.2.1 Crystalline Basement Rocks

Basement 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. Neoproterozoic penetrative NNE-trending sub-vertical ductile planar fabrics are associated with NNE- to NE-trending upright tight folds. In Abay 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 channel filling Paleozoic sediments.

2.2.2 Adigrat Sandstone Unit

This 300m thick unit is also known as the Adigrat Sandstone and 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 lower sandstone (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).

They described upper part of this formation is composed of alternating carbonaceous mudstones, carbonaceous siltstones and sapropelic coals.

2.2.3 Gohatsion Formation (Gypsum-Shale Unit)

This unit, 450m thick, also known as the Gohatsion Formation, is of Early–Middle Jurassic (Toarcian to Bathonian) age, as determined from micro– and mega–fossil studies by Assefa (1981). It consists of interbeded sandstone, siltstone mudstone, and shale in its lower part and alteration of gypsum, dolomite limestone and shale in its upper part. 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 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).

2.2.4 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) and Atnafu (2003), 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 and Atnafu 2003). The upper part (50 m thick) comprises laminated oolitic and reefal limestones, which was interpreted to indicate the return of shallow water conditions.

2.2.5 Mugher Mudstone Unit

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. In its type locality, it is 260 m thick and conformably overlies the Antalo Limestone. Based on Assefa (1991) and Russo et al. (1994) it is subdivided the unit 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 (240 m thick) is characterised by interbedded sand- silt and mudstones with local occurrences of lignite layers and scattered plant fragments. This siliciclastic succession was interpreted by 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.

2.2.6 The Debre Libanose Formation

This unit is unconformable overlain by tertiary basalts, is composed of sandstone interbeded by conglomerate and shale (Getaneh, 1991). It is widely exposed in the valley of the Zega Wodem River and it is tributaries area. 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 A hmed, 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, 2004). This unit is interpreted as a deposit of sandy-braided rivers on a broad alluvial plan (Getaneh Assefa, 1991).

2.2.7 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 (1991) describe there is thick massive food lavas chiefly of basalt, unconformably overly the Paleozoic and Mesozoic sediment.

2.3 Jurassic Fossils in Carbonate units of Ethiopia

Preveous works such as Jaboli, 1959; Canuti and Radrizzani (1975), Russo, et al. (1994), and Mansour (1975), reported that many micro and macro fossils occur in carbonates of Ethiopia. However the detail paleontological works is neither described nor figure out mainly in Abay Basin.

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).

Based on the work of Russo et al. (1994), the carbonate unit of the Abay Basin is dominated by the most important macro and micro invertebrate fossils contents. From those Pholadomya somaliensi, Mactromya daghaniensis, Homanya inornata, Musculus somaliensis, Daghanirhynchia daghaniensis and some Gastropods like Ampullina sp. And Gryphea costellata macrofossils are common in the Antalo limestone.

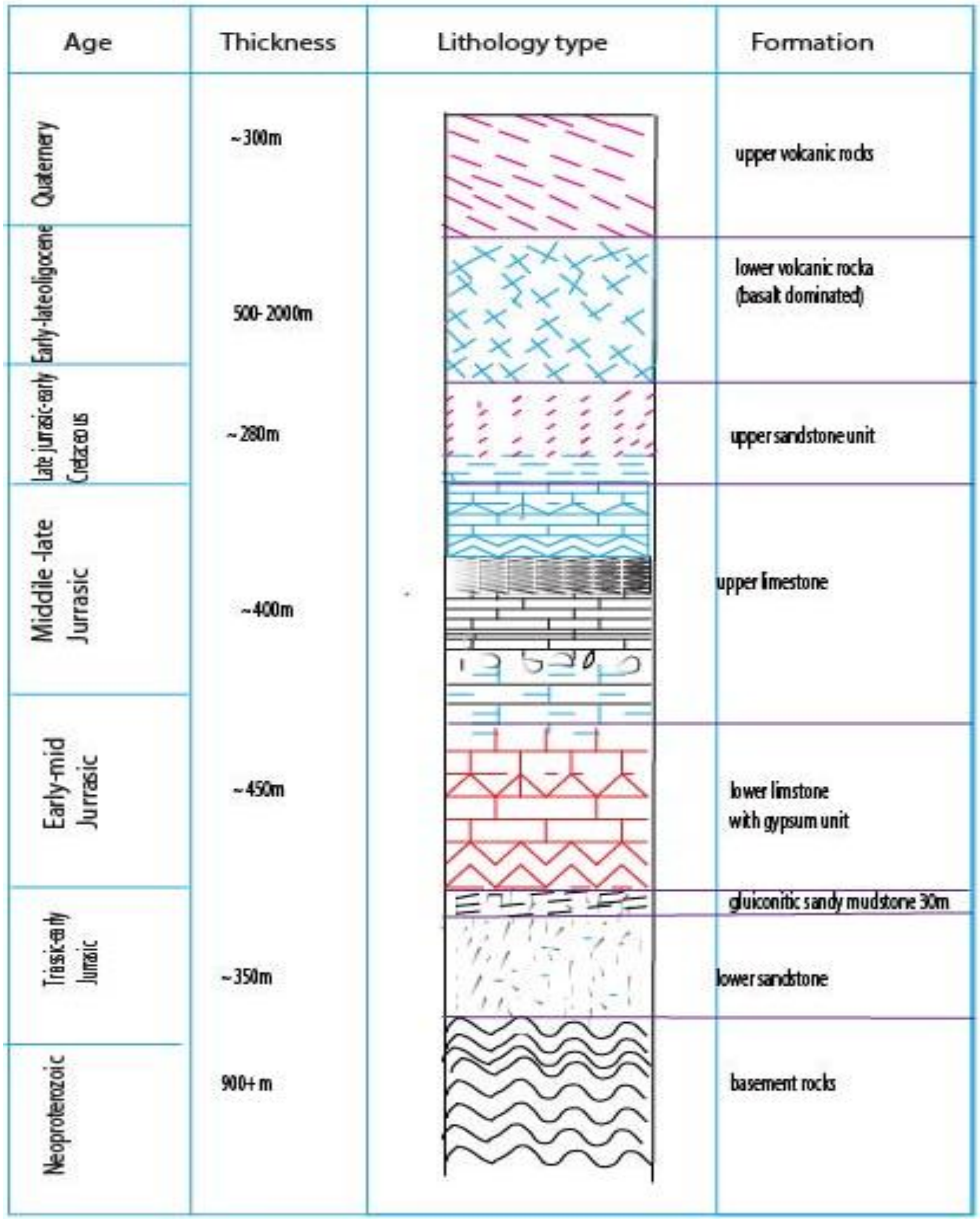


Figure 2.2: Generalized lithostratigraphy of Blue Nile basin modified from (Wolela Ahamed, 2004).

CHAPTER THREE

3. Lithostratigraphy of the Mugher Area (Sodoble Section)

3.1. Introduction

Sodoble section is found in north western part of Ethiopia around Mugher area. Carbonate unit of sodoble section is very thick deposit (320m) in Mugher area sedimentary rocks. Its thickness is varying from place to place throughout the area, which most probably shows the response to the tectonic disturbance and local sea level fluctuation during their depositions. From top to bottom the carbonate unit is overlain and underlain by upper sandstone and Gohatsion formation respectively. In some place upper part of carbonate unit in sodoble section is unconformably overlies by Quaternary volcanic deposits.

In addition to this, the area is the most Northwestern escarpment of the main Ethiopian rift valley and due to this; there are a lot of marginal normal faults and fractures. Especially the major faults in the area are manifested by displacing and dispersing the major stratigraphic units of the area around Togo ridge. Even it is difficult to differentiate some limestone units of the area as their exact stratigraphic position due to displacements by tectonic activities.

Through the field observation the detailed lithostratigraphy of sodoble section of carbonate successions of the area, were described and measured. The carbonate sequence of the sodoble section is known by the name as ‘Antalo Limestone Formation’ by different workers, throughout northwestern and central Ethiopia and it is the main objective of the present study. The complete section is measured at different three local areas to get the lower and upper boundary. Its lower part is bounded by Gypsum dolomite bed (Gohatsion Formation and the upper part is bounded by sandy mudstone layer (upper sandstone/ debrelibanose sandstone.

Lithologically, carbonate sequence of Mugher area (sodoble section) consists of some dolomitic bed, calcareous mudstone with fossiliferous limestone which upgrades to Biopelodial to oolitic limestone at top of the lower parts, colonial organism bearing bed, blackish, greyish, thin-thick bedded micritic limestone with thin clastic shale beds to bioclastic wackestone/packstone at middle parts; and some intermixed shale, calcareous mudstone with fossiliferous micritic limestone and cherts interbeded micritic limestone beds and some colonial organism bearing limestone layer at its top part

The common facies and lithologic change observed in all sections is vertical change. The dominant lithofacies type is bioclastic Wackestone to packstone and marl bioclastic limestone but micritic limestone, calcareous mudstone, bioclastic and planar oolitic packstone to Grainstone were also observed. In the lower part there is colonial organisms like coral reef bearing limestone and fine grained dolomitic limestone bed is observed. The detail lithological and facies descriptions of this carbonate succession observed in field are discussed in the following sections:

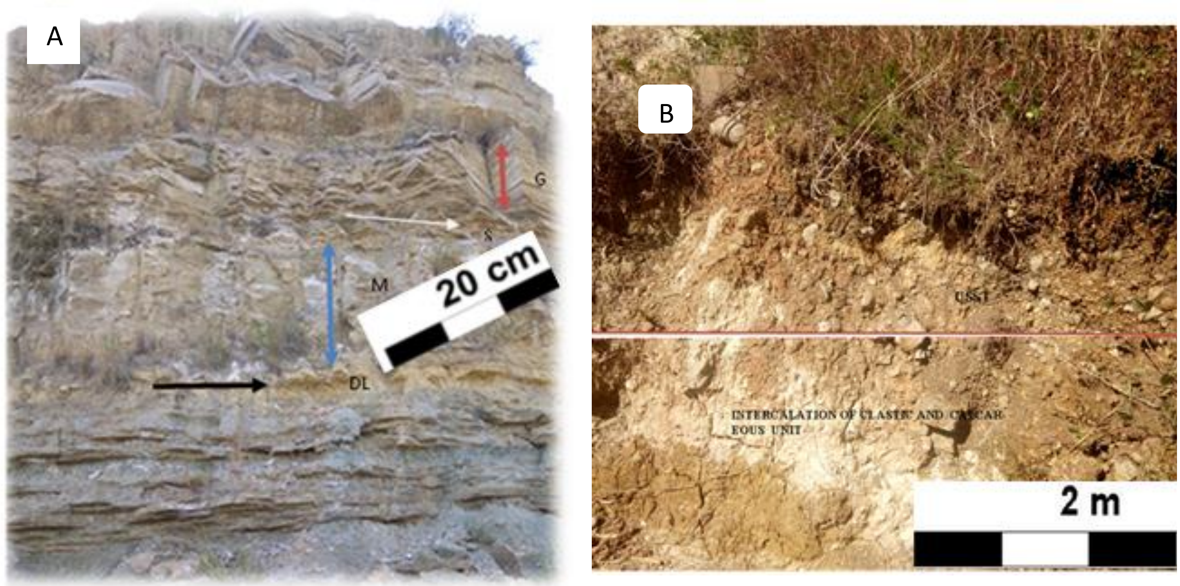


Figure 3.1: The field microphotograph that shows the upper part and lower part of the Sodoble stratigraphic carbonate section boundary area **(A)** the lower part that is underlay by gypsum dolomite intercalation beds (Gohatsion Formation); the white and dark arrow indicates thin beds of dolomitic limestone, the blue arrow(clastic mudstone) and the red arrow indicates laminated gypsum unit and **(B)** intercalated clastic and calcareous which is from contact area of upper part of carbonate unit and upper sandstone.

3.1.1. Field Descriptions for Carbonate Unit of the Mugher Area (Sodoble Stratigraphic Sections)

The carbonates deposits of the area were logged and measured at three selected local stratigraphic sections (Kersa section 1, Kersa section 2 and Togo ridge section). Each section were selected based on the quality of exposure and accessibility to observe carbonate units of the area (sodoble section). The sections are also named by the name of the nearest locality (village). At all these three local sections, the exposed carbonate layers are described based on their facies types (lithology, colors, sedimentary structures, textures, fossil contents, stratigraphic relationships and their geometries) .

Kersa section one is measured and logged at about 3 km to the south of Mugher cement factory. At this section the top to middle part of carbonate of the area is measured and conformable contact with upper sandstone units were noted. According to

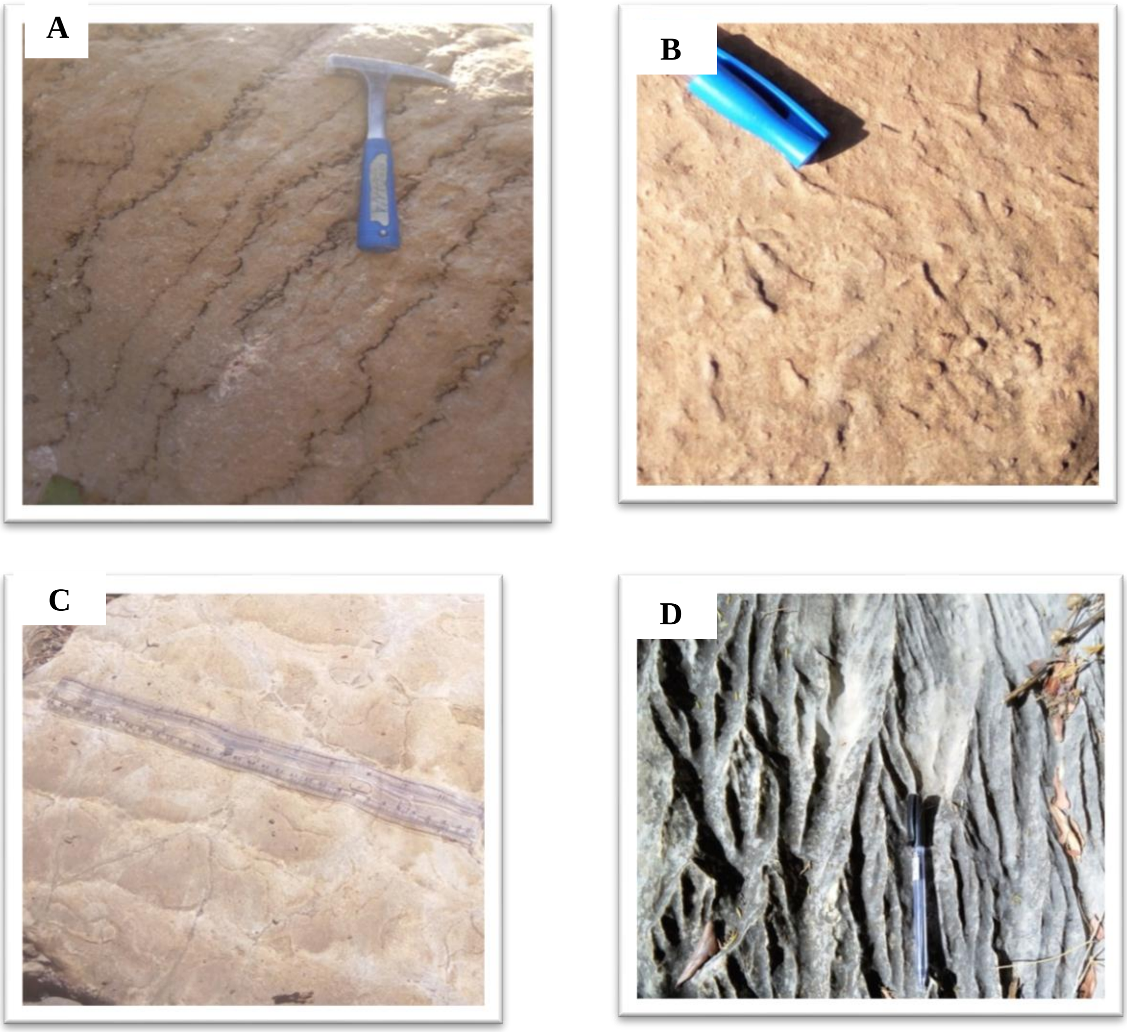


Figure 3.2: field photograph that showing different erosional and diagenetic structureson Kersa section one; **(A)** stylolite structure on fossiliferous limestone layers at upper Kersa one section **(B)** trace fossil of organisms (*Thalassinoides)* on the upper part of Kersa section one from lower part, **(C)** ripple structure from upper part of Kersa section one, **(D)** Mega Erosional structure (groove) on massive dark micritic limestone which is observed at the lower part of Kersa sub section one along Kersa river side.

the field observations the carbonate units exposed at this section has a total thickness of about 128m and they are grouped into five sub–lithofacies; which are clastic muddy shale and marly limestone at the top part, fossiliferous micritic layers with calcareous mudstone intercalation, thick micritic limestone with thin shale lamination and dark bioolitic limestone at bottom. In this subsection various types of trace fossils, ripple mark, bioturbation and other biogenic and diagenetic structures like stylolite features are observed. The upper part of this section is covered an average thickness of 2-5m calcareous mudstone and clastic shale. The upper sandstone is not directly contacted with Antalo limestone because of that transition zone is observed between them (see fig 3.1B).

Kersa section two is logged and measured at about 4km distance from Mugher cement factory along Kersa River. At this section, the middle sub-unit (at lower) and some part of the upper unit of the formation are described based on stratigraphic position and

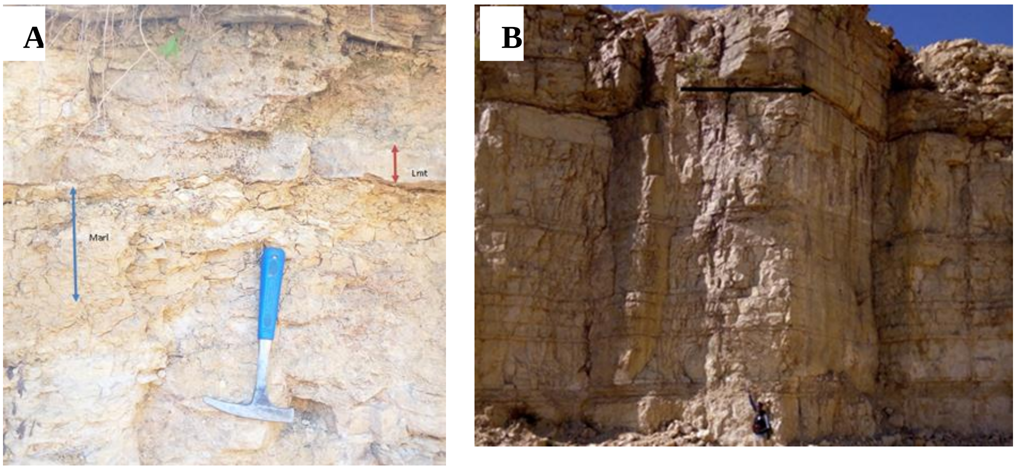


Figure3.3field photograph from Kersa section two **(A)**that showing fossiliferous limestone intercalated by marl layers at upper part of Kersa two section; the red arrow shows the micritic limestone thin bed and blue arrow shows thick marl layer **(B)** thick thin micritic limestone bed with thin laminated shale (arrow) from middle part of Kersa sub section two **(C)** dark bioclastic to oolitic limestone with thin shale beds from lower part of Kersa two.

carbonate components. The carbonate exposure at this section has a total thickness of about 136m. They are subdivided into five sub-litho layers, based on their major components and observable sediment features in the field. Those are: calcareous mudstone (marly) layer at the top, intercalated marl with fossiliferous limestone, Micritic limestone with thin shale beds at middle, bioclastic to oolitic Wackestone, and oolitic packstone-grainstone layers at the lower part of section. In this section, the oolitic limestone is dark in color with small or fine macrofossils are observed by hand lens (see fig. 3.2).

Togo ridge section: in this section the lower part to middle of sodoble were logged and measured. At bottom part of this section is overlain by thick layer of a Gohatsion

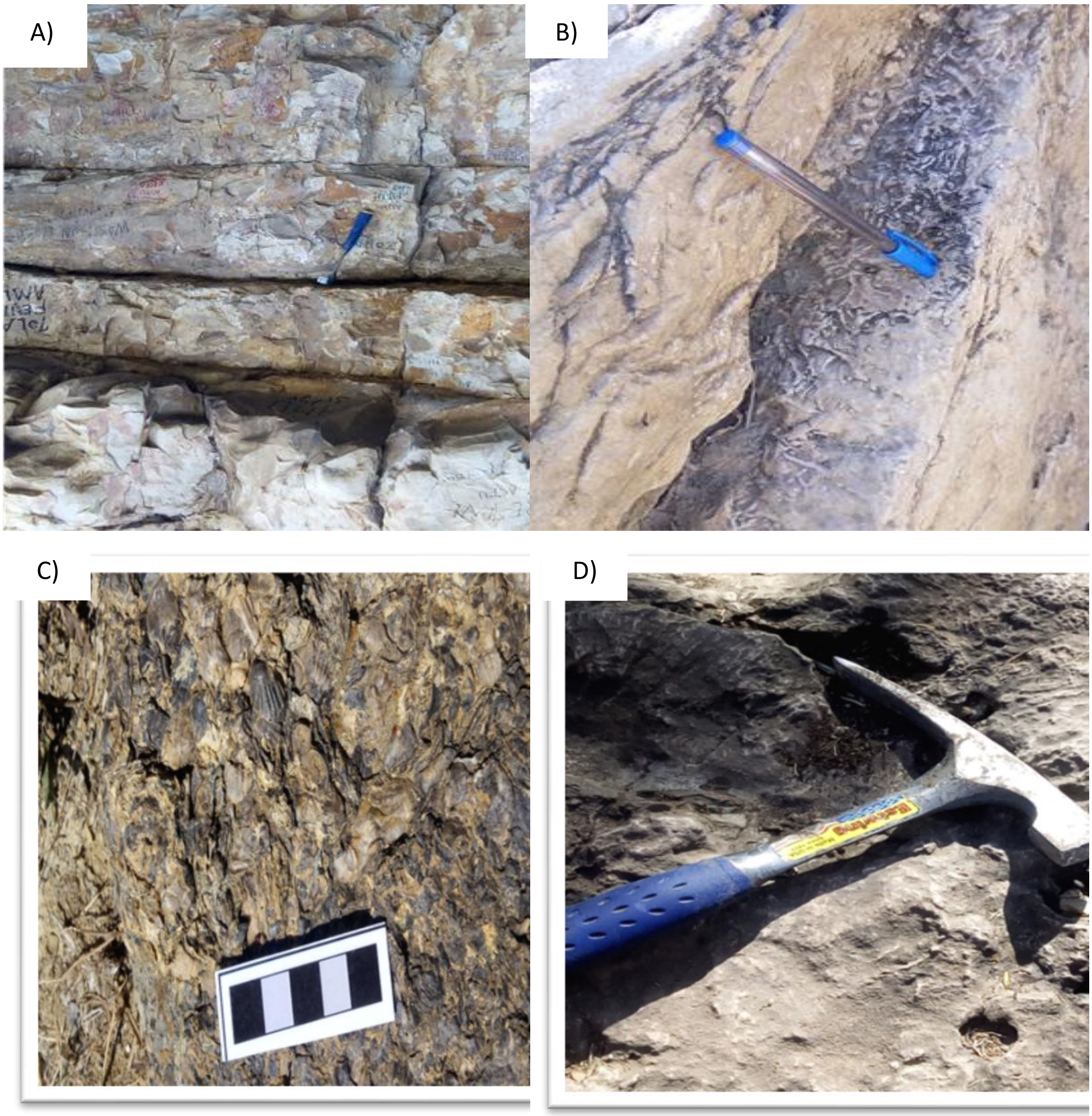


Figure 3.4: Field photograph from Togo ridge **(A)** dark thick micritic limestone bed from middle part of Togo ridge, **(B)** micritic limestone interbeded with dark chert unit from upper part of Togo ridge, **(C)** coquina bioclastic limestone at the lower part of Togo ridge, broken brachiopods shells are highly preserved on the dark lime stone bed,**(D)** Colonial coral reef at the lower part of Togo ridge.

Formation exposed about 20m in thickness (See fig 3.1A) and is overlain by marly fossiliferous limestone unit of about 20m thick. The carbonate exposure at this section has about 119 m of total thickness, which forming steep slope of the area. The exposed carbonate layers at this section includes: dark fossiliferous limestone to micritic layer interbeded with chert unit at the top part, bioclastic Wackestone to packstone with highly cemented limestone and thick bedded massive limestone at middle and marly highly fossiliferous limestone with colonial organism and dolomitic bed at the bottom (Fig.3.4).

Generally, from the present field observations at these three local stratigraphic sections and throughout the area, the carbonate units (Antalo Limestone Formation) of Mugher area, having about 320m total thickness. This section is sub-divided into three sub-units. These are lower, middle and upper sub-units, from bottom to top and are measured at different sections parts.

The detail descriptions and distinctions among those three sub-units will be given later in composite stratigraphy section, but their detail field descriptions of carbonate exposures within each sub-unit as observed from three local stratigraphic sections are given as below.

3.1.1.1. Lower sub-Unit

The lower sub-unit conformably overlies at Gohatsion Formation (Fig. 3.1A). As measured and logged at Togo ridge section and lower Kersa section one, this unit is characterized by a calcareous mudstone (marl unit) carbonate and fossiliferous limestone facies association with anumerous bioturbated beds and dolomitic facies at its bottom part.

The lower intercalation part of this sub-unit is about 20m thick, which is underlain by Gohatsion Formation of the area and it has gradational contact with this gypsum- shale to calcareous mudstone and dolomitic bed. Gohatsion unit comprises various alternating beds of gypsum unit clastic mudstone to shale and dolomitic bed. This intercalation of the gypsum and other clastic input indicates there was fluctuation of sea level (drying and shallowing of sea). On the top of the Gohatsion Formation, the Antalo limestone sequence of this section is started by dolomitic limestone and calcareous mudstone to bioclastic wackestone and oolitic limestone at the top were observed. In this sub unit the abundant fossil include bivalves as a mold, brachiopods shell fragments, echinoids and colonial corals are observed.

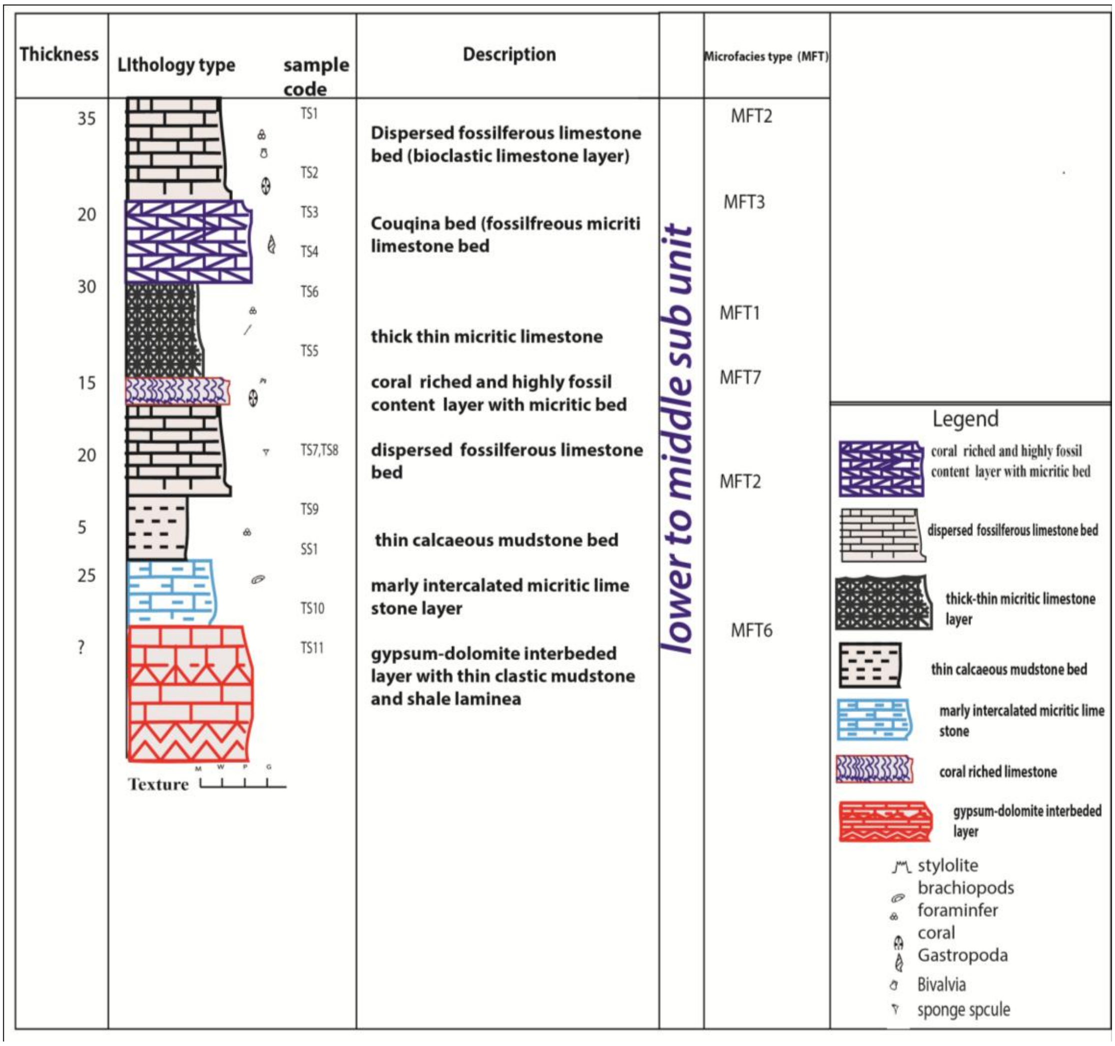


Figure 3.5: Stratigraphic column of carbonate exposures at Togo ridge section, Mugher area, that Show the description for each lithologic units, collected samples and their microfacies type (not scaled).

3.1.1.2. Middle sub-Unit

The middle sub-unit of the carbonate units of the area is measured and recorded at upper Togo ridge section and at lower part of Kersa section one and two. This sub-unit consists of limestone layers showing various components, colors, beds, bedding styles, and bed thickness throughout the unit. All these components are ranging in size from finer to sand- sized and greater carbonate grains. The bottom part of middle sub unit is consists colonial organism bed which is directly overlain by oolitic rich packstone to grainstone layers on the top of lower sub unit. At this sub unit the amounts of grains increases upward and matrix materials decreases upwards then it’s topped by larger fossils fragments bioclastic packstone. The main sedimentary structures observed in this unit are thin-thick massive bedding, laminations and by dominance of various carbonate allochems embedded within sparry calcite cements or micrite. It has about 162m total thickness.

It is differentiated from the lower and upper sub- unit by the absence of clastic layers, its fossil contents and by the dominance of carbonate allochems thoroughly within this unit. In this sub-unit reefal limestone, massive micritic limestones, bioclastic wackestone to packstone layer and marly fossiliferous limestone layers are logged.

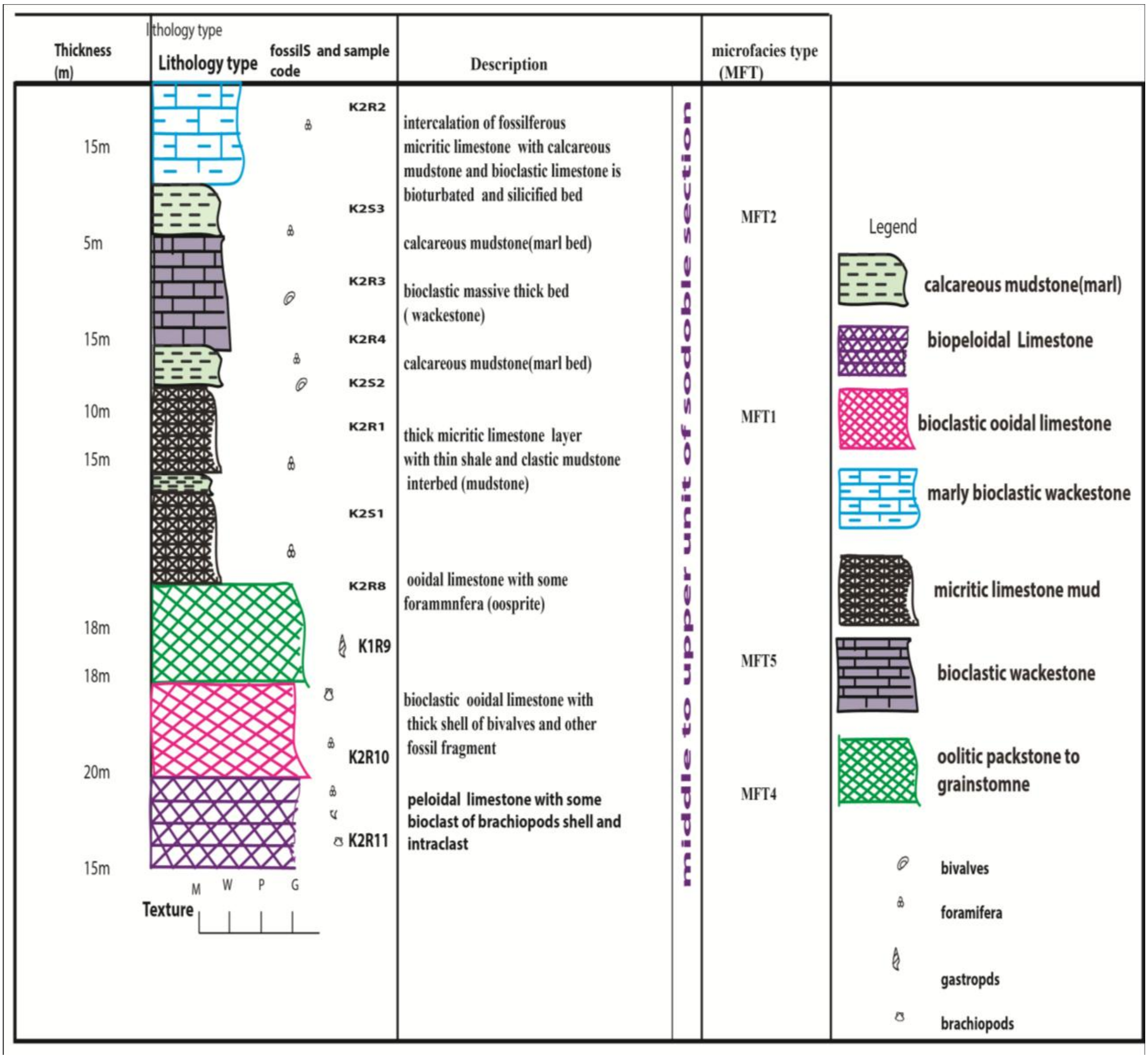


Figure3.6: Stratigraphic column of carbonate exposures at Kersa section two, Mugher area, (not scaled).

3.1.1.3. Upper sub-Unit

This sub-unit is measured partly at upper part of Kersa section one and partly at Kersa section two. It has a total thickness of about 40m. This unit overlies conformably by the upper Sandstone Formation.

All its contents, facies pattern and its stratigraphic positions made this unit different from both the lower and middle sub-units. This unit has dominance fine grained micritic limestone layers intercalation with calcareous mudstone, and thick calcareous mudstone deposit and some nodular and lenses of chert in bioclastic wackestone layer. The macrofossils like corals, echinoids, mollusks and gastropods shells are observed during field investigation. Some sedimentary and diagenetic structures like ripples, stylolite and bioturbation are also seen in this sub unit.

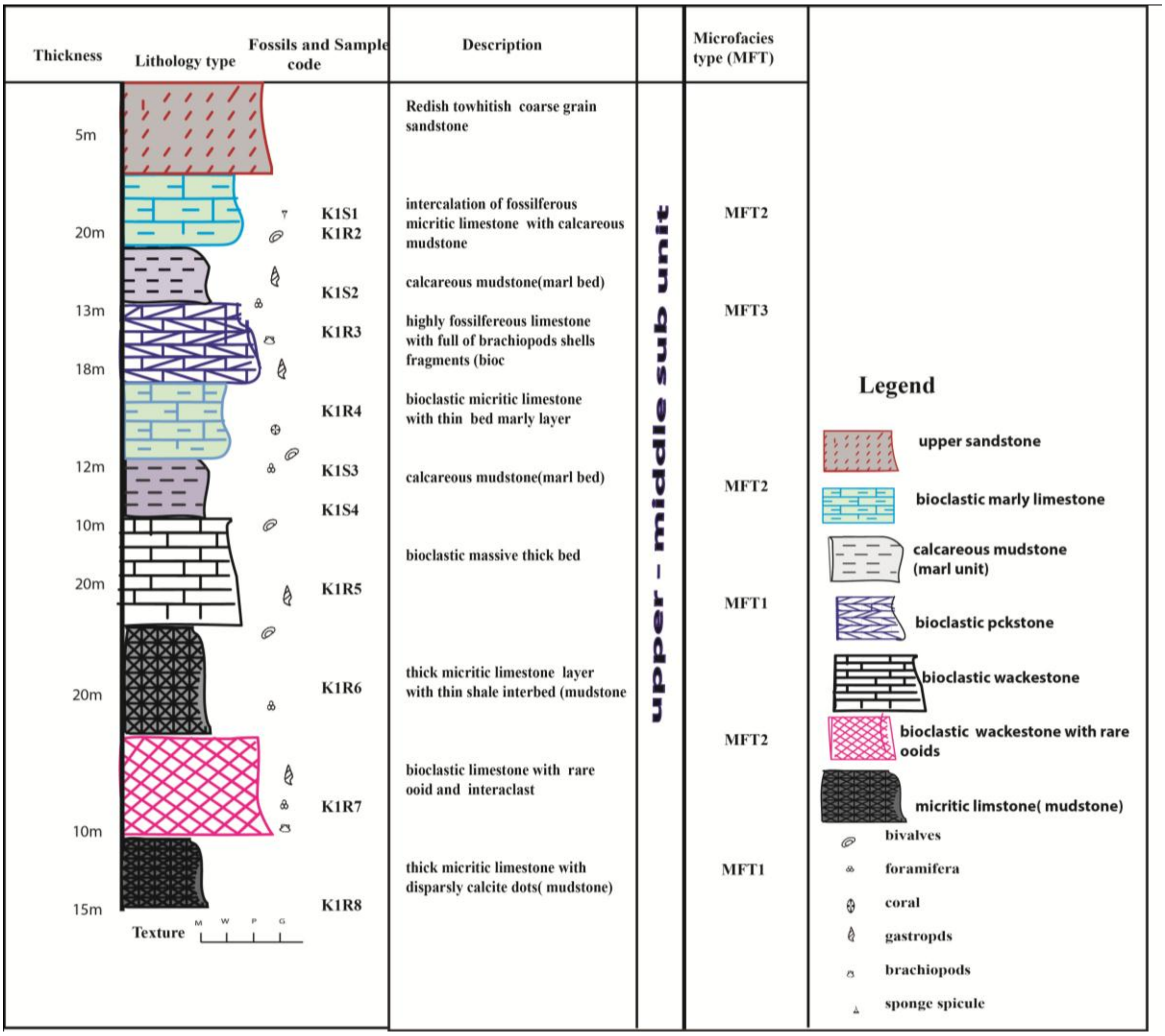


Figure 3.7: Stratigraphic column of carbonate exposures at Kersa section one, Mugher area, (not scaled).

All of the above mentioned carbonate units which are found Mugher area (sodoble section) are logged at Sodoble composite stratigraphic section according to their ascending order in latter section and described as various facies types according to key features such as sediment color, bed thickness, bedding geometry, grain components, sedimentary texture, sedimentary structures and fossil content.

3.1.2. Sodoble Section Lithofacies Type

3.1.2.1. Micrite Limestone Facies

This unit is found at the middle part of Kersa section one and two and upper part of the Togo ridge section. It is red, dark gray blackish and dominantly greyish in colour. In Sodoble section this layer is about 62m interbedded with clastic shale and calcareous mudstone. Within these micrite layers, the carbonate grains like bioclast, intraclast or ooids are rare or uncommon. Along the Togo ridge, micritic limestones are highly bioturbated but at some place they are free from any bioturbation.

This lithofacies type of about 17 m thick beds of fine grained, light gray micritic limestone with rare calcite or quartz cement along the fracture zone are observed at Togo ridge. In upper sub unit micritic limestone layers are contain some bioclast grain like bivalves and brachiopods and intercalated with marl. On the other hand Medium- to thin-bedded dark cherty beds occur in the upper part of the Togo ridge section (fig 3.4B). The fine grain nature and low diversity of fauna of this lithofacies indicates that it depostional seting is restricted nearshore lagoon under quitewater condition.

Figure3. 8: field photograph of micritic limestonewhich shows thin-thick bedding structure, fracture zone and some disturbance of the area at Togo section.

3.1.2.2. Marly Bioclastic wackestone Facies

This unit underlies at some study area (Togo ridge section) with deep micritic limestone layer and overlain the bioclastic wackestone bed of upper sodoble section as discussed above. It has a total thickness of about 55m of light-grey to bluish-grey limestone with thin intercalations of marl. This unit consists of many alternative layers of micritic and calcareous mudstone layers and micritic beds in this layer have rare amounts of allochems like fossils and intraclast.

The most top and bottom of Sodoble section is dominated by grey calcareous mudstone intercalated with micritic and fossiliferous limestone. In particular this calcareous mudstone facies followed by carbonate mudstone indicates that quite water deposition (deepening).

Fig 3.6 field photograph of alternative layer of micritic limestone and calcareous mudstone from middle part of Kersa section one.

3.1.2.3 Bioclastic Marl Facies

This facies is observed at upper and lower part of Sodoble section with light-grey color and diverse skeletal components bivalves, brachiopods, insitu colonial corals, gastropods, echinoids (Fig. 3.4 C). Beds of this facies are interbedded with open deep-marine mud lime (mudstone). The marlstone units in the study area is semi consolidated which vary, from 2m to 6m in thickness in upper part of the sodoble section. This facies has been repeatedly found in the upper and lower part of the sodoble section. On the upper part of sodoble section, this unit has mud dominated layers topped by gypsumferous shale, which are truncated by the fluvial clastic unit, which is called Upper Sandstone Unit, exposed of about 10m thick.

3.1.2.4 Bioclastic Wackestone to Packstone Facies

Bioclastic limestone facies is dominantly observed at the lower and upper part of the Mugher area (sodoble stratigraphic section) carbonate unit. It has dominantly yellowish color. Its facies is varies from bioclastic Wackestone to packstone that indicate from bottom to top of this layer the sequence is shallowing of the environment. The dominant macrofossils are bivalves and brachiopods at lower part and gastropods and broken brachiopod shell at upper part. There are also some corals and echinoids are found in this lithofacies. Most corals at the lower part of middle sub unit are building coral reef structure or colonial form (fig 3.4D) and many Secondary structures like stylolite, biogenic structures and ripples are observed (see on fig 3.2 A and B). In this facies type, the perecence of broken skeletal components indicates high water energy and wave action. According to willson (1975) facies types are mostly depostped at restricted shelf lagoon when wave skeletal debriswere derived from near shoal area or reef.

3.1.2.5 . Bioclastic to Oolitic (Bioolitic) Packstone-Grainstone Facies

These units are characterized by various dominant grains of peloids and ooids with some intraclast and bioclasts. Thin mudstone and shale beds are also present in this lithofacies type. It is measured only at Kersa section two and one sample is taken from Kersa section one which is highly foraminiferal fossil rich oolitic limestone layer. They are dominant at the top part of lower part Sodoble stratigraphic section. The grains are embedded within the sparite dominantly with rare amounts of matrix as observed in thin section (thin section part is not included) They are greyish to black in colour and have the total thickness of about 20m. This layer can be subdivided again into two sub-layers, the bottom to the top: peloidal and bioclastic rich part and middle ooid rich part. From the bottom to the top the bioclast grains are increasing and the layers become dominated with the peloidal intraclastic, Ooidal to bioclastic grains rich.

CHAPTER FOUR

4. Petrographic Description and Microfacies Analysis

4.1. Petrographic Descriptions

Carbonate rocks can be classified based upon their criteria characterizable (such as matrix, cement and carbonate grains) either in thin-sections or hand specimens. There are different types of carbonate rock classification system based on different criteria's (facies and microfacies types). Among these the most commonly used classifications system is Folk, (1957) and Dunham (1962); is also used in this work. Both classifications are based on the particle fabric (texture) and on the kind of particle binding during sedimentation.

In addition to field observations done in sodoble stratigraphic section detail descriptions on 26 representative carbonate rock samples were made under petrographic microscope. According to the petrographic analysis major carbonate components like allochems (skeletal grains, ooids, peloids and intraclast) and interstitial materials (microcrystalline calcite ooze/micrites and sparite) were identified to classify carbonate rocks of sodoble section in to different microfacies type.

From analysed samples, 25 thin sections are pure calcitic limestone and one fine grain dolomitic limestone was observed. Those pure limestone samples are varying in abundances and sizes of components and allochems from place to place throughout the studied section and show various carbonate textures ranging from mudstone (6 of total sample), Wackestone (13 of total), Packstone (5 of total) to Grainstone (1 of total). All these petrographic properties with their depositional environment interpretation are also discussed and some the photomicrographs of the thin section with their petrographic descriptions are given in section. The total proportion of the grain, matrix and cement and the naming of the limestone rocks according to Folk and Dunham classification system are also labelled below on the table.

Table 4. 1: Petrographic descriptions of carbonate rocks samples collected from Sodoble section

Sample no	Major rock components							Rock name		
	Allochem				Interstitial materials		Others	Dunham	Folk	MFT
Sample code	Ooid	Bioclast	Intra	Peloids	Micrite	Sparry				
K1R2	0	48	10	0	32	6	4	wackestone	Biomicrite	MFT2
K1R3	0	72	3	0	14.3	8	2.4	Packstone	Biomicsprite	MFT3
K1R4	0	30	3	0	56.4	10.7	3.4	wackestone	Biomicsprite	MFT2
K1R5	0	14.9	0	0	79.3	2.8	3.6	wackestone	Biomicrite	MFT2
K1R6	0	0	2.7	0	69.3	17.1	3	Mudstone	Micrite	MFT1
K1R7	10	43.6	2	8.6	8.5	22.8	3	wackestone	Biooosprite	MFT2
K1R8	0	5	0	0	86.4	5.4	3.1	Mudstone	Micrite	MFT1
TR1	0	23.6	3	0	60	9.3	4.1	wackestone	Biomicrite	MFT2
TR2	0	19.1	4.8	0	69.4	2.5	5	wackestone	Biomicrite	MFT2
TR3	0	71.25	4.8	0	18.75	5.6	0	Packstone	Biomicrite	MFT3
TR4	0	66.9	9.5	0	9	14.6	0	Packstone	Biosprite	MFT3
TR5	0	10.1	1.7	0	84.6	3.8	0	Mudstone	Micrite	MFT1
TR6	0	17.8	0	0	4.5	77	0	Framestone	Biosparite	MFT7
TR7	0	36.4	2.8	0	52.8	7.8	0	wackestone	Biomicrite	MFT2
TR8	0	40	5	0	48.5	5	0	wackestone	Boimicrite	MFT2
TR9	0	41.4	8	0	45.7	9.3	0	wackestone	Biomicrite	MFT2
TR10	0	47.1	3.6	0	41.4	9.3	0	wackestone	Biomicrite	MFT2
TR11	0	5	2	0	11	25	57	Dolomitic	Dolomicritic	MFT6
K2R1	0	8.7	0.7	0	90.7	1	0.7	Mudstone	Micrite	MFT1
K2R2	0	36.7	1.4	0	58.3	3.8	0	Wackestone	Biomicrite	MFT2
K2R3	0	36.7	3.8	0	58.3	1.4	0	Wackestone	Biomicrite	MFT2
K2R4	0	9.3	0	0	83.6	7.1	0	Mudstone	Micrite	MFT1
K2R5	0	25	0	0	70.7	4.3	0	Wackestone	Biomicrite	MFT2
K2R8	0	5.3	0	0	89	6	0	Mudstone	Micrite	MFT1
K2R9	60	6.8	0	13.1	1.8	18.1	0	Grainstone	Oosprite	MFT5
K2R10	45	24.7	2	13.3	8.3	18.3	0	Wackestone	Oosprite	MFT5
K2R11	17	28.9	0	23.7		17.1	0	Packstone	Biopelsprite	MFT4

4.2 Microfacies Analysis

Microfacies refer to the total of all the paleontological and sedimentological criteria appearing under thin section (microscope). Microfacies analysis of carbonate rocks exhibit depositional criteria reflecting environmental constraints acting during sedimentation. Every facies of one depositional environment has its own distinct petrographical, geographical and paleontological properties which can be clearly differentiated from other facies (Flugel, 2004).

Microscopic study is the most important of the various levels of observation possible in the broad field of carbonate petrography. However, despite the advantages that identifiable carbonate particles offer to environmental interpretation, detailed petrographic study of limestones and dolomites may be difficult because of their susceptibility to diagenetic alteration (Wilson, 1975).

The interpretation of depositional environment from microfacies data needs detail characteristic of the rock. MFT's can be distinguished based on a depositional texture, grains fabric, as well as qualitative and quantitative compositional data of rock. In general view of microfacies types also leads to categorizing of the common microfacies data into 'Standard Microfacies Types or association' (SMFT).

In order to establishing the microfacies type of the sodoble section the texture of the carbonate like allochems type (skeletal grains, peloids, intraclast and ooids) and Intersstial materials (matrix an d sparite) are used

Allochem (carbonate grain) categories are a primary descriptive approach to microfacies type identifcation. For example; oolitic limestones reflect particular paleoenvironmental conditions such as water energy 'and transport processes and depositional settings. The skeletal grains are also significant proxyes for paleoenvironmental conditions because they are highly sensitive to processes characterizing specific depositional environments.

The composition of bioclastic carbonates depends on many factors including skeletal mineralogy and the path of taphonomic and diagenetic processes examined. The type and association patterns as well as the abundance of grains are the basic criteria for the discrimination of significant microfacies types and depend on textural and compositional criteria.

Different depositional environments of carbonate unit are described by different numbers of microfacies types. The number of MFT's is highly variable by its depostionl environment because of the differences in the frequency of deposited material, energy and depth of basin

(Flugel, 1982). Generally, the quantitative differences of rock constituents, diversity and abundance of biotas, the relationship of one biota and sedimentary structures aid in making microfacies types identification.

On the basis of indicative microfacies and lithofacies criteria observed from field and thin sections for carbonate unit of Sodoble stratigraphic section seven microfacies types were identified. The classification of the MFTs was based on Dunham (1962) and Folk (1962) classification system. All these major microfacies types are described based on their its components, supported with photomicrograph, interpreted with respect to their depositional environments and compared with standard microfacies types (SMFT) and facies belts (FB) of (Wilson, 1975,;Appendix 1). The detail explanation for each of them is given as follows:

4.2.1 Micritic Microfacies (MFT1)

Description: Micritic Microfacies of sodoble section is characterized by numerous numbers of thick to thin limestone layers. In some area this layer contains rare grains of skeletal and non-skeletal grains which are less than 10% from average components. Extremely rare foraminifers are well preserved in this microfacies type. It's common throughout the all measured stratigraphic sections at deferent levels and is obtained from sample number (K_1R 6, 8, k2R1, 8 and TR_5). Micritic limestones with dots of sparry calcite cements (k1R8) are also observed at lower part of Kersa section one. In the lower Sodoble these microfacies have a thickness of around 10m and consist of thin-thick bedded micritic limestones with rare fossils. In the upper Kersa section one and Togo ridge these microfacies layer have rare amounts of bioclasts with some Silicification. These micritic microfacies are also highly fractured and those fractures are filled by sparry calcite cements at places (Plate 4:1 B).

Interpretations: Calcareous mud in warm water setting comes from the breakdown of green calcareous algae, in organic precipitations from sea water and from disintegration of large skeletal particles into their smallest crystallographic unit. These muds accumulated in quite water areas that are not affected by tidal or strong oceanic currents (Tucker& Wright, 1990). Such habitats are found in deep water shelf/ramp areas below

Plate 4.1 Microphotos of micritic microfacies

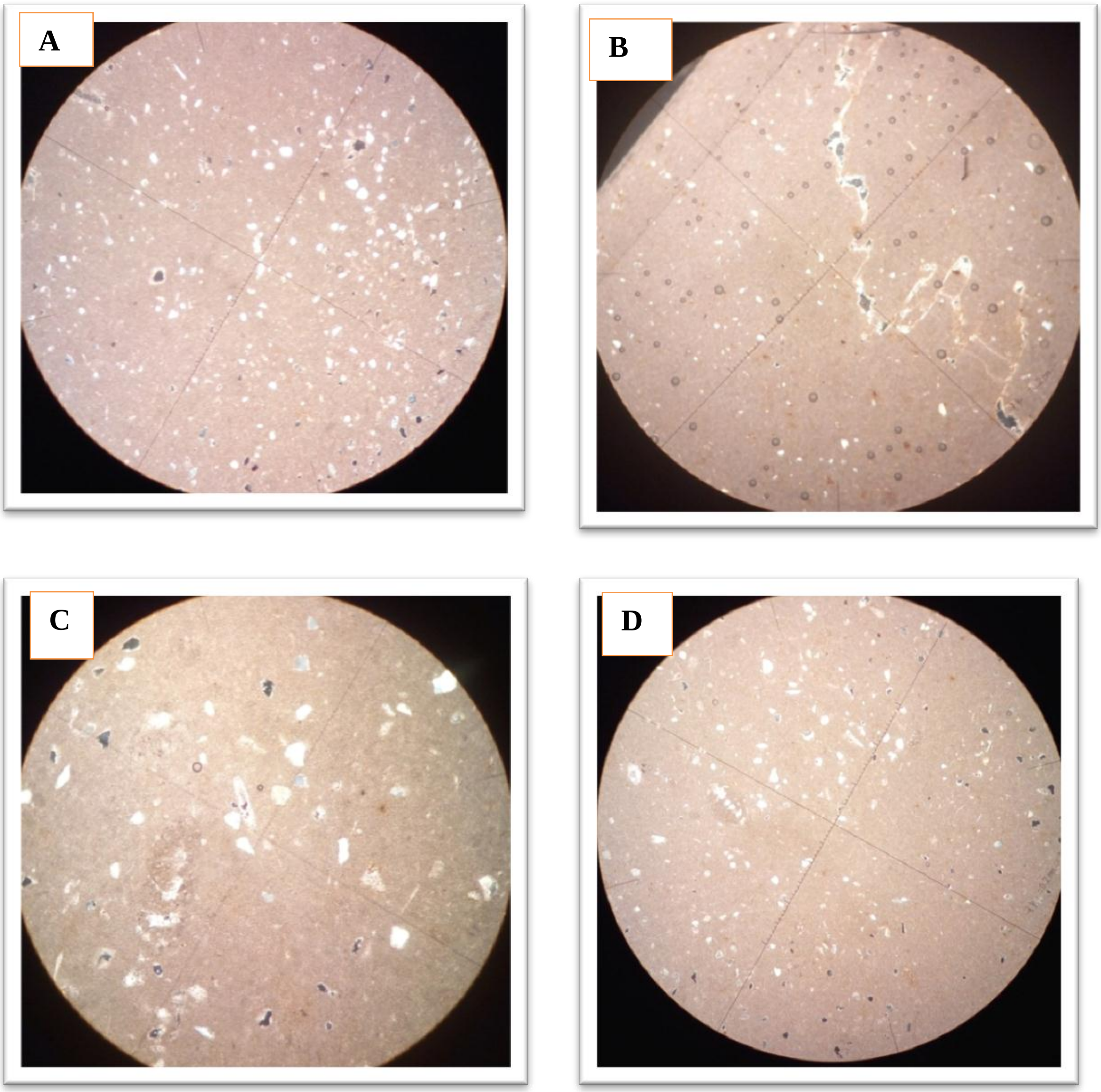


Plate 4.1: Micritic limestone micrograph; (**A)** micritic limestone microfacies with sparsely calcite dots **(B)** the fractured micrite layers and form stylolite like structure (Fracture filled partially with calcite cements, which are the results of burial compaction processes. From microphoto of sample K1R8, x40) and from sample no K2R1 30xX under PPL respectively **(C)** dark greyish micritic layers with coarse calcite cement at pore spaces (white spaces) formed by the dissolutions of micrite and cemented with calcite mineral, and large forams grain from Sample K1R6, under PPL **(D)** Micritic microfacies with fine calcite dots and nauthiculina foraminifera shell grains sample K1R6 under PPL x40.

wave base or in the lee of islands and shoals (Brain and Andre, 1992). These microfacies are associated with some clastic shale, chert and silica layers, at places and also they are fine grained, massively bedded and dark to grey in colour in field observations. And it's compared with SMF type 3 of Wilson belongs to facies belt 3 which, is deposited in deep shelf margin or basin margin.

4.2.2 Bioclastic Wackestone/Floatstone Microfacies (MFT2)

Descriptions: These microfacies were characterized by mostly greyish colour, thin to medium bedded, hard with some shell fragments during field observation. It is characterized by low fossil diversity, high mud content under petrographic study. Fossils of brachiopod, bivalves, echinoids, corals, foraminifera (*Kurnubia palastiniensis*), *dysacladean algae*, *sponge spicule* and gastropod shells imbedded within micrite materials and very rare amounts of sparite are very commonly seen. In lower part of middle sub unit of sodoble section (K1R7) this microfacies observed with some ooids grain and dominated bioclasts. The allochems size is varies from fine to sandy and its grain proportion is less than 50% from total limestone texture. In field observation these layers are mostly seen intercalated with marl and observed in various levels throughout all sections. The best example of this microfacies is obtained from sample no k1R2, 4, 5, K2R3, 4, 7and TR1, 7, 8, 9, 10; those are from all sub-units as located on stratigraphic sections. In this microfacies type the stylolite and some cementation are the most common diagenetic processes. Some microphotographs of thins section for this microfacies is given in (Plate 4:2 A-D).

Interpretations: - These microfacies types are accumulated on warm water platforms where current activity has been insufficient to remove out the mud (Flugel, 2004). As such they tend to be located away from the edges of platforms or on deeper parts of ramps where there is some protection (Brain & Andre, 1992; Walker, 1992). During field observation this microfacies layer is highly intercalated with calcareous mudstone at lower and upper part of sodoble section. It is compared with SMFT 9 of Wilson (1975) which belongs to facies belt 7or 2, which deposited in open platform or shelf lagoon, or open sea shelf.

Plate 4.2 Microphotos of bioclastic wackestone microfacies

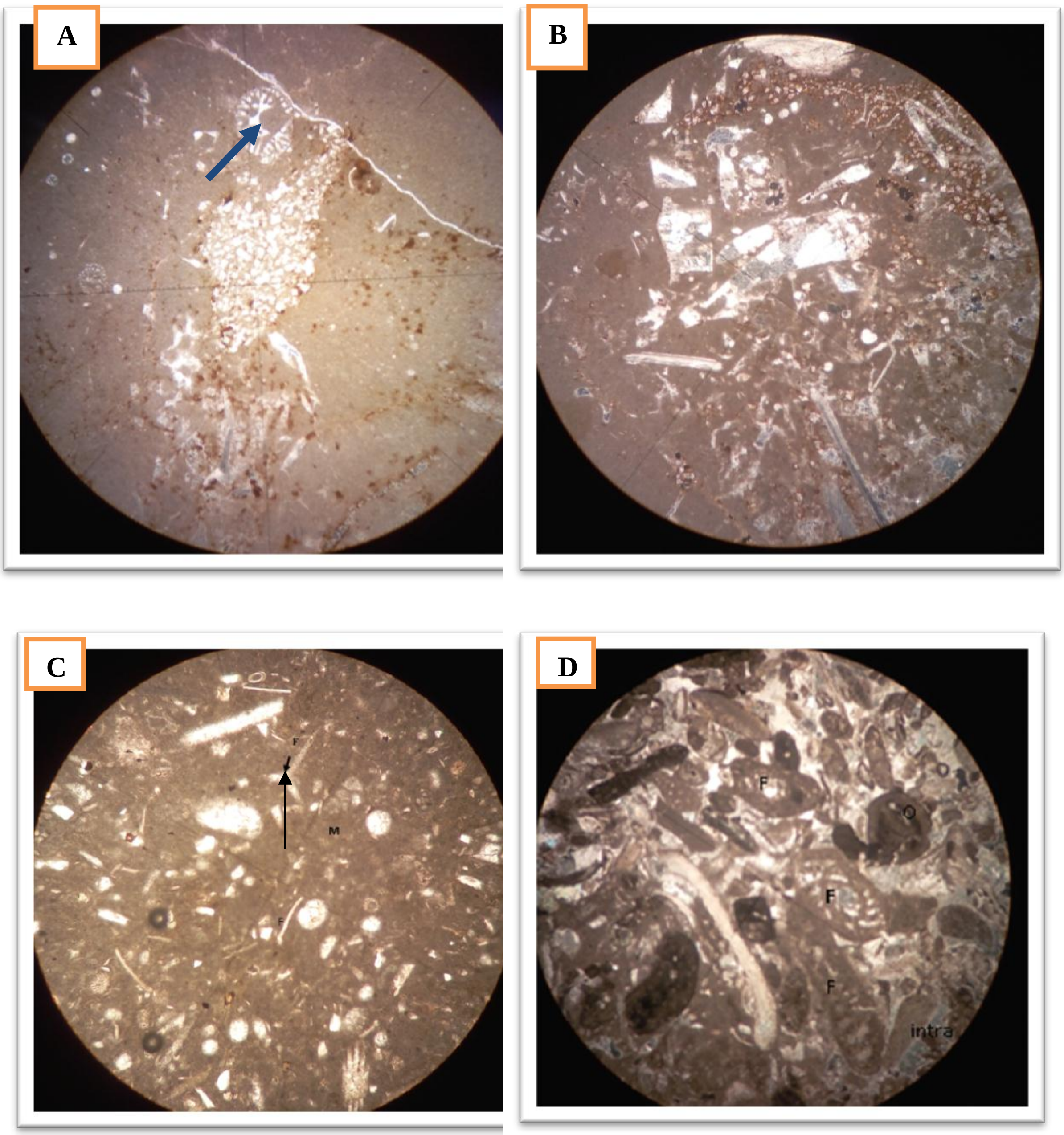


Plate 4.2: A- D) Bioclastic wackestone microfacies bearing various shell fragments within the micrite fine materials. **(A)** Bioclastic wackestone containing Kurnubia palastniensis (arrow) x40 under PPL Sample K1R5 6. (**B)** Highly bioturbated Bioclastic wackestone containing varieties of shell fragments x10 under PPL from Sample no TR8. (**C)** Bioclastic wackestone containing valvulina .sp (arrow) and sponge spicule(black arrow) with micrite matrix from Sample TR10 under PPL with x40 magnification.(**D)** Photomicrography that showing Bioclastic wackestone microfacies in which micritized ooid grain scarcely dispersed matrix the photo is taken x30 magnification under PPL, from Sample no k1R7.

4.2.3 Bioclastic Packstone /Rudstone Microfacies (MFT3)

Description: This microfacies type is mainly measured at the upper part of the study area (sodoble stratigraphic section). Sample number K1R3 and TR4 are indicates the

Plate 4.3 Microphoto of bioclastic packstone microfacies

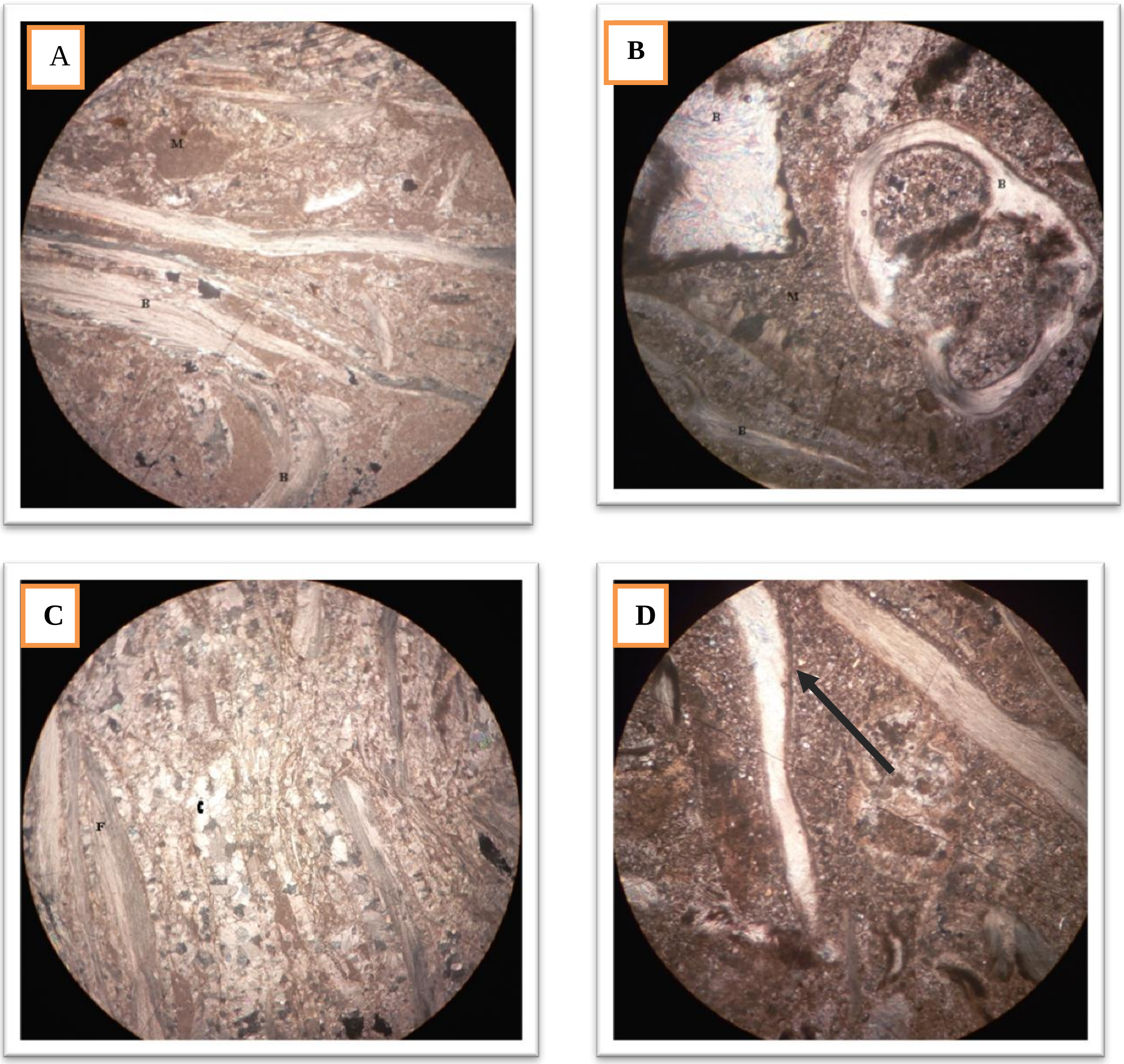


Plate 4.3: A) photograph of a thick-bivalve shell that showing the foliated calcite structure, from sample K1R3, under PPL, x30 **(B)** bioclastic packstone that contain the varieties of shell fragments that embedded with micrite matrix and thick gastropod mold is observed sample TR4 under PPL x30 **(C)** bioclastic packstone that shows the shell fragments is replaced by calcite aragonite mineral: photo is taken from sample K1R3 it is also under PPL **(D)** shows the brachiopods shell with micrite envelope and imbedded by micrite matrix sample from TR4, under PPL 30x magnification.

bioclastic packstone layer of Sodoble section. It consists of very coarse and large fragment of fossil and other components which is embedded by micrite matrix. Those fossils are thick shell fragment of bivalves like oysters and brachiopods shells and gastropods. Most gastropods shells in this microfacies type are dissolved and its mold is filled by carbonate mud. In the field observation this microfacies layer is interbeded by calcareous mud and dark coquina like bed (see fig 3.4 C).

Interpretations: This microfacies shows the character of carbonate slope deposits. The slope deposits mainly contains carbonate grains like mud-free sediments, intraclast packstone-rudstone, other boulder- rich sediments and most of them are resedimented (Brain & Andre ,1992). In this microfacies type is observed in the lower and opper part of soddble section and it is compared with SMF Type 5 and 10, which belongs to Facies belt 4 and 2 of Wilson respectivley, those are fore slope and sometimes in offshore deposits.

4.2.4 Biopelodial Packstone- Grainstone (MFT4)

Description: This microfacies type is measured along Kersa section two lower parts from sample no K2R11. It contains the dominant of peloids an average 40%, ooids account for 10% and fine to coarse grained intraclast and bioclasts including gastropods, benthic foraminifera and thick brachiopods for average 30% of the total volume. There is also some aggregate grain were observed in this microfacies type. In some view the fossil shell and ooids are also micritized. In the field observation this microfacies layer is dark and coarse grain with fine fossils are observed.

Interpretations: Mud peloids are characterized by the similar composition of the micrite forming the peloids and the micritic matrix; irregular contact between areas with and without peloids (interpreted as bottom reworking). They area formed by synsedimentary and post sedimentary reworking of carbonate mud and micrites (Flugel, 2004). Many Wackestone and packstone are formed of pellets that reflect the activity of burrowing animals. If cemented early such fecal pellets are preserved and become the dominant constituents of resultant wackestone or packstone.

In addition, poor sorting, a broad spectrum of peloids shapes and sizes as well as repeated occurrence within a stratigraphic profile provide evidence for interpreting the grains as lithicpeloids. They tend to form away from edges of platforms (Burchette and Wright, 1992; Walker, 1992). In field observations this peloidal packstone layer is associated with oolitic microfacies; therefore, this facies is compared to microfacies type 12 and facies belt 6 of Wilson (1975), which deposited in platform area.

Plate 4.4 Microphotos of peloidal wackestone microfacies

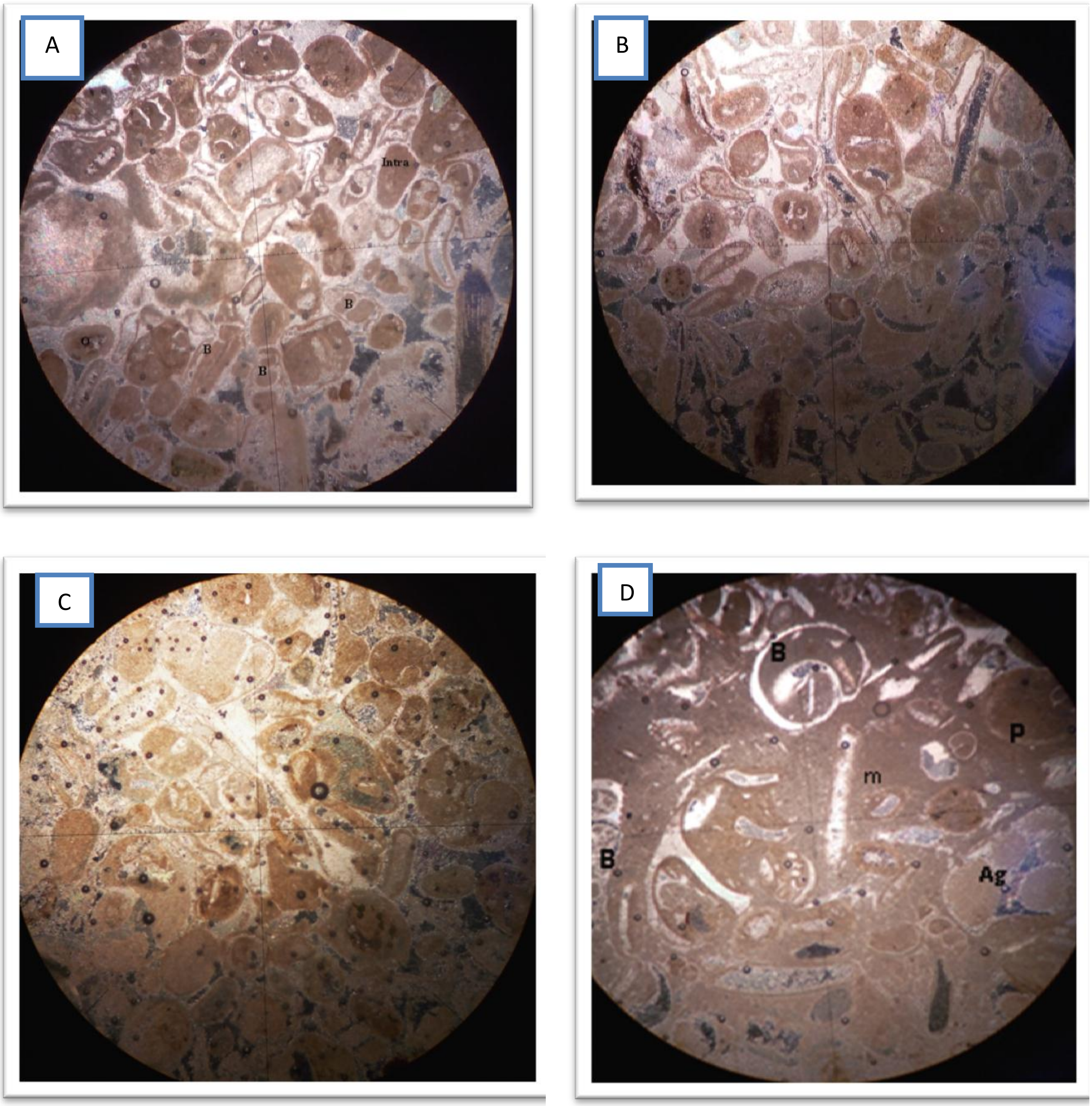


Plate 4.4: **A-C**) Microphoto of sample K2R11 that Showing the Biopelodial packstone in which contain fossil fragment and various shaped carbonate clasts (Intra) are imbedded in the micrite matrix and the grains are poorly sorted and irregular in shape. (**D)**Microphoto of the same sample showing the bioclastic packstone showing the aggregate grain of peloids(**Ag**) and are imbedded together by micrite matrix, from sample K2R11 under PPL by 30X magnification.

4.2.5 Oolitic Packstone to Grainstone Microfacies (MFT5)

Descriptions: This microfacies is the most dominant facies at lower part of the carbonate unit at Kersa section two and obtained from sample K2R9 and K2R10. The tangentially structured ooid grains ~ 60% are imbedded in the sparite cements (Plate 4: A-D). Some of the ooid grains have quartz grains as their nuclei. There are also rare amounts of micritized skeletal fragments and non-skeletal grains and detrital quartz grains observed in this facies. The grains in the facies are moderate to well-sorted and reaching carbonate sand in size. The ooid grains are calcified and also dissolved at places and larger crystal cements are observed between grains. There are also some micritic envelops on the skeletal grains and on some ooids grains mainly preserving their shape. This microfacies type is observed at the top part of lower sodoble sub unit.

Interpretations: This microfacies is interpreted to be deposited around high energy area such as carbonate shoals and Barrier Island or beaches. Warm water grainstone formed of bioclasts, ooids, and peloids are usually occurring around high energy areas such as shoals, and beaches in inner ramp/shelf (Burchette and Wright, 1992; Reading, 1996). These carbonate sand bodies and material in the form of bioclastic debris and ooids is reworked by wave action into ridges that form strand plains along the coast or barrier islands separated from the shore by a lagoon (Wright, 1984; Tucker & Wright, 1990). The texture of carbonate sediments deposited on barrier island and strand plain beaches is typically well-sorted and with a low mud matrix content (grainstone and packstone), which is characteristics of this microfacies. The lower beds of this microfacies are full of ooids; subsequently alternations of ooids and bioclasts succeed. Up-section bioclasts increased in abundance and the uppermost beds are fully bioclastic. This microfacies is compared with SMF Type 15 of Wilson, belongs to Facies belt 6, which is deposited in winnowed platform edges.

Plate 4.5: Microphoto of oolitic microfacies

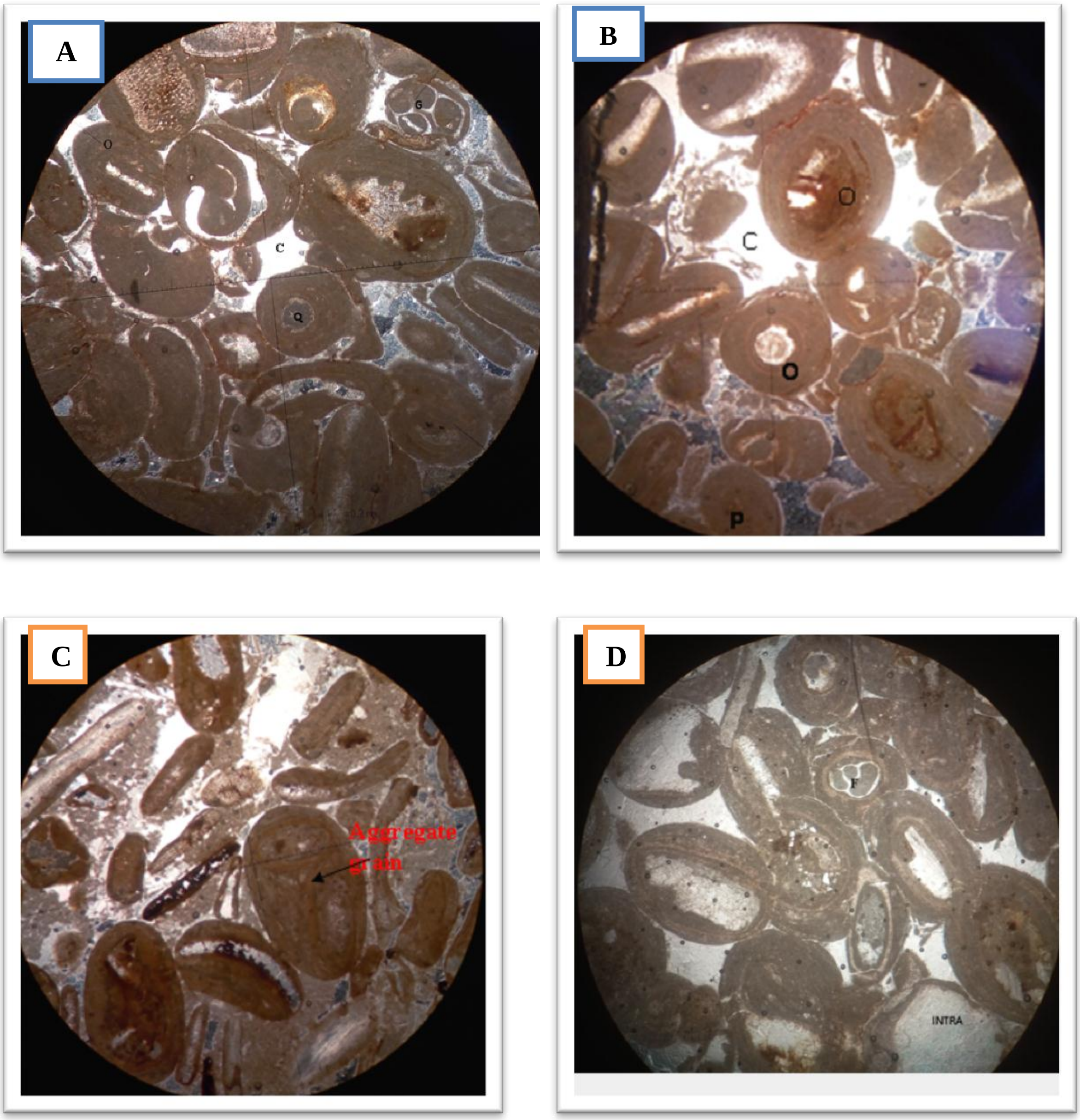
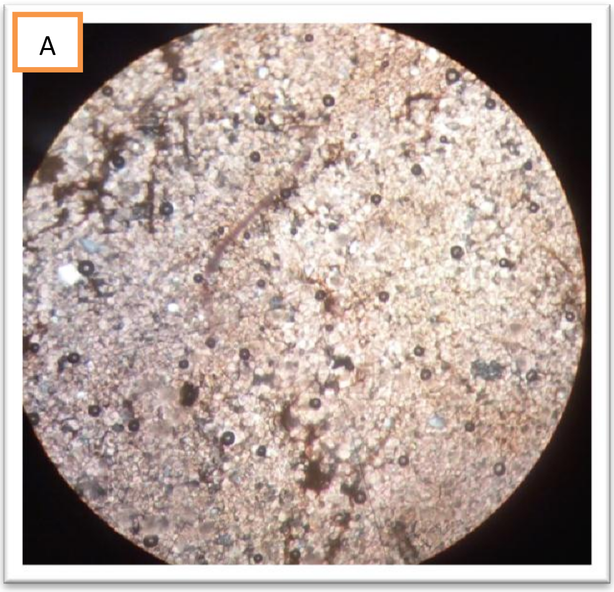


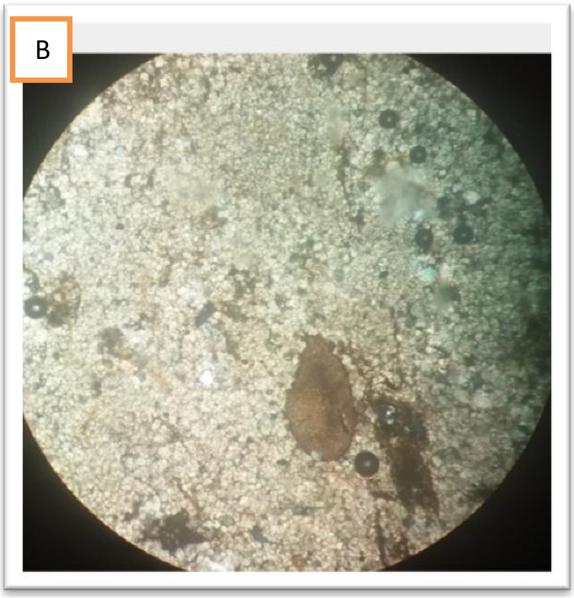
Plate 4.5: **(A&B)** Photomicrography showing the oolitic grainstone microfacies in which ooid grain spherical shaped with internal nucleus, labelled with rare amounts of quartz grains and fossils are imbedded within the sparite cements, quartz grains (Q) as the nucleus of ooid grain are also observed. Ooid grains are coarser in size and moderately sorted, the ooid grains in **(B)** are micritized from sample K2R10, PPL and with magnifications of 40X **(C)** Showing the larger aggregated Ooid grains (high energy environment product) surrounded by micrite matrix. From the same sample (**D)** Micritized concentric ooid grain and intraclast cemented together forming carbonate sands, also most of the grains are compacted and broken. Microphotograph **C** and **D** are taken from sample K2R9 under PPL.

4.2.6 Dolomitized Micritic Microfacies (MFT6)

Descriptions: This microfacies is observed at the lower sub unit of sodoble section at Togo ridge. In this microfacies fine grain dolomite crystal imbedded with calcite cement and small micrite was observed. It is not common in studied sections and obtained from only samples collected of lower Togo ridge sections (from sample No.TR11). At this microfacies the relics of original carbonate grain is limited. However some micrite and micritized fossil fragments are gives some evidence to that the rock is limestone and which presumably originally aragonitic shell preferentially replaced by

Plate 4.6: Microphoto of dolomitic microfacies





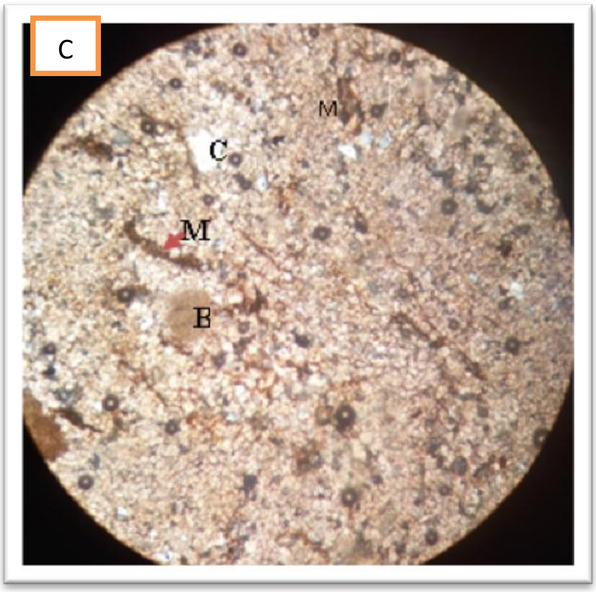


Plate 4:6A- C) The partially dolomitized micritic-bioclastic limestone, in which micrites are replaced by some smaller dolomite crystals (sample TR11, collected from lower of Togo section). In photo **(C)** some micrite and dissolved bioclast preserved that indicates the bioclastic limestone is micritized and the bioclast grains are replaced All photographs in this plate are under XPL, with 40X magnification

dolomite or dissolved. In the field observation this facies layer is slightly react with hydrochloric acid that indicates limestone is highly dolomitized. The particular dolomitization photomicrographs examples are given in (Plate 4:7A-C).

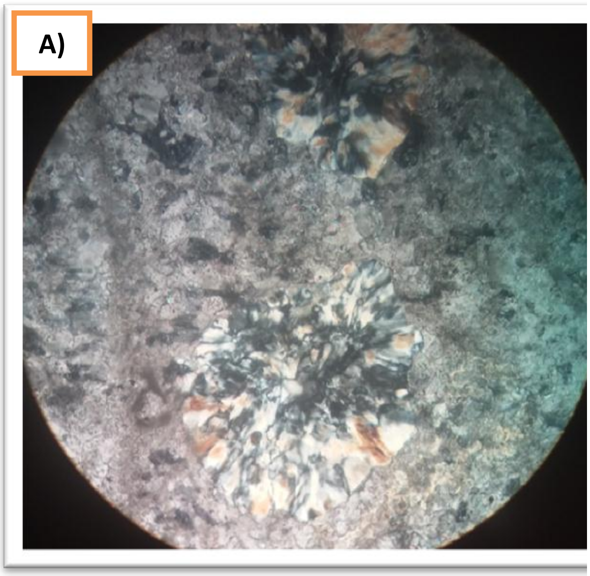
Interpretations: This microfacies is deposited under low energy conditions of restricted environments, shallower part of lagoons of tidal flat environments. Owing to their very shallow water origin peritidal carbonates are liable to freshwater invasion, leading to early diagenetic alterations by meteoric processes and dolomitization (Wright, 1984). These dolomites are most probably mixing zone replacement dolomites. In the field observation this microfacies is observed at the contact area of the beds of gypsum, dolomite layers and some clastic layers of mudstone (Togo ridge). Therefore it's compared with facies belt 8 of Wilson (1975), which is deposited in restricted platform.

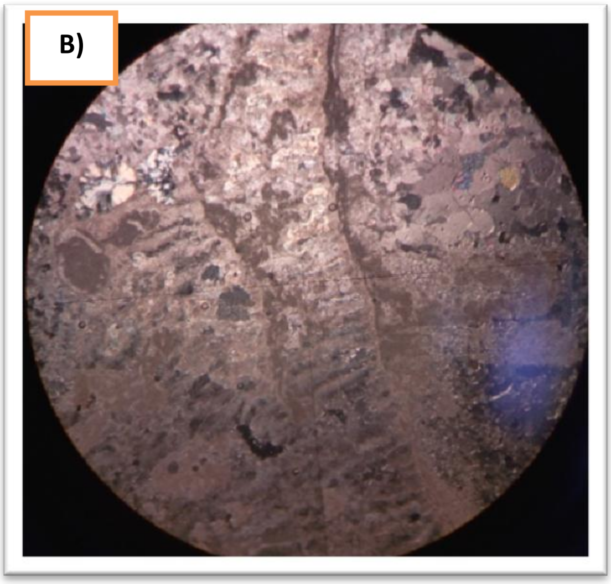
4.2.7 Boundstone (Reefal) Microfacies (MFT7)

This microfacies type is recognized in carbonate succession of middle part of Togo ridge from sample no TR6. In the field observation this layer is reached by colonial corals which is highly silicified and coarse light minerals is clearly observed and massive upright and robust forms and insitu massive coral fossils which construct a ridged framework.

Interpretation: The reef debris deposits (MFA2) in association with coral-stromatoporoid-microencruster Boundstone (MFA3) are interpreted as an equivalent of the fore-reef/upper-slope "Plassen"-type limestones, described by Schlagintweit and Gawlick (2008) from the Northern Calcareous Alps. They also resemble the platform- margin *Ellipsactinia* facies of the Central Apennines (Rusciadelli *et al.*, 2011), characterized by similar sedimentary settings. Other close facies associations have been described from several areas of the Romanian Carpathians (Bucur, 1978; Bucur and Sãsãran, 2005; Bucur *et al.*, 2010a, b; Bucur and Sãsãran, 2012). Therefore this microfacies is related by encrusting massive fossils which construct a rigid framework and is belongs to standard microfacies type 7 which is facies belt 5 of Wilson, which is deposited in organic buildup environment.

Plate 4.7: Microphoto of reefal boundstone microfacies





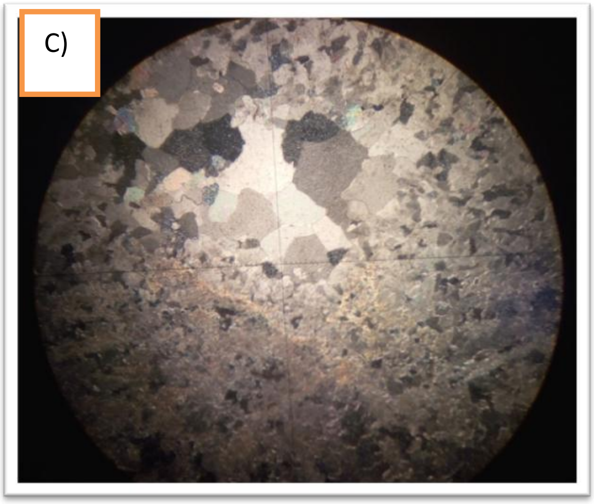


Plate 4:7 photomicrography that shows Diagenetic alterations of the corals. (**A)** Silicification of septa form fibrous quartz crystals (chalcedony) or replaced by microcrystalline quartz; (**B)** the whole Skeleton of coral is mostly micritized (m), other parts of septa are changed into equant calcites, cavities among septa are filled (**C)** All skeletal elements are changed to blocky calcite crystals in the late stage of diagenesis All photo is taken from sample TR6, under XPL x40 magnification.

4.3 Diagenesis

Diagenesis is the term used to define all the changes which occur in sediments during the interval between deposition and lithification. These diagenetic changes may take place in the submarine, subaerial fresh water and subsurface environments. The various diagenetic processes usually produce mineralogical changes, dissolution, precipitation and textural modification of carbonate rocks (Al-Dabbagh, 2006). It includes processes such as compactions, cementation, mineral recrystallization, replacement etc. Diagenesis occurs more readily in limestones than in terrigenous siliciclastic rocks because calcium carbonate is easily soluble.

The field and petrographic observations of Mugher area (Sodoble section) carbonates indicate as they undergo several diagenetic processes. Compaction, fractures, stylolization cementation, micritization, dissolution, dolomitization and Silicification are common diagenetic features observed in Sodoble section. These processes are described in the following section.

4.3.1 Cementation

Cementation is the one of diagenetic process of filling of the pore space or cavity filling through chemical precipitation from solution. It is one of the most common diagenetic processes (Prothero and Schwab, 2014). It's the process in which chemical precipitates (in the form of new crystals) form in the pores of a sediment or rock, binding the grains together (McIlreath and Morrow, 1990). In the Mugher area (sodoble section) cementation is the most diagenetic feature which is found in different places and some example is given (plate 4.3 A).

4.3.2 Compaction

Compaction of carbonate sediments occurs through pressure due to overburdens and deep burial. Compactions may be physical or chemical. Physical compaction is the diagenetic process under which the inter-grain space reduces and results in the overall reduction of porosity of the rock (Adams and Mackenzie, 1998). Stylolite (Fig 3.2: A) which found in upper Sodoble stratigraphic section is indicator of chemical compaction of carbonate sediments in the area. Chemical compaction is result due to increasing overburden, which cause the grain to grain contacts take place first and then simple grain contacts developed into sutured grain contacts. Later on dissolution of grains starts at these contacts (Adams and Mackenzie, 1998). In the sodoble section some ooid grains and other carbonate allochems are compacted in middle section (plate 4:5, D).

4.3.3 Micritization

Micritization is a process of alteration of original skeletal grain fabric to a cryptocrystalline texture by repeated algal microborings and subsequent filling of the microborings by micritic precipitate (Bathurst, 1966). In sodoble section micritization is abundantly seen in upper part of Kersa one and Togo ridge section, the micrite envelopes are mainly around skeletal grains (pate 4.5, C), rarely around some ooids.

4.3.4 Dissolution

Dissolution occurs when the rock -water system is out of equilibrium (Mcilreath and Morrow, 1990). Dissolution produces pore space by dissolving pre-existing minerals. Most of the time dissolution produces voids where aragonitic or high-Mg calcitic fossils were dissolved (Prothero and Schwab, 2014). Dissolutions of carbonates grains are seen on some skeletal and non-skeletal components of the section carbonates. Mostly it forms different pore spaces also at places these pore spaces are in turn infilled by the late stage sparry calcite cements (Plate 4.1: A).

4.3.5 Stylolization

Stylolites are serrated surfaces within a rock mass at which mineral material has been removed by pressure dissolution, in this process total volume of rock decreases. Insoluble minerals, such as clays, pyrite and oxides, remain within the Stylolites and make them visible (Adams and Mackenzie, 1998). Stylolite formation is associated with thin water films that allow solutes to move away from sites of dissolution. In Sodoble section as discussed above macro-stylolite on lithologic units at out crop scales are observed in the upper Kersa section one (Fig.3.2: A).

4.3.6 Silicification

Silicification is the diagenetic process in which the carbonate minerals are replaced by silica (SiO2) (McIlreath and Morrow, 1990). The silica which replaces carbonate minerals is mostly derived from biogenic; therefore, it is especially prevalent in deep-marine sediments from active upwelling zones and shallower-water carbonates from nutrient-rich carbonate shelves. But also detrital quartz grains that are transported by the wind to carbonate banks can be a source (Prothero and Schwab, 2014). One of the most important diagenetic features which observed in the studied section is the Silicification on corals, which is found either as pore-filling among corals (plate 4:7 A, B) or as partial to complete replacement of skeletons (plate 4:7 C, D). They precipitated in the form of fibrous quartz as spherulitic chalcedony. This feature is observed in both petrographic study (TR6) and field investigation as chert unit interbeded with micritic limestone.

4.3.7 Dolomitization

Dolomitization is the processes of calcite to dolomite conversion and results in volume reduction and an increase in porosity (McIlreath and Morrow, 1990). According to the same author this conversions takes place in two main environments: 1) coastal areas where mixing of meteoric waters and seawater takes place, this process form coarse-grained dolomite, and 2) Sabkha (supratidal) areas where Mg-rich, Ca-poor brines/seawater seep/percolate into limestones and form fine-grained dolomite. In Sodoble stratigraphic section dolomitic limestone are observed at Togo ridge which is formed by more or less dolomitization processes. This unit is identified under petrographic study. In this layer the limestone is completely dolomitized but there is some micrite preservation observed (plate 4:6A-C).

CHAPTER FIVE

5. Paleontology of Mugher Area (Sodoble Section)

5.1 Introduction

Palaeontology concerns the evolution, morphology, and taxonomy of fossils. Fossils can be used in different ways in geology. In biostratigraphic zones they are the main tool to study the relationship with rocks. In particular Foraminifera are important biostratigraphic tools because they typically evolve rapidly, are abundant, widespread and species or groups of species often became extinct quite suddenly (Hallock, 1982). Many species can therefore be used for local or even regional correlations and aging.

Also study of fossil help to inferring their behaviour when they were alive, their habitats, and mutual relationships. Therefore depositional environment analysis of a rock is highly depends on identification and interpretation of fossils that the rock contains (Selley, 1996). Since fossils are rock builders as in limestones, study of them help is used to know relationship between facies analysis, biostratigraphy and fossil.

In the carbonate rocks of the sodoble section different macro and microfossils are present. Conversely those invertebrate fossils are preserved predominantly as mold and cast. Due to poor preservation and removal of body shell, their taxonomic identification has made some difficulties. Then it was prepared and identified down in the laboratory to the species and genus level wherever possible. In addition the classification was made based on identification and description of observable fossil mo rphology and comparison of previous related works. From macro fossils recorded during fieldwork including Bivalve (Pholadomya. sp. Eligmus SP., Musculus somaliensis), Brachiopod: (Daghanirhynchia sp), Gastropods (Ampullina. sp) are identified at gnus level.

Micropalaeontological analysis of collected samples from studied sections has led to the identification of about 120 foraminiferal taxas from which at least 17 Genus and 10 species have been recognized. Those microfossils like *Kurnubia palastiniensis* (Henson, 1948), *Lenticulina subalata* (Reuss, 1854), *Alveosepta jaccardi* (Schrodt, 1894), *Lenticulina quenstedti* (Gümbel, 1862), *Pfenderina gracilis* (Redmond, 1964), *Verneuilinoides minuta* (Said and Barakat, 1958), *Haplophragmoides bartensteini* (Kalantari, 1969), *Nautiloculina olithica* (Mohler, 1938) and *Choffatella.sp*) as well as sponge spicules, algal species and ostracods (*Cytherelloidea sp.*, *Bairdia sp., Cytheropterina sp., Procytheridea sp. cypridia sp .and paracypridia sp.)* are identified.

The comparison with published paleontological work from country like Egypt, Saudi Arabia, India, Israel and Lebanon as well as Ethiopia etc is done. Identification of fossils under thin section has been also carried out during petrographic study. The micro and macro fossils those collected from Sodoble section those listed above are described and discussed as follows:-

5.2 Foraminifera

Foraminifera are small, predominantly marine protists that construct chambered shells (tests). The group belongs to the phylum Sarcodinall and the class Rhizopoda. They usually develop shells (test) like: chitin, agglutinated, calcareous or rarely siliceous material. It is very important microfossil type in time markers for biozonations of shallow and deep marine carbonates. They are also excellent environmental indicators and help in reconstruction of ancient depositional environment.

The cell of foraminifera is enclosed by a test consisting of a single chamber or several chambers each connected by one or several openings. Most foraminifera are multi chambered. The chambers are arranged in whorls or septa. They may be uniserial (forming a single linear series), or multi-serial (two or more chambers per whorl). Chambers of foraminifera are divided by suture. Aperture is an opening which found in the foraminifera mostly in the final chamber of wall. The external surface of their tests is smooth or variously ornamented (e.g. spines and keels). Particularly calcareous foraminifera are often highly ornamented; this is due to an excessive amount of calcareous material (Cushman, 1928).

Foraminiferal species are identified one from the other by their wall composition, microstructure, chamber arrangement, depression or elevation of sutures, apertural characters, chamber form and ornamentation. Wall composition and microstructures are the most important features used in the classification and taxonomic differentiation of foraminifers on a generic level (Cushman, 1928). Organic (protinaceous), agglutinated and secreted calcium carbonate or more rarely silica are the basic wall compositions of foraminifera. During field investigation 9 (nine) marl samples are collected from Sodoble section; from this more than 120 foraminiferal taxa of calcareous benthic forams were extracted.

The brief description and characterization of each foraminiferal specimen which are extracted from Sodoble stratigraphic section sediments as well as thin section data is done. In the

"Remarks" important references to the respective taxa are cited, their geographic distribution with referenced materials and some diagnostic properties is described. The image for all described species is given in plates 2.

The systematic classifications of Cushman (1928; 1933; 1950), Alhussein, (2014), Said and Barakat, (2014), Youssef and El-Sorogy (2015), Yabe & Hanzawa, (1926) and Henson (1948) are used for identification of foraminifera species.

The taxa recovered from Sodoble section includes; *Lenticulina subalata* (Reuss, 1854), *Lenticulina quenstedti* (Gümbel, 1862), *Kurnubia palastiniensis* (Henson, 1948) *Nautiloculina olithica* (Mohler, 1938), *Verneuilinoides minuta* (Said and Barakat, 1958), *Haplophragmoides bartensteini (*Kalantari, 1969), *Pseudocyclammina lituus* (Yokoyama, 1890), *Alveosepta jaccardi* (2001) and *Choffatella sp*. Description for each species is given as follows:-

Alveosepta jaccardi spices

Kingdom Protista, Hogg, 1861

Phylum Sarcodina, Schmarda, 1871

Class Rhizopoda Siebold, 1848

Order Foraminiferida, d' Orbigny,

Family HOTTINGERITIDAE Loeblich and Tappan, 1985

Alveosepta Hottinger, 1967

Type species: *Cyclammina jaccardi* Schrodt, 1894.

1894. *Cyclammina jaccardi* Schrodt, p. 754, tfs.

1926. *Pseudocyclammina sequana* (Merian) – Tobler p. 714, taf. XXVII.

1928. *Pseudocyclammina personata* Tobler p. 213, Pl. 24, Figs. 1–3.

1938. *Pseudocyclammina sequana* (Merian) var. minor Mohler, p. 16, Pl. 1, Figs. 5, 6.

1938. *Pseudocyclammina sequana* (Merian) var. major Mohler, p. 16, Pl. 1, Figs. 3, 4.

1964. *Pseudocyclammina jaccardi* (Schrodt, 1894)-Redmond, p.406, Pl.1, Fig.2–4,Pl. 2.

1967. *Alveosepta jaccardi* (Schrodt) – Hottinger, p. 79, Pl. 15, Figs. 15–18.

1967. *Alveosepta jaccardi personata* (Mohler) – Hottinger, p. 80, Pl. 15, Figs. 1–3.

1984. *Alveosepta jaccardi* (Schrodt) – Pélissié et al. p. 487, Pl. 2, Fig. 4.

1993. *Alveosepta jaccardi* (Schrodt) – Tasli, p. 56, Pl. 15–22.

2001. *Alveosepta jaccardi* (Schrodt) – Clark & Boudagher- Fadel, p. 681, Pl.1, Fig. 3–6.

Materials: 5 tests from thin section

Description: Test coiled, microspheric early stage streptospiral, megalospheric test and microspheric adult planispiral, adult may rarely tend to uncoil; wall agglutinated, exoskeleton with subepidermal network, lining apertural face and septa, as well as lateral and peripheral chambers walls, exoskeletal projection that forms a median lamella which partially or completely bisecting the chambers; aperture consists of large openings at the base of the apertural face. In sodoble section this foraminifer species are dominated on upper sub unit (plate 6: A, 7: A-B) with association of psedeocyclamina sp. and choffotela sp.

Remarks: Alveosepta is morphologically close to *Choffatella sp.* and *Pseudocyclammina sp*. but differs in that it possesses the characteristic narrow space in the distal part of the hypodermis of the septa (Banner and Whittaker, 1991). It is studied at peri-Mediterranean area. This species was proposed by Schrodt (1894) from the Kimmeridgian of Col des Roches, Neuchâtel Jura, in Switzerland. A. jaccardi has also been observed in the Early Kimmeridgian of the Hanifa Formation and in the lower part of the Jubaila Formation from Saudi Arabia (Redmond, 1964) and central Lebanon of lower strata of the Bikfaya Formation (Clark and Boudagher- Fadel, 2001) which is similar with this specimen.

Pseudocyclammina lituus species

Genus *Pseudocyclammina (*Yabe & Hanzawa, 1926)

***Pseudocyclammina lituus* (**Yokoyama, 1890**)** (Figs. 5.B & 6.A-B)

1890. C*yclammina lituus* n. sp : - Yokoyama, p. 26, Pl. 5, fig. 7.

1926. *Pseudocyclammina lituus* (Yokoyama, 1890) –Yabe & Hanzawa, p.10, Pl.2, fig. 3.

1995. *Pseudocyclammina lituus* (Yokoyama, 1890) – Bucur *et al.* , p. 358, Pl.1, fig. 3-4.

2006. *Pseudocyclammina lituus* (Yokoyama, 1890) – Kobayashi & Vuks, p. 840, Fig. 5.

Description: - In this specimen the Planispirally enrolled medium to large-sized test tending to uncoil and Wall alveolar, coarsely agglutinated; septa are very thick. Aperture is areal, multiple, across the apertural face. It is observed in sample no K14 which is also upper part of Sodoble section (plate 6: C, J).

Remarks:- This species type is also identified from India and dated Kimmeridgian-lower Valanginian range of age and Saudi Arabia from upper most Jurassic age(Steineke et al.,1958) and barriasian –valagian age is assigned at Oman(dson & Chatton, 1959).

Lenticulina quenstedti species

Family Lenticulinidae, Chapman, Parr and Collins, 1934

Genus Lenticulina, Lamarck, 1804

Type Species: - *Lenticulina quenstedti* Gümbel,

1862. *Lenticulina quenstedti*, Gümbel, 1862, (Plate 1: C)

197. *Lenticulina quenstedti* (Gümbel) forma- A Wernli, : 322, pl. 4, figs. 23, 27; pl. 10.

1989. *Lenticulina quenstedti* (Gümbel) -Morris & Coleman: 226, pl. 6.3.8, fig. 12.

Species types 1989 Material: two tests

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 is identified from sediment sample TS1 which is from lower Sodoble section (plate 2: H).

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

Kurnubia palastiniensis species

Superfamily a taxophragmiacea Schwager, 1877

Family pfenderinidae Smout and Sudgen, 1962

Subfamily KURNUBINAE Redmond,

1964. Kurnubia Henson, 1948

Species type *Kurnubia palastiniensis* Henson, 1948.

1948. *Kurnubia palastiniensis* Henson, p. 609, Pl. 16, Figs. 8, 11, Pl. 18, Figs. 10, 11.

1966. *Kurnubia palastiniensis* Henson – Maync, p. 12, Pl. 5, Figs. 1–7.

1967. *Kurnubia palastiniensis* Henson – Hottinger, p. 167, Figs. 30–34, 38–48,

1984. *Kurnubia palastiniensis* Henson – Pélissié et al., p. 486, Pl. 2, Fig. 14.

1988. *Kurnubia palastiniensis* Henson – Loeblich and Tappan, p. 154, Pl. 165, Figs. 1–6.

2004. *Kurnubia palastiniensis* Henson - Ivanova and Koleva-Rekalova, p. 226, Pl. 3, Figs. 3.

Type Species: *Kurnubia palastiniensis* Henson, 1948.

Material: - 12 specimen (Plate 2: G, 6: D, L 7: G)

Description: Test elongate, early chambers trochospiral about a central column, with chambers somewhat 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. The aperture part is not clearly seen in this specimen. This specimen is identified from both sediment K2s4 and hard rock sample K1R5.

Remarks: this species is described by Henson (1948), from Kurnubia in Palestine, and is frequent in the late Jurassic limestone of the Mediterranean area, including Eastern Morocco (Bou Haidor Formation), where Hottinger (1967) considered it as Early-Middle Jurassic age.

Kurunbia cf. morrisi species

Family Pfenderinidae (Smout &Sugden, 1962)

Subfamily Kurnubiinae (Redmond, 1964)

Genus *Kurnubia* (Henson, 1948)

Species *Kurnubia* cf. *morrisi (*Redmond, 1964)

Kurnubia cf. *morrisi* Redmond**,** 1964 (Pl. II, Figs. 8-12, 14)

Kurnubia morrisi new species.- Redmond, 1964 p. 253, pl. 1, fig. 4.

Kurnubia cf. *morrisi* Redmond, 1967 - Hottinger, p. 93, pl. 19, figs. 35-37.

Description: Septal sutures are obscure. The wall is calcareous, microgranular without agglutinated grains, possessing a complete hypodermic network. The primary aperture is set in the inner margin of the peripheral zone where the septa do not meet the central column. The central zone has a trochoidally laminated appearance which recalls the apertural plate's intergrown with pillars in the Pfenderinidae. The base of the test is strongly convex in the center and very obliquely set to the axis of coiling.

Remarks: *K*. cf. *morrisi* has a larger test and central column, and a wider peripheral zone than all other described species of *Kurnubia* and a complete hypodermic network consisting of two generations of partitions in the adult stage.

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. Lenticulina subalata Reuss, 1854 (Pl. 1)

1854. *Cristellaria subalatan. sp.* − Reuss: 68, pl. 25, fig. 13.

1969. *Lenticulina subalata* (Reuss) − Kalantari: 41, pl. 1, figs. 5-8.

1978. *Lenticulina subalata* (Reuss) – Bhalla & Abbas: 180, pl. 6, fig. 6; pl. 10, figs. 1-4.

1991. *Lenticulina subalata* (Reuss) – Bhalla & Talib: 99, pl. 2, fig. 8.

1993. *Lenticulina subalata* (Reuss) – Pandey & Dave: 198, pl. 6, figs. 4-6.

2008. *Lenticulina subalata* (Reuss) − Saad: pl. 3, fig. 6.

2009. *Lenticulina subalata* (Reuss) − Gaur & Talib: 238, pl. 2, fig. 1

Material: 5 tests (plate 2 A)

Description: 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 is extracted from sediment TS1 which is lower part of Sodoble 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. *Verneuilinoides minuta*, Said and Barakat, 1958 (Plate 1: E and F)

1958. *Verneuilinoides minuta* Said and Barakat, p. 242, Pl. 4, Fig. 25.

1966. *Verneuilinoides minuta* Said and Barakat-Maync, Pl. IV, Figs. 10, 11.

1996. *Verneuilinoides minuta* Said & Barakat-Kuznetsova et al., p.164, Pl. XIII, Figs.3 5.

2004. *Verneuilinoides minuta* Said and Barakat-Galal and Kamel, p. 66, Fig. 4/3.

Material: 23 (Plate 2: D)

Description: Test small, tapering, and subtriangular in section, periphery rounded; successive subglobular chambers slowly increasing in size and regularly arranged; composed of four whorls; sutures depressed; 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 Sinai (Egypt), Said and Barakat (2014); from Jurassic sedimentary rocks of Khashm Al-Qaddiyah central Saudi Arabia and Oxfordian and Kimmeridgian of Syria, (Youssef and El-Sorogy, 2014).

Haplophragmoides bartensteini species

Family Haplophragmoididae, Maync, 1952

Genus Haplophragmoides, Cushman, 1910

Type Species :-*Haplophragmoides bartensteini*, Kalantari,

1969. *Haplophragmoides bartensteini* Kalantari, 1969 (Plate 1: I and J),

1969. *Haplophragmoides bartensteinin.* sp.− Kalantari: 19, pl.7, figs.16-18a, b; pl. 8,

1993 *Haplophragmoides bartensteini* Kalantari− Pandey& Dave: 122, pl. 1, fig. 3-5.

2009. *Haplophragmoides bartensteini* Kalantari− Gaur& Talib: 233, pl. 1, fig. 5.

Material: 17 test (plate 2: B and C)

D**escription**: Test large, planispirally coiled; involute; periphery rounded; close coiled, with depressed umbilicus; chambers are six in this specimen and increase gradually in size as added; the last whorl show strongly enlarged chambers, sutures distinct and somewhat curved; wall finely arenaceous. Aperture is not clearly visible, but probably terminal. This specie is extracted from lower marl TS1 and middle marl unit K1S4 of sodoble section.

Remark: These species also known from Middle Jurassic of Kachchh Basin, Western India Alhussein, (2014), Bajocian of Iran Kalantari, (1969) and Callovian to Oxfordian of India Pandey and Dave, (1993); Gaur and Talib, (2009).

Choffatella cruciensis species

Subclass TEXTULARIIA Mikhalevich, 1980

Ord. LOFTUSIINA Kaminski, 2002

Family CYCLAMMINIDAE Marie, 1941

Subfamily Choffatellinae Maync, 1958

Genus CHOFFATELLA Schlumberger, 1904

Type species: - ***Choffatella cruciensis***

Material: 10 specimens (Plate 2: I and J)

Description: -Test are relatively large, compressed; planispirally coiled; partial involute to evolute, chambers are numerous and are separated by strongly oblique sutures curving into the peripheral keel on the spiral side, and by slightly depressed sutures on the umbilical side. Involute umbilical side and chamber walls are finely perforate. It is extracted from sediment sampleK1S3 which is from upper Sodoble section.

Remark: Choffatella is known from Jurassic of Saudi Arabia Youssef and El-Sorogy (2015) also from Kimmeridgian of Egypt, Said and Barakat (1958).

Pfenderina gracilis species

Family: Pfenderinidae

Subfamily: Pfenderininae

Genus Pfenderina Henson 1948

Type species *Pfenderina salernitana* Sarton et Crescenti, 1962

Pfenderina gracilis Redmond, 1964 (Plate 1, Fig. 14)

Pfenderina gracilis Redmond, new species Plate 1, figures 14-16

Material: 2 specimens ((plate 2: F)

Description: small test, fusiform and an elongate trochoid spiral. Simple chambers with smooth surfaces and moderately inflated; both lateral and spiral sutures are distinct, their surfaces having a finely granular aspect; wall consisting of imperforate microgranular calcite; apertural plates small and almost hemispherical. This species is extracted from sediment sample of sodoble section.

Remarks: This species is known from Bathonian –Callovian age of Saudi Arabia, C. D. Redmond (2014).

Nautiloculina oolithica species

Superfamily Lituolacea Blainville, 1827

Family NAUTILOCULIDAE Loeblich and Tappan, 1985

Nautiloculina Mohler, 1938

Type species: *Nautiloculina oolithica* Mohler, 1938.

1938. *Nautiloculina oolithica* Mohler, p. 19, Pl. 4, Figs.1–3, Pl. 19, th. 6, Pl.4, Figs. 1-3.

1988. *Nautiloculina oolithica* Mohler – Loeblich and Tappan, p. 71, Pl. 54, Figs. 10–12.

2001. *Nautiloculina oolithica* Mohler – Clark & Boudagher- Fadel, p. 226, Pl.2, Fig. 10.

Materials: from thin section (plate 6: B)

Description: Test lenticular, planispiral and involute followed by numerous chambers that increased gradually in size, interior simple, sutures radial to slightly arched; wall agglutinated structure without subepidermal network and umbonal region also progressively thickened as chambers are added. This species are more dominated at middle part of Sodoble section and the abundance decreases towards upper part.

Remarks: this species is known from Saudi Arabia, India and Egypt. Banner and Wood (1964) record j. oolitluca as ranging from Callovian to Aptian, in Umm Shaif Field, Abu miabi Marine Areas, Trucial Coast, Arabia.

5.3 Ostracods

Ostracods are 0.2 mm to 2.0 mm- sized crustacean arthropods, known since the late Cambrian to occur in nearly all types of aquatic environments. They are valuable proxies for paleoenvironmental conditions including salinity, oxygenation, substrate and water depths.

Ostracods are characterized by a bivalved shell (carapace) that is typically ovate or kidney-shaped in outline. The carapace encloses the soft parts and consists of two valves which overlap each other. The valves are mostly equally shaped and articulated by teeth and sockets hinge line. The surface of the valves is smooth or sculptured into ridges, ribs, spines or nodes. Fossil ostracods are defined by the shape of the carapace, carapace surface feature, type of hinge, placement of pores and muscle insertion scars.

In sodoble section more than 50 different ostracod fossils are extracted from washed marl sediment but the identification of them is difficult due to the poor preservation. In the entire collected ostracod sample, their hinge, placement of pores and muscle insertion scars are not visible under binocular reflecting microscope. For these reasons the classification of ostracods are taken to genus level where possible and some figures of the collected ostracods is given in plate 1.

The systematic classifications of ostracod taxa follow (Schudack et al 2013; Bate 1972; Sames, 2009; Beher et al., 2010; Sheppard, 1981; Andreu et al., 2012 etc). The taxonomy is taken up to genus level.

Cytherelloidea. sp

Phylum Arthropoda Schwartz, 1998

Class Crustacea Brünnich, 177

Subclass Ostracoda Latreille, 1802

Order Podocopida Miiller, 1894

Family Cytherellidae Sars, 1866

Genus Cytherelloidea Alexander, 1929

Type species: - *Cytherelloidea, sp*

Material: - 2 carapaces (Plate 1: A and B)

Description: - Carapace subrectangular in lateral view; incurved ventrally and narrower anteriorly. Dorsal margin is straight slightly sloping downwards towards posterior. Ventral margin strongly incurved. Muscle scars and hinge are not visible. Wide peripheral rib on both valves is present.

Procytheridea sp.

Family Cytherideidae Sars, 1925

Genus Procytheridea Peterson, 1954

Type species: *Procytheridea Sp*.

Material: - Three carapace (Plate 1 D)

Description:- Carapace subtriangular in lateral view; greatest length at mid-height; anterior margin rounded; posterior margin reduced and rounded triangular in shape; dorsal margin convex; ventral margin almost straight and subparallel to anterior margin. Teeth, hinge, muscle scars and marginal pore canals not visible.

Paracypris sp.

Family Paracyprididae Sars. 1923

Genus Paracypris **Sars**. 1866

Description:-Shell small, elongate sublanceolate-subreniform; dorsum convex; venter concave; anterior rounded; posterior acuminate, strongly extended below; valves compressed, left valve larger than right; surface smooth. Hinge consists of simple contact of right valve in slight furrow on left valve; inner lamellae broad; radial canals may bifurcate; adductor muscle scar a median group of six or more spots.

Bairdia Sp.

Superfamily Bairdiacea Sars, 1888

Family Bairdudae Sars, 1888

Genus, Bairdia, McCoy, 1884

Material: (Plate 1, H)

Description:-Large, thick shelled carapace with broadly arched dorsal margin that becomes concave terminally, especially towards posterior. Carapace surface is ornamented by evenly spaced small pits. Carapace is highest and widest medially and longest at ventral of mid-point. Anterior margin rounded, posterior margin small and pointed. Left valve larger than right valve which it overreaches on all sides and overlaps mid ventrally; Hinge and Muscle scars not observed.

Carapace subdeltoid in lateral outline, convex dorsally. Dorsal margin high with steeply inclined anterior and posterior slopes. Posterior margin acuminate, upturned. Shell surface finely punctate.

Cypridea sp.

Class Ostracoda

Order Podocopida

Suborder Podocopina (Sars, 1866)

Superfamily Cypridacea (Baird, 1845)

Family Ilyocyprididae (Kaufmann, 1900)

Subfamily Cyprideinae (Martin, 1940)

Genus Cypridea (Bosquet, 1852)

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

Material: (plate 1, E and F)

Description:- Shell medium sized, sub-quadrate to sub-trapezoidal in side view; highest one-fifth from anterior end; dorsal margin nearly straight; cardinal angles broadly obtuse ; ventral margin slightly convex, sinuous terminally, converging toward dorsum posteriorly; anterior margin broadly curved, truncate above, anteroventral marginal bend extended as a blunt beak, and marked posteriorly by a notch; posterior margin narrower; right valve much larger than left, overlapping and extending beyond right along free margins; along dorsum left valve overlaps right; valves not strongly convex; surface finely pitted except marginal zone which is smooth; anteroventral furrow and hood well developed.

Remark: - Sub-quadrate to sub-trapezoidal, medium-sized Cypridea having right valve larger than left, finely pitted surface medially and smooth marginal zones.

Progonocythere sp.

Superfamily Cytheracea Baird, 1845

Family PROGONOCYTHERIDAE Sylvester-Bradley, 1948

Subfamily **Progonoc Ytherinae** Sylvester- Bradley, 1948

Genus P**rogonocythere** Sylvester-Bradley, 1 948 ended).

Description: - rectangular outline, strongly dimorphic. Carapace has tapering to blunt posterior, steep poster ventral slope. Valvesare uniformly convex in dorsal view and ventral overhang of the valves. The carpace is also smooth .This ostracod genus specimen is identified from lower Sodoble section.

5.4 Bivalvia

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.

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.

All Bivalve fossils collected from Sodoble section are preserved as a mold and cast which makes it difficult to identify and name these fossils. Then comparison with Jaboli (1943) and Keissling (2011) is made. The systematic classifications of invertebrate taxa follow more recent published works done on the respective taxa where ever possible and the image of identified bivalve fossil is given in plate 3. From the field investigation of present study the most Bivalvia are collected from lower Sodoble section on and their shell is not preserved.

Pholadomya sp.

Subclass AnomalodesmataDall, 1889

Order Pholadomyoida Newell, 1965

Superfamily Pholadomyoidea King, 1844

Family: Pholadomyidae Gray, 1847

Genus Pholadomya J. SOWERBY, 1823

Species type: Pholadomya (Pholadomya) inornata SOWERBY, 1837Fig. 8G–I

1837. Pholadomya inornata sp. nov.—Sowerby: pl. XXI, fig. 8.

1916. Pholadomya inornata Sowerby—Douvillé, p. 55, pl. IV, fig. 5.

Material: Two complete internal mold specimens (plate 3: C and D)

Description: Shell is equivalved and inflated below the umbo and has prosogyral, commissure plane closed. The studied specimens are internal molds but have traces of concentric ornamentation. In this specimen the hinge line is very sharp towards the dorsal from umbo.

Remark: This species was recorded by Douvillé (1916) from the Callovian of Sinai, Egypt. It also recorded from the Middle Callovian lower Tuwaiq Mountain Formation of central Saudi Arabia. In this study this fossil is collected from lower Sodoble section.

Pholadomya somaliensis species

Phylum Mollusk, Linnaeus, 1758

Class Bivalvia Linnaeus, 1758

Family Pholadomyoidea King, 1844

Genus: Pholadomya Sowerby, 1823

Material: one double valved specimen **(Plate 3: C and D)**

Description: They have equally spaced growth lines and style of ribbing is both radiating and concentric, umbo is small with very short hinge line.

Remarks: Genus Pholadomya are recognised by their unique perfectly spaced growth lines. In the present available material internal features are not observed, but overall shape and style of ribbing closely correspond to species of Genus pholodomya as described by (Jaboli, 1959).

Eligmus sp

Family ELIGMIDAE GILL, 1871

Genus Eligmus Eudes-Deslongchamps, 1856

1868. Eligmus Integer (Douville, 1916) Fig. 7j–K

1916. Heligmus Integer, Sp. Nov.-Douvillé, P. 33, Pl. 2, Figs. 13–16.

1979. Eligmus Integer Douvillé-Hirsch, Pl. 3, Figs. 1–4.

Material: two specimens (plate3 A)

Description: - Shell moderate in size, equivalved, ovate, distinctly elongated, and often crescent-shaped. Both valves are equally convex, ornamented with radial ribs. Zigzag commissure is slightly observed. Umbo is terminal and occupying a medium position, with a small attachment area. This macrofossil type is collected from lower part of marly limestone unit in Sodoble stratigraphic section.

Remarks: This specimen is also recorded from late Bajocian rocks in northern Sinai, Egypt (Hirsch, 1979) and Middle Callovian upper Tuwaiq Mountain Formation of the Khashm Al Giddiyah and Dirab sections.

Mactromya sp.

Subclass Heterodonta Neumayr, 1883

Order Veneroida ADAMS and ADAMS, 1856

Family Mactromyidae COX, 1929

Genus Mactromya AGASSIZ, 1843

Material: Six internal molds (Plate 3: B)

Description: This species is marked by its straight hinge line and arc-like shell. It is ornamented by concentric striations. A groove extending from the ventral to the dorsal margins is observed.

Remarks: This species is recorded from the Middle Callovian upper Tuwaiq Mountain Formation of the Dirab section.

5.5 Brachiopods

Brachiopods are bilaterally symmetrical sessile marine organisms with an external shell consisting of two dissimilar but equilateral valves. Based their morphology they have been divided into two major groups as inarticulate and the articulate. 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. The body of brachiopods is enclosed by a valve except for the pedicle which serves to attach the animal to the substrate. The larger valve on the ventral side of the body is the pedicle valve, the smaller valve on the dorsal side the brachial valve. In Sodoble section fossils of brachiopod is identified as its image is given in plate 4.

Daghanirhynchia SP.

Phylum Brachiopoda Duméril, 1806

Subphylum **Rhynchonelliformea** Williams et al. 1996

Class **Rhynchonellata** Williams et al. 1996

Order **Rhynchonellida** Kuhn, 1949

Superfamily **Hemithyridoidea** Rzhonsnitskaya, 1956

Family **Tetrarhynchiidae** Ager, 1965

Subfamily **Tetrarhynchiinae** Ager, 1965

Genus Daghanirhynchia Muir-Wood, 1935

1935. Daghanirhynchia –Muir-Wood, p. 82-83.

1989. Daghanirhynchia. – Cooper, p. 26.

1993. Daghanirhynchia. – Shi and Grant, p. 73.

Material: three body shell (plate 4: A-C)

Description: - Emended diagnosis (from Muir-Wood, 1935). Shells are medium-sized, sub triangular to subpentagonal, subglobose, dorsaly biconvex, and often with large and curved ventral beak. It has Uniplicate and with distinct dorsal fold. Lateral commissure is straight.Beak acute, erect to in curve. Crura nearly horizontal, raduliform, and slightly too strongly incurved ventrally.

Remark: - This macrofossil spices is collected from lower part of Sodoble section and it is Bathonian to Oxfordian (Middle to Upper Jurassic) (Manceñido et al., 2002, 1347); of Somalia, Kenya, Ethiopia, Jordan, Egypt (Sinai),

5.6 Gastropods

Gastropods are class of phylum mollusk that has mostly an externally univalved shell usually coiled. The exterior of gastropod shells may be smooth or ornamented with ribs and spines. The shells of different gastropods vary enormously, and these variations are used to distinguish one species from another. The gastropod fossil collected from Sodoble section carbonate are described and figure for identified fossil is given in plate 5 and it is also collected from lower part of Sodoble section.

Ampullina sp.

Phylum Mollusk Linnaeus, 1758

Class Gastropod, Cuvier, 1795

Order Littorinimorph, Golikov and Starobogatov, 1975

Family Naticidae, Guilding, 1834

Genus Ampullina, Lamark 1821

Material: three internal molds (Plate 5: A-C)

Description: Thick, medium-sized; number of whorls about 3; whorl gently rounded; aperture is absent. The material is low spired gastropods composed which are highly asymmetrical in size and thickness. This gastropod specimen is collected from upper part of Sodoble section and there are also many gastropods shells fragments under thin section but it is difficult to identify it species.

Remark: The aperture and apex is not preserved so it's impossible to estimate whole number of whorls. But overall shape closely corresponds to *Ampullina. Sp.* as of (Jaboli, 1959).

5.7 Fossils under Thin Section

Thin-section fossils present only a part of the biota present in the rock, for this that thin-section diversity is not equivalent to biotic diversity. Identifying fossils in thin sections may be difficult, because, randomly cut sections of microfossils may exhibit very different shapes and outlines, resulting in an often confusing taxonomic situation of 'thin-section fossils', Racki and Sobon-

Podgorska (1992), diagenetic alterations may produce 'diagenetic taxa', the lack of modern equivalent of many extinct fossils may cause very different opinions varying from author to author regarding the systematic position and classification of fossils known only from thin sections and Some fossils (e.g. larger foraminifera) common in thin sections require oriented sections to follow defined planes because they may be rare in randomly cut samples (Flugel 1982).

According to Flugel (1982) most of thin-section fossils comprise six informal groups of cyanobacteria (calcimicrobes) and calcareous algae, foraminifera and other protozoa (radiolarians, calpionellid benthic sessile organisms (sponges, corals, and bryozoans), shell-bearing organisms with valves (brachiopods, molluscs, and ostracods) and multi-plate shells (trilobites, crustaceans, echinoderms). All these have their own system of identification one from another, Eg, foraminifera are identified in thin sections based on wall structure, arrangement of chambers and the form and position of the aperture. Some of foraminifera are identified under thin section in the present work. However taxonomic determination of foraminifera in thin sections of limestones may be difficult because only randomly oriented sections are commonly available and wall structures are often destroyed by digenesis.

Thin-section of fossils with shell-bearing organisms characterized by bivalve or univalved shells such as brachiopods, molluscs', ostracods and etc are difficult to identify. An identification of these bioclasts as to higher systematic levels is possible when original shell microstructures are preserved or unique diagnostic criteria are visible. In Sodoble section different fossils are seen under thin section and based on their observable and diagonitic feature some of them are identified as their image is given in Plate 5 and 6.

CHAPTER SIX

6. Discussion

6.1 Introduction

Thick layers of Jurassic carbonate unit (Antalo Formation) which deposited in Mugher area (Sodoble section) were investigated in field and lab analysis. The studied sections consist of micritic limestone to bioclastic packstones/rudstone, biopeloidal to oolitic limestone layer and marly limestone layer with micrite and/or sparry calcite cement. It is dominated by benthic foraminafera with minor brachiopods, echinoderms, bivalves, corals, ostracods and gastropods invertebrate macro and micro fossils. Combining information from both fossils and rocks collected in the field and has allowed for reconstruction of the depositional environments, to determine relative age of the carbonate rock of the section and to correlate with other sections and regional basins.

Based on varying of their facies types and sedimentological features which obtained from the carbonate unit of the study area: depositional environments, facies patterns and association, age, composite stratigraphy of the area and correlation of the section with other area are discussed as follows:

6.2 Composite Stratigraphy of Sodoble Section

As given in (Fig 6.1), the carbonate stratigraphic succession of the sodoble section which has a total thickness of about 320m is studied based on field investigations and data analysis from lab. The sodoble section carbonate unit is underlain by Gohatsion formation and overlain by upper sandstone unit. Based on their facies contents observed in the field and thin section analysis the carbonate unit of the section which are grouped into lower, middle and upper Sub unit.

Lower sub unit has a thickness of around 141m has dominant fine grained micritic layers with marl and rare dolomitic bed at its bottom followed by bioclastic wackestone to peloidal grainstone and at its top part oolitic packstone to grainstone microfacies. Allochems are seen embedded within micrite cements and/or in sparite. Micritic limestones are usually purely micrite matrix and in rare cases some sparry calcite crystals and quartz grains are observed. Thin to medium bedded bioclastic wackestone and peloidal grainstone rarely intercalated with marl is followed the micrite facies. Ooid grains dominate the upper part of the lower sub unit. Sedimentary structures such as bioturbation, thin-thick bedding is common at bottom of lower sub unit. The lower Sub unit shows relatively successive facies which comprise: lagoonal facies and carbonate shoals to platform facies successively. As observed from petrographic analysis and microfacies result interpretation of micritic, bioclastic wackestone and peloidal to oolitic grainstone microfacies; the facies pattern are comprise to represent lagoonal facies at bottom and the top part of lower sub unit which is dominated by ooid microfacies with rare bioclastic grainstone show deposition on carbonate shoals to platform. Macro and microfossils such as: Ampullina sp., dasycladecean algae, Pfenderina gracils (k1s4), Kurnubia palastiniensis (K2S3), Nautiloculina oolitic, Lenticulina sp. Haphlophragmoides sp., etc are present.

The Middle sub-unit: is characterized by dominance of various carbonate allochems embedded within sparry calcite cements and/ or micrite. These allochems are mostly embedded within sparry calcite cements and in rare case within micrite, the dominance of allochems shows deposition under shallow marine condition. Thick layers of reworked sediments observed on these layers show depositions around unstable high energy depositional site like that of the slope area, behind the carbonate barriers toward the sea. According to petrographic description and microfacies analysis middle sub unit contains, bioclastic wackestone with rare ooids to reefal limestone bed at bottom, bioclastic wackestone microfacies (MFT2) to micritic microfacies (MFT1) marly bioclastic limestone and coquina bed at top part.

The upper sub unit with marly limestone and bioclastic layer which overlying the Allochem rich layers of middle sub unit. Micritic microfacies (MFT1) and bioclastic wackestone packstone microfacies are also common microfacies types of upper sub unit which indicate offshore depositional environment.

The composite Sodoble stratigraphic section is made from three locally selected sections (Kersa one, two and Togo ridge sections). Its correlation is made based on by comparing the physical characteristics of strata, (stratigraphic position and lithofacies and biofacies data from the field observation as well as microfacies analysis).

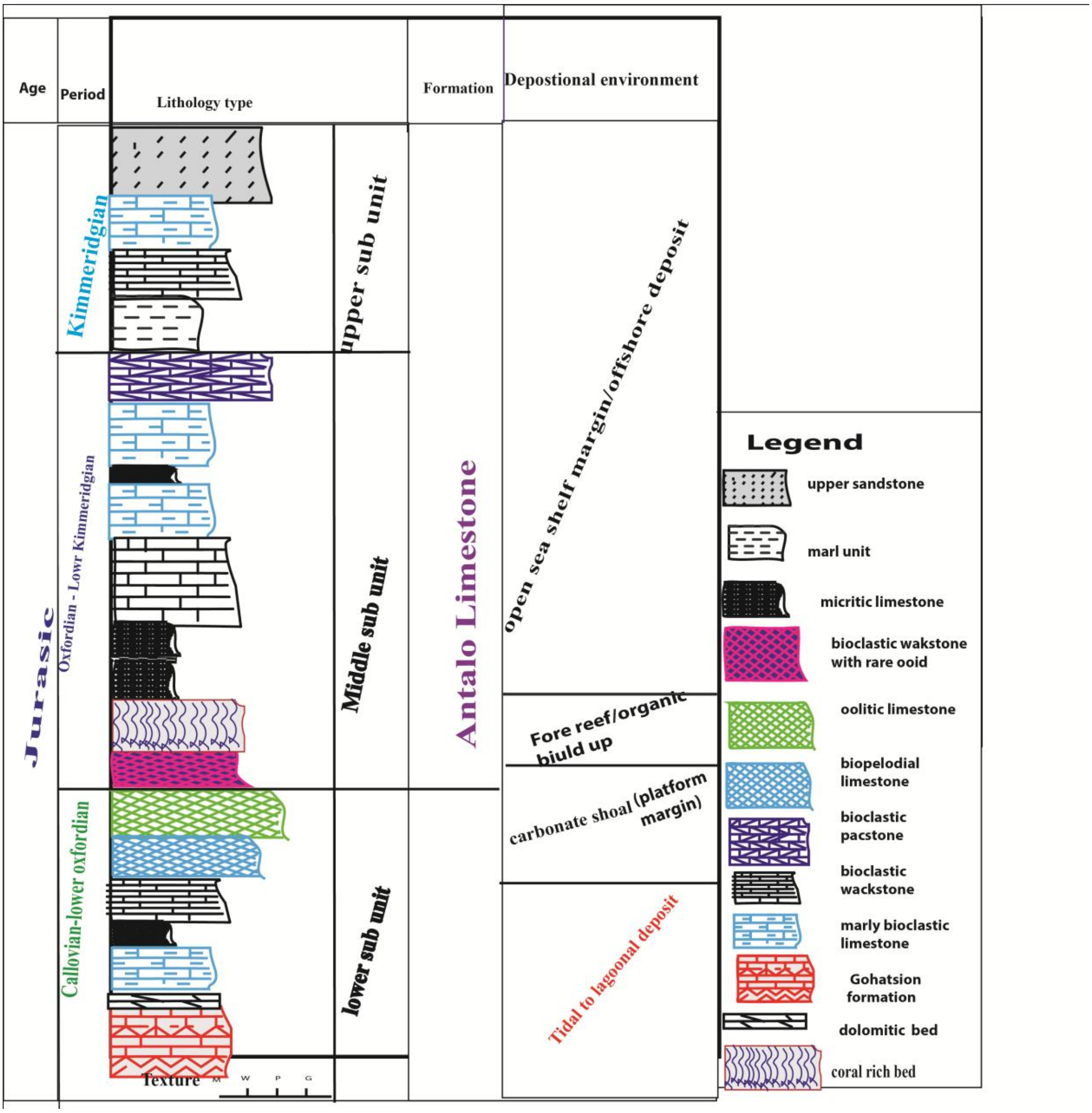


Figure 6.1Composite stratigraphy of Mugher area (Sodoble section) carbonate unit with detailed age, lithology and depositional environments (not scaled).

6.3 Biostratigraphy and Age of Mugher area Carbonates Unit

Biostratigraphic units or biozones are bodies of strata that are defined or characterized on the basis of their contained fossils. They help for correlating and assigning relative ages of strata by using the fossil assemblages contained within them. A biostratigraphic unit may be based on a single taxon, on combinations of taxa, on relative abundances, on specified morphological features, or on variations in any of the many other features related to the content and distribution of fossils in strata. To be useful in biostratigraphic correlation and to determine the relative age of a rock, fossils have to be index fossils which are defined as geographically widespread, rapidly evolving, abundant or easy to find in the rock record and easy to preserve and to identify.

In Ethiopia biostratigraphy of carbonate unit; foraminifera is used in determination of age an d for correlation of strata studied with carbonate succession of other near section to present studied section in Southeastern and Northwestern plateau sedimentary basins of the country. The major/significant number of stratigraphically important microfossils encountered in all investigated carbonate unit of Sodoble section led to the proposal of microfossil zonation.

Pfenderina gracilis and rare Kurunbia palastiniensis, Kurunbia morisis and Kurunbia jurassica foraminiferal species are found in the lower to middle part of the Sodoble section (K2s4) with association of *Lenticulina subalata*, *Lenticulina quenstedti*, *Haphlophragmoides bartensteini* (TS1), N*autiloculina sp*., *Verneuilinoides minuta*, *amboculite sp*, brachiopods, bivalves, gastropods, *Dysacladean algae*, *sponge spicules* and etc. In the middle sub unit of sodoble section the *nouthiculina olithica* and *Kurnubia palastiniensis* is dominated. However in the upper Sodoble section the abundance of *Pfenderina sp. Lenticulina sp.* and *Kurnubia sp*. is infrequent and *Alveosepta jacaradi* (K2R4), *Psedeocyclamina litus* and *choffotela sp*. (K1s3) become more dominant with assemblage of echinoids brchchiopods, *nouthiculina olithica* and *Haphlophragmoides bartenstei.*

According to Sartoni and Crescenti (1962), Tasli and Tiner (2010) and Tasli (2001), *Pfenderina gracilis* is used as an index fossil for the upper Bathonian to Callovian age at eastern Arabia (Hewaidy& Al-Saad, 2000). It is also from upper Callovian age of Yemen (Al-Wosabi, 1993). Monsour and Houston, (1975) also state that Ethiopian Pfenderina is derived from Bathonian and younger strata which are always directly overlain by *Kurnubia palastiniensis*. *Kurnubia palastiniensis* is an index fossil of Callovian to lower Kimmeridgian in age (Monsour and Houston, 1975; Sartoni and Crescenti, 1962). In Sodoble section this Pfenderina gracilis is associated with *Kurunbia palastiniensis* and *Kurunbia jurassica* which are occurring from upper Callovian age (Hassan et al., 1978, Kuznetsova et al., 1991 and Simmons & Al-Thour, 1994). Therefore the *Pfenderina gracilis* is an index fossil for Callovian age of Sodoble section.

The *Alveosepta jaccardi* used previously by Ascoli (1981, 1988) and Williams et al. (1990) to characterise the Kimmeridgian of Canada and Sarfi & Yazdi-Moghadam (2016) and as a late Oxfordian-early Kimmeridgian zone in northwest Iran. It is also used as index for Kimmeridgian age of Saudi Arabia. In Sodoble section the association *Alveosepta jacaradi* with *psedeocyclamina litus*, *nouthiculina olithica* and *choffotela sp.* which their occurrence starts from lower Oxfordian age of carbonate unit is indicate that an index fossil for Kimmeridgian age. In general based on the presence of index (zonal markers) of foraminifer fossils such as, *Pfenderina sp., Kurnubia sp.* and *Alveosepta jacaradi* the Sodoble section carbonate rocks age is entirely of Jurassic age, particularly from the Callovian to Kimmeridgian age has to be assigned in this work. In Abay canyon section the carbonate succession is also dated Callovian to Kimmeridgian from index fossils of foraminifera species (Russo et al. 1994) which is correlated equvalent with present section based on lithostratigraphy and chronostratigraphy.

6.4 Correlation

The thick carbonate unit of sodoble section is logged in the study area is situated; in the Northwestern Ethiopian plateau; which is equivalent with the carbonate unit of other Blue Nile Basin area and other Ethiopian sedimentary basins based on their facies content and microfacies as well age similarity. some identified and established stratigraphy by different workers and authors from some proximal area of NW Ethiopia plateaus of the Blue Nile basin in local range and within other basins of Ethiopia (Mekele from the NW and Ogaden basins from the SE) in regional are made in (Fig.6.2 & 6.3) below.

6.4.1 Correlation of Sodoble Section with other Blue Nile Basin Sections

Carbonate rock deposits of Northwestern central Ethiopian plateau is studied by many authors in different ways and some local area sections likes Gindebereti , Jema, Ejere and Gundu maskel are correlable with the present studied unit (Serawit Amene Tamrat Mojo, 1996; Melkamu Mengstie et al. 2010) (Fig. 6.4). These all area is located to Blue Nile basin; present study area is also one part and their lithology and age information is more or less similar which are described as follows.

Oxfordian to lower Kimmeridgian Antalo limestone deposits which has a thickness of 400m is studied in Jimma section. It is grouped into three microfacies groups based on their petrographic and paleontologic analyses. The lower and middle Sodoble section is corralble with this section based on microfacies as well as biostratigraphy.

In Gindebereti jeldu the carbonate section is white sometimes pale-yellow, dark-gray, in places dolomitized at lower and mainly yellow, white, friable with yellowish marl and clay inclusion, with interbeds of fossil rich (mainly brachiopod bivalves) micritic limestone at middle part. The lower-middle part of this section is corralable with the present studied section with it facies type.

The limestone exposed both Gundu maskel and Ejere sections as thick as 550m. Lithologically 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 lower to upper part of Sodoble section based on facies type respectively.

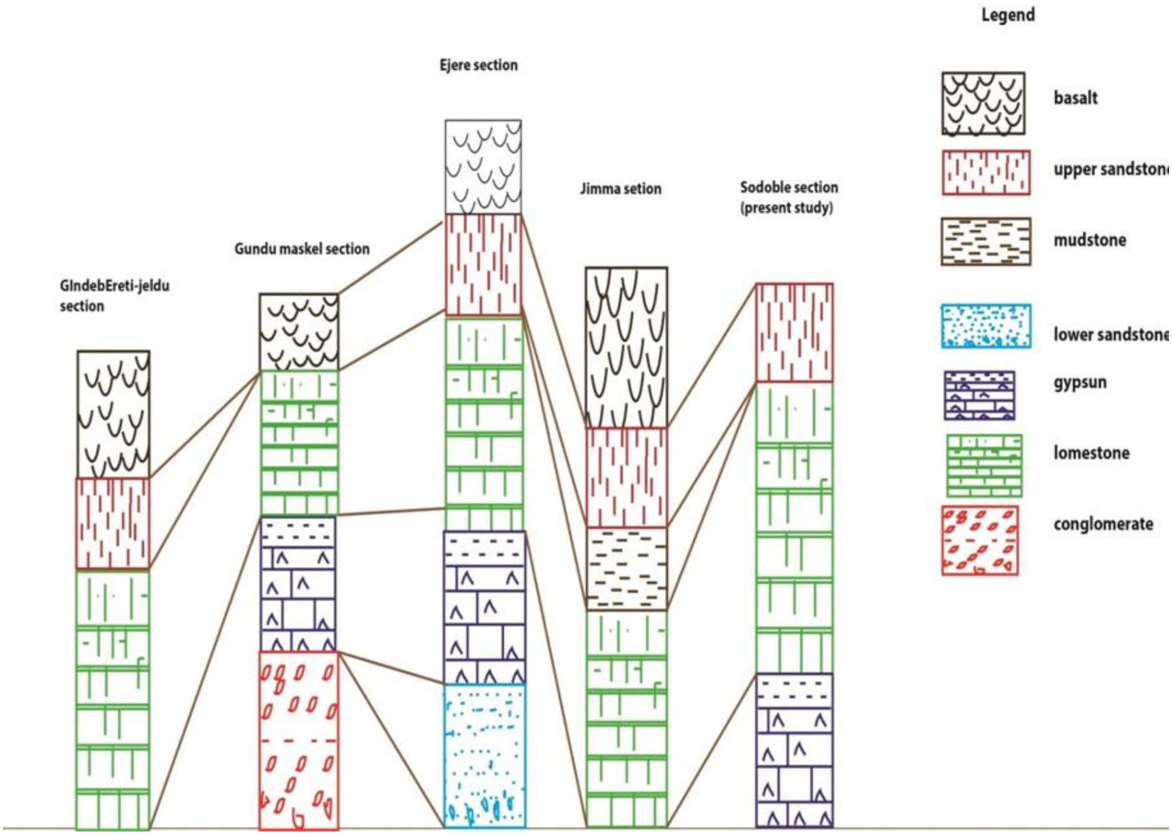


Figure 6.2: Mesozoic stratigraphy correlation between some areas from NW Ethiopian plateau, Sources: Gindeberet-jeldu, (Tamrat mojo and Tibebe G/Selassie, 1997), Gundu maskel and Ejere (Serawit Amen and Tamrat Mojo, 1996), Jimma (Melkamu Mengstie et.al, 2010) and Sodoble (Present work).

6.4.2 Correlation of Sodoble Sections with Other Ethiopian Basins

Tectonic evolutions throughout NE-Africa and sea level fluctuations through geologic time have the great roles for the formation of Ethiopian sedimentary basins and thick sedimentary deposits within them. The Mesozoic sediment deposits of Ethiopia occur mainly in Northwestern and Southeastern plateau (Russo, et al., 1994). They are possibly related to the drifting 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 occurred during early Jurassic – Oxfordian in different basin (indicates the time of marine transgration) (Bosellini, 1989; Russo et al., 1994).

Extensive carbonate Mesozoic deposits of Ethiopia are present in Mekele outlier, Blue Nile Basin (including central part of Ethiopia) in north western Ethiopia and in the Ogaden Basin in the southeast. The correlation of Sodoble section with these basins is based on general chronological and lithological correlation due to its relationship and correlable. Detail microfacies correlations are difficult because of there is scarcity of detail carbonate microfacies studies on these basins. The general chronological and lithological correlation of Sodoble section in Mugher area with major basins of Ethiopia (Mekele basin, Blue Nile basin and Ogaden basin) is given in fig:6.4, and described in the following sections.

Beyth (1972a; 1972b) and Bosellini et al., (1995) described the carbonate limestone unit occur in the Mekele basin known by the name 'Antalo Limestone' in detail. In Mekele outlier the thickness of the succession ranges from 300 m in the West to 800 m in the East. Beyth (1972a; 1972b) identified four facies for this unit, those are (i) well bedded to laminated, cross-bedded sandy oolite and coquina with minor amount of marl and a few chert beds, with macrofauna including mainly corals, gastropods, and echinoids, (ii) interbedding of marl and fine grained hard limestone with abundant brachiopods and some algal and chert beds, (iii) cliffs of coral and algal reef limestones interbedded with marl and biostromes, and (iv) black to grey microcrystalline limestone interbedded with marl. Bosellini et al., (1997) state that the limestone succession of Mekele outlier composed of thickening and shallowing up cycles which are deposited in a homoclinal ramp or on a wide cratonic margin and gently dipping to the southeast. The age of this Antalo limestone is Late Callovian to Kimmeridgian. Thus, the Antalo limestone of the Mekele basin is correlable with carbonate unit of Sodoble section by its biostratigraphy (age similarity).

The Ogaden Basin found in Southeastern Ethiopian plateau is studied by different authors in different direction. Abiyyu Hunegnaw et al.,(1998), Shigut Geleta (1998) and Tamerat Worku and Astin (1992), state that the carbonate sediments of Ogaden basin are present overlying the Adigrat sandstone and they are; Lower, Middle and Upper Hammanlei formations which represent an early Jurassic to Callovian syn-rift marine sequence, and consist of the following lithologies: in the lower section it contains limestone with intercalated shales, anhydrite, dolomite, and in the middle part of the section contains limestones with local oolitic and stromatolitic beds and bioclastic oolitic limestones in the uppermost section.

The Callovian- Oxfordian Urandab Formation is composed of dark, laminated marls and limestones containing a pelagic marine fauna and corresponds to the maximum flooding sequence deposited during the break-up transgression. Based on various fossils obtained from them the age of lower Hammanlei (Hettangian-Pliensbachian) , middle Hammanlei (Pliensbachian-Bajocian), upper Hammanlei (Bajocian-Callovian), Urandab Formation (Oxfordian) ,Gabre Darre formation (Kimmeridgian- Tithonian) and Gorrahei formation

(Berrisian-Albain) were assigned respectively by (Shigut Geleta 1998). The Urandab and lower Gabre Darre formation is more or less correlable with the present work (Sodoble section).

In Ethiopia, overall regres sion was thought to prevail during latest Jurassic (Tithonian) and Berriasian times (Getaneh Assefa, 1991) which terminate carbonate deposits and clastic deposits start overlain carbonate unit and in Sodoble section it is indicated by upper sandstone unit.

According Russo et al., (1994) the name of carbonate succession as 'Antalo limestone formation' is described in Blue Nile basin Ethiopia. The Antalo limestone formation in Blue Nile basin can be generally subdivided into three parts; lower, middle and upper Antalo limestone. The lower part is consisting of a 180m scarcely fossiliferous and burrowed mudstone that grades into an oolitic limestone rich in corals, stromatoporoids, bivalves, gastropods, foraminifers and ostracods with occasional patches of, nerineids indicating a shallow water environment.

The middle part often referred as marly limestone consists of a 200 m thick highly fossiliferous inter-bedding of marly limestone, marls and silty limestone. Based on the presence of some Ammonites, Terebratuline associated with Nanogyra, Rhynchonellid brachiopods and infaunal siphon-feeders shelf to open marine environment was inferred for Abay basin carbonate successions. The upper part has a total thickness of around 40m and it is composed of planar laminated oolitic and reefal limestone. Based on the occurrence of oolitic bars, coral patches, offshore and more protected facies inshore, this unit is interpreted to represent shallow water environment similar to the lower unit. The presence of some benthic foraminifera such as Pfenderina sp. and Nautiloculina oolithica) at the base of the Antalo limestone and occurrence of Kurnubia palestiniensis, Parurgonina caelinensis, Conikurnubia sp. and Salpingoporella annulata at the top of the unit suggests Callovian to Kimmeridgian age. The lower and middle part of this Abay basin limestone is more or less correlable with sodoble section; the upper part is probably correlable with the upper sub unit of the present area by the age concern, but there is no ooilitic and observable reefal limestone layers are identified section.

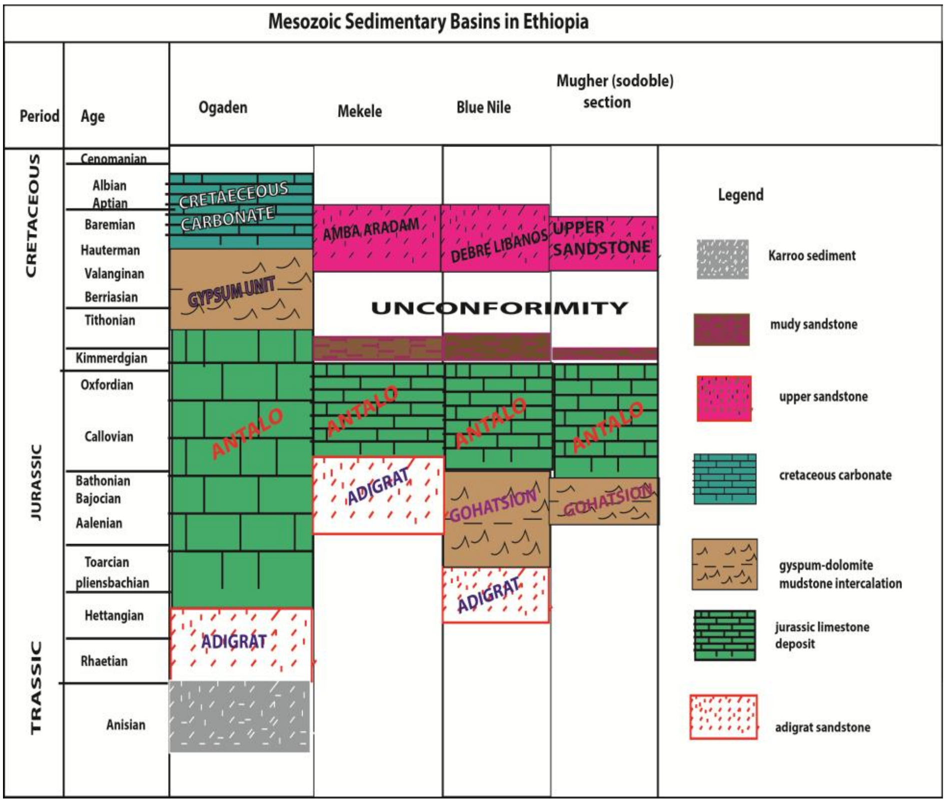


Figure 6.3: Mesozoic stratig raphy correlations throughout Ethiopian basins (Mekele, Blue Nile, Ogaden and Sodoble section. Sources: Mekele (Beyth, 1972a:1972b; Bosellini et al., 1997), Blue Nile (Russo et al., 1994), Sodoble section (from present work) and Ogaden (Tamerat Worku and Astin, 1992; Abiyyu Hunegnaw et al., 1998; Shigut Geleta, 1998).

6.5 Facies Associations and Depositional Environment

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, colour and geometry (Flugel, 1982). In order to reconstruct Paleoenvironment microfacies types (which determine the compositional and textural constituents of carbonate rocks based on examination under thin sections) are grouped and different constraints methods or approaches are used (Flugel 2004).

Analysis of carbonate rock samples collected from Sodoble section has revealed/showen of seven main microfacies repeating them in cyclic manner. It is dominated by skeletal fossil grains of benthic foraminifera, brachiopods, bivalves and gastropods with minor echinoderms, corals and ostracods. The general successive facies and facies belts of the carbonate units of Sodoble section from field investigations and microfacies results shows entirely shallow marine water environment. The distribution pattern of those microfacies reflects transgression from tidal environments of the inner ramp at the base with occasional interrupted episodes indicating a relatively high-energy environment to relatively low energy deep margin environments of the outer ramp at the top of the succession. Some cyclicity of the components is varying with thickness of the beds bearing them throughout the area vertically. This cyclicity of the layers is most probably caused by depositional energies, depositional processes, small changes in sea levels and the change of morphologies of the depositional sites locally during their depositions. The cycles of the facies are mostly shallowing-up pattern at the lower and upper Sodoble sub units and some deepening up pattern at the middle Sodoble units which show the more sea level increments and deepening of the basin during the deposition of middle successions.

The existing of finer dolomitic layer, algae, sponge spicules, borrowing structures, micritized skeletal and non-skeletal grains (shown in microfacies type of 1, 2 and 6) those compared with 8 and 7 facies belts of Wilson (1975) are best indicators of shallow marine carbonate depositional environments of inner ramp. In the middle Sodoble section there is bioclastic wackestone with some ooids and thick micritic layer is observed which is compared by facies belt 5-7 of Wilson (1975) probably correspond to sandy shoals and banks of the inner ramp to deep shelf of mid outer ramp. The alternative cycling of facies within this sub-unit also shows local change in sea levels or other processes during deposition.

In the upper part of Sodoble section there is succession of open-marine/offshore fossils like brachiopods shells and echinoderms in marl intercalated facies with micrite and the corresponding lack of high-energy facies, this show that deposits formed in a relatively low-energy outer ramp environment. It is compared with facies belt 2 and 3 of Wilson (1975) which is deposited at basin margin to open lagoonal conditions.

Generally Sodoble section facies type indicates depositions ranging from open shallow platform (shelf lagoon) to basin margin to open sea/offshore conditions when as compared with the facies belt of Wilson, 1975. Commonly carbonate facies of the area shows various sub-shallow marine depositional environments ranging from the carbonate deposits of low energy platform interiors of lagoon, high energy platform margin carbonate sand bodies, slope deposits/fore reef and some deposits of basin margins and offshore/open sea. The overall facies associations of carbonate deposits of the area are showing a low gradient of depositional dip from domains of lagoon and shoreline high-energy shoals deposits to areas of foreshoal/basin margins and open sea low energy deposits as given in Fig 6.4. These are described as follows:

6.4.2.1 Lagoonal Carbonates

Lagoons form along carbonate coastlines where a beach barrier wholly or partly encloses an area of shallow water they 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). Lagoons generally develop along coasts where there is a wave-formed barrier and are largely protected from the power of open ocean waves (Reading and Collinson, 1996). Carbonate lagoons are sites of fine-grained sedimentation forming layers of carbonate mudstone and wackestone with some grainstone and packstone beds deposited as wash over's near the beach barrier. In the lower Sodoble section bioclastic wackestone with some dyscladean algae and sponge spicule (TR9) overlay the dolomitic limestone (TR11) layer that indicates of restricted tidal to lagoonal type deposit.

6.4.2.2 Platform margin Carbonate Sand bodies

Bioclasts, ooids, and peloidal grainstones are usually occurring around high energy areas such as shoals and beaches in inner ramp/shelf (Burchette and Wright, 1992; Reading, 1996). These carbonate sand bodies and material in the form of bioclastic debris and ooids is reworked by wave action into ridges that form strand plains along the coast or barrier islands separated from the shore by a lagoon (Wright, 1984; Tucker and Wright, 1990). For this oolitic microfacies is interpreted to be deposited around high energy area such as carbonate shoals and Barrier Island or beaches. The texture of carbonate sediments deposited on barrier island and strand plain beaches is typically well-sorted and with a low mud matrix content (grainstone and packstone) which is seen on this microfacies. Carbonate sand bodies made up of bioclastic and oolitic sands occur extensively at the margins of carbonate platforms of all ages reflecting the dissipations of most wave and tidal energy at such margins (Tucker and Wright, 1990). Carbonate sand bodies are a prominent feature of high energy sub-tidal to intertidal in many platform settings. Their formation shows that the presence of barrier/islands at this margins. Barrier is a wave-dominated environment where wave action reworks marine sediment such as bioclastic material and other sediment due to long shore drift to form a barrier (Nichols, 2009).

Carbonate platform are shallow marine depositional environment of carbonates. The oolitic microfacies (MFT4 and MFT5) and some part of bioclastic microfacies layers of lower unit those comprises large size ooids (reaching sand sizes) and rare amounts of skeletal within sparite cements (as shown in plate 4: 6) are the typical facies of platform margin carbonate sands/ oolitic sand barrier deposits. The grains in these microfacies are well sorted, well-rounded, tangential ooids; lithified forming horizontal beds of grainstone and some grains surrounded with micritic envelops which is the result of reworking by wave and tidal currents at these margins. Ooids reflect physical and chemical conditions of the depositional environments in marine settings and they are proxies for water energy. Ooids are formed in both high-energy and low-energy environments and have various shapes. In thin-sections tangential ooids are recognized in the laminae. Concentric (tangential), micritic ooids, broken or distorted ooids are indicators of very shallow environment and common in high energy setting Flugel (2004) which are typical of ooid grains in this microfacies (plate 4:6 A-D).

6.4.2.3 Carbonate Foreshoal Environment

The foreshoal environment is represented by packstone to grainstones with varied skeletal and non-skeletal components (Bádenas and Aurell, 2010). According to Brain and Andre (1992) carbonate grains like mud-free sediments, intraclastic packstone/rudstone and other boulder rich sediments are deposited under slope deposits and most of them are resedimented. The abundances of intraclastic carbonate grains in this facies also indicate that the instability of the slope surfaces. Foreshoal areas can be characterized by accumulation of ooids, skeletal grains and peloids which occurring separately or associated together to form packstone to grainstone textures (Flugel, 2004).

The allochems rich layers are simply passing to the micritic dominating fine grained wackestone to mud stone layers. This shows the accretionary slope (low angle) type deposits (Reading, 1996). These deposits have alternative layers of mudstone, wackestone, packstone and grainstone layers with varying thickness. The sediment supply toward the platform foreshoal may be from number of sources (Walker, 1992). In the middle Sodoble the Carbonate unit have coarser grained deposits of resedimented wackestone to packstone- grainstone facies (MFT 3 and 6) those are dominantly intraclastic, various sized peloidal grains and some skeletal (like molluscs, echinoderms, ostracods, corals, foraminifers etc).

6.4.2.4 Offshore Carbonate Facies

Offshore is zone of outer shelf area below storm wave base predominantly a region of mud deposition. On these areas carbonate sedimentation is dominated by fine-grained deposits and chert nodules which are formed by redistribution of silica from the skeletons of siliceous organisms within the beds are also common in offshore environment (Nichols, 2009). The depositional area which is dominated with very fine materials of low energy deposits are the depositional area away from high energy in protected sites or in basin margin to open sea conditions(Reading, 1996). Calcareous mud (marl) in warm water setting comes from the breakdown of green calcareous algae, in organic precipitations from sea water and from disintegration of large skeletal particles into their smallest crystallographic unit. These mudstones accumulated in quite water areas that are not affected by tidal or strong oceanic currents (Tucker and Wright, 1990). Such habitats are found in deep water shelf/ramp areas below wave base or in the lee of islands and shoals (Brain and Andre, 1992).

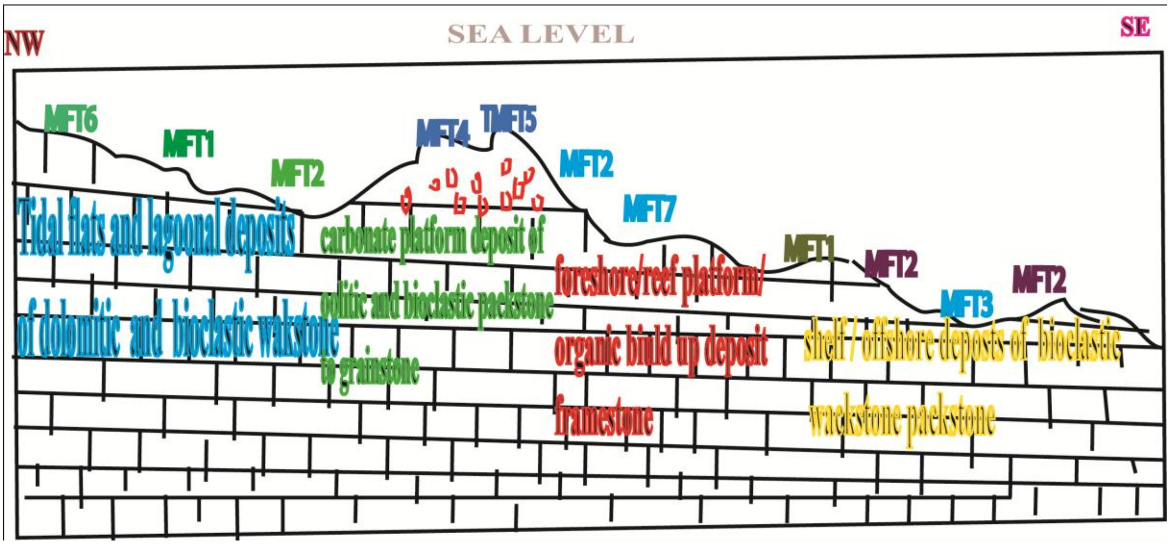


Figure 6.4: simple depositional environment model of Sodoble section.

The upper Sodoble section carbonate successions are mainly fine grained marly micritic limestone interbeded with chert and bioclastic wackestone layers. Micritic rocks are composed of fine-grained calcite crystals and particles formed in place or by the accumulation of fine-grained pre-existing carbonate material. The presence of calcareous mudstone dominated layers with chert interbeded micritic layers in upper sub unit of sodoble section is the most typical example of carbonate deposits of low energy of outer shelf/ramp setting at basin margins or open sea conditions.

6.5 Paleographic Setting

In general for the paleographic setting, the major carbonate deposits throughout NE-Africa and neighbouring areas are the results of relative sea level fluctuation of continental scale. During the Jurassic time the sea flooded the large continuous continental parts of Gondwana (Africa, Madagascar, India and Arabia) (Bosselliniet al., 1997; Bosellini, 1989) and according to the general stratigraphic relationship it seems very likely that carbonate deposits was deposited on a homoclinal ramp (Bossellini et al., 1997) or structurally speaking on a wide cratonic margin, gently dipping to southeast.

Starting from the early Liassic, the sea started to advance on this varied landscape, first flooding low topographic regions of near the eastern continental margin of future Indian ocean (Meregh Formation of Somalia (Bosellini, 1989)) or various rift basin dividing Gondwana continent (Mandera- Lugh and Al Mado basins in Somalia, Ogaden, Blue Nile basin in Ethiopia) and only later (middle to late Jurassic) the inland and more elevated regions of the craton. As a consequence, the first flooding is time transgressive , its Liassic in northern Kenya, central Somalia and part of Ogaden basin (Riccardi,1991), Bathonian in Dire Dawa and late Callovian-early Oxfordian in Yemen and northern Ethiopia.

Based on the available previous works on the paleogeography of the NE-Africa the early – middle Jurassic (Toarcian- Callovian) and late Jurassic (Kimmeridgian) times, which the sodoble section carbonate deposits were formed at this particular time of Callovian-kimmerdgian age. The paleogeoraphic maps of NE-Africa and Arabian platforms during the early Jurassic (Toarcian time) and late Jurassic times, those can shows the paleographic conditions in Ethiopia and some surrounding areas, during the depositions of this carbonate units.

The Early to Middle Jurassic (Toarcian-Callovian) times: During the Late Triassic, the time before Jurassic, in the north-eastern part of Arabia and East Africa, including Ethiopia formed part of a stable and slowly subsiding craton (Reynolds et al. 1997).

A shallow gulf invaded from the northeast onto wide areas of the Arabian platform and propagated as far southeast as central Ethiopia. Along the East African margin rifting occurred again during the early Jurassic superimposed on the older Karoo structures, indicating that time is the full separation of East and West Gondwana (Reynolds et al. 1997). Crustal extension and rifting that continued throughout the Middle Jurassic, enhanced by global eustatic sea level rise (Haq et al., 1987), caused marine transgressions that flooded wide areas of East Africa.

CHAPTER SEVEN

6 Conclusions and Recommendations

6.4 Conclusions

On the basis of field observation, microfacies analysis and micropaleontological investigation, the Sodoble section is representative of Antalo formation in Blue Nile basin.

Stratigraphically, about 320m thick Callovian-Kimmeridgian age carbonate succession (Antalo formation) of Sodoble section are subdivided into lower, middle and upper Sodoble, from bottom to top. This grouping is based on their stratigraphic position, facies pattern, faunal and floral and microfacies analysis. Lower sub-unit is about 141 m thick, conformably overlain by Gohatsion Formation; and consists of dolomitic limestone and bioclastic wackestone to mudstone.

Middle sub-unit is about 162m thick, conformably overlies the lower sub-unit and consists of micritic facies with some of colonial organisms; bioclastic wackestone facies; and, skeletal packstone-grainstone limestone beds of varying thickness. This unit has various foraminiferal species, corals and mollusks and dated to be Oxfordian-lower Kimmeridgian by occurrence of Kurnubia palastiniensis. The upper part of Sodoble sub unit overlain by upper sandstone and consists of marly fossiliferous limestone and bioclastic wackestone to packstone layer.

The microfacies type of this carbonate rocks are identified based on their petrographic study and divided into seven major microfacies types (MFT 1-7), those are designated as: MFT (1) Micritic microfacies, 2) Bioclastic wackestone microfacies, 3) bioclastic packstone/rudstone microfacies, 4) Bioclastic peloidal packstone-grainstone microfacies. 5) Oolitic microfacies, 6) dolomitic limestone 7) reefal/boundstone microfacies. Each of this microfacies where described, interpreted and also compared with SMFT of (Wilson, 1975). For generalization these seven microfacies type were again compared with facies belts of Wilson (1975) ranging from open sea to restricted platform (2-8) from top to bottom, as their detail respective matching were given in microfacies analysis section.

Accordingly, the microfacies analysis of carbonates units of Sodoble section has been deposited in shallow marine conditions of lagoon (MFT1, MFT2 and MFT6), platform margin (MFT 4 andMFT5) for lower Sodoble sub unit and middle Sodoble show deposition in organic build up/slope (MFT) and deep shelf margin environment (MFT1 and MFT2). Some marginal basin to open sea depositional condition of offshore (MFT1, MFT2 and MFT3) is indicated for the upper

Sodoble sub units. Carbonate deposits of the Mugher area (Sodoble section) consists of some cyclicity of facies (which may be the results of small changes in sea levels) and shows the overall transgressions patterns of deposits; in which the deep offshore carbonate facies of upper parts are overlain the more shallower marine carbonate facies deposits of middle and lower units.

Carbonate rocks of Sodoble section has various macro and microfossils. From these, Microfossils of Foraminifera such as (*Kurnubia palastiniensis* (Henson, 1948), *Lenticulina subalata (*Reuss, 1854), *Lenticulina quenstedti* (Gümbel, 1862), *Verneuilinoides minuta* (Said and Barakat, 1958), Haplophragmoides bartensteini (Kalantari,1969) and *Choffatella sp.* and Ostracods of *Cytherelloidea. Sp.*, *Progonocythere. sp*., Procytheridea sp., *Bairdia sp.*, and *Paracypris .sp* and invertebrate macrofossils of Bivalves such as: *Pholadomya sp*., Gastropods *Ampullina sp*. and Brachiopod species are identified. The age of Sodoble section carbonates unit is determined and dated to be Jurassic, particularly Callovian-Kimmeridgian by occurrence of index fossils *Pfenderina gracil, Kurnubia palastiniensis* and *Alveosepta jacaradi species.*

Mugher area carbonate successions(Sodoble section) are correlable with some of the chronostratigraphic equivalents and lithologically similar deposits of some near area of North western Ethiopia plateau of (Gendiberit-jeldu, Gundu meskel, Jema and Ejere section), and; within other Ethiopia basins (Mekele and Ogaden basins).

6.5 Recommendation

This study covers the depositional environment interpretations, paleontology and age assignments of the Sodoble stratigraphic section. However, the following recommendations were given for further works beyond the present works, for additional values:

Identification of the depositional environment was based on microfacies analysis through petrographic study. This may face ambiguity on precise determination of depositional environment when it is applied in a small scale area. It needs detailed facies, particularly microfacies analysis of more sections with more or less uniformity in sampling. Therefore, for more understanding of the depositional environment and to reconstruct the facies model of the area, detail facies and microfacies study in more sections is essential to see its lateral variations and continuity.

The Sodoble section carbonate unit is Jurassic sedimentary rocks those microfossils which are extracted from the sediments have not well preserved morphology. This makes some difficulty in the identification of foraminifer species and ostracods. There for the absence of scanning electron microscope make challenge in microfossils analysis.

The carbonate deposits of the area comprise so many varieties of skeletal grains; these can reveal much interesting informatiobioosn for tratigraphy, paleoclimate and paleoenvironmental studies. Due to this, detailed biostratigraphic, micropaleontological and micropaleontology research works over the area will be worthy.

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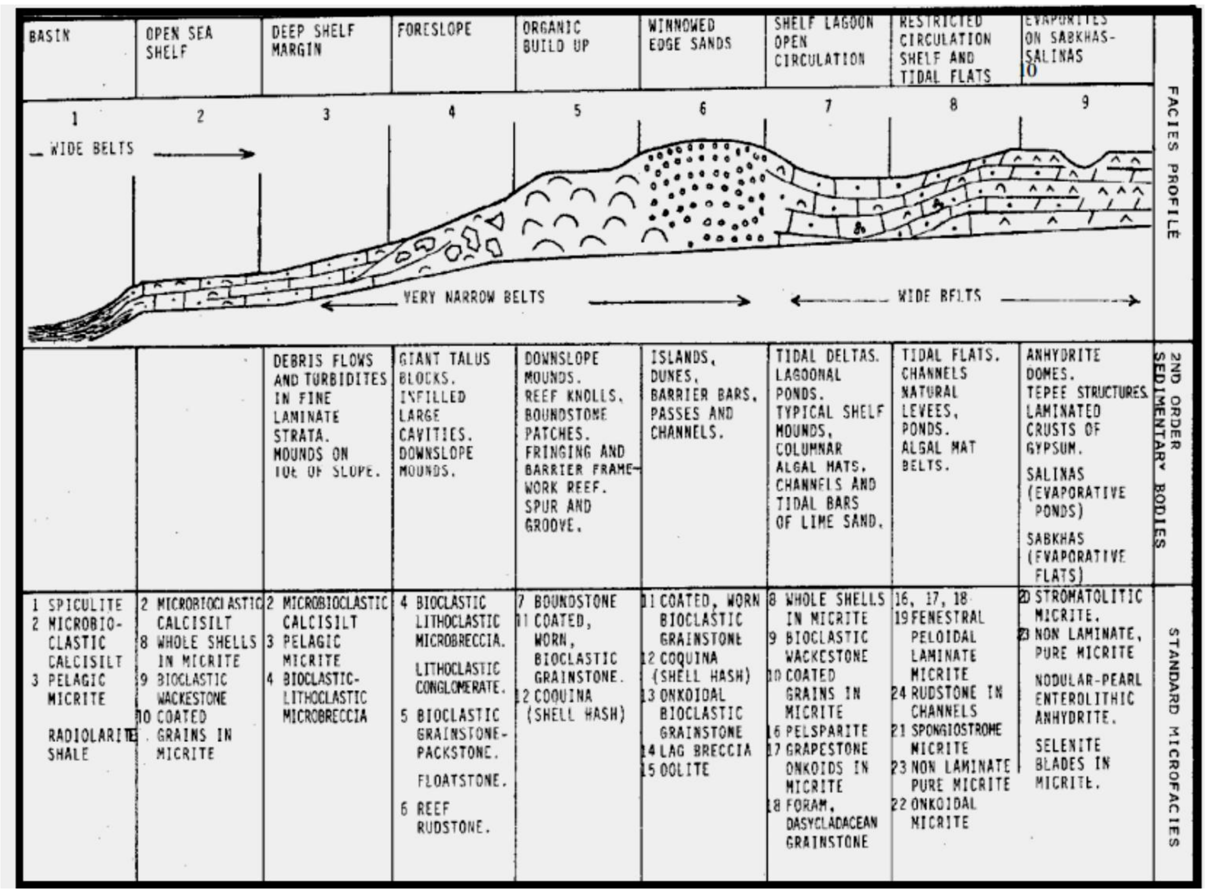
APPENDIXES

Appendex1 shows the distributions of SMFT and Facies belts on the generalized carbonate platform morphology taken from Wilson (1975).



The picture shows the distributions of 24 SMFT within 10 facies belts on the generalized carbonate platform morphology after Wilson (1975) and they are used in this paper for comparisons and depositional environment interpretations for the presently obtained carbonate microfacies from the study area, as cited in the body.

Plate 1: Ostracods extracted from the sediment

A-B) Cytherelloidia sp., K2S4,

C) Procytheridea sp., TS1

D) Progonocythere sp., K2S1

E-F) Cypridia sp. Under x 35 maginification, TS1

G) Paracypridia sp., dorsal view, TS1E

H) Baridia SP, K1S3,

This all above specimen are taken under magnification of x35

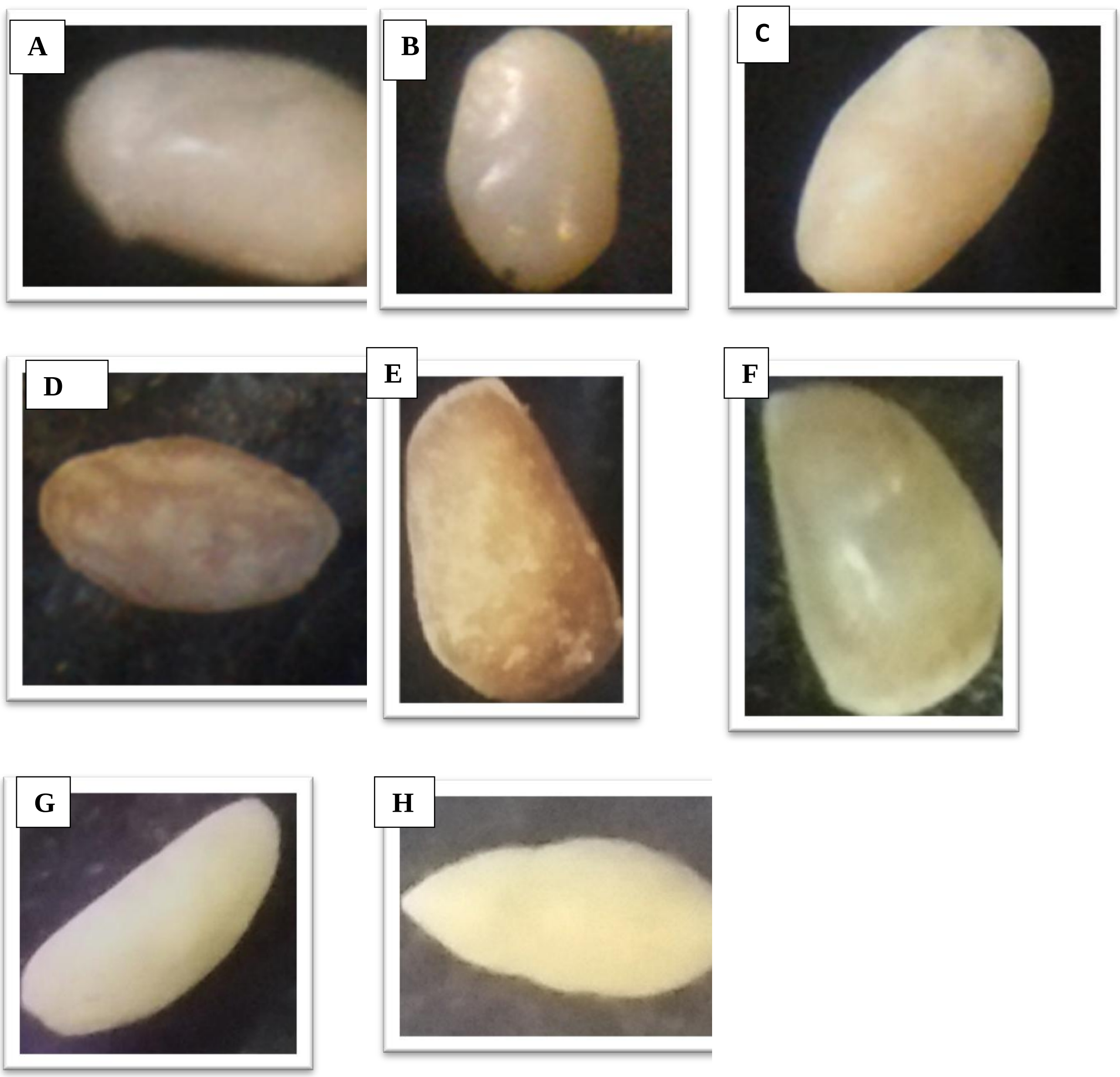


Plate 2: Foraminifera species extracted from the sediment

A) Lenticulina subalata, axial section TS1

B-C) Haplophragmoides bartensteini subequlateral section, TS1 and k1s4

D) Verneuilinoides minuta, axial section, k2S4

E) Kurnubia Jurassica vertical view,K2S4

F) Pfenderina gracilis, holotype, axial section, K2S4

G) Kurnubia palastiniensis, axial view K2S4,

H) Lenticulina quenstedti, axial view, Ts1

I-J) Chofotella cruciensis, (Pictet & Renevier, 1858) k1s3, under x35 magnification

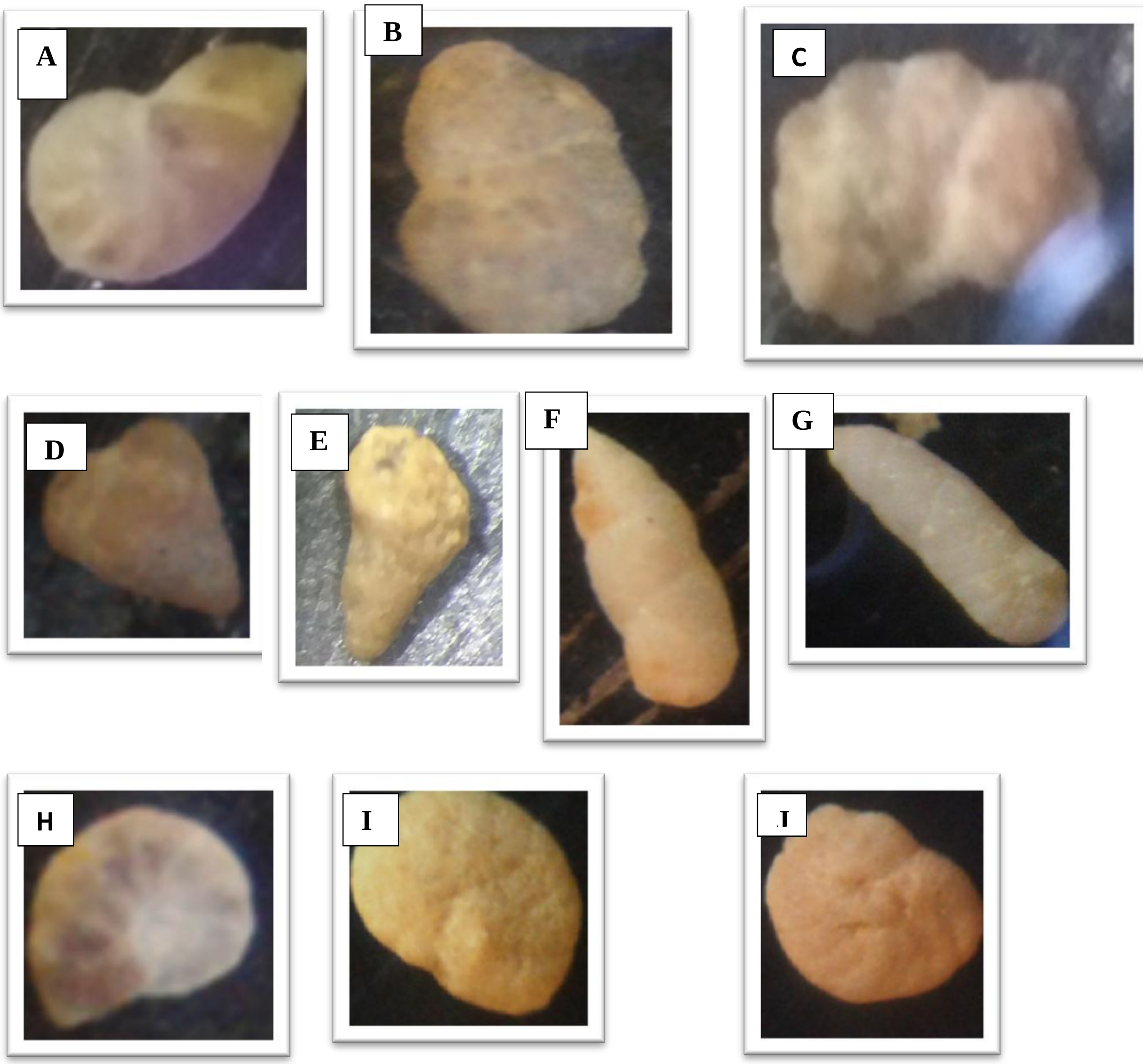


Plate 3: Bivalvia fossils

A) Eligmus SP. from lower Sodoble

B) Mactromya sp

C-D) Pholadomya sp.

E-F) Pholadomya somaliensis

All this bivalve species are internal mold except **(A)** which is body shell

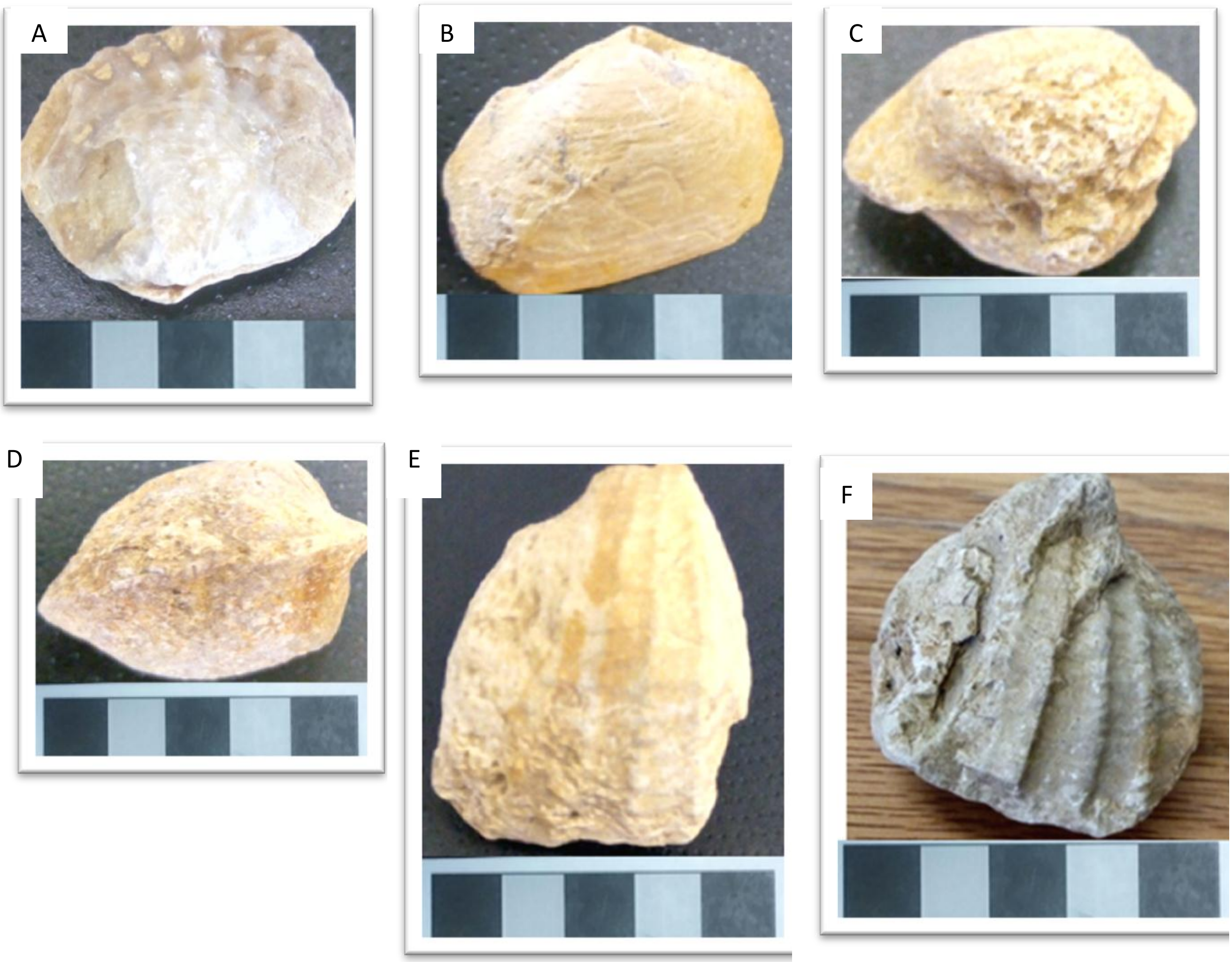


Plate 4: Brachiopods fossils

A-C) Daghanirhynchia sp., body shell from lower part of Sodoble section

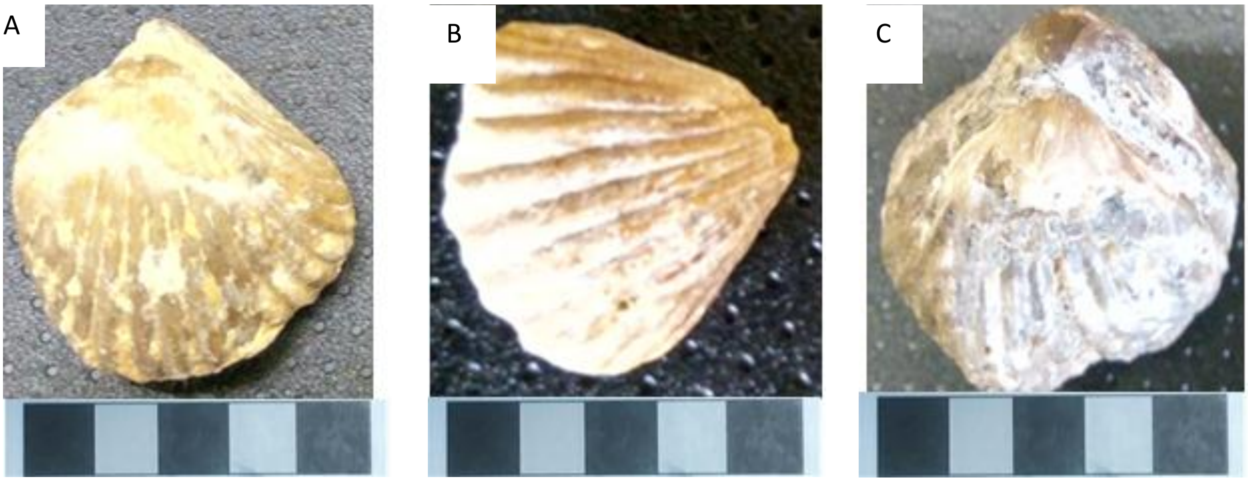


Plate 5: Gastropods fossils

A-C) Amphulina sp. at scale of 5cm

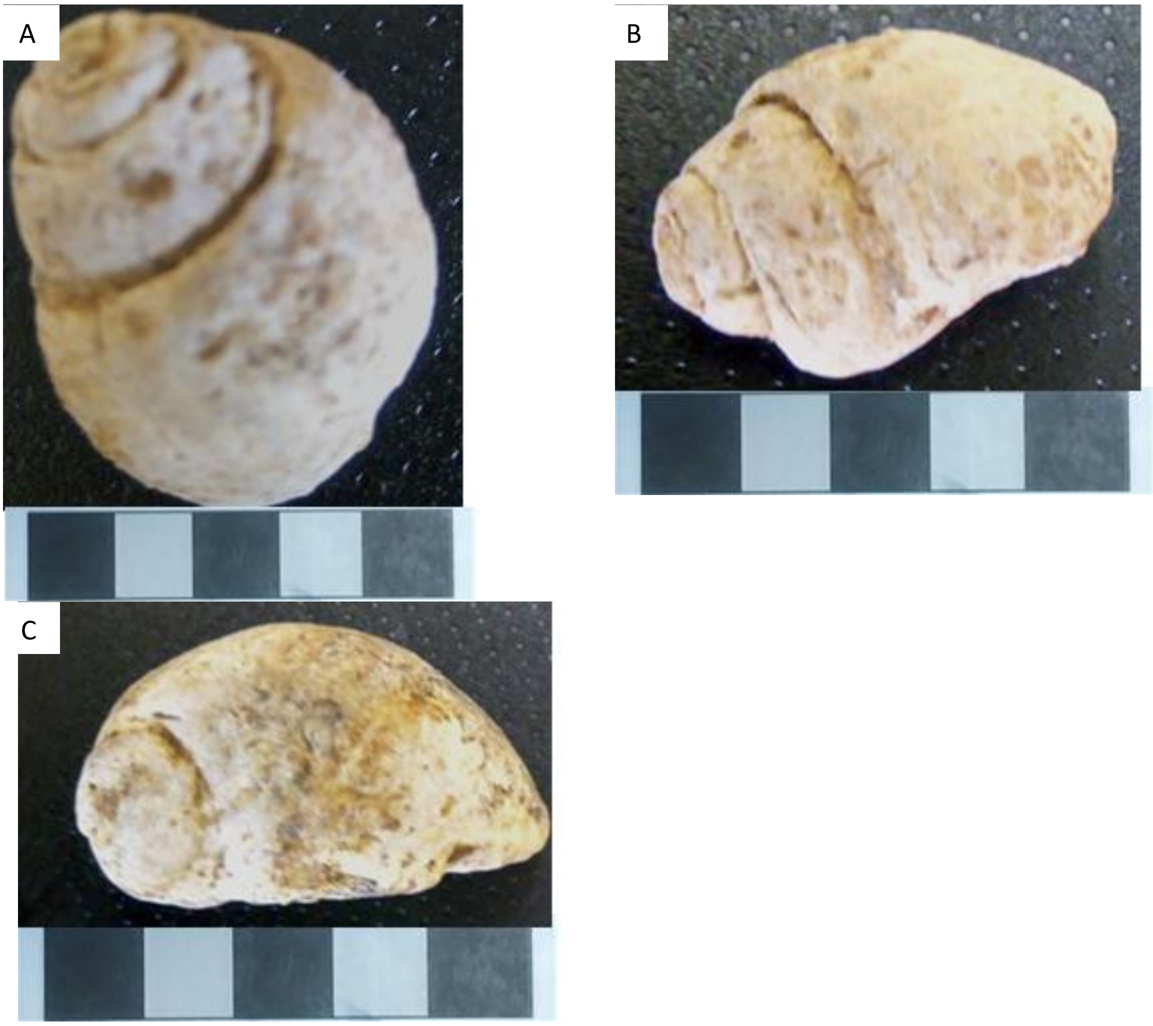


Plate 6: foraminifera and algae species from thin section

A) Alveosepta jacaradi, subaxial view,K1R4

B) Nautiloculina oolitica, Axial section K2R4

C) Psedeucyclamina litus axial view, K2R4

D) Kurunbia palastiniensis transverse section, from sample

E) siphovalvulina sp., axial section,K2R4

F) Parurgonina sp., Transverse section; from sample number K2R2

G) Verneuilinoides sp., Axial section,TR10

H) Ambacolite sp. Vertical section view, TR10

I) Lenticulina sp., axial view, TR7

J) Psedeocyclamina sp. K2R3 subaxial section,

K) Kurnubia palastiniensis, equilateral section K1R5

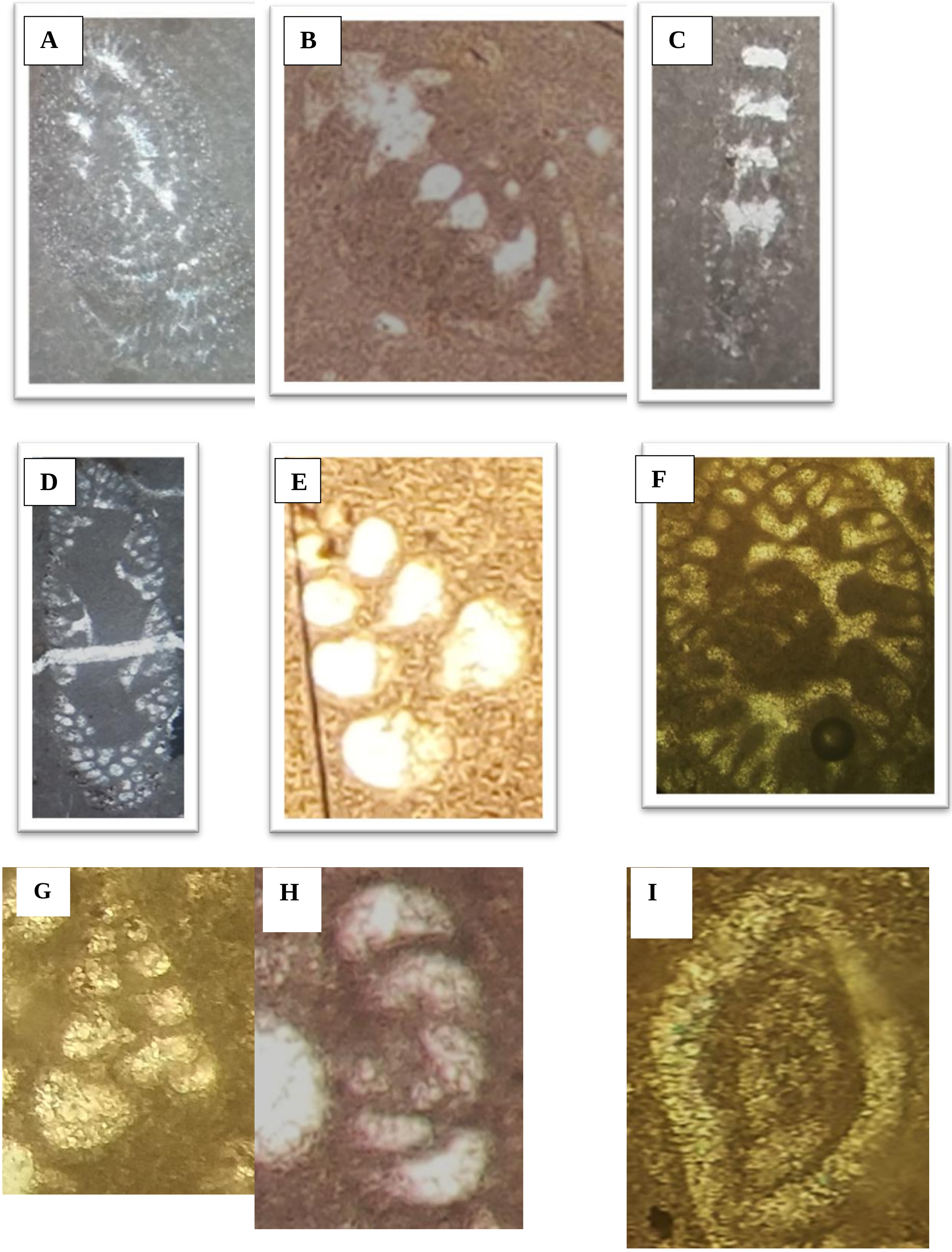
L) Kurnubia cf. morisis equilateral view, K1R4

M) Dasclydean algae, equilarreral section, TR7

N) Nouthiculina sp. axial view K2R4

O) Conicokurnubia sp. subaxial section, K2R3

P) Chofotella sp. Axial view,K2R4


A
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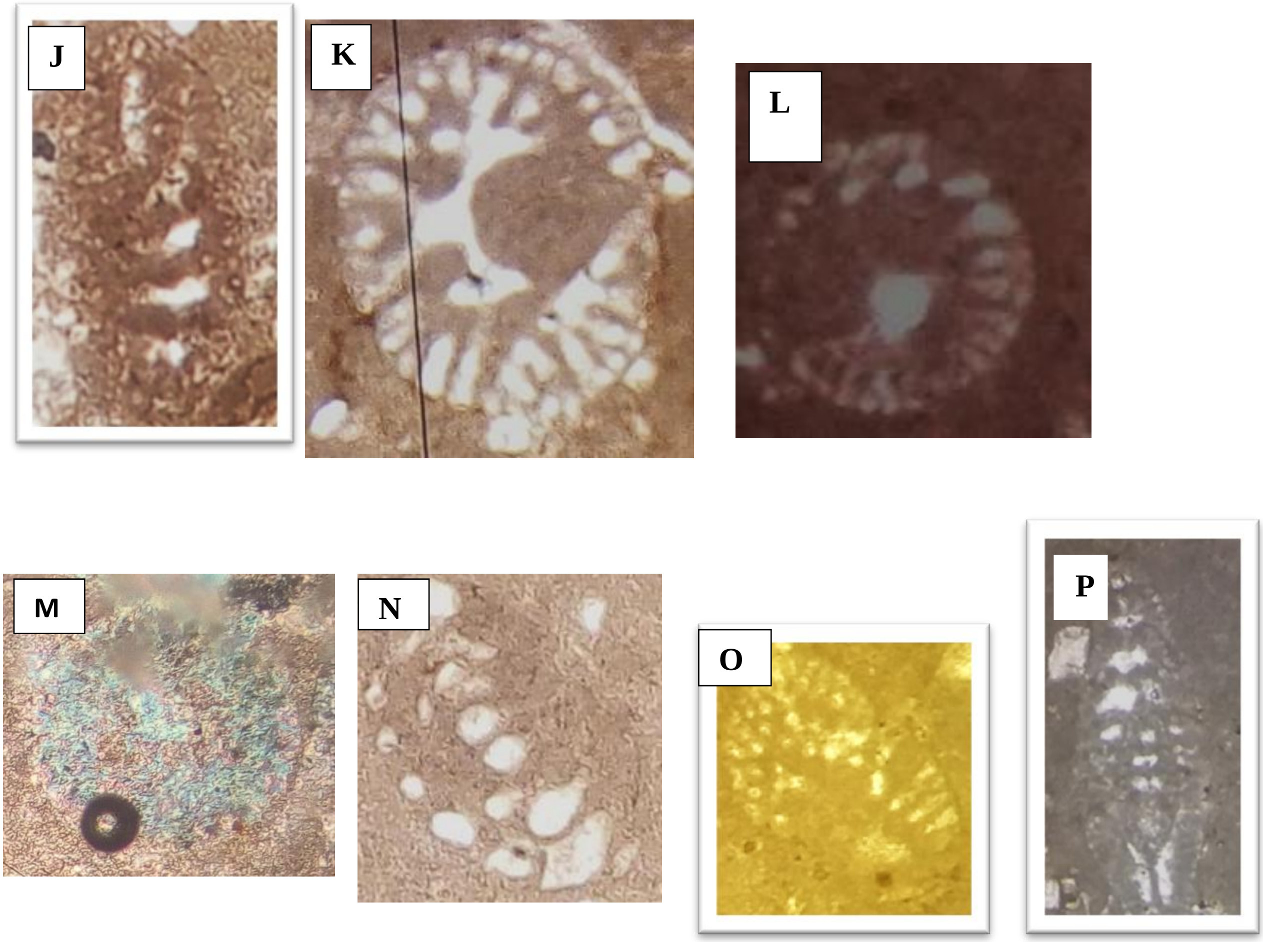
J
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Plate 7: Index foraminifera species from thin section

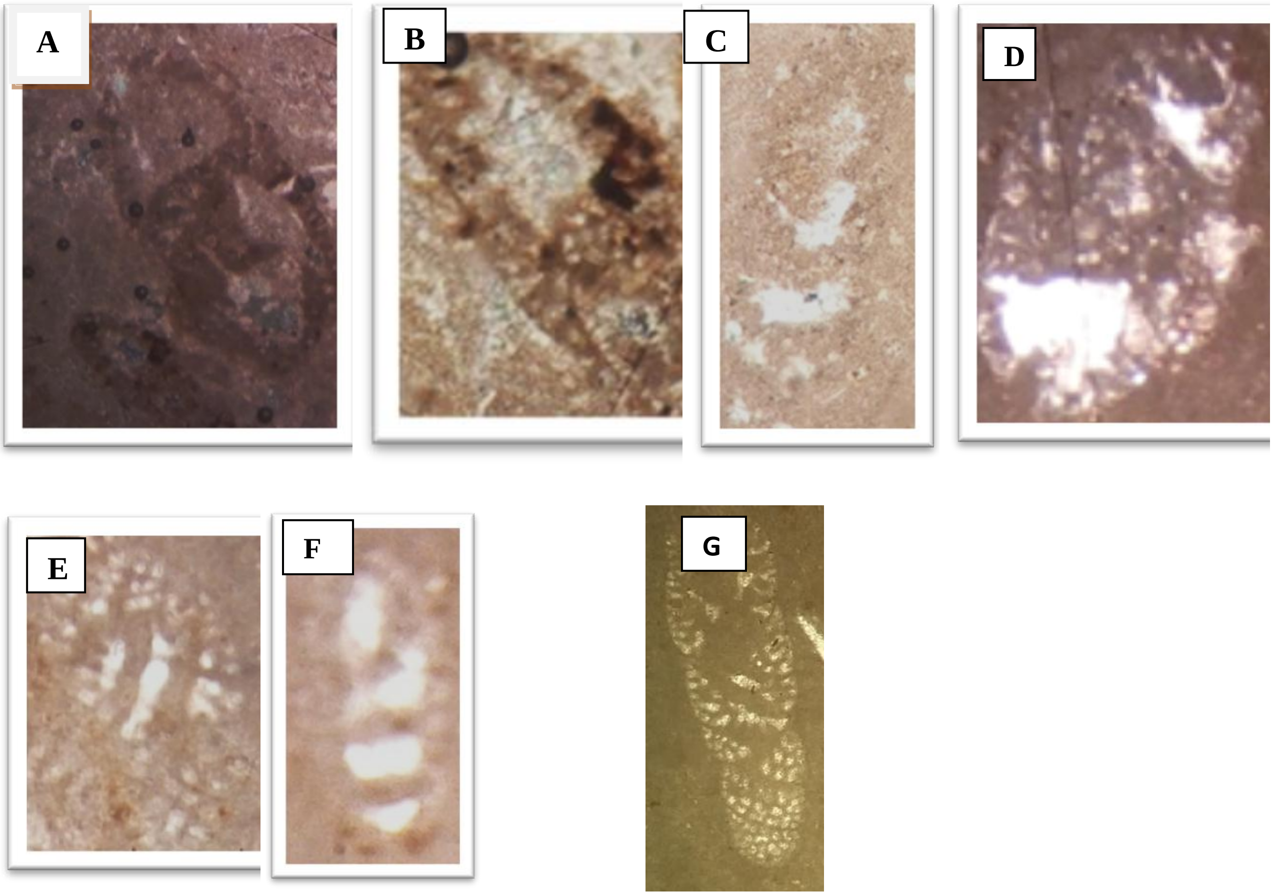
A-B) Alveosepta jacaradi both are axial view, K2R3

C) Everticyclammina Sp., axial section, K1R4

D) Pseudocyclammina lituus, axial view K2R3

E-F) Pfenderina sp., subequlateral view, TR8

G) Kurunbia palastiniensis, axial section, K1R6



Declaration

I hereby declare that this is my original work prepared under the supervision of Dr. Balemwal Atnafu during the year 2018 for the partial fulfillment of the Degrees Masters of Sciences in Geological Sciences (paleontology and paleoenvironment). I further declare that this work is not presented has not been presented for a degree in any other university, and all sources and materials used for the thesis have been duly acknowledged.

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Bertukan Gebre (Student) Date

This is to certify that the above declaration made by the candidate is correct to the bests my knowledge and it has been submitted to examination with my approval as a university advisor.

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Dr Balemwal Atnafu (Advisor) Date

30/5/2018

Addis Ababa, Ethiopia