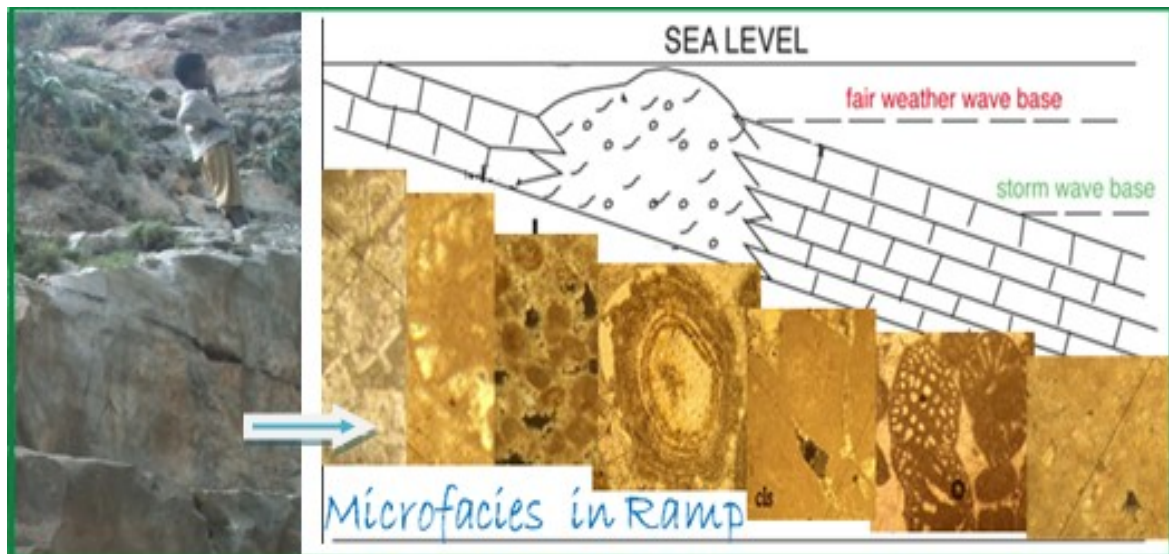


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Addis Ababa University
College of Natural sciences
School of Earth sciences

MICROFACIES ANALYSIS OF MESOZOIC CARBONATE UNITS OF DIRE DAWA AREA, SOUTH EASTERN ETHIOPIA



A thesis submitted to the school of Earth Sciences, Addis Ababa University, in partial fulfilment of the requirement for the degree of Master of Science in Earth sciences (**Sedimentology** and **Stratigraphy**)

By

GERAMU FUFA NEGARI

May, 2014

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Advisor: Balemwal Atnafu (PHD)

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Msc Thesis

By

Geramu Fufa Negari

Approved by Board of Examiners:-

Signature

- | | |
|------------------------------------|-------|
| 1. <u>Seifu Kebede (PHD)</u> | |
| Chairman, School of Earth Sciences | |
| 2. <u>Balemwal Atnafu(PHD)</u> | |
| Advisor | |
| 3. <u>Mulugeta Fisseha(PHD)</u> | |
| Examiner | |
| 4. <u>Mulugeta Allene (PHD)</u> | |
| Examiner | |

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Abstract

The lithostratigraphy and microfacies analysis of three selected stratigraphic sections were studied using field data and about thirty four thin sections analysis. These were used to understand the depositional environments, diagenetic settings and age of the carbonate succession (the Antalo Limestone Formation) of the Dire Dawa area, in South Eastern Ethiopia.

The field observations, microfacies analysis, and biostratigraphic examinations on the carbonate successions of the area, which sandwiched between lower and Upper Sandstone units, reveal that: these carbonate units have about (~306 m) thickness, have been deposited during Bathonian-Kimmeridgian time; and can be sub-divided into three sub-units, according to their facies contents and stratigraphic positions. These, from older to younger are: (1) The lower sub-unit (Bathonian-Callovian) which is (~119m) thick and consists of mixed siliciclastic - carbonates units of tidalflat-lagoon deposits; and peloidal and oolitic grainstone facies of carbonate shoal/barrier deposits of the shallow marine setting, (2) The middle sub-unit (Oxfordian-lower Kimmeridgian) is about (~84m) thick, conformably overlies the lower sub-unit, consists of the foreshoal facies of thick, allochemical rich wackestone-grainstone limestones, mainly dominated by reworked intraclastic grains and rare amounts of patches of colonial organisms, and (3) The upper sub-unit (Kimmeridgian) is about (~103m) thick, overlies the middle sub-unit conformably and topped unconformably by the Upper Sandstone. It consists of low energy deposits of fine grained dark micritic limestones with some cherts and clastic shale interbedded at its lower; and some colonial and carbonate buildup organism bearing layers at its upper part.

The overall microfacies and facies successions throughout the unit shows a carbonate ramp depositional setting, under which various submarine depositional environments ranging from shoreline carbonate deposits (including low energy tidalflat and lagoon) and high energy platform margin carbonate sand bodies) of inner ramp, foreshoal deposits of mid-ramp to the offshore deposits (basin margins and open sea) of outer ramp, successively from bottom to top.

The diagenetic sequence of these carbonate units, when ordered from early to late stage, comprises the following: micritization, dissolution, early marine cementation, meteoric calcite cementation, mechanical and chemical compaction, fractures; stylolite formation, dolomitization, silicification and burial cementation. These processes have taken place with varying intensities and occurrence throughout the area.

Lastly deposition and facies patterns throughout this unit are related to already established paleogeographic changes particularly involving the transgression of the sea on the horn of Africa. These deposits are also correlated with some of equivalent deposits in major Ethiopian sedimentary basins and with the Sana'a basin of Yemen.

Key words: Dire Dawa, microfacies, diagenesis, depositional environments, ramp.

Chapter 1: Introduction

1.1. Research problems and Background notes

This study is about the microfacies analysis of carbonate units of the Dire Dawa area, South Eastern Ethiopia, mainly for the setting and interpretations of the depositional environments for these carbonate successions. Microfacies 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.

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.

Carbonate sedimentary rocks are also an economically important group of rocks because limestones and dolomites are useful for agricultural and industrial purposes, they make good building stones and most importantly, they act as reservoir rocks for more than one-third of the world's petroleum reserves. Because carbonate minerals in general are soluble in slightly acidic waters, they often have high porosity and permeability, making them ideal reservoirs for petroleum. Most importantly they contain at least 40% of the world's known hydrocarbon reserves (Tucker & Wright, 1990). Carbonates are especially interesting for the diversity of their origins. Most limestones are ultimately biogenic in origin and an appreciation of biological and palaeobiological factors is essential in understanding their formation. Their simple mineralogy, usually mono-mineralic, belie their petrographic and chemical complexity and highly sophisticated microscopic and analytical techniques are required to decipher their diagenetic histories. To get all such interesting information's and resources of carbonates deposits, detail studies should be done by varies methodologies. Among them Facies analysis is one most powerful method for the detail investigations of sedimentary deposits. Facies has five defining parameters: geometry, lithology, palaeontology, sedimentary structures, and paleocurrent pattern, i.e. facies can be defined as 'a particular combination of lithology, structure, palaeontology and textural attributes that characterises features different from other rock bodies' (Walker, 1992; Selley, 2000).

Facies analysis on different lithologies 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, etc.

Among the facies analysis methods ,microfacies analysis, which is followed in this work, is the most important way for interpretations of carbonate rocks ,those are less interpretable in the field like that of clastic rocks. 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 Flugel (2004) the term ‘**microfacies**’ is the total of all the paleontological and sedimentological criteria (qualitative and quantitative) which can be classified in thin sections, peels, and polished samples at magnifications of up to approximately x 200. Microfacies analysis has the advantages over traditional sedimentological approaches of being interdisciplinary, and integrating sedimentological, paleontological and geochemical aspects. Wilson (1975) suggests that a 'short-hand' method of studying limestone is to compare them with Standard Microfacies Types (SMFT). He also recognizes 24 standard microfacies assignable to nine standard Facies Belts (FB) (as shown in appendix 3). Each facies has a distinctive composition which should be diagnostic for a particular environment, and this comparing method is followed in the present work, for comparing carbonate microfacies of the Dire Dawa area with that of Wilson SMFT and FB, as given in chapter 4 of this paper.

In case of Ethiopia, there are so many sedimentary deposits in different basins those are indicated by many authors at regional level, but with scarcities of detail local works. 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 (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 Palaeozoic and continued up to Tertiary. The Ogaden, Abay and Mekele basins are presumed to be intra-continental rift basins formed as a result of extensional stresses induced by the break-up of Gondwanaland in Upper Palaeozoic. The Mekele and Abay basins are located at Northern and central part of the country respectively.

The Ogaden Basin, which is the proximal continuation of the present study area, is located in the area extending from the East to Southeast part of Ethiopia, is constituted of tri axially rifted troughs trending NW-SE, N-S, and ENE-WSW.

Throughout all these larger basins, there is thick Paleozoic to Mesozoic sedimentary deposits identified by various workers, but still it needs more local and detail works on these sedimentary resources. Mainly carbonate rocks are less studied, so detail studies like microfacies analysis is required and can give chance to know resources and uses them for the country’s economic purposes and for supporting scientific ideas in other ways. The present work is focus on carbonate deposits of the area around the Dire Dawa, which is located on the Southern border of Ethiopian Rift and continuation of Ogaden basin deposits, to do the detail microfacies analysis on the carbonate deposits of the area at very local detail scale of study.

1.2. Study area descriptions

1.2.1. Location and Accessibility

From the three main geomorphologic features of Ethiopia, (the North-western Plateau and the South-Eastern Plateau, those are separated by the Ethiopian Rift Valley), the present

study area is located in SE Ethiopia Plateau, around Dire Dawa city, at about 500 km distance from Addis Ababa, capital city of the country, along the main road from Addis Ababa to Dire Dawa city (fig.1.2).

The study is undertaken on three locally selected stratigraphic sections throughout the area. These are: 1) Lange section: which is located between Kersa and Lange villages, along the main road from Dire Dawa to Hirna, 2) Military section: located near Dire Dawa city at about 5km distance from Dire Dawa town to the South East, along the main road to Dengago, and 3) Dachatu River section: located near Dachatu river to the East of Dire Dawa city.

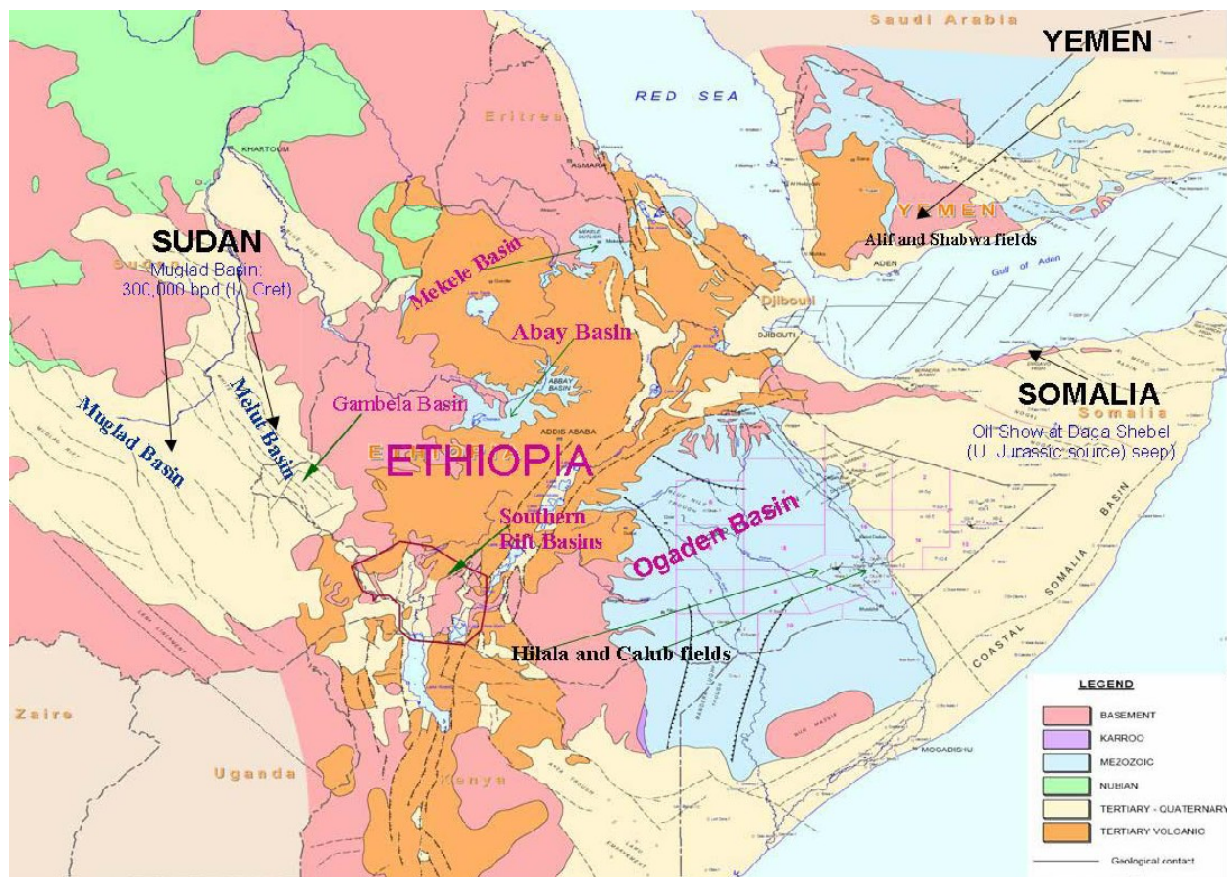


Figure 1.1 Sedimentary basins of Ethiopia (Source: Ethiopian ministry of mine, 2011b). Not scaled.

The study area is accessed through the main asphalt road from Addis Ababa to Dire Dawa city, East of Ethiopia in general and the three local sections are accessed through on foot short distances away from main asphalt roads and following some river cuts, gullies and clumping the cliffs to access the outcrops of the rock units throughout the area.

1.2.2. Physiography and drainages

The study area is the Southern margin of the Afar depression; and due to this, physiography of the area is mainly controlled by volcanoes and tectonic activities. The area is characterized by successive short running E-W oriented faults forming half graben and horsts. The geomorphology of the study area can be classified into different major features: the

escarpments (cliff parts), the transitional gentle sloping and the alluvial plains (flat topography) filled by quaternary deposits.

The escarpment area is characterised by steep slopes formed by limestones and sandstones mainly, gullies and dry wadies mainly underlain by sedimentary and metamorphic rocks.

As the result of step faults tilting the sedimentary rocks towards the South, a number of bench shape plateaus with southerly dip form the escarpment areas and there are also book shelf model forming limestone beds are observed throughout the escarpment areas. Wadies mostly cut across these rocks mainly following the NE trending fault systems. In these areas runoff is high due to the steep slope and the rock surfaces permitting low retention period.

The alluvial plains are characterised by gentle to flat topography. Except some volcanic hills of younger age, the Mesozoic and the tertiary rocks are buried deep under quaternary sediments.

The presence of high relief in the area made it dissect by many tectonically controlled small intermittent rivers, which are tributaries to the main perennial river Awash. Most of the rivers run N-S to NNW-SSE following the trend of the major faults running lineaments which cross the rift margins. All the rivers found in the area are seasonal and with short duration floods.

1.2.3. Climate of the study Area

Dire Dawa area is a grouped in the Kolla and semi-kolla climatic zone. According to the Ethiopian National metrological agency (from the Dire Dawa metrological station), the mean annual rain fall and temperature of the area are about 636.0 mm and 25.3⁰c respectively. The area receives: the minimum temperature during the winter season, maximum temperature of about 27.30c during the summer season, minimum rain fall about 72.4 mm during the winter season, maximum rain fall during the summer season about 310.2 mm and medium both the temperature and rain fall during the spring seasons (as the data recorded from Dire Dawa meteorological station which is located at longitude and latitude of 811000 ⁰E, 1061000 ⁰N and elevation of 1260 m a.m.s.l.). The full meteorological data are given in appendix 1.

High temperature prevalence as well as low rainfall are the climatic constraints strongly influencing the different land cover/uses in general as well as the composition of the physiognomic vegetation in particular in the area, and various scattered shrubs and grassland like *Euphorbia*, *Aloe*, *Opuntia*, *Deacaena*, *Acacia Blanites aegypitiaca* and *Moraceae spp.* are becoming the dominant types of vegetation founds in the area.

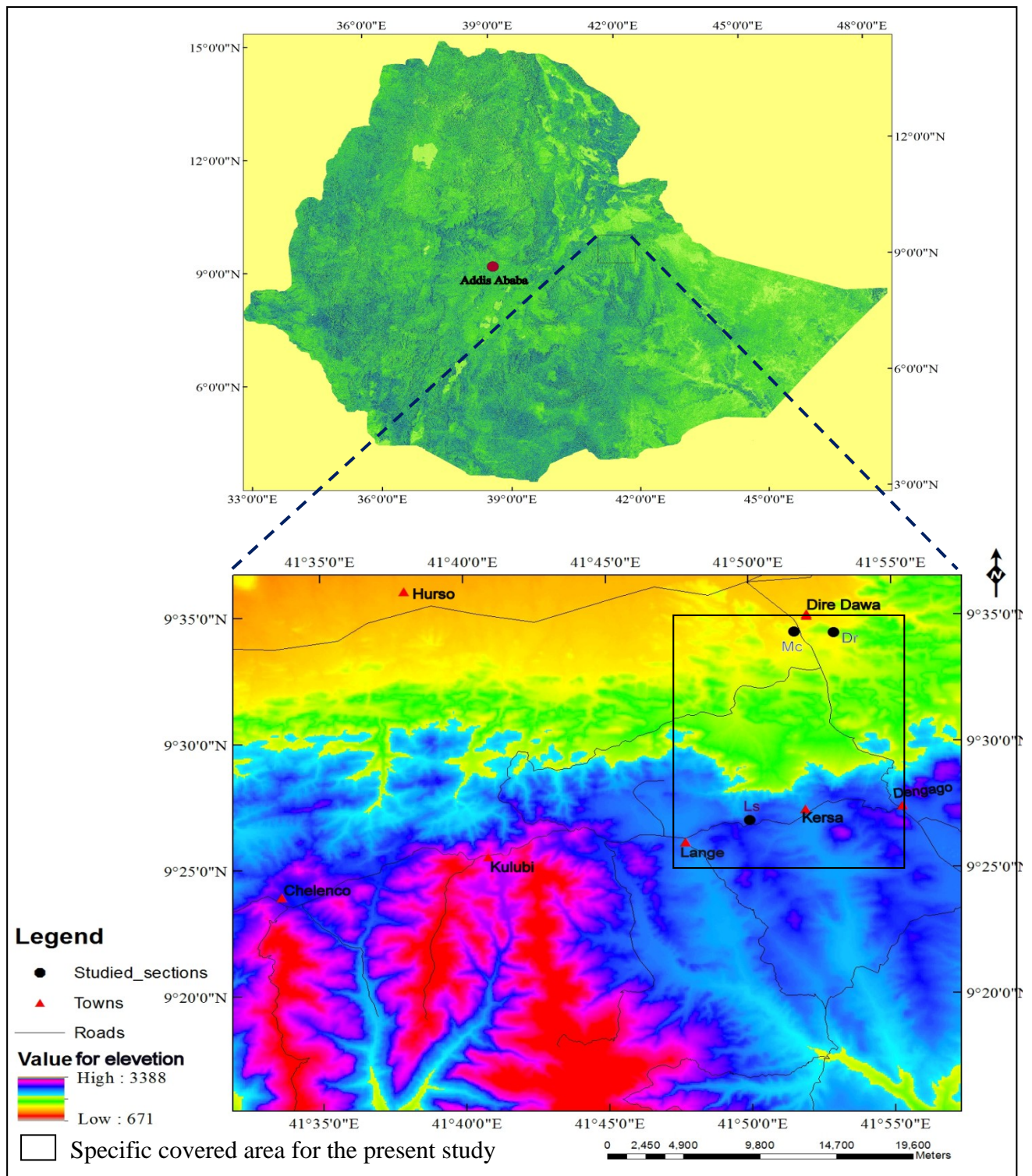


Figure 1.2. Location map of the study area. This map shows the physiography, elevations and location of studied sections. The smaller rectangle includes the local studied sections.

1.3. Previous works

On major sedimentary successions of Ethiopia in general, and on the south-eastern parts of Ethiopia in particular a lot of regional geological studies were undertaken by different authors at different times. Even though the carbonate units are rarely studied in detail separately, they

are discussed by different authors within the regional concepts or within gross stratigraphical studies of the areas. Among them:

The name 'Antalo Limestone Formation' was first given for carbonate units by Blanford (1869, 1870) from its type locality town name 'Antalo' (N 13°18'/E 39°19') in northern Ethiopia. In the Northern Ethiopia, the unit was well described by Levitte(1970), Beyth (1972b) and Bosellini et al. (1997). According to Beyth (1972 b), in Northern Ethiopia, the thickness of the succession ranges from 300 m in the West to 800 m in the East. This author identified four different facies, which are briefly outlined, from bottom to top, as follows: (i) a cross-bedded sandy oolite and coquina with minor amount of marl and a few chert beds, with microfauna including mainly corals, gastropods, and echinoids, (ii) interbedding of marl and lithographic limestone with abundant brachiopods and some algal and chert beds, (iii) cliffs of coral and algal reef limestones interbedded with marl and biostromes, and (iv) black to grey microcrystalline limestone interbedded with marl.

Later on, Bosellini et al. (1997) attempted to subdivided the limestone unit of the same area into four depositional sequences (A1 to A4), which are composed of thickening and shallowing up cycles.

In other part of the country, in Blue Nile basin, about 420 m thick carbonate succession, as described by Assefa(1991) and Russo et al. (1994)), conformably overlies the Gohatsion Formation.

When we come particularly to the Dire Dawa area, a part of South Eastern Ethiopia, microfacies analysis of the Antalo lime stone of the area was studied by Ficarelli et al., (1975). According to this study the Microfacies analysis of carbonate units of the area reveals that shallow marine environments of depositions during the depositions of Antalo Lime Stone and with the existence of bars of oolitic sand near to the coasts and high energy of environments at low part. Later on, the geological map of Dire Dawa sheet is produced at the scale of 1:250,000 (Berhe, 1985) which provided valuable information for understanding the regional geology of the area and indicating the distributions of carbonate units of the area ,which are the focus of the present work.

In more recent time, according to Bosellini et al. (2001) the Mesozoic succession of Dire Dawa area consists of lower fluvatile sand stone (Adigrat Sandstone Formation), intermediate carbonate marly units (Antalo Lime Stone Formation), and upper fluvatile sandstone (Amba Aradam Formation). According to this study the intermediate unit, Antalo Limestone Group, contains four different formations grouped into two depositional sequences. The base of lower sequence (Antalo super sequence) is time-transgressive (plienbachian to oxfordian) and is result of the first flooding of this sector of Gondwana continent during the Mesozoic. The second major sequence boundary is also time-transgressive and corresponds to an abrupt deepening of East Africa and Southern Arabia shallow water ramps and carbonate platforms , a collapse most probably related to the separation of Madagascar from Africa , a major tectonic event occurred in early cretaceous from northern Ethiopia to Yemen and Southern Ethiopia and Somalia. But they mainly depend on the facies at out crop scale level, rather than microfacies.

Even though all these investigations were under taken, still there are the scarcities and limitations regarding data, detail microfacies analysis, depositional environments concepts, age and diagenesis concepts for the carbonate units of Dire Dawa area, And this work give more detail microfacies analysis, diagenetic setting, comparison of major microfacies types of the carbonate deposits of the study area with well known standard microfacies types (SMFT) established by Wilson (1975), age and the detail depositional environment interpretations for these carbonate successions.

1.4. Objectives and Scope of the Present Works

Facies analysis of any sedimentary deposit is essential whenever the sedimentological concepts of the deposit is concerned, to give logical and convincing interpretations and conclusions about depositional environments, the geometry, sedimentary structures, sedimentary textures, and fossil contents of that deposits. In particular the microfacies analysis give the microscopic level supported detail of facies analysis which can help to identify the smaller sediment contents, microfossils and structures of any sedimentary deposits in details, and it needs to be understood well. In addition the detailed interpretation of the depositional environment supported from various data sources for any sedimentary succession is needs to be understood well.

When we come to our country, Ethiopia, there is scarcity of detail studies and documentation of sedimentological, paleontological and stratigraphic features of the carbonate units in broad sense and particularly in the south-eastern Ethiopia. So the aim of this study is to reduce this scarcity a little bit and to apply the microfacies analysis concepts only on the carbonate deposits of the Dire Dawa area.

To confirm all such studies the present work has the following general and specific objectives:

1.4.1. General objective

The general objective of this work is describing and interpreting the depositional environments of carbonate units of the Dire Dawa area based on detailed microfacies analysis of the units.

1.4.2. Specific objectives

The specific objective includes:

- ✓ Detail microfacies analysis of carbonate units of the area
- ✓ Giving the classifications of the carbonate rocks of the area, based on field observations and the petrographic analysis under microscope, using the common classification schemes for carbonate rocks.
- ✓ Discussions about the diagenetic features of the carbonate units of the area.
- ✓ Grouping the carbonate deposits of the area into various microfacies types and comparing them with common microfacies model (with that of FB and SMFT of Wilson, 1975).

- ✓ Descriptions and Interpretations for the microfacies and facies associations, and giving facies models for carbonate deposits of the area
- ✓ Producing detail composite stratigraphy of the carbonate units of the area.
- ✓ Age determination for carbonate units of the area.

1.5. Materials and Methods

To achieve the general and specific objectives of the present study different materials and methodologies were used for collecting, organizing, analysing and interpreting of the data, in fields and in laboratory.

A detailed analysis of the microfacies succession on the selected stratigraphic sections was the main tool used in this research for the depositional environment interpretations and carbonate units analysis's. To do detail microfacies analysis two different methodologies were used: the field methods and the laboratory methods, with the aids of different instruments. Each of them is discussed in detail as follow:

1.5.1. Field methods

In general, for the present study twice field works (two weeks in April and 2 weeks in September, 2013) around the Dire Dawa area, were done by using materials like topographic map of the study area with 1: 50,000 scale and regional geological map of the study area with 1:250,000 scale in addition to basic geological instruments like; Global Positioning System (GPS), compass, tape meter, hammer, hand lenses and etc.

During the field works three stratigraphic sections were selected (Lange section, Military camp section and Dachatu river section). These sections were selected due to their good exposure to represent carbonate deposits of the area and due to their accessibility.

Rock sampling, graphic logging and an intensive bed by bed scale description of carbonate exposure at each of these selected sections based on lithology, texture, rock color, bedding, sedimentary structures, diagenetic features, fossils and biogenic structures were done during field works.

Samples and Sampling techniques

From the field about 50 rock samples were collected, for both hand specimen and laboratory studies. For the sampling of those samples lateral and vertical variations within; rock units, the beds and intra-beds were given more attentions. Simple random sampling techniques are used. Bottom, middle and the top parts of thick bed was sampled when there are observable little or more variations in lithology and some other sedimentary aspects, only one sample per bed/s if there is no observable variations . The sections were measured from bottom up to its tops to locate stratigraphic positions for the taken samples. The samples were named (given codes) logically during the field works to eradicate later confusions in laboratory and interpretations of the results obtained from them.

Graphic logging of the stratigraphic sections

Graphic logs are visual representations of the information you collect like : thickness of units (vertical axis), Texture (average grain size-horizontal axis), lithology, Sedimentary structures, fossils, diagenetic features, contacts between units, they may also contain additional descriptions, notes, measurements and so on if required about the outcrops (Tucker,2003)

For this study each of the three selected stratigraphic sections were measured and logged separately, based on bed-by-bed scale descriptions in the field up to about (~306m) total thickness carbonate successions, from the summations of each local sections, were logged throughout the area, as their stratigraphic logs are given in chapter 3 and 6 (in fig 3.3, 3.10, 3.15 and 6.2 respectively).

1.5.2. Laboratory methods

Carbonate rocks, like other sedimentary rocks, can be described in only a limited way in the field; the details are revealed through studies of thin-sections and peels.

For this work the **petrographic analyses** of about 34 thin-sections have been performed under the petrographic microscope, at Addis Ababa University, Earth Sciences school, in mineralogy laboratory, for the study of the mineralogical compositions, textures (grain-size, degree of sorting, roundness), varies non-skeletal and skeletal grains, fossils, matrix identifications, diagenetic feature descriptions and other features indicative of a particular depositional environments.

After all, using the extensive conceptual reviewed from literatures and integrations of data from field's works and laboratory analysis, major works were done to arrive at conclusions. Including : The carbonate rocks of the area were classified and named according to the Dunham (1962) and Folk (1962) classifications schemes, about ten major microfacies types were identified and grouped with their detail descriptions and interpretations, these major microfacies types were compared with FB and SMFT of Wilson(1975), carbonate successions of the area are subdivided into three subunits based on lithological and facies patterns, facies model and depositional environments interpretations for overall carbonate successions of the area were given, composite stratigraphy of the area, mainly in detail for carbonate parts were made and at the end the correlations of carbonate units of the area with some studied carbonate deposits of SE Ethiopian plateau and with other larger basins carbonate deposit like that of Mekele basin, Blue Nile basin and Ogaden basins(of Ethiopia) and Sana'a basin(of Yemen) were made.

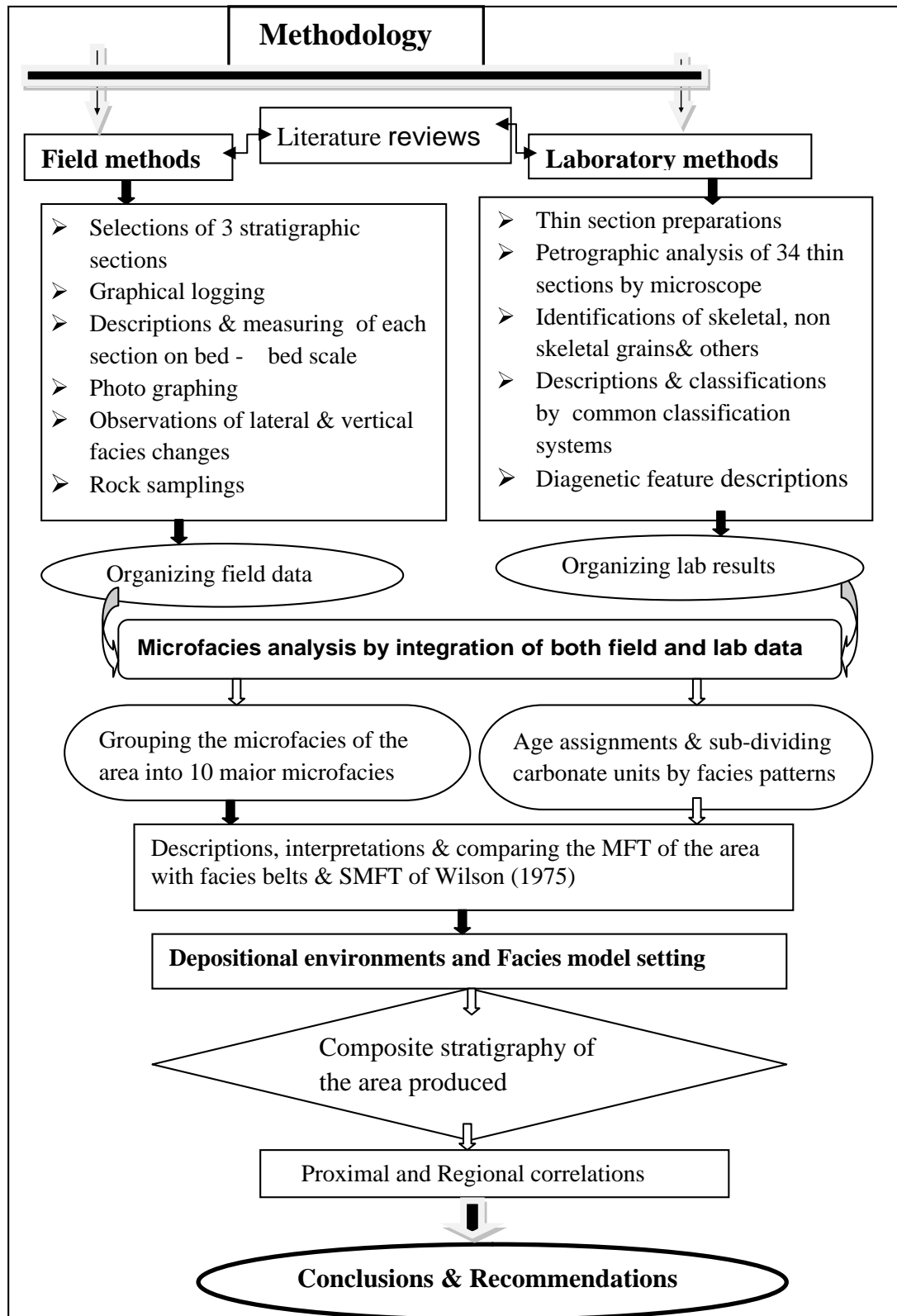


Figure 1.3. Conceptual flow chart for methodology

Chapter 2: Regional Geological setting

2.1. Geodynamic setting and sedimentation in Ethiopian Sedimentary basins

Sedimentary basins are regions of prolonged subsidence of earth's crust which can accumulate the sediments (Philip and John, 2005). The driving mechanisms of subsidence are ultimately related to processes within the relatively rigid, cooled thermal boundary layers of the earth known as lithosphere. The lithosphere is composed of a number of plates which are in motion with respect to each other. There are three basic lithospheric mechanisms forming the sedimentary basins. Those are, purely thermal mechanisms (by heating or cooling), changes in crustal/lithospheric thickness (by extension) and loading / unloading. Sedimentary basins therefore exist in a background environment of plate motion. The essential element of the concept is tectonic creation of relief, to provide both a source of sediment and a relatively low place for the deposition of those sediments.

Basins formed by stretching or thinning of the continental lithosphere fall in the evolutionary sequences: these includes : Early stages of the sequence, which corresponds to the development of intra-cratonic rifts often associated to crustal doming , such rifts may evolve to ocean spreading centres or may be aborted to form **failed rifts** or aulacogens. With sea floor creation and drifting of the continental edge away from the spreading centre, **passive margin basins** develop. The sequence has been termed the rift-drift suite of sedimentary basins. The mechanisms of interest with in these evolutionary sequences are primarily the thermal and mechanical behaviour of lithosphere under tension and the thermal contraction of lithosphere following stretching.

When we come to the Ethiopian sedimentary basins, as stated in previous sections 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(fig.1.1). Tectonic evolutions throughout NE-Africa and of the country and sea level fluctuations through geologic time in general have the great roles for the formation of these basins and thick sedimentary deposits within them. The development of most of these basins is related to the extensional tectonic events that have taken place intermittently since the Late Palaeozoic and continued up to Tertiary. The Ogaden, Abay and Mekele basins in Ethiopia are presumed to be intra-continental rift basins formed as a result of extensional stresses induced by the break-up of Gondwanaland in Upper Palaeozoic.

The Ogaden Basin, located in the area extending from the East to Southeast part of Ethiopia, is constituted of tri-axially rifted troughs trending NW-SE, N-S, and ENE-WSW (Worku & Astin, 1992; Shigut, 1998). The Abay (Blue Nile) Basin is a NW-SE trending branch of the Ogaden intra-continental rift basin (Gani et al., 2008) and Mekele basin found at north part of the country(Beyth, 1972b).

In addition to the tectonically controlled formations of the Ethiopian basins, the fluctuations of the sea level by tectonic activities and climatic conditions throughout different geologic time on East Africa in general and on Ethiopia particularly made the depositions of different sedimentary successions in those basins.

Thick Permo-Triassic sediments, ranging from continental clastics to lacustrine argillaceous types, were deposited in the Ogaden region in the Karoo rifting stage and equivalent sediments are also represented in the Blue Nile and Mekele basins (Worku & Astin, 1992).

A large scale down warping of the entire East African continent took place during Upper Triassic to Lower Jurassic time and consequently fluvio-deltaic sediments deposited over a large area, extending up to the Western and Northern regions of Ethiopia. Further rifting and subsidence of the region, including the Saudi Arabia and Yemeni areas, led to the transgression of the sea from the East and Southeast, flooding an extensive area; this event is probably related with the tectonics of separation of Madagascar from the Africa coast and the opening of the Indian Ocean.

Starting from late Jurassic time, East Africa was characterized by various tectonic events: including, the separation of Eastern Gondwana (Madagascar, India, Antarctica and Australia) and Western Gondwana (Africa, Arabia and South America) which was characterized by a sea-floor spreading between Madagascar and Africa at about 165 Ma (Coffin and Rabinowitz, 1988). During the Neocomian, an oceanic seaway developed that extended from Southern Africa via the Somali basin into the Eastern Neotethys, marking the birth of the proto- Indian Ocean.

Marine sediments, varying from shelf to deep basin types, deposited over a large area of the East African region and in wide areas of Yemen and Saudi Arabia. Moreover, lateral variation of the sedimentary facies had been controlled by sub-basins formed by recurrent faulting and tilting of fault blocks during the Jurassic. The NW-SE trending basins of Yemen and Northeast Somalia are believed to have been formed by the Jurassic rifting and subsidence events in the Horn of Africa and southern Arabia (Ricardi, 1991).

The regression of the sea from the region began in Late Jurassic as the result of arching and doming of the Arabian- Somalian massif, and sediments of varying facies (restricted marine, lagoonal and supratidal to inter-tidal) were deposited in structurally controlled domains. By Late Cretaceous, the sea completely withdrew leaving behind regressive continental clastics deposits.

Later on the formation several basins related to East Africa rift systems took place; the Gambela Basin is part of the Central African Rift System and it's the Southeast extension of the Melut Basin (White Nile rift) of South Sudan. The Southern Sudan basins and the Anza Basin of Northern Kenya are also failed rift basins of the Central African Rift System.

Paleogene rifting, along with volcanism was responsible for formation of the N-S – trending extensional rift basins in Southern, central and Northern Ethiopia. Rift basins/grabens of significantly large size have also been formed at Neogene in relation with or as a consequence of tectonic events that contributed to the development of the East African Rift System. Prominent among the Southern Rift Basins of Ethiopia are the Omo and Chew Bahir basins (Tilahun Mammo, 2012).

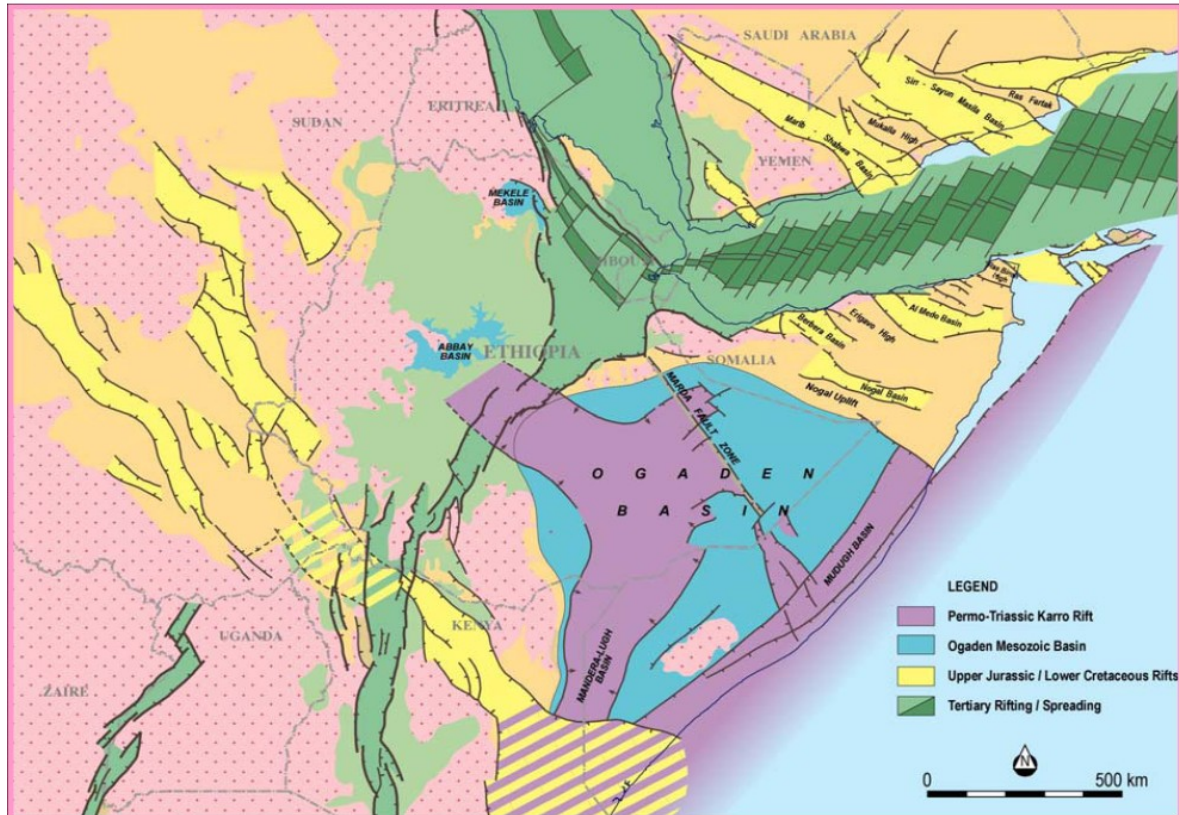


Figure.2.1. Regional setting of Ethiopian sedimentary basins (taken from Ethiopian ministry of mine, 2011)

2.2. Jurassic limestone Formations within Ethiopian sedimentary basins

From all Paleozoic to quaternary thick sedimentary successions within various Ethiopian sedimentary basins discussed above, when we look at the distributions of Jurassic limestone deposits, part of which will be a focus of the present works at particular Dire Dawa site, they are the results of the wide spread transgressions and extensional deformation related to the breakup of Gondwanaland taken place on all horn of Africa starting from early Mesozoic time (Bosellini, 1989).

Early Jurassic – Oxfordian time a major transgression probably related to the drifting phase and a major sea level highstand occurred all over East Africa with the drowning of the craton and documented by the Limestone Formations in different basins (Bosellini, 1989; Russo et al. 1994). Particularly, extensive limestone beds are exposed in three regions in Ethiopia: the Mekelle Outlier in the North (Tigris), the Blue Nile (Abay) Basin in central Ethiopia and the Ogaden Basin (including Western Hararghe region) in the Southeast (Beyth, 1972b; Assefa, 1988,1991; Shigut, 1998; Asrat et al, 2008), as given in (fig3.2.). These Jurassic limestones have various names according to its type locality throughout the country. Example: Antalo Limestone Formation (in Abay, Mekele and Dire Dawa area), Hamanlei Formation, Urandab and Gabredarre Formation (in Ogaden basin). In more specific the best exposures and most interesting deposits of the Antalo limestone are found in the central part of the Abay valley, and within the tributaries of Abay River including the Jemma, Wonchit and Muger river valleys, Delga Chebsi limestone located 23 km Northeast of Dire Dawa, Hakim Gara

limestone occurring near Harrar and Mesobo limestone near Mekele. Among these Mesozoic limestone deposits, in the country the present study is focus on the Jurassic limestone of Dire Dawa area, SE Ethiopia. Later on, in Ethiopia, overall regression was thought to prevail during latest Jurassic (Tithonian) and Berriasian times (Assefa, 1991; Schimidt and Werner, 1998) which terminate carbonate deposits. Throughout most part of Ethiopia clastic deposits overlies carbonate units starting from this time.

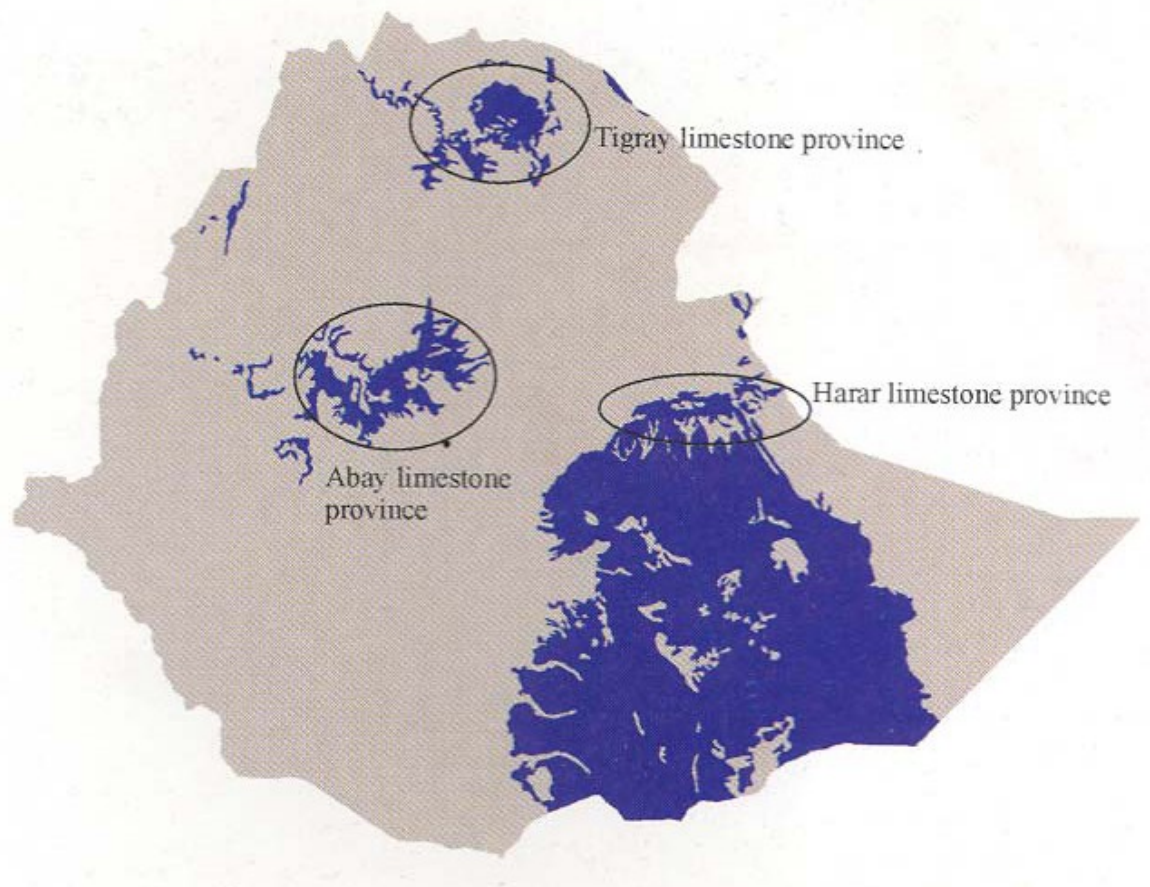


Figure 2.2. Locations of Mesozoic sediments of Ethiopia (Source: Ethiopian ministry of mine, 2009).

2.3. General Stratigraphy of Dire Dawa Area

Various geological formations of different ages are exposed and buried throughout all the geomorphologic features of Ethiopia. Ethiopia is generally known by geological formations that range from Precambrian to recent times (Kazmin, 1973), those can be grouped into major stratigraphic units, namely:

1. Precambrian basement rocks,
2. Late Paleozoic to Mesozoic sedimentary rocks and
3. Cenozoic volcanics and sedimentary rocks

About a quarter of the country's landmass is occupied by Precambrian metamorphic rocks, a quarter by Mesozoic sedimentary rocks and half by Cenozoic volcanics and sediments (Ministry of mines, 2011).

Almost all of these geologic units/stratigraphic units of Ethiopia are also exposed in the Eastern part of the country and particularly at the present study area (around Dire Dawa city). Generally the regional geology in comparison with local geology is described based on their regional stratigraphic position, from the older to younger as follows:

2.3.1. Precambrian rocks and related intrusions

The Precambrian basement rocks are poly-deformed and metamorphosed high grade gneisses and schists associated with low-grade meta-volcano-sedimentary rocks. They are the oldest formations in the country, with age of about over 600 million years, up on which all the younger formations were deposited.

These rocks are found in four major regions of Ethiopia: West and South-western; North; South; and Eastern regions of the country (Kazmin, 1973). The Precambrian metamorphic rocks comprise litho-tectonic low-grade volcano-sedimentary assemblages (of mica, feldspathic, amphibolites, chlorite, etc) with associated mafic to felsic intrusive (such as granites, granodiorites, diorites, basic dykes, gabbro and etc) and high-grade orthogneisses and paragneisses assemblages (Tadesse et al., 1999). These crystalline basement rocks have undergone poly-phase deformations and metamorphism (amphibolites to granulite metamorphism). Thick successions of the low-grade metavolcanosedimentary assemblages including the island arc and dismembered ophiolites assemblages are commonly termed as Upper complex of the Precambrian basement. Linear belts of mafic and ultramafic rocks are commonly confined to major shear zones often marking the contact between the two assemblages. Gneissic terrains (Lower Complex) are generally considered to be older than the volcano sedimentary assemblages. The Precambrian rocks of Ethiopia lie at the unique position of the northern part of the Mozambique belt and southern tip of the Arebonubian shield.

Precambrian outcrops in Eastern Ethiopia around the city of Dire Dawa (the present study area) are dominated by migmatitic gneisses showing well-developed gneissic layering.

2.3.2. Palaeozoic- Mesozoic sediments

Late Paleozoic-Mesozoic sedimentary rocks are widely distributed in the northern, central, Eastern and South-eastern parts of the country, overlying basement rocks.

Paleozoic is poorly represented with the exception of well-documented Permo-Triassic Karoo sedimentary rocks at the base of Ogaden basin and the presumed Ordovician glacial deposits in Northern Ethiopia (Shigut, 1988).

Late-Paleozoic to Early Mesozoic marine and continental sedimentary rocks are exposed in some parts of Ethiopia (Tefera et al., 1996). They are mainly sandstone and minor tillite, shale, siltstone, Limestone and conglomerates, which filled channels in the Precambrian basement. The Enticho sandstone and Edaga Arbi glacial deposits in the Tigray region, Permian sandstone in the Ilubabor and Kefa regions, the middle Abay tillite exposures, Waju sandstone, Calub sandstone, Gumbro sandstone, Bikh shale from deep bore-holes in the Ogaden region (Tefera et al., 1996), and the Genale basin's glacial tillites are some of these occurrences.

Thick Mesozoic sedimentary sequence is extensively exposed in Eastern part of the country extending as far as central and northern Ethiopia beneath the tertiary volcanic and overlain unconformably on the basement rocks. The geodynamic event responsible for the deposition of these rocks coincided with the end of the transgression of the Indian Ocean.

The sedimentary sequence represents the Jurassic transgression of the Indian Ocean from the East (in the Ogaden) towards North and west and then subsequent regression to the sea.

The Mesozoic rocks composed of the major stratigraphic sediments of Triassic sandstone (Lower sand stone or Adigrat Sandstone Formation), Jurassic Limestone of Antalo Group and the Cretaceous (upper) sandstone with intercalations of mudstone and marl.

In Dire Dawa area, a part of South Eastern Ethiopia, All this Mesozoic successions are exposed and they are unconformably overlies the basement rocks of the area and over lied by the volcanic rocks and quaternary deposits (as shown in figure 2.4). According to Bosellini et al. (2001) the Mesozoic stratigraphical successions of Dire Dawa area is generally divided into three stratigraphic units, as given in (fig.2.3). Form old to young, they include:

- Adigrat Sandstone Formation
- Carbonate marly units (Antalo Limestone Formation) and
- Amba Aradam Formation. Each of them is described below separately.

2.3.2.1. Adigrat Sandstone Formation

At the base of Mesozoic successions, Adigrat Sandstone Formation is unconformably overlies the basement rocks. Adigrat sandstone is the name given by Blandford (1870) for the basal clastics in Tigris (North Ethiopia), where Adigrat sandstone locally overlies horizontal glacial rocks of paleozoic age (Sexana and Assefa ,1983; Dawit, 2010)).The same formation name is used for the basal clastics units of Somalia (Bosellini,1992) ,where as equivalent terrigenous deposits are called Kohlan Formation in South Arabia (Yemen, Oman) (Lamare ,1930) and Mansa Gudda Formation in northern Kenya (Ayers,1952).

The Adigrat Sandstone of Dire Dawa area is normally quite thin (0- 100m thick), it's entirely absences in places suggests that depositions on a basement with highly irregular surfaces relief. Some shale, probably lagoon, occurs to top, where as several quartz, pebble conglomerates characterize the lower part.

According to the Bosellini et al., (2001) the sandstone of this area are grey or red and very coarse, arkosic in compositions, reflecting the underlying the basement rocks, mainly pink granite intruding biotitic gneiss. The formation is of fluvial origin and the entire stratigraphical and sedimentological context suggests a pediment or braided deposits for the Adigrat Sandstone of Dire Dawa. Both the lower and upper boundaries of the Adigrat Sandstone are probably diachronous (Bosellini, 1989). The age of the lower boundary can be Triassic to early Jurassic or even Permian. The age of upper part is taken as the age of beginning of marine transgression and is probably late liassic to Bajocian.

2.3.2.2. Antalo Super Group

It is the carbonate bearing units of the area, overlying the Adigrat Sandstone Formation. This Antalo Super Group is the focus of the present study, as raised in the next successive chapters. Based on their local study sections and areas, Bosellini et al., (2001) subdivided the Antalo Super Group of the Dire Dawa area into: Antalo Limestone Formation, Dire Dawa Formation, Daghani shale and Gildessa Limestone, when listed from bottom to top.

Antalo Limestone Formation: they give this name only for the lower parts of the carbonate units of the area; consist of two distinct members grossly described and recognised by Grietizer (1970). The two members are well defined morphologically and characterized by thickening upward sequences. The lower part is made of fossiliferous bioturbated dark grey marls and marlstones capped by dark grey grainstones. The upper part is made of dark sandstones and grainstones. Its thickness is about 100 m. according to various fossil assemblages of fossils; they give Callovian-Oxfordian age, for this formation.

Dire Dawa Formation: This formation is named by Bosellini et al. (2001) and represents the abrupt flooding of underlying grainstone parasequence sets of Antalo limestone Formation. It starts with thinly bedded 10-15 m slightly nodular black-bluish mudstone, with thin lenses and layers of black chert. After 20-25 m fine grainstone beds (20-50 cm) alternate with marly wavy-bedded limestone. Bioturbation is quite common, small coral fragments and fine skeletal debris and existence of the black micritic limestones rich in ammonites and belemnites. At Dire Dawa toward the top, five breccia layers each 2-6 m thick occur interbedded with the cherty dark grey mudstone. Most probably they document tectonic instability of the basin floor. Thickness of Dire Dawa Formation is 80m in Dire Dawa and 12-24 m near Gildessa. This Formation age is Early Kimmeridgian by stratigraphical position, as the upper member of the underlying Antalo limestone is Late Oxfordian (*Alveosepta jaccardi* zone) and overlying Daghani Shale is Middle to Late Kimmeridgian.

Daghani shale: in particular site above the shallow water Bihen Limestone, Bathonian-Callovian in age, a thick succession (~ 580 m) of the deeper water sediments (Gahodleh shale, Wanderer limestone, Daghani shale) of early to middle Kimmeridgian age follows.

Daghani shale succession is about 25 m thick, rich in belemnites and ammonites and occurs above Dire Dawa Formation and overlaid unconformably by above Amba Aradam Formation. The Daghani shale of Dire Dawa consists of a lower segment about 10 m thick of bioturbated marly limestone (beds of 30-50 cm) black shale interbeds. Belemnites (*Belemnopsis tanganesis*) are very abundant in the ten basal meters of the unit, and are associated with brachiopods (*Terebratulina suprajurensis*) and molluscs (*Falcomytilus jurensis*, *Mytilus (modiolus) imbricatus*, *Ceramyopsis* sp.). The upper 15-20 m part is represented by alternation of shale /marl and thin nodular limestone. Ammonites, *subplanites* sp., *Orthosphinctes vandelli*, *Sima spiroceras irregularis*, *Sutneria* sp., *Ataxioceras (para toxioceras)* are very common. According to Bosellini et al., (2001) the age of Daghani shale is Kimmeridgian.

Gildessa Limestone: It is carbonate units that disconformably lies on the ammonite rich succession of Daghani shale. Its thickness is about 15-20 m. Gildessa Limestone is a classic

reefal its, except for a few meters at the base where a crinoidal grainstone occurs, it largely consists corals (mainly *Dermoseris irregularis* and rare colonies of *Apocladophylla konia kensis*) in growth positions. According to fossil contents and stratigraphic positions its age is Early Tithonian. This unit documents a sudden shallowing of basin and in places it is exposed to subaerial erosion.

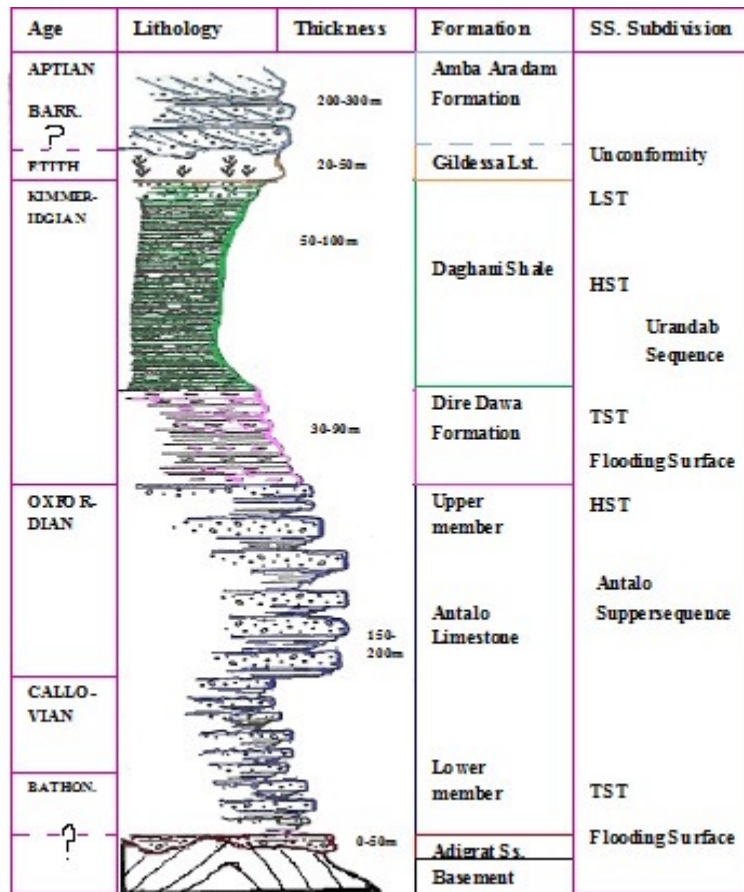


Figure.2.3. Gross stratigraphy of Dire Dawa area geologic units. With their age and sequence stratigraphy subdivisions (after Bosellini et al., 2001).

2.3.2.3. Amba Aradam Formation

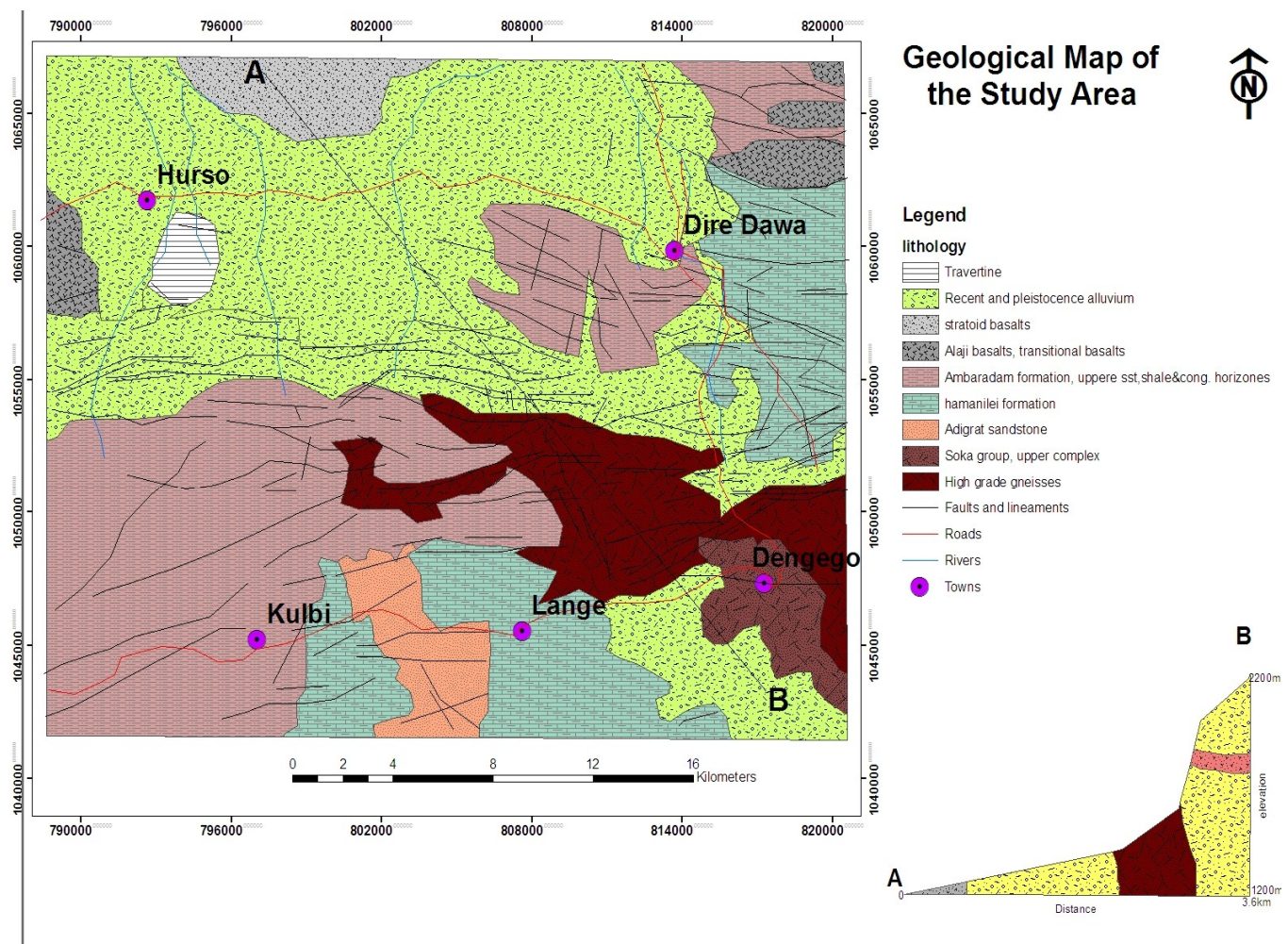
The Jurassic succession of Dire Dawa is cut by an angular unconformity overlain by siliciclastic sediments so called 'Upper Sandstone' or 'Amba Aradam Formation' (Shumburo, 1968). In this area the Amba Aradam Formation is about 150-200m thick, mainly consists of fluvatile sandstone and minor shale. It is overlain by trap basalts.

These sandstones are coarse grained, cross stratified and commonly with quartz conglomerate lenses, very mature, yellowish or white quartz arenites. The entire Amba Aradam Formation appears organised in fining up ward cycles (point bar sequences). The overbank shale however is quite thin and often missing, suggesting the lack of a well developed meandering fluvial system. Amba Aradam Formation in Ethiopia is generally undated. At other section like Graua and Gara Mullata, about 50 Km south of Dire Dawa, 15-20m thick lime stone intercalation rich in varies species of orbitolina and pelecypods, indicates Early Aptian age

for this formation (Bosellini et al., 1999). Paleo-magnetic investigation of Intercalated marine limestone beds within the Upper Sandstone unit in South-eastern Ethiopia, around Hirna area, also gave Aptian-Albian age by Atnafu and Kidane (2012).

2.3.3. Cenozoic volcanics and sediments

The Tertiary - Quaternary geology of Ethiopia is related to the evolution of the East African rifting. Highland of Ethiopia is underlain by Tertiary volcanics, mainly basalts. Tertiary as well as Quaternary volcanics and sediments characterize the rift valley. Tertiary sediments are known in the Ogaden, Danakil Depression and in the lower Omo River Valley. Quaternary sediments occur throughout the country. As a result of epirogenic uplifting of the Afro Arabian (East Africa) basement (and their transgressive sediments) due to mantle plume, enormous quantities of basaltic magma (late Mesozoic) generated in the lithosphere, came through crustal fissure and brought formations of continental flood basalt province, known as Trap series of Ethiopia. The flood basalt volcanism culminated by the formation of alkaline basaltic shield volcanoes some of which rise above 4,000m above sea level on both western and south-eastern plateaus of Ethiopia.



Chapter 3: Lithostratigraphy

3.1. Introduction

The present study area, Dire Dawa area, is generally very interesting geological site in that, you can get various types of lithologic units of different rock types having different ages all together at specific locality, which can help you to enjoy the differences among rocks of various types easily. Among them, basement rocks of Precambrian age unconformably overlaid by sandstone units of Triassic age which in turn overlaid conformably by carbonate units of Jurassic age (fig.3.1), which is topped by Upper Sandstone (Amba Aradam Formation) and also by quaternary deposits at some places.

In addition to this, the area is the most south-eastern escarpment of the main Ethiopian rift valley, due to this, there are a lot of marginal normal faults, and fault related fractures and joints observed throughout rock units of the area. Especially the major faults in the area are manifested by displacing and dispersing the major stratigraphic units of the area and also by tilting the different limestone and other units. Even it is difficult to differentiate various geologic units of the area as their exact stratigraphic positions locally due to displacements by tectonic activities.

Under this section the detail local stratigraphy, mainly for carbonate successions of the area, are described based on the present field observations and at the end their generalized petrographic descriptions, as from representative samples analysis, will be elaborated.

Stratigraphically carbonate succession of the area, which is our focus, is conformably overlying on the Adigrat Sandstone Formation, which in turn unconformably overlying on the Precambrian basement rocks and carbonate units are topped by the upper sandstone (Amba Aradam Formation) and also by quaternary deposits at some places. But, Upper Sandstone units are exposed only at some limited sites throughout the area, like at Dachatu River near Dire Dawa city and at Kulubi area, which is at the most western part of the study area.

From below, the Adigrat Sandstone Formation in the study area has varying thickness locally (0-100m) (Bosellini et al., 2001). From the present observations, this sandstone units are pink to reddish in color, arkosic in compositions, fine- to coarse-grained sandstones with mudstones beds and clastic shale layers. Sandstone units are massively bedded and at places crossly-bedded and it's fluvial in origin. According to the Gortani and Bianchi(1937)(cited

in Bosellini et al.(2001)) the age of Adigrat sandstone of Dire Dawa area is probably late Liassic to Bajocian.

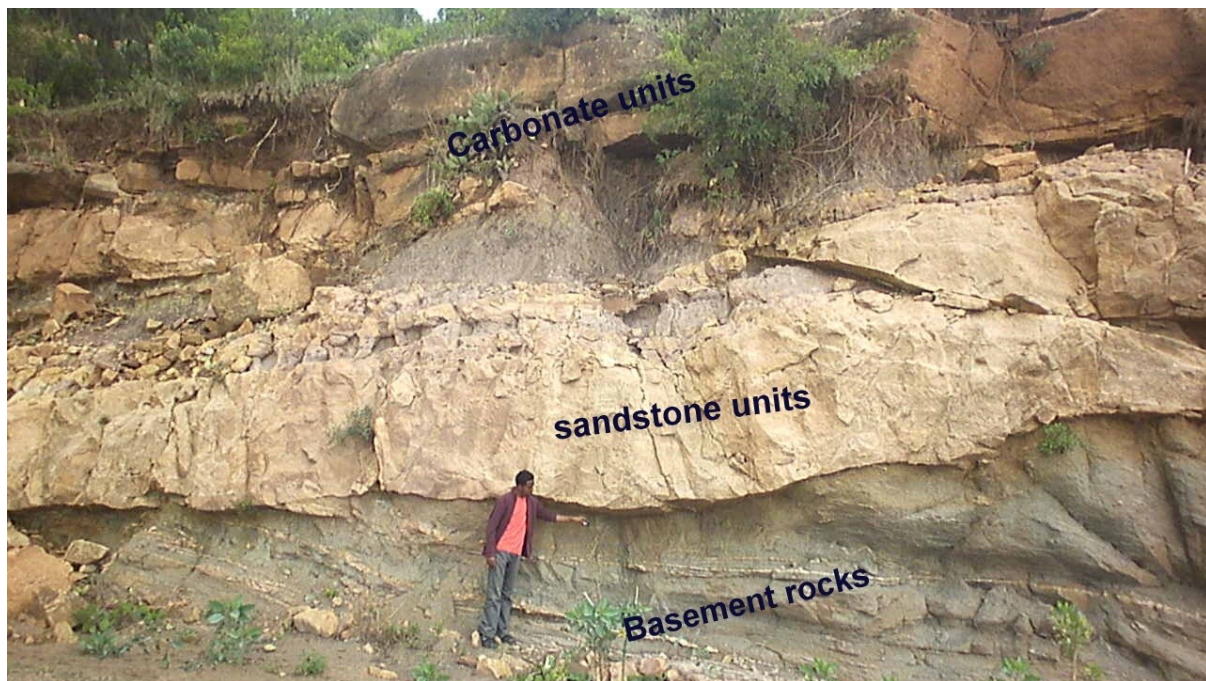


Figure 3.1. Field photo showing three different major rocks of the area, at Lange section.

Overlying this Adigrat Sandstone Formation there is carbonate successions, forming the gradational contacts with it, which is known by various names like ‘Antalo Limestone Formation’, Hamanlei Formation and ‘Antalo Super Group’ by different workers, throughout South-eastern Ethiopia. This carbonate succession is the main objective of the present study and we prefer to use the name ‘**Antalo Limestone Formation**’ for these carbonate units.

The carbonate units of the area are thickest Mesozoic deposits of the area and their thickness are varying from place to place throughout the area, which most probably shows the response to the tectonic disturbance and sea level fluctuation during their depositions.

Lithologically this carbonate deposits consists of some intercalations of clastic layers of sandstones and mudstone layers with dolomites beds(fig.3.2) at its lower parts and thin-thick bedded, blackish, greyish limestones of various components, with rare dolomite beds at middle parts; and some intermixed clastic shale and cherts within micritic limestones beds and rare colonial organisms at its top part.

For getting the necessary detail data and sufficient information from these carbonate deposits and to achieve the objectives of the present work, during the field work more attentions were given to lithology and facies patterns of these deposits. The common facies and lithologic change observed in all sections is vertical change. Lateral facies changes are uncommon, and when existing they shows relatively deepening to ward East and South East part of the study area, which is most probably the characteristics of transgression sequence. The detail lithological and facies descriptions of this carbonate succession observed in field are discussed in the following sections.

3.2. Field Descriptions of carbonate units of the area

During field works of this study, for giving the detail bed to bed descriptions, the carbonates deposits of the area were logged and measured at three selected local stratigraphic sections (Lange, Military camp, and Dachatu River sections (fig.1.2)). Each section are selected for their good exposures and accessibility to show full carbonate units of the area and also labelled as nearest locally known village and area names. At all these 3 local sections, the exposed carbonate layers are described based on their lithology, colours, sedimentary structures, textures, fossil contents, stratigraphic relationships and their geometries.

Lange section is logged and measured at about 30 km from Dire Dawa City along the Kersa road, between Kersa and Lange villages. The area lies in longitudes and latitudes of about (0803465 – 0809321) °E and (1044108 - 1044411) °N and elevation of about (2085- 2167) m above mean sea level. At bottom part of this section there are exposures of basement rocks of about 3m thick which is over lied by Adigrat Sandstone unit of about 20m thick unconformably and this sandstone unit has a gradational contact with overlaying carbonate unit of the area (fig.3.1). The lower sub unit of the carbonate unit is logged and measured at this section and carbonate exposures at this section has about (~119 m) of total thickness, forming steep slope of the area. The exposed carbonate layers at this section includes: mixed siliciclastic-carbonate(intercalation)units, bioclastic Peloidal grainstone, oolitic grainstone layers, pisolite bearing thin layer and oolitic layers in ascending order(fig.3.3).

Military camp section is logged and measured at about 4km distance from Dire Dawa city, along the Dengago road (fig.1.2). The area lies in the elevation about (1281-1339) m and latitude and longitude of (08139977-0820026) °E and (1047315-1059399) °N. At this section, the middle subunit (at lower) and some part of the upper unit of the formation are

described. The carbonate exposure at this section has a total thickness of about ~159m. They are subdivided into nine sub-litho layers, based on their major components and feasible sedimentological features in the field. According to their ascending order, they are: a) Micritic layers, b) Peloidal wackestone, c) Intraclastic wackestone, d) Cavernous micritic, e) packstone-grainstone layers (of the Middle subunit), f) Black- dark gray micritic layers, g) The unit bearing alternative layers of mudstone and shale unit, h) Bioclasts, intraclast and peloidal bearing packstone layers and they are topped by micritic limestone layers at its top end (of the upper subunit) as their respective vertical log is given in (fig.3.10).

Dachatu River section is measured and logged at about 7 km to the East of Dire Dawa city. At this section the top part of carbonate of the area is measured and unconformable contact with upper sandstone units were noted. According to the field observations the carbonate units exposed at this section has a total thickness of about 28m and they are grouped into 3 sub-litho units; which are micritic layers, micritic with colonial organisms unit and carbonate build up bearing unit.

Generally, from the present field observations at these three local stratigraphic sections and throughout the area, according to their lithological characteristics, faunal and floral contents and stratigraphic positions, the carbonate units (Antalo Limestone Formation) of Dire Dawa area, having about (~306m,) total thickness (from summations of three sections), are subdivided into three subunits. Those are **lower**, **middle** and **upper** sub-units, from bottom to top.

The lower sub-unit consisting of mixed siliciclastic (sandstone layers, clastic mudstone and shale) and carbonate (dolomite and micritic limestone, peloidal and oolitic grainstone) layers are measured and described at Lange section, the middle subunit is the allochemical rich thick carbonate layers, showing deepening up secessions, measured at lower part of military camp section, and the upper sub unit is dominated by fine grained micritic limestone layers with some cherts, clastic shale interbedded and some colonial organism bearing layers, measured mainly at Dachatu river section and this subunit is overlaid unconformably by clastic upper sandstone layers. The detail descriptions and distinctions among these three sub-units will be given later in composite stratigraphy section, but their detail field descriptions of carbonate exposures within each subunit as observed from three local stratigraphic sections are given as below.

3.2.1. Lower sub-unit

The lower subunit conformably overlies the Adigrat Sandstone Formation. As measured and logged at Lange section, this unit is characterized by a mixed carbonate and siliciclastic facies association with a heterogeneous lithologic character at its bottom part and thick

peloidal and oolitic grainstone limestone layers of high energy deposits at its top part (fig. 3.3).

The lower intercalation part of this sub-unit, of about 100m thick, overlies Adigrat Sandstone Formation of the area and it has gradational contact with these sandstone units. This intercalation unit comprises various alternating beds of sandy limestone, calcareous sands, dolomite layers, clastic mud and/or clay bearing layers (fig.3.2) and carbonate mudstone to bioclastic wackestone layers.

These intercalation units show the general fining up cyclicity of the components, in which sandstone layers overlain by dolomite which in turn overlain by other beds of sandstones or clastics. But they are not well exposed for detail description for each bed separately, during the present field work.

On the top of these intercalation units there is about 3m thick, bioclastic peloidal packstone to grainstone layers, which have dominant peloids grain with rare amounts of skeletal grains imbedded within sparry calcites. The fossils in these peloidal units include bivalves, gastropods and some algae showing some micritic envelopes, as given in plate 3.

Above this unit a 2 m thick greyish color oolitic grainstone layer is exposed, which is upward changed to a 1m thick pisolite bearing layers, which has micritic layer at its lower portion and pisolite on its surfaces with some amounts of dispersed fossils. The pisolite is usually formed inorganically, usually in subaerial environments. This pisolite bearing layer gradationally changed to about 12.8 m thick ooidal grainstone units which has ooids of various sizes with rare amounts of bioclasts, and peloids. All these components are ranging in size from finer to sand sized carbonate grains. On the top of this oolitic rich grainstone layers, there are various sized carbonate boulders in the exposed subaerial parts. At top end part of this unit amounts of ooidal and other grains decreases upward and matrix materials increases upwards and its topped by larger boulders, at subaerial parts.

The main sedimentary structures observed in this unit, are thin-thick massive bedding, laminations and some groove and hollows structures in subaerial parts.



Figure 3.2. Clastic and carbonate layers intercalations A) the thick dolomite bed and clastic, variegated clay deposits, B) Dolomite beds and thin sandstone layers, both pictures are from the intercalation part of lower sub-unit, taken from at Lange section.

3.2.2. Middle sub-unit

The middle sub-unit of the carbonate units of the area is measured and logged at military camp section. This sub-unit consist of limestones layers showing various components, colors, beds, bedding styles, and bed thickness throughout the unit. This sub-unit is characterized by dominance of various carbonate allochems embedded within sparry calcite cements and/ or micrite. It has about (~84m) 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. This subunit comprises a) micritic limestones, b) thin peloidal wackestone limestones, c) intraclastic wackestone rich limestone layers, d) dolomitized cavernous micritic limestone layers with some patches of colonial organisms and e) Peloidal, bioclasts and intraclastic rich packstone to grainstone thick limestone layers according to their ascending order; those are logged at Military section as given in (fig.3.3) and as described below:

a) Micritic limestone layers: It's about 1.5m thick beds of fine grained, light gray micritic limestone, exposed at the base of military section and also form the base of the middle subunit of the carbonate unit of the area. Within these layers there are some cyclic, alternations of the components upward. It comprises thin layer of fine grained carbonate mud with rare amounts of bioclasts at lower 55cm and associated with patches of colonial organism, nodular and lenses of chert layers at its top part.

b) Peloidal wackestone limestones: overlying the micritic layers discussed above, there is 50 cm thick gray limestone layer consisting of some amounts of peloidal grains dispersed in micrite background. In this unit there is the very thin cyclicity which shows the repetitions of the layer containing dominant micritic at bottom, dispersed peloids and bioclasts layer at middle, and more concentrated allochems at its upper part. The grains are poorly sorted.

c) Intraclastic wackestone limestone unit: are intraclast grains dominated limestone layers overlaying the peloidal wackestone layer below it. It has a total thickness of about 18.8m. This unit is light gray in color and has larger clasts at its lower 12m and there is a minor break with in this unit, on this break there are more dominant amounts of intraclasts. Above this break the alternative layers of rudite clasts and fine intraclasts are observed. At its top part there are rare amounts of bioclasts and peloids overlaid by thinly bedded micritic layers; those are again topped by a meter thick crystalline calcite layer. The intraclastic grains have varying size, ranging from (1mm- 6cm). The internal body of the larger intraclasts are dominantly micrite and also rare amounts fossils, peloids and other detrital grains. This dominance of micrite intraclasts show that the reworking of the grains are not from outside of basins, it's reworking within the basin and resedimentations of these larger carbonate grains within depositional basins. Depositions of such facies took place under moderately water conditions above wave. Based on Wilson (1975) this facies can be compared with SMFT4, which is deposited in facies belt 4, fore slope depositional area.

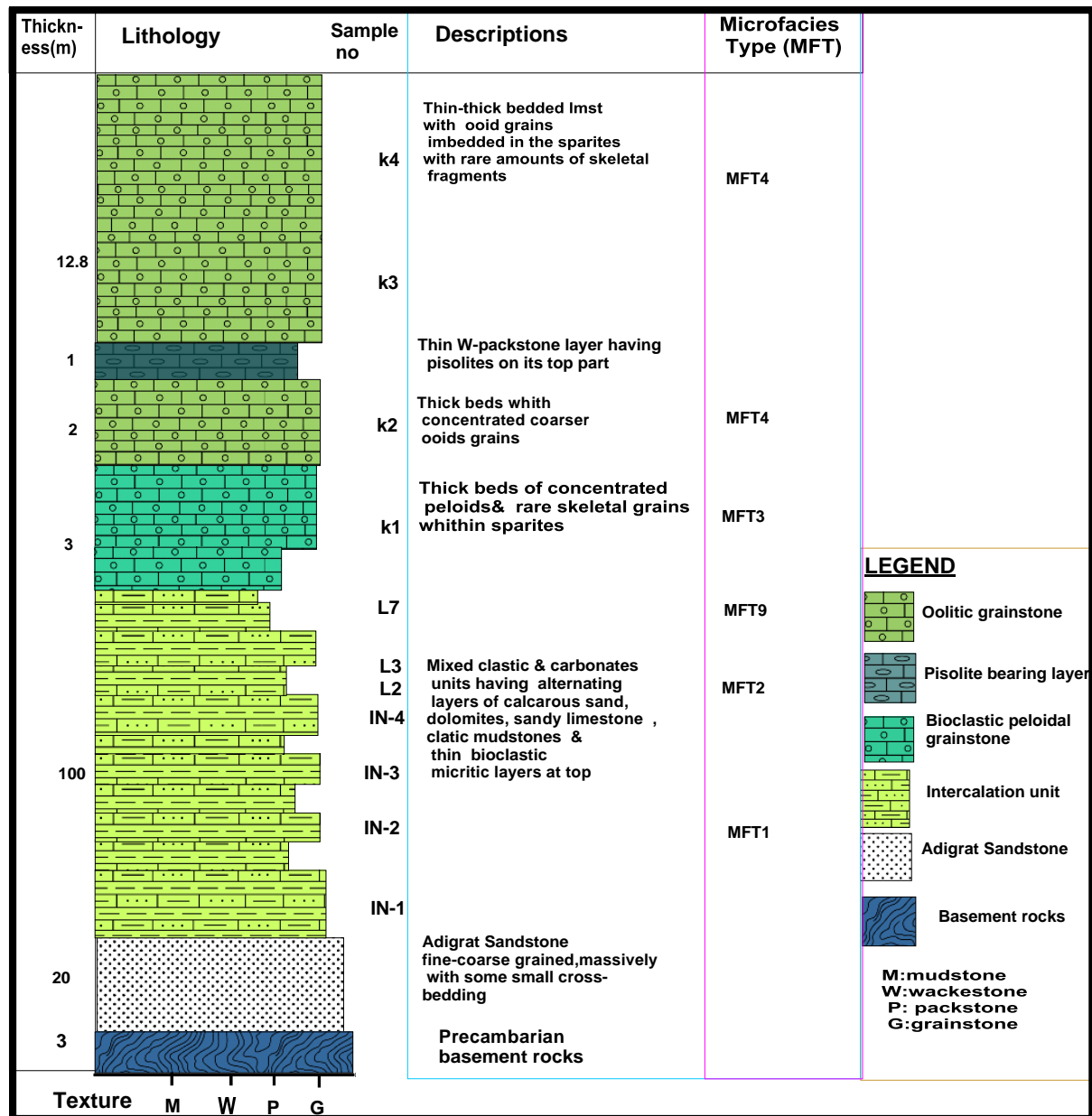


Figure 3.3. Stratigraphic column of carbonate exposures at Lange section, Dire Dawa area, (Its not scaled)

d) Cavernous micritic limestone layers: These layers are massively bedded light gray micritic with rare wackestone limestone units and have a total thickness of about 25.45m. It has smaller cavernous throughout its surfaces, the opening of the cavernous ranging in size from (0.5 - 50 cm) in diameters at its lower parts. In this cavernous unit there are alternating layers bearing rare amounts of intraclasts, bioclasts and peloids grains. This unit is totally cavernous at its lower 2.4m, partly cavernous at middle 2m and again densely cavernous at top 6m (fig.3.6). These cavernous shows the subareil diagenesis processes affecting the carbonate exposures after the depositions.



Figure 3.4. Field photo showing nodular(A) and Lenses of chert(B) within micritic limestone beds.



Figure 3.5. Massively bedded intraclastic wackestone layer. It contains larger intraclasts(I) grain within micritic matrix..

The patches of colonial organisms also observed on this unit (fig.3.7). At upper 5.45 m, this unit develop into dominantly bioclasts dispersed in micrite background. The concentrations of bioclastic grains are varying from its bottom to top part, in this unit and different concentrated layers with in this unit are separated by stylolite structures at various levels through the unit. Stylolites are mostly parallel to beddings. The layer below the stylolite structure has less concentrations and the layer above it contains more concentrations of bioclasts components.

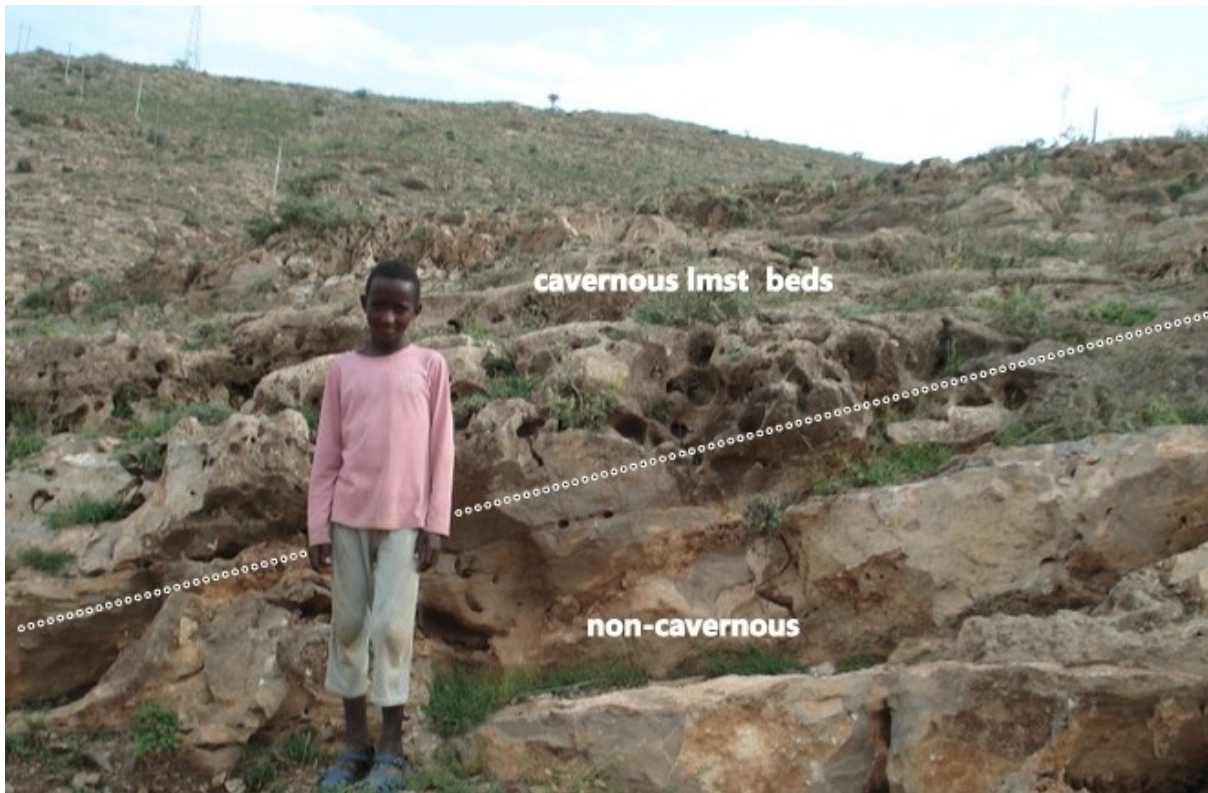


Figure 3.6. Cavernous and non-cavernous micritic limestone layers at military section.



Figure 3.7. The remains of colonial organisms (patch reef) on micritic limestone layers.

e) Packstone-grainstone limestone layers: They are overlaying the micritic layers below and it has various carbonate grains (mainly peloids, skeletal and intraclast) embedded within the sparry calcite cements dominantly and with rare amounts of micrites at places. Relatively when compared among the grains throughout these layers, the amounts of intraclastic grains are more dominant than other grains at lower part. This unit cover extensive area of this section, having the total thickness of about 38m. Most layers are thin to thick massive beds of light gray limestone. The bedding thickness ranges from (0.5- 2) m in average.

This layer can be subdivided again into two sub-layers, the bottom peloidal rich part and upper bioclasts rich, but, intraclast grains are dominating in both upper and lower part. At lower part of this unit, there are numbers of alternating layers bearing peloidal rich part(at bottom) and fossiliferous layers(at top) those are separated by very minor depositional breaks and stylolites. These alternating layers are again topped by another alternating layers of 1.2m thick, those consisting of thin fossil rich zone(at bottom) and very thin clastic shale units(upper), again these clastic shale units are topped by other thick layer consisting cyclic thin layers of fossil zone and micritic layers with dispersed fossils, peloids and intraclasts. These alternating layers are mostly separated by stylolites. Stylolites are mostly parallel to bedding surfaces. At the toper part of this unit the intraclast grains are decreasing and the layers become dominated with the peloids and bioclastic grains.

In general the repeating components in this thick grainstone layer are showing upward deepening throughout this layer, in that, the lower wackestone-packstone topped by small break and/or stylolites which is again topped by packstone to grainstone above it, those inturn overlaid by next mudstone to wackestone layers above it. This unit is overlaid by deep dark gray micritic layers of the upper sub-unit. The skeletal grains observed in these layers are brachiopods, gastropods, bivalves, echinoderms, rare corals, varieties of foraminifers and etc.

3.2.3. Upper sub-unit

This subunit is measured partly at upper part of Military section and partly at Dachatu river section. It has a total thickness of about 103m. This unit overlies the middle unit conformably and truncated unconformably by the upper clastic unit (Upper Sandstone Formation) above it. 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, intermixed clastic shale layers and some nodular and lenses of cherts.

Even though some unit repeat themselves at different level throughout the unit, This unit comprises of a)black-dark gray micritic limestone layers, b)alternating layers of mudstone and shale unit, c)massively bedded bioclasts, intraclasts and peloids bearing wackestone-packstone limestones, d)massively bedded micritic limestones, e) micritic limestones layers with colonial organisms , f)carbonate build up bearing mudstone layers and g)micritic limestone layers, according to their ascending order, (those are described in upper part of Military section and at Dachatu river section in detail as given in (fig.3.10 and fig 3.15 respectively) and each of this layers are described as below:

a)Black- dark gray micritic limestone layers : This unit has most dominantly fine grained dark micrite materials with very rare amounts of bioclasts, overlying the bottom grainstone layers of the middle subunit conformably and it forms the base of upper subunit of the carbonate deposits of the area. This unit is thinly to thick bedded limestones and has a total thickness of about 14.7m. Each beds range (5-20 cm) in thickness. Its top 2.7m layer is weathered micritic limestone. Its black- dark gray in color and rare amounts of bioclastic components is randomly distributed within this unit. The amounts of micrites increases upward and at top it's completely micritic layers. They are massively bedded in overall look.



Figure 3.8. Field photo showing thin-thick bedded dark gray micritic limestone layers. Photo taken at upper part of military section, Dire Dawa area.

b) Unit bearing alternative layers of micritic limestones and shale unit: This unit overlies the deep micritic limestone layer discussed above and has a total thickness of about 38.55 m. This unit consists of many alternative layers of micritic and thin clastic shale layers. Micritic beds in this layer have rare amounts of allochems like peloids, fossils and intraclasts.

Starting from its lower part there are dispersed amounts of peloids and bioclasts bearing unit which is topped by very small break. On this break there are thin layers of clastic shale deposits, comprising some mega fossils. These bioclastic peloidal grainstone topped by shale units layer, those are separated by very small breaks repeats themselves number of time, in the lower 26.75m part of these specific layers. And upper part of this unit has mud dominated layers topped by clastic shale, which again repeats itself up to top end of the units. Within

this unit there are also many stylolite and thin chert layers, those indicates their depositions in deep low energy environments.



Figure 3.9. Thin clastic shale layers (arrowed) imbedded between massively bedded micritic limestone layers.

c) Bioclasts, intraclasts and peloids bearing wackestone- Packstone limestone layers

These layers are the carbonate layers overlaying the above discussed micritic and shale bearing unit, and they consists cyclic layers consisting of intraclasts, some amounts of bioclastic, peloids carbonate grains, and some clastic shale. They have about 11m total thickness. In these cyclic layers, the skeletal, intraclasts and peloidal grains richer grainstone bottom parts are topped by thin clastic shale layers, repeating numbers of time with various thicknesses up to giving total thickness of this layer. At military section this unit are topped by about 10.5m thick massively bedded micritic layers containing some lenses of cherts.

d) Micritic limestone layers: These layers comprises fine grained massively bedded micritic layers of about 10.5m thick overlying the above discussed layers at the top part of military section and about 1.7m at the bottom of Dachatu River section. Within this micritic layers there are very rare amounts of other allochems like peloids and skeletal grains. This micritic unit has rare amounts of bioclasts with some lenses of cherts at different level within it and thickness of beds ranges from (4- 40 cm).

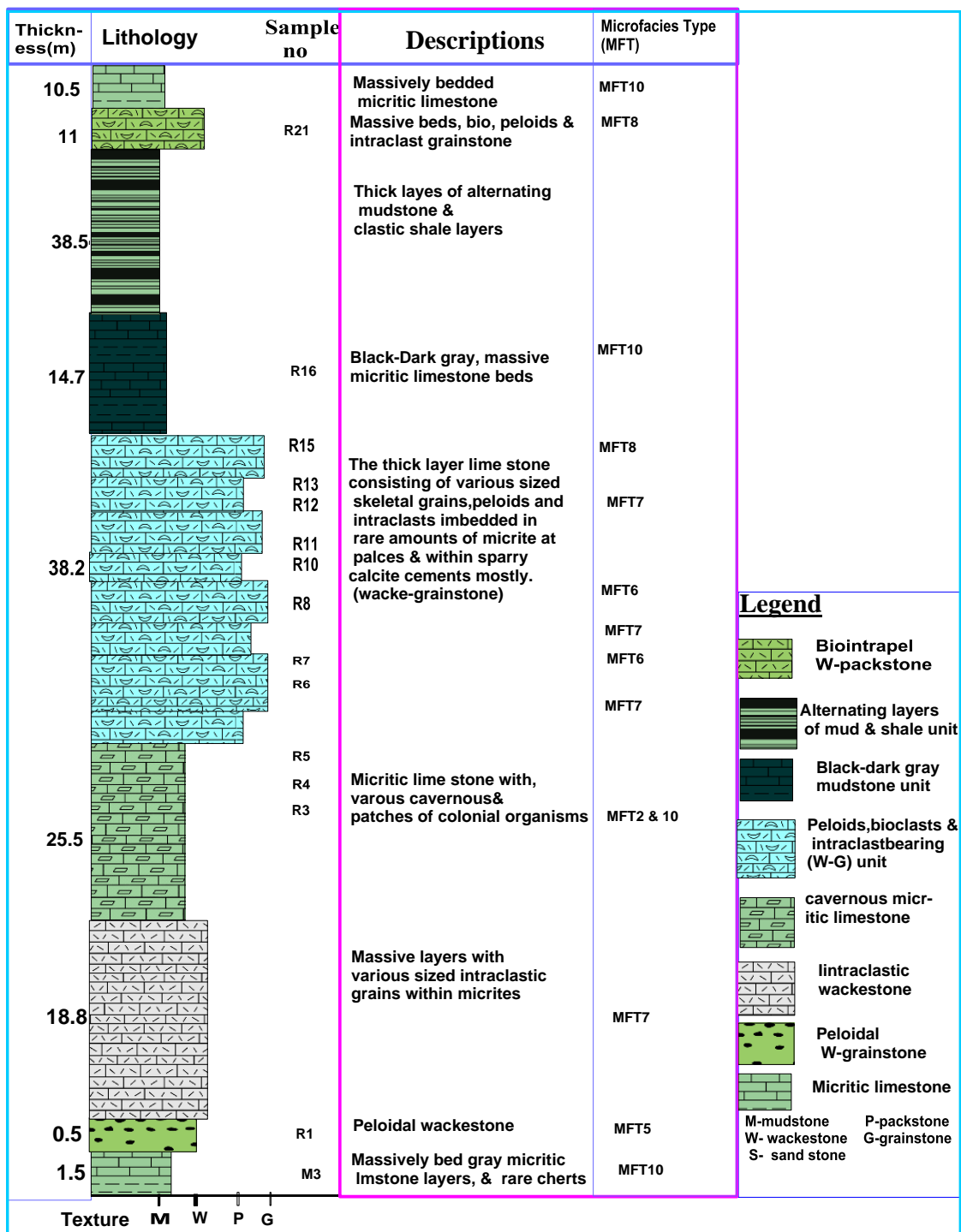


Figure 3.10. Stratigraphic column of carbonate exposures at military camp section. Not scaled.

e) Colonial organism bearing micritic limestone layers: This unit conformably overlies the mudstone unit described above with gradational contacts and has 4.7 m thick. This unit contains dark colour preserved remains of unidentified colonial organisms in their growth positions on the micritic limestone beds. The colonial organism remains in this unit are not

identified in the field because of the absence of their structures. There are also dispersed amounts of fossils and rare other allochems in this unit. There are alternative layers of colonial organism rich and allochemical rich layers, in this unit. There are also nodular, lenses of silica layers and stylolites on this unit at different levels. At bottom part micritic with colonial organisms, at middle, micritic with other allochemicals and at top again micritic with colonial organisms with very rare amounts of allochems. Above this colonial unit there is rarely exposed part of about 10m thick micritic limestone layers at this section, due to vegetation covers, which is topped by well exposed thin layer of 10cm, thinly bedded micritic limestone.



Figure 3.11. Chert lenses imbedded within massive micritic limestone. Field photo taken from Dachatu section.

f) Carbonate build-up bearing limestone units: Above the thinly bedded micritic layer, there are 6m thick carbonate build up bearing unit. It's the limestone which is formed by small in situ accumulations or build-ups of carbonate materials (most probably). This unit has lateral elongations of about 50-60m long. This build ups are built on micritic dominated layers without the high relief above micritic layers. The structures of carbonate building up organisms and units are not clearly observed and not identified, the dark, silicified remaining parts alone observed in the field. These carbonate build up units has about 1m thick, thinly bedded mudstone layers between them ,which has lenses of silicified layers. Above this thin beds of micritic, the carbonate build up layers come again, which is again topped by micritic layers. This carbonate build-up bearing units at this sections has no enough morphology to be called reef carbonate.

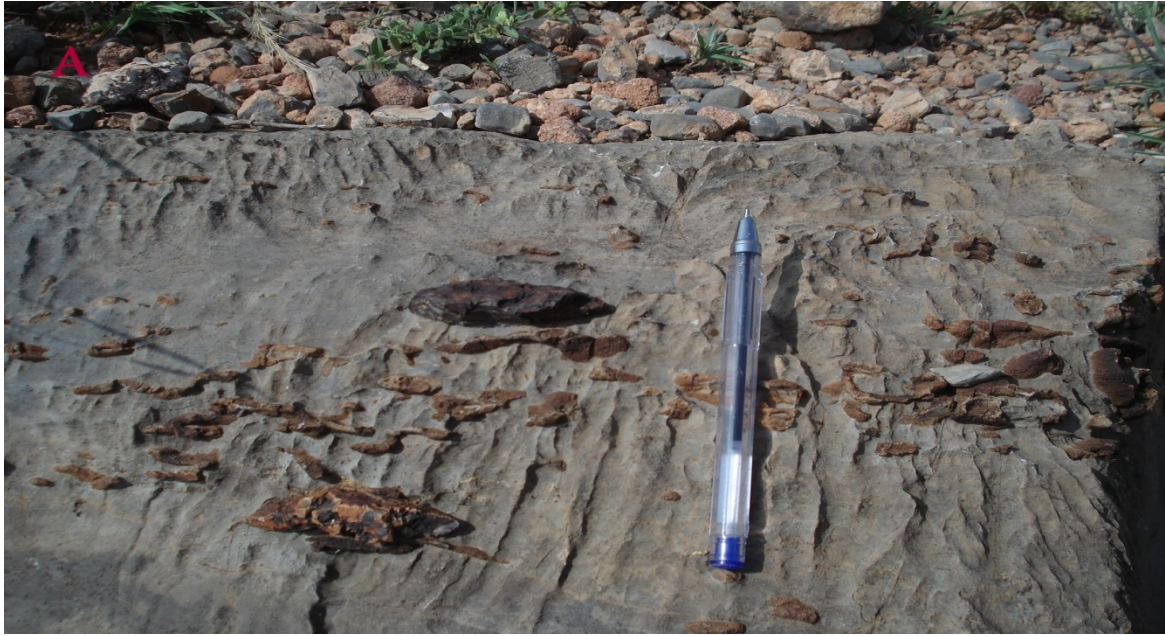


Figure 3.12. The limestone layers with their preserved remains of carbonate build-ups. **A - B)** Beds of micritic limestone which has remains of colonial organisms, the black colored silicified parts, taken from Dachatu section, Dire Dawa area.



Figure 3.12. continued . **C)** Beds of micritic limestone which is sandwiched between carbonate build up units with thin layer of silicified part. **D)** Massive beds with concentrated preserved remains of colonial organisms (the black parts shown by white arrows).

At the most top part of this upper sub-unit, at the top end of Dachatu River section, above the carbonate build-up bearing unit, there are again micritic layers of about 4.6 m thick. It's thinly bedded at lower part with dispersed amount of intraclasts, fossils and peloids, and at its upper part thickly bedded layer, each bed ranges 20-40 cm thick. At its top part this mudstone unit changes to complete micritic layers, which are truncated by the fluvial clastic unit, which called Upper Sandstone Unit, exposure of about 5m. The contact between these units is the angular unconformity types of contact. The Upper Sandstone unit at this site are fine to medium grained, shows fining up cycle, which is the point-bar sequence type. This upper sandstone is not described in detail during the present field work, since it's out of the objective of this study.



Figure3.13. Thick beds of mudstone layer exposure at upper part of Dachatu river section.

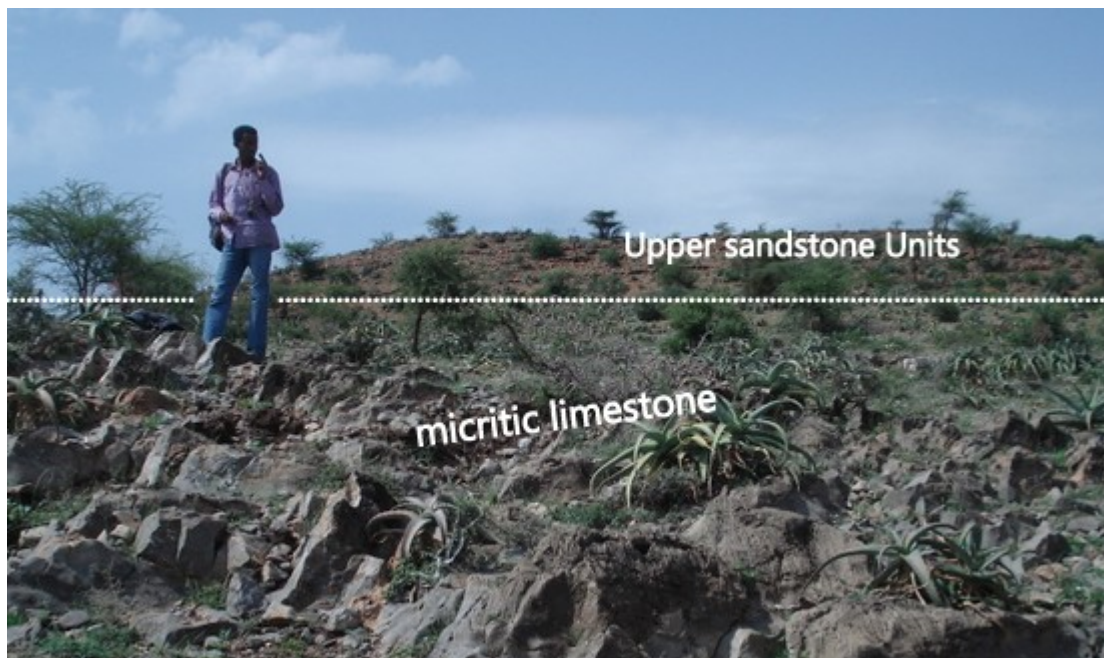


Figure 3.14. Field photo showing the micritic limestones of upper sub-unit and upper sandstone unit's contact at upper part of Dachatu river section, Dire Dawa area.

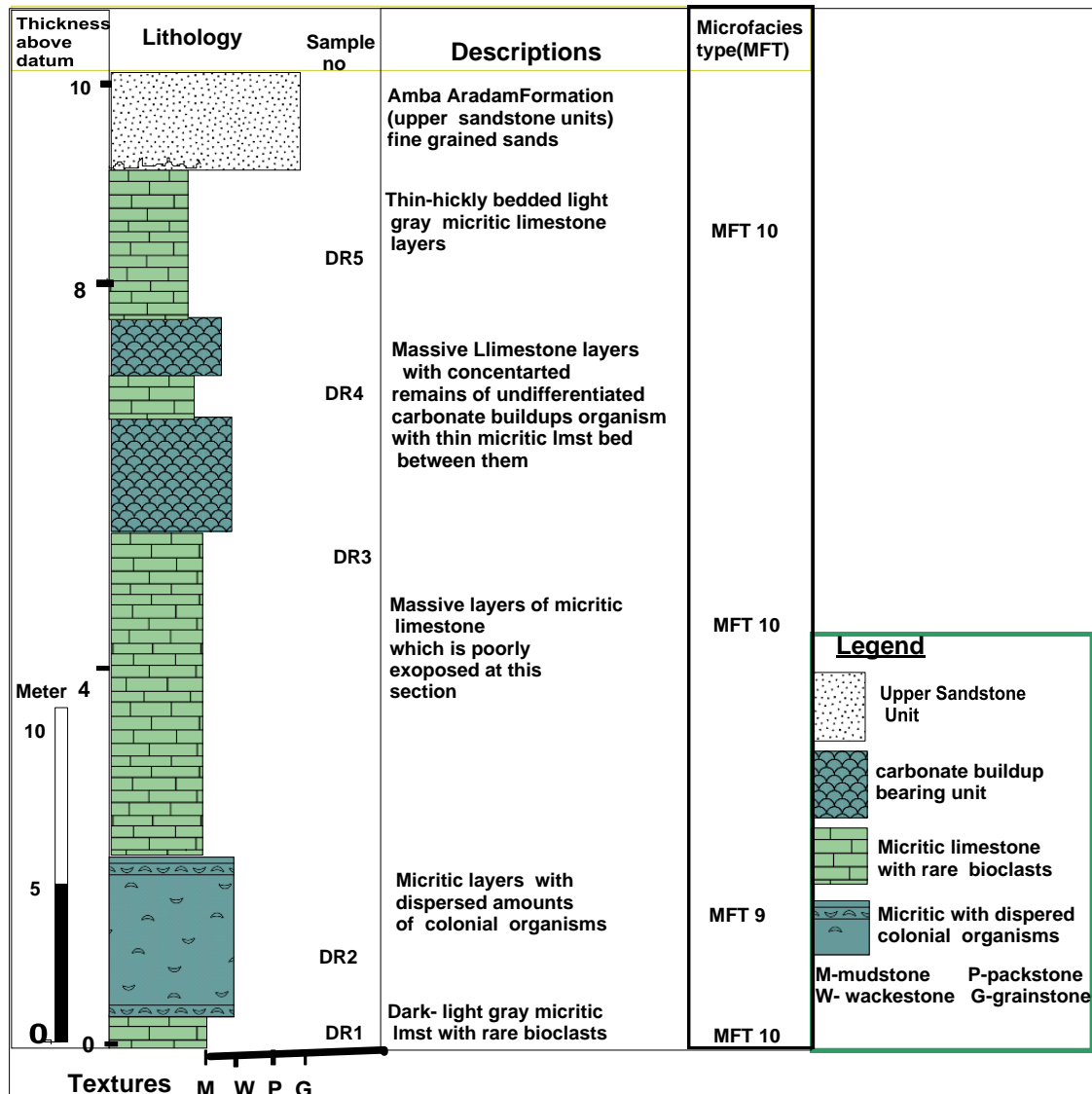


Figure 3.15. Stratigraphic column of carbonate exposures at Dachatu River section. Showing the description for each lithologic units, collected samples and microfacies obtained from their samples.

3.3. Petrographic descriptions

Under petrographic microscope the detail explanations for 34 representative samples with regard to their microscopic features, compositional identifications were made to enhances/confirm field observations. According to the petrographic analysis from these representative samples, carbonate rocks of the study area revealed various major carbonate components like allochems (varieties of skeletal grains and non-skeletal, ooids, peloids and intraclasts) and interstitial materials (microcrystalline calcite ooze/micrites and sparites), textures, diagenetic features (like compactions, cementations, dissolutions, stylolitization and silicification) and small-scale sedimentary structures.

There are also other minor components like porosity, cortoids, quartz grains, and cherts, insoluble materials (mainly iron oxides, along stylolites and as cementing materials). All these components are varying in abundances, in sizes, colors, from place to place throughout the studied sections. Most of the analysed samples are limestones (they contains > 50% calcite minerals), except few of them containing replacement coarser dolomite minerals, cherts; and some quartz grains those obtained from clastic intercalated layers. The proportions among various carbonate components in all collected samples were identified and the rocks are classified according to Dunham (1962) and Folk (1962) carbonate classification schemes as shown in appendix 2.

Texturally; the collected samples shows various textures ranging from mudstone (10 of total sample), wackestone (8 of total) packstone (2 of total) to grainstones (10 of total), unwinnowed to winnowed and poorly sorted to well sorted. There are also 4 samples (IN1-4) collected from the intercalation unit, those have mixed siliciclastic and carbonate components, in which detrital quartz grains (20-80%) are cemented by calcite minerals (as given in appendix 2 and plate1).

From this petrographic descriptions: the lower sub-unit of carbonate unit consists of calcareous sandstone, dolomitic mudstone, bioclastic wackestones, peloidal grainstone and oolitic grainstone; the middle sub-unit consists of dolomitic mudstone, mudstone, bioclastic and/or intraclastic wackestone and wackestone, packstone- grainstones of peloids, skeletal and intraclasts grains with various ways of their combinations. For the upper sub-unit the limited sample exists and they have mudstone-wackestone with some skeletal grains.

All these petrographic properties and other like diagenesis are discussed in the next, chapters (4and 5), as per their relevance's and the photomicrographs of most of the collected samples with their petrographic descriptions were given in (plate 1-10) attached at the end part of this paper.

Chapter 4: Microfacies Analysis and Interpretations

4.1. Introduction

Microfacies analysis from thin sections of carbonate rocks exhibit depositional criteria reflecting environmental constraints acting during sedimentations (Flügel, 2004). For the seek of these interesting information for the carbonate units of the Dire Dawa area, in present wok about 34 thin-sections prepared from representative rock samples, those collected from the three stratigraphic sections throughout the area , were examined under the petrographic microscope for detail microfacies analysis. For the microfacies analyses the criteria like: lithologies, carbonate components, compositions and sedimentary structures from both field observations and thin sections views are used as the input data and various microfacies types (MFT) with descriptions and interpretable separately are revealed as out-put of the analysis.

Accordingly, all the components obtained from the Dire Dawa area carbonate successions are grouped into **ten** major microfacies types (**MFT1- MFT10**) based on their diagnostic microfacies criteria observed from thin sections and with the supports of field observations. All these major microfacies types are described based on their characteristic components, supported with photomicrography, interpreted with respect to their environments of depositions and also most of them are compared with standard microfacies types (SMFT) and Facies belts(FB) of Wilson (1975),(which is shown in appendix 3),as given in the following successive sections.

4.2. Major Microfacies Types of the area

4.2.1. Mixed siliciclastic - carbonate microfacies (MFT1)

Descriptions: This facies is recorded from the base of lower sub-unit of carbonate units of the study area, from intercalation part. It consists of the mixed carbonate components with various size detrital quartz grains. In this microfacies the angular to sub rounded detrital quartz grains (60- 80%) are cemented together by sparry calcite the cements. There are no fossils in this facies. The number and sizes of the clastic quartz grains in this unit is decreasing and its roundness increases upward from the lower Adigrat Sandstone Formation contact to the carbonate dominating parts, as recorded from successive taken samples (plate 1: **IN1-4**) from bottom to top.

Interpretations: Sediments composed of mixtures of carbonate and siliciclastic materials are common in near-coast environments, inner shelf settings (Flugel, 2004; Walker, 1992). It shows that the supply of detrital quartz grains from nearby exposed continental part into the marine carbonate basin during its depositions. These are areas where processes of siliciclastic and carbonate sedimentation interact and produce a depositional regime dissimilar to that present in the more familiar carbonate or siliciclastic systems. Mixed carbonate-siliciclastic deposition is usually described within the context of a simplistic framework in which siliciclastic sediments occur in shoreward areas and carbonate sediments occur outward on a shelf or platform surface (Reading, 1996; Walker, 1992; Tucker and Wright, 1990). As the Adigrat Sandstone Formation below is gradually passes upward to carbonate dominating units, there is decreases in the amounts of clastic materials and detrital quartz grains in taken samples successively upward in the measured sections (IN1-4) and increase in the calcite components up to complete dominance of carbonate rocks at top. In the field observations there are associations of successive clastic deposits (calcareous sand, clastic mud and clay) and carbonate, mainly dolomite beds, which help to interpret this facies as marginal facies and compared with facies belt 8 of Wilson (1975), which deposited in restricted platform conditions.

4.2.2. Dolomitized Micritic microfacies (MFT2)

Descriptions: This microfacies is a facies in which there are numerous numbers of dolomite rhombohedra within the calcite micrites. This microfacies is not so much common in studied sections and obtained from samples collected randomly from lower part of Lange , military and Dachatu sections (from sample No. L1, L2, L3, H2, DR2, R3 and R4). At some places the micrites are partially dolomitized (with dolomite < 20%) and at places the micrites are highly to completely dolomitized (dolomite up to 50-60) forming dolomite rocks. The particular dolomitization photomicrographs examples are given in (plate2: A-D and plate 14 A-B). The dolomite grains are mostly coarse grains and planar euhedral in shape.

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 associated with beds of dolomite, dolomitic limestone layers and some clastic layers at places (mainly at lange section). Therefore it's compared with facies belt 8 of Wilson (1975), which is deposited in restricted platform.

4.2.3. Peloidal grainstone microfacies (MFT3)

Descriptions: This is the microfacies obtained from lower sub-unit at Lange section. In this microfacies abundant number of peloids grains (> 70%) and rare amounts of skeletal like bivalves, algae and brachiopods shells are imbedded in the sparry calcite cements(plate 2: A-C). Texturally it shows some patterns of winnowing, packstone- grainstone type and the peloids grains are smaller in sizes, and grains distributions are moderately sorted. Some peloids grains are completely dissolved at places forming moldic type porosity (pelmoldic) and there are also some primary types of pores spaces observed between the grains. Some skeletal grains are also covered by micritic envelopes, forming cortoids.

Interpretations: Peloids are either product of reworking or of faecal origin (Flügel, 2004). Most pellets are lithified organic excrements (fecal pellets). Carbonate fecal pellets are produced in tropical marine and in non marine environments, but are more commonly preserved in sub tidal and lower intertidal zones of inner platform or ramp setting sand in lagoon, with low water energy and reduced sedimentation rates(Burchette and Wright, 1992),. Therefore this peloidal microfacies are interpreted to have been deposited under restricted marine conditions and compared to SMFT 16, which belongs to facies belt 7(open platform, shelf lagoon) or Facies belt 8(restricted platform) of Wilson (1975).

4.2.4. Oolitic microfacies (MFT4)

Descriptions: This microfacies is the most dominant facies at lower part of the carbonate unit of the area, at Lange section and obtained from sample K2-K4. The tangentially structured ooid grains (~ 60%) are imbedded in the sparite cements (plate 4: A-C). Some of the ooid grains have quartz grains as their nucleus. There are also rare amounts of micritized skeletal fragments and non-skeletal grains and detrital quartz grains observed in this facies. The grains in this 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 envelopes on the skeletal grains and on some ooids grains mainly preserving their shape. All these components form the characteristic carbonate sand bodies at this site.

Interpretations: This microfacies is interpreted to be deposit around high energy area such as carbonate shoals and Barrier Island or beaches. Warm water grainstones 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 the character of this microfacies. Ooids are formed in both high-energy and low-energy environments. But high-energy environments are indicated by concentric (tangential) or micritic ooids, and broken or distorted ooids, which are typical of ooid grains in this microfacies (in plate 4: A-D). This microfacies is compared with SMF Type 15 of Wilson, belongs to Facies belt 6, which deposited in winnowed platform edges.

4.2.5. Peloidal wackestone microfacies (MFT5)

Descriptions: This facies is the microfacies in which dominant, larger size mud peloidal grains (~ 30%) are imbedded in the micrite dominated fine materials (Plate 5: A-B). This microfacies is obtained from middle part of the carbonate unit of the area and it contains larger size mud peloid grains imbedded within the micrite, what make it different from the above discussed peloidal grainstone microfacies type. It's obtained from sample R1, which is collected from the lower part of military section. In this microfacies there are rare amounts of skeletal and intraclastic grains. The grains have various sizes and poorly sorted.

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 syndimentary 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 lithic peloids. And they tend to formed away from edges of platforms (Burchette and Wright, 1992; Walker, 1992).

In field observations this Peloidal bearing wackestone layer are also associated with micro-breccias and some colonial organisms, therefore, this facies is compared to facies belt 4 of Wilson (1975), which deposited in foreslope area.

4.2.6. Bioclastic intraclast grainstone microfacies (MFT6)

Descriptions: This is the most common microfacies of middle sub-unit, at military section. It comprises the dominant amounts of skeletal and varies sized carbonate clasts imbedded within the sparry calcite cements. Skeletal grains in this microfacies include bivalves, gastropods, brachiopods, echinoderms, bryozoans, foraminifera and corals. This microfacies is obtained from the samples (R6, R8, R10, R11 and R12) collected from middle subunit of the carbonate unit of the area, at military camp section and covering large area. This facies also contains very rare amounts of peloid and other grains. Most grains in this microfacies are coarse grained (forming rudestone), altered, and compacted, mud-free, cemented by various phases of cementations, reworked and poorly sorted. Some examples are given in plate 6.

Interpretations: This microfacies shows the character of carbonate slope deposits. The slope deposits mainly contains carbonate grains like mud-free sediments, intraclastic packstone-rudestone, other boulder- rich sediments and most of them are resedimented (Brain & Andre ,1992).The abundances of intraclastic carbonate grains in this facies indicate that the instability of the slope surfaces and reworking of the surface by high energy along the slope and resedimentations of carbonate grains. This microfacies is also compared with SMF Type 5, which belongs to Facies belt 4 of Wilson, those are fore slope deposits.

4.2.7. Bioclastic intraclast packstone microfacies (MFT7)

Descriptions: This facies contains dominant amounts of intraclastic grains and some bioclasts with rare peloids and other grains imbedded within sparry calcite cements and in rare amounts of micrite (plate 7). This facies are obtained from sample R12 and R13, which are collected from middle- upper part of military section. The grains are poorly sorted and irregular in shape, showing the instability of the depositional surface during the deposition.

Interpretations: This microfacies also shows the character of slope deposits as the above discussed microfacies type. In the field observation it's also associated with some clastic shale layers and smaller breccias. So, this microfacies is compared with SMFT 4, which belongs to Facies belt 4 of Wilson 1975, deposited in foreslope area.

4.2.8. Bioclastic Peloidal packstone-grainstone microfacies (MFT8)

Descriptions: This microfacies contains more dominant smaller skeletal and peloidal frame working grains imbedded within the sparry calcite cements with rare amounts of micrite at some places. This microfacies is obtained from the upper part of military camp section, from

the upper part of middle subunit and lower part of Upper subunit. The major skeletal grains in this microfacies are foraminifera (dominant), gastropods, bivalves, echinoderms and other shell fragments. Smaller peloids of various sizes and shapes are dominant components of this facies. There are also some rare amounts of carbonate clasts observed in this facies. The grains are poorly sorted and compacted. This microfacies is obtained from sample no R13, R15 and R21, (as given in plate 8). It's different from the above microfacies type 7, by the dominance of peloid grains in this facies.

Interpretations: In outcrop this microfacies is also associated with some clastic shale, silicified layers, cherts, and massive limestone layers, those indicates some shallow deep environments of depositions, at the base of foreslope toward the basin . The basin margin at the base of the slope consist mostly the storm deposits and some clastic shale (Brain & Andre, 1992), for which the facies can be best example. This facies compared to FB 3 of Wilson ((1975), which deposited in deep shelf margins or basinal margin.

4.2.9. Bioclastic wackestone microfacies (MFT 9)

Descriptions: It's the microfacies in which various bioclasts like foraminifera's (*Orbitolinids* and *miliolina*, *Paleopfenderina trochoidea-salernitana*), bivalve, gastropods, sponges and brachiopods fragments are imbedded in micrite materials with very rare amounts of sparite. In this microfacies the micrites are more dominant (about 60%-80%) components than any other components. This microfacies is mainly observed in various levels throughout all sections. The best example of this microfacies is obtained from sample DR1, M1, H1, L4, L5, L6, and L7; those are from all subunits as located on stratigraphic columns. Some examples are given in plate 9.

Interpretations: Wackestone and packstone are transitional between low energy mudstone and high energy grainstone deposits. They are generally 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; Burchette and Wright, 1992). This facies deposited in shallow water with open circulation and compared with SMF type 9, which belongs to facies belt 7 or 2, which deposited in open platform or shelf lagoon, or open sea shelf.

4.2.10. Micritic microfacies (MFT10)

This is the most common microfacies in the studied sections. This microfacies is micritic limestone layers dominantly and also it contains very rare amounts of bioclasts like molluscs,

foraminifera, ostracods, and other shells fragments. It's common throughout the military section and Dachatu river stratigraphic sections at different levels. Micritic with some spicules are also added to this microfacies. It's obtained from sample number DR1, DR4, M3, M4, L1, L2, L3, H2 and H1; those are collected randomly from lower part of military, Lange and lower to upper part of Dachatu section, from middle and upper subunit respectively. These micritic facies are highly fractured and dissolved, those are in turn filled by sparry calcite cements at places (plate 10: A). At some places, like at upper part of Military camp section the micritic layers are black dark gray in color and associated with rare amounts of skeletal grains. This microfacies is also associated with some silicified and cherts layers at the same stratigraphic section (example in Plate 14: C).

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 mudstones accumulated in quiet 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 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 in color in field observations. And it's compared with facies belt 3 of Wilson which, is deposited in deep shelf margin or basin margin.

Chapter 5: Diagenesis

5.1. Introduction

Highlights for diagenesis concepts and detail discussions of diagenetic features affecting the carbonate units (Antalo Limestone Formation) of the study area with their environmental settings are discussed in this section.

Diagenesis can be defined as the changes which occur in the character and composition of sediments, beginning from the moment of deposition, and lasting until the resulting materials (rocks) are moved into the realm of metamorphism (McIlreath and Morrow, 1990). It includes processes such as compactions, cementations, mineral recrystallizations and replacement, sub-surface solution-leaching, coalification and the degradation of organic material and generation of hydrocarbons.

In other words, diagenesis is a continually active process by which sedimentary mineral assemblages react to regain equilibrium with an environment whose pressure, temperature and chemistry are changing. Some controlling factors of diagenesis are composition, pressure, temperature, grain size, porosity, permeability, and the amount of fluid flows. The mechanisms of diagenesis may be mechanical, biological, or chemical, or several of them in some combinations.

Limestones formed on carbonate platforms and may maintain near sea level for extended periods are particularly susceptible to drastic, early diagenetic modifications. The reason behind this is that, marine carbonate sediments consist of metastable carbonate phases, like aragonite and magnesian calcite; which are easily dissolved and recrystallized by fresh meteoric waters or mixtures of meteoric and marine waters, such as are encountered in surface and shallow subsurface conditions.

Since rock-water interaction is the primary force driving carbonate diagenesis, a key factor in the diagenesis equation is surface and subsurface fluid compositions. Water most commonly in contact with carbonate rocks and sediments are marine, meteoric or deep subsurface in origin. With time as carbonates are deposited, precipitated, buried, eroded, exposed and reburied, they are subjected to interaction with these different fluids, each of which reacts with the sediments or rocks in a special way and leaves a unique diagenetic signature. In this synthesis three major diagenetic environments are recognized; 1) Meteoric, distinguished by fresh water vadose and phreatic zones and shallow phreatic region of mixed fresh and marine water. 2) Deep burial, where pores are filled with water that may once have been marine but have been moderately to drastically modified by burial diagenesis and 3) Sea floor and underlying shallow marine phreatic zone, characterized by marine water, together with the strandline bathed in mixed marine and fresh waters.

As microfacies analysis from thin sections of carbonate rocks exhibit depositional criteria reflecting environmental constraints acting during sedimentation, the diagenetic **criteria**

brought about by processes affecting carbonate sediments and rocks after initial deposition until after lithification. These processes take place in freshwater (meteoric), marine and burial environments and are recorded in thin sections by criteria related to pore-filling cementations, compaction and pressure solution, recrystallization, dolomitization and others. These all properties and criteria's are considered for the investigations of diagenetic features of carbonate units of Dire Dawa are as elaborated in the following sections.

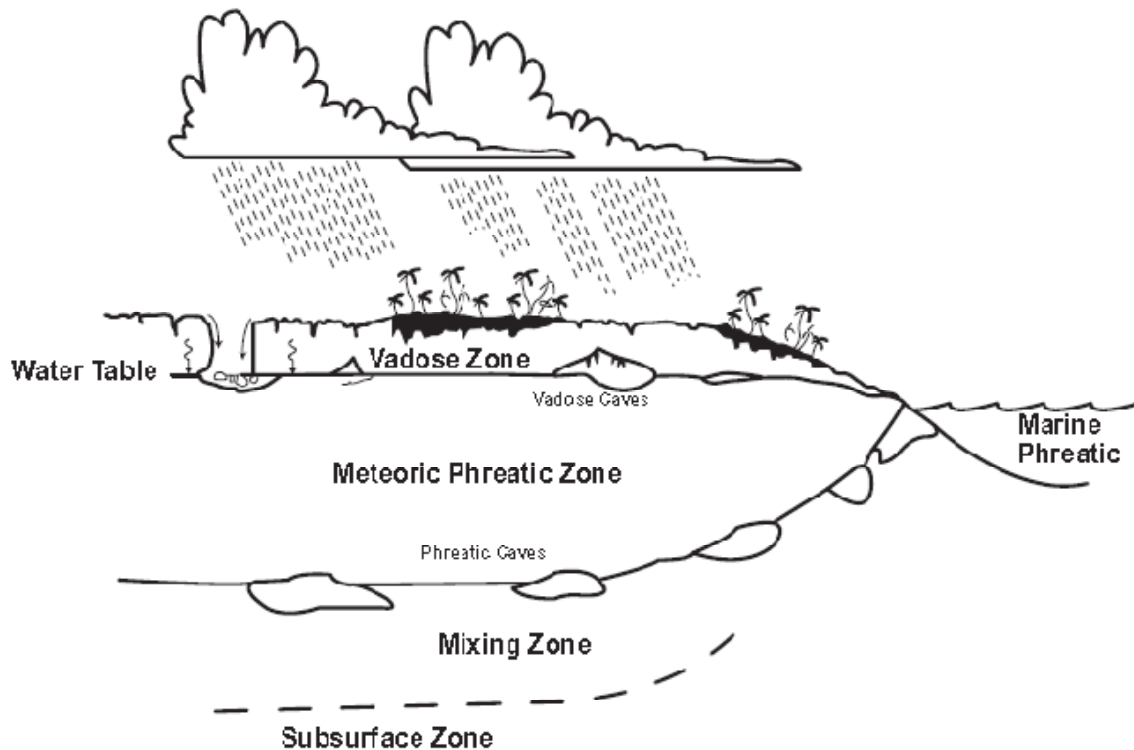


Figure 5.1. A sketch showing the principal diagenetic environments: from the surface vadose environment through freshwater and marine phreatic, to the mixing zone, to the shallow - and deep - burial environments. (Picture taken from an illustration in McIlreath and Morrow, 1990).

5.2. Major Diagenetic features in the study area

In case of this study, the petrographic analyses of collected carbonate' samples and field investigation were conducted to decipher the diagenetic settings of the Antalo limestone Formation from the studied sections. Accordingly, the carbonate unit of the area is affected by various early marine and meteoric (phreatic and vadose) to late burial stage diagenesis processes. The extensive diagenetic processes affecting the carbonate units of the area are: Compactions, fractures, Stylolitization, micritization, dissolutions, cementations, dolomitization and silicifications, with varying intensities and occurrence throughout the studied sections. All of these diagenetic processes are discussed, assigned to different diagenetic environments and supported with various field and photomicrographs in detail as below:

5.2.1. Compaction

Compactions of different carbonate grains and sediments are the dominant diagenesis processes throughout the studied sections. Compactions of carbonate sediments are due to burial and increasing overburdens. Compaction processes is mainly the indicative of early to late burial stage diagenesis (McIlreath and Morrow, 1990; Adams and Mackenzie, 1998; Peter and Dana, 2003; Ahr, 2008). Compactions may be physical or chemical, both of which are abundant throughout the study area.

Physical compaction of the carbonate sediments is the diagenetic process under which the inter-grain space reduces which results in the overall reduction of porosity of the rock. In case of poorly cemented sediments the component grains may break due to this compaction and the embayment among grains are also present. This and other factors produce fractures and ultimately enhance the porosity and permeability of the rock. In general mechanical compaction is evident by fracturing and the formation of sutured and concavo-convex contacts. These features are commonly observed in the micritic, oolitic, peloidal, skeletal and intraclastic packstone to grainstones facies of the studied sections, mainly at Lange and military camp sections. Some examples are given in plate 11, A-B.

In chemical compaction of carbonate sediments, as a result of increasing overburden, first the grain to grain contacts take place and then simple grain contacts developed into sutured grain contacts. Later on dissolution of grains starts at these contacts. In the present study chemical compaction is commonly observed almost in the entire studied sections of carbonate units of the study area. This is indicated by stylolites that are commonly observed in mudstone and other facies in all observed sections (e.g. in plate 11: E-G).

5.2.2. Fractures

Fractures are the results of compaction processes and commonly found at various levels in the measured sections. It[s particularly effective and common in carbonate rocks because of the brittle nature of carbonates relative to the more ductile fine-grained siliciclastic with which they are often interbedded (Longman, 1980). Fracturing can take place at practically any time during the burial history of a carbonate sequence starting with shallow burial because of common early lithification. In this study mudstones facies are particularly bearing more fractures, which at places are highly fractured with several phases of fracturing. Fractures are also found in other microfacies, sometimes along with stylolites, almost all of these fractures are filled with late stage spar cements (plate 11: D). Fractures within other microfacies are cross cutting many carbonate grains like bioclasts, ooids and peloids, showing that as it post date them (e.g. for fractures are in plate 11 B-D).

5.2.3. Stylolitization

The stylolites are actually manifestation of a diagenetic phenomenon, named as pressure-dissolution or chemical compaction. It's formed by chemical dissolution, is marked by concentration of insoluble materials (like clays, iron oxides, and others) along its irregular

surface, that make stylolites dark. The surface represents pressure-induced zones of dissolution with differential grain interpenetration depending on the relative solubility's of grains present on each side of the surface. Stylolite formation is associated with thin water films that allow solutes to move away from sites of dissolution.

In addition to grain-to-grain suturing, pressure-solution seams commonly develop approximately parallel to bedding. The rock “closes up” along such surfaces, as the carbonate minerals (usually calcite) are dissolved and then removed from the vicinity by solution flow. Presumably, the reason stylolites are usually parallel overall to bedding is that bedding surfaces are usually the paths of easiest flow of pore solutions.

In the present observed sections, various stylolites and solutions seams are developed at various levels starting with micro-stylolites observed under thin sections (plate 11E-H) to macro-stylolite bounding and/on different lithologic units at out crop scales (fig.5.2).



Figure 5.2. Multi-macro-stylolites at out crop level, on the exposed micritic limestone. Field photo taken at Dachatu river section, Dire Dawa area.

5.2.4. Micritization

In the shallow marine environments, some light-dependent boring organisms (blue-green algae) also called endolithic algae, may bore into skeletal materials. The borings, around

10µm in diameter, are filled with micrite after the death of the algae. If the process continues, the margin of a shell fragment or entire grains may become completely replaced by micrites. The process is known as **micritization** and the replaced shell margin as a **micrite envelope**. Incomplete micritization leads to the formation of cortoids, whereas the complete micritization results in grains showing an appearance similar to peloids. Micritization processes take place almost everywhere but it is most prevalent in quieter water locations (Longman, 1980) and most of the time it's in early shallow marine warm water environmental diagenesis.

In present studied sections, micritization processes are mostly observed at lower part of the carbonate units of the area, at Lange section. The micrite envelopes are mainly around skeletal grains, rarely around some ooids (plate 12; B) and at places the micrite are replacing the whole skeletal grains (in plate 12; A). These micritic envelopes are mostly preserving the morphology of the dissolved grains.

5.2.5. Dissolution and porosity

Dissolution of carbonate rocks and sediments may occur at any point in the burial history of the sequence. Dissolution occurs when the rock – water system is out of equilibrium. In such a case, the water is **under-saturated** with respect to CaCO₃. Its generally occurs in response to a significant change in the chemistry of the pore fluid, such as a change in salinity, temperature, or others. These changes are most likely to occur early in the history of burial (eogenetic stage), such as in a meteoric water system in a shallow shelf and late in the history of burial (mesogenetic stages). Dissolution makes the increments of porosity.

If the topography is sufficient there may be raised ground where carbonate sediment, or previously lithified limestone, occurs in the vadose zone above the water table. The pores of the vadose zone will be full of air and thus chemically inert. When rain falls, however, the pores will be flushed with acidic meteoric waters. This will tend to corrode the carbonate minerals, generating moldic and vuggy porosity, and enlarging pre-existing fractures in lithified rock. This is, of course, epidiagenesis. If this process continues uninterrupted then cavernous porosity may develop, leading ultimately to karstic topography.

Aragonite and Magnesian calcite are stable phases in the marine environment, but they are very unstable in other environments. In freshwater lakes, or in vadose or phreatic zones, pure calcite is the stable phase. Dissolution of metastable phases may often be selective, and originally aragonitic parts of shells may be dissolved while Magnesian calcites remain intact.

In case of the present studied sections there are various dissolutions of carbonates grains and rocks, at out crop level as well as under microscopic levels (an example shown in plate11). In the out crop there are surface dissolutions of carbonate layers at many levels throughout the studied sections, which show the subaerial diagenetic effects most probably due to climates, on the exposed layers, those are meteoric zone diagenesis. Most of the surfaces of the carbonate exposures at Lange and Military sections are not smooth; they have irregular

surfaces and some smaller hollows. An example of surface dissolution in the area is shown in (fig.5.3.), in which the exposed layers are dissolved selectively, leaving some un-dissolved.

Under the microscopic level , there are partial to complete dissolutions of some carbonate components (like skeletal grains, peloids, ooids, intraclasts and micrite) forming different pore spaces and but in most places these pore spaces are in turn infilled by the late stage sparry calcite cements. Due to these lateral infilling cements the dissolved grains and the resulting voids are rarely identified and absent. But, some time the morphology of the infilled void spaces are used rarely to determine the original grains (e.g. in plate 12; B).

In general, due to these dissolution processes and other diagenetic effects, there are some types of secondary porosity developed in the studied sections, like intra and inter-grains and moldic types of pore spaces and increments of pre-existing pores. For example as shown in (plate 12: C) the micritized gastropod shell is partly dissolved at the top left end of the picture and some peloids dissolutions forming secondary pore spaces, the black color shown by the arrows.



Figure 5.3. Field photo taken from lange section showing the limestone layers dissolved due to subaerial exposure.

5.2.6. Cementation

Cementation is the most dominant diagenetic processes throughout the studied sections of Dire Dawa carbonate units. 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. Cementation can occur several times in the diagenetic history of a carbonate rock beginning with cementation in the marine environment just after deposition (early cementation) and continuing through vadose, shallow, intermediate, and deep - burial environments (late stage cementation).

Cementation is an important diagenetic process, which endows strength and stability to the concerned microfacies. The well developed cement, always, resists physical, as well as, chemical compaction and fracturing episodes.

The mineralogy, shapes and crystal forms of carbonate cements changes as water chemistry and diagenetic environments change from marine phreatic to meteoric phreatic to shallow and deep subsurface waters (Ahr, 2008). This character helps to identify origins of various cements. Marine phreatic cements in today's oceans are Mg - calcite or aragonite because abundant Mg favours precipitation of aragonite and Mg - calcite. Freshwater vadose and phreatic cements crystallize as calcite with blocky crystals and bladed rhomb crystal habits. Burial stage cements are coarser and shine relative to others cements.

In the present study various types and many phases of cementation are found at various levels throughout the area. The cementation occurred in the studied sections are also showing various settings like meteoric, marine and burial stages of cementations; those are differentiated on the basis of cements' morphologies, shape, patterns, color, sizes and relation with various substrates. The commonly observed cement types are: inter-granular, meniscus, isopachous, circumgranular, microcrystalline crusts and syntaxial types of cements. They will be discussed in the following sections.

5.2.6.1. Inter-granular equant or blocky crystal cements

They are cements those filling the voids and totally occupying the space between various carbonate grains. These cements are mainly observed at lower part of carbonate unit of the area, in oolitic facies mainly (in sample K2-K3) (shown in plate 13). At places these inter-granular cements are forming drusy mosaic fabric cements, cements with crystal sizes are increasing away from the substrate toward the center of cavities. According to McIlreath and Morrow (1990), Adams and Mackenzie (1998), Peter and Dana (2003) & Ahr (2008) inter-granular drusy mosaics coarser cements are from meteoric (phreatic zone) diagenetic environments. In the phreatic zone, where pores are saturated with water, cements are precipitated as equant circum-granular crusts along on the surface boundaries of grain and if conditions continue then later filling all pore spaces forming totally cemented grains.

Not only the phreatic cements are inter-granular, burial stage calcite cements are also found as intra and inter-granular cements at various levels in studied sections. It's common in military section and rare in samples of Lange section. Burial diagenesis represents alteration that occurs below the zone of near-surface water circulation (i.e., below the meteoric phreatic mixing zone or below the zone of active seawater circulations). Burial-stage calcite cements are low-Mg calcite. Most crystals grew slowly, and thus are relatively imperfection free, clear (limpid) crystals as compared with marine and even meteoric precipitates (Peter and Dana, 2003). They are coarse grained and lack drusy mosaic fabric.

The burial cements are recognized by paragenetic relations (the relative timing of features). Thus, cements that postdate earlier cements, or are coeval with or postdate stylolites, compaction features, tectonic fractures, saddle dolomite, silica cements, or similar features,

are probable burial-stage (mesogenetic) or uplift-stage (telogenetic) cements. Examples of burial stage cements are shown in plate 11 A-D, plate 13: D, E, J and K.

5.2.6.2. Meniscus type cements

These cements are not abundant in the study area and mainly observed at Lange section in peloidal facies. In the vadose zone, cements are concentrated at grain contacts and the resulting pores have a distinct rounded appearance due to the meniscus. Therefore they are meteoric vadose zone cements. Example of this cement is given in plate 12: I.

5.2.6.3. Isopachous cements

Isopachous cements are characterized by single or multiple cement rims growing with equal thickness around grains. The cement rim may consist of fibrous, bladed, or microcrystalline crystals. Thickness of the rims is within the range of tens of microns to several millimetres. They are common in marine-phreatic and marine-vadose environments (Flugel, 2004). Below water table, in phreatic zone environments, pores are totally filled with water and cements grow more evenly on all surfaces and larger equant crystals are coating the grains, that is how isopachous type of cements are formed (McIlreath and Morrow, 1990). This indicates that, isopachous rims of equant crystal cements are phreatic in origin. These types of cements are abundant at Lange section. Mainly it's found in oolitic facies of the area, in sample K3 and K4 (examples are given in plate 13 B-C).

5.2.6.4. Circumgranular cements

Circumgranular cements are characterized by a cement rim around grains, consisting of equidimensional crystals forming the first generation of pore-lining cements. The rim is commonly thinner than isopachous cement rims. These types of cements are common in meteoric phreatic environments according to McIlreath and Morrow (1990) and Flugel (2004). These are observed at military section and the example is given in plate 13: D.

5.2.6.5. Microcrystalline crusts cements

They are very fine grained space filling and circumgranular cements types. According to McIlreath and Morrow (1990); Adams and Mackenzie (1998); Peter and Dana (2003) and Ahr(2008)the microcrystalline crust types of cements are marine in origin.

These types of cements are very common, mainly in sample collected from military and Dachatu river sections of the study area. The best example for them are given in plate13: A,

5.2.6.6. Syntaxial overgrowth

The syntaxial rim cement grows over the host grain in optical continuity. It is common in many carbonate rocks. It usually develops on echinoderm shells in optical continuity and recognized by simultaneous extinction. Because echinoderm fragments act as single crystals, they are commonly nucleation sites of calcite cements. Clear calcite is added in optical continuity to the echinoderm fragments. These cements may begin in the marine

environment, they can certainly precipitate in meteoric settings, but in many cases, they continue to grow in the burial environment as well.

In the present study area these cements are found at upper part of military section and in Dachatu river section in wackestone facies, on some echinoderm grains. Mostly its related with compacted grains in this sections, due to this it can be interpreted as burial stage of diagenesis. An example of this type of cement is shown in plate 13, L.

5.2.7. Dolomitization

Dolomite, $\text{CaMg}(\text{CO}_3)_2$, is one among the major component of limestones. It is usually secondary, replacing pre-existing carbonate minerals. No staining is used in the present works, so dolomite is identified by its euhedral rhombic shape, often zoned, untwined habit.

Dolomitization is the processes of calcite to dolomite conversion and results in volume reduction and an increase in porosity. 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 seep into limestones and form fine-grained dolomite.

Given one mechanism or another, dolomite can form at virtually any stage of diagenesis. Syndimentary dolomite forms as replacement of high-Mg calcite or aragonite in hypersaline sabkha sediments and also in other tidal flat deposits; mixing zone dolomite cementation and replacement affect somewhat older sediments in marine-meteoric phreatic mixing zones; and burial dolomitization affects carbonate deposits of any age in the intermediate to deep subsurface(Peter and Dana, 2003).

In the present work, dolomitization processes are observed mainly in lower and middle subunits of the carbonate units of the area, at Lange and lower part of military sections. Some of the grains are partially dolomitized and some others are totally dolomitized. Aragonite and high-Mg calcite are far more susceptible to dolomitization than low-Mg calcite. This can lead to partial dolomitization followed by leaching of un-dolomitized remnants (forming dolomoldic porosity)(e.g. Observed in sample R3). Most of dolomite crystals observed in present analysed samples from the study area are mostly coarse grained, showing that dolomites of the area are formed from mixing zones, by replacing precursor calcite minerals. Many replacement dolomites have cloudy cores (initial growth phase's rich in undigested host-rock mineral inclusions or early, metastable precipitates) and clear exteriors, which are the character of dolomite of our area. Mixing zone dolomites are ranging from microcrystalline replacements to limpid, zoned replacements and cements. The best examples of dolomitization processes are observed in sample R3, R4, and H2 and some of their photomicrographs are shown in plate 2: A-D and plate 14: A-B.

Some of the dolomitized samples are also showing rare indication of the reverse processes, dedolomitization. Dedolomitization is a reverse process in which the dolomite is calcitized. These processes are very rarely observed in those samples by some darker finer micritic

inclusions within the clear dolomite rhombohedral, as shown in the photographs (e.g. in plate 14: D)

5.2.8. Silicification

Silicification processes are also affecting some carbonate exposures in the study area. Silicification is the diagenetic process in which the carbonate minerals are replaced by silica (SiO_2). It is a widespread diagenetic mineral in carbonate rocks. Silica may occur as cement or it may be found as a replacement of original or diagenetically altered sediments.

The major source of silica for diagenesis is biogenic opal; therefore, silica is especially prevalent in deep-marine sediments from active upwelling zones and shallower-water carbonates from nutrient-rich carbonate shelves (Ahr, 2008). Sponge spicules, diatoms and radiolarians are the most common biogenic contributors and are diagenetically unstable when compared to siliciclastic grains. Silica diagenesis is most typically a product of burial diagenesis. This is due to the timing of the conversions of biogenic opal to stable microquartz or megaquartz (Peter and Dana, 2003).



Figure 5.4. Field photo from upper military section, showing thin lenses of silica layers between micritic limestone beds.

In the present study area silicification products are mostly occurred mainly at upper part of Military section, and Dachatu River sections, both in the field views and within the thin section of sample collected from these sites. In the field views, the silicified units are

observed mainly as nodular or as thin lenses of darker silica layers within and between micritic limestone exposures (fig.5.4.) and under thin section microcrystalline quartz (showing some whitish and dark bandings) are replacing calcite(plate 14: C).

5.3. Sequence of diagenetic events

Diagenetic sequence displays the sequence of events during burial diagenesis as the sediments go through burial processes (McIlreath and Morrow (1990)). As burial proceeds and interstitial water composition changes, cement mineralogy and crystal form change accordingly, those are useful for putting diagenetic events orderly. The first stage of diagenesis is at sea floor (bioturbation, micritization, marine cementations in the form of an acicular, isopachous rim around the grains and microcrystalline cements). The next stage is exposures of sediments and rocks to meteoric environments, under which there are dissolutions of unstable minerals and precipitations of meniscus (in vadose zone) and blocky equant cements(in phreatic). Finally, the sediments may undergo burial mechanical or chemical compactions which may be followed by fractures, Stylolitization, silicification and late stage coarser burial calcite cements, marking the last of the episode of diagenesis.

In the carbonate diagenesis of the present study area, the diagenetic sequence do not fit to full stages and passes of the carbonate rocks diagenesis at all places, but at some places there are good indications of diagenesis sequences those are discussed as follow sequentially, from early to late stages of diagenesis.

1. Micritic envelops

It's the first diagenetic phase in the study area; it takes places in the early marine diagenetic environments. It's mostly developing around grains which have original aragonitic compositions. This envelop serve to define and preserve outline and morphology of carbonate grains they are covering. From the present study area, its highly developed in the lower subunit of the carbonate units of the area, mainly in peloidal and oolitic grainstone facies.

2. Disolution and marine cementation

Next to the micritic envelops the dissolutions of the unstable grains were took places, indicated by the existences of some dissolved parts near the micritic envelops. The metastable minerals like aragonites and high Mg- calcites are susceptible for early dissolutions. Even most of the grains are totally dissolved up to losing their internal structures and these dissolved minerals are precipitated as some early marine cementations. In early marine setting of sediments, before undergoing burial, marine cementation like isopachous rim cements and microcrystalline cements within the pore spaces and around grains are abundant mainly at lower part of the carbonate units of the area.

3. Dolomitization

The conversions of calcite to dolomite in this area is most probably at mixing zone, which is most probably after marine diagenesis and before meteoric diagenesis, that may be next to

dissolutions processes. But this dolomitization is rare to localized and absent at more places. It's also found at more depth at some places throughout the sections rarely, such dolomitization may be the late stage of diagenesis.

4. Precipitations of meteoric calcite cements

Next to the early marine cementations phases, whenever the sediment was exposed to meteoric environments, there are precipitations of meniscus and equant blocky calcite crystals those are meteoric vadose zone and meteoric phreatic cements respectively, at localized places. Such meteoric cements are observed mainly in oolitic facies of the area and rare or absent at other places. The absence of this meteoric cements at places may show that either the sediments were didn't stayed enough time before burial in this environment or the late stage diagenetic feature obscured and hid the meteoric products.

5. Mechanical compaction and Fractures

Mostly next to marine cementations and rarely following the meteoric cementation phases, as the burial of sediments and overburden increases, there are mechanical compactions and fractures among various carbonate grains throughout the study area, which are recognized by fitted grains, fractures, brittle deformations of grains and early cements.

6. Chemical compactions and Stylolitization

Next to the mechanical compactions, as the depth and overburden increases more, the compacted grains' boundaries start to be fitted more, sutured and dissolved and forming solution seams and stylolites features, along which insoluble materials will be concentrated, and help to recognize such structures.

7. Silicification

At great depth of burial in carbonate deposits, silicification processes is the active one among other diagenetic features throughout the area. Sponge spicules, diatoms and radiolarians are the most common biogenic contributors to form biogenic opal and are diagenetically unstable at the depth. This biogenic opal is the major source of silica for diagenesis. And it needs long time of burial for the conversions of biogenic opal to stable microquartz or megaquartz, that make the silicifications process the deep or late stage of diagenesis.

8. Burial cementations

At the end/ late phase of diagenesis of carbonate units of the area, there are precipitations of burial stage cements, which contain very coarser and clear calcite cements, those postdating all other diagenetic features.

Chapter 6: Discussion

6.1. Introduction

According to the present field investigations and lab analysis, the Dire Dawa area Jurassic carbonate deposits (Antalo Limestone Formation) shows thin-thick carbonate rocks, mainly limestone rocks, having various distributions of carbonate skeletal and non skeletal grains within micrite and/or sparry calcite cement backgrounds throughout the area, forming varying beds of micritic to grainstone limestone sequences of having various sedimentary structures, various textures and various diagenetic features throughout the units. These varying contents and varying sedimentological features obtained throughout the carbonate units of the area are very essentials and give ways for linking the deposits of the area to existing regional scenarios and discussions of various information's like, age of the formation, depositional environments, facies patterns and facies models, the composite stratigraphy of the area, paleogeographic settings and correlations with some other areas' equivalent deposits. All these concepts for the carbonate deposits of the area were discussed under this section as follow.

6.2. Biostratigraphy and age

No detail attentions and measured biostratigraphic zonation were made during this study, but from the randomly collected samples from the lower, middle and upper parts of the carbonate successions of the area as per their lithological aspects, the following fossils and fossil assemblage were identified:

From the lower part of the unit: there are assemblages of Molluscs, echinoderms, algae and foraminifers (*Pfenderina trochoidea-salernitana* (from sample L7), as given in plate 15). According to Sartoni and Crescenti(1962); (De Castro, 1987 and Chiocchini and Mancinelli, 2001(as cited in Kemal et al. 2008)) *Pfenderina trochoidea-salernitana* is used as an index fossil for the Bathonian to Callovian age.

At middle part of the unit: there are assemblages of fossils like Molluscs, echinoderms, *Naulithica oolithica*(in sample R11and R12) and *Kurnubia palastiniensis*(in sample R10,R11, R12 and R15). According to Sartorio and Venturini (1988) *Naulithica oolithica* is Bajocian to Tithonian in age (this is long range & so not used for short age determination). According to Septfontaine (1988) and Velic (2007)(as cited in Kemal et al, 2008), the *Kurnubia palastiniensis* is index fossil of Upper Jurassic, Oxfordian – lower Kimmeridgian in age.

At upper parts of the unit fossils assemblages of foraminifera's, bivalves, echinoderms, ostracods and brachiopods are found, but, their age is difficult to determine.

Age assignments: Based on those fossils and fossil assemblages identified (mainly index fossils of foraminifers obtained are used), the carbonate unit of the Dire Dawa area is dated to be Bathonian-Callovian-Oxfordian-Kimmeridgian age. In which, the Lower sub-unit (Bathonian-Callovian) by occurrence of *Pfenderina trochoidea-salernitana*, middle sub-unit (Oxfordian-Lower Kimmeridgian) by occurrence of *Kurnubia palastiniensis* and For the upper part of the unit, no age indicative fossils found, but, the Kimmeridgian age was assigned, based on: 1) Its stratigraphic position, as it overlies the middle unit (of Oxfordian – lower Kimmeridgian age) conformably and 2) Bosellini et al., (2001) also assigned Kimmeridgian age for 'Daghani shale' carbonate succession, exposed at the Eastern part of the present studied sections around Dire Dawa city, which is correlable with this Upper sub-unit by other sedimentological features and by stratigraphic positions.

6.3. Depositional environments

According to the present field observations and lab data analysis, the general carbonate facies patterns through the area shows the transgressions pattern of deposits; mainly at the lower part of the unit the existence of dominant amount of the detrital quartz and some other clastic layers (as shown in figure 3.2) within the carbonate layers indicate that as there were continental source areas nearby. When we go upwards, these bottom mixed clastic and carbonate layers change into the thick completely carbonate of middle and upper subunit layers overlying them. This indicates that the transition from fluvial continental to the marine conditions of depositional environments. The carbonate successions of the area also show some cyclicity of the components, within varying thickness of the beds bearing them throughout the area vertically. This cyclicity of the layers is most probably caused by the small changes in sea levels, depositional energies, depositional processes, and the change of morphologies of the depositional sites locally throughout during their depositions. The cycles of the facies are mostly shallowing-up pattern at the lower sub-units and some deepening up pattern at the middle and upper subunits, which show the more sea level increments and deepening of the basin during the deposition of middle and upper parts of the successions.

As some descriptions and interpretations were given in the previous sections in terms of depositional environments, based on the various skeletal and non-skeletal sediment obtained and the dominating depositional processes, the carbonate deposits of the study area shows the depositions under shallow marine conditions for the lower and middle sub-units and some offshore system (marginal basin to open sea) depositional conditions for the upper sub-units.

The existing of dominant clastic layers intermixing carbonate layers, dominant finer peloidal grains, boring structures, micritized skeletal and non-skeletal grains, and coarser oolitic

grains of high energy deposits (shown in microfacies type (MFT 1-4)), those compared with 8, 7 and 6 facies belts of Wilson (1975), throughout the lower sub-unit of these carbonate successions are best indicators of shallow marine carbonate depositional environments.

In the middle sub-unit the dominances of various skeletal grains and non-skeletal grains (like peloids, intraclasts and rare ooids) and some local smaller patches of colonial organisms, all indicate its depositions under shallow marine conditions. Still the alternative cycling of facies within this sub-unit also shows local change in sea levels or other processes during depositions.

The Upper subunit of the succession is dominating with fine grained dark to dark gray micritic layers, with some intermixing of thin clastic shale layers, nodular and lenses of silica layers at its bottom parts. Rare skeletal grains like: forams, bivalves and echinoderms are also imbedded in these micritic layers at places. From this subunit the bioclastic wackestone and micritic microfacies (MFT 8-10), those compared with facies belt 2 and 3 of Wilson (1975), those deposited at basin margin to open sea conditions. And also the facies through this subunit shows deepening up; those may be due to highly rise in the sea level during their depositions. All these properties show the low energy deposits of outer ramp/offshore depositional conditions for this upper subunit.

But, at the top most part of this upper sub-unit there are silicified colonies of organisms and carbonate buildup layers observed at Dachatu river section, as described in chapter three. These layers may show the locally uplifted, shallow environments favourable site or conditions for shallow organisms to grow; those may be the results of local tectonics.

As described in section four of this paper, the carbonate facies of the area are compared with the facies belt 8, 7,6,4,3 and 2 of Wilson (1975), from bottom to top of the units. Those facies belts indicate depositions ranging from restricted shallow platform interior to basin margin to open sea conditions. Generally carbonate facies of the area shows various sub-shallow marine depositional environments ranging from the shore line carbonate deposits of low energy platform interiors (of tidal flat and lagoon), high energy Platform margin carbonate sand bodies, slope deposits and some offshore deposits (of basin margins and open sea) deposits. Those described as below.

6.3.1. Tidal flat deposits

Lower part of the carbonate units of the area is deposited under low energy conditions of tidal flat. This lower unit comprises the successive intercalation of calcareous sandstone, sandy limestone, dolomite and some clastic mudstone deposits. Mixed siliciclastic-carbonate microfacies (MFT1) and dolomitized microfacies (MFT2) of the area are the characteristic deposits of tidal flat. Carbonate tidal flats occur in settings which are protected from open ocean waves by wide shelf lagoons, which dampening the incoming waves and by its position behind barrier land those separate back shoal lagoons from Open Ocean (Walker, 1992; Reading, 1996). Tidal flats are partly sea and partly land. Tidal flats are areas that flood

during high tides and are exposed during low tides, that is why they contains clastic and carbonate layers alternatively, as observed in lower intercalation unit.

6.3.2. Lagoon deposits

The thin bioclastic wackestone layers (MFT9), top part of the lower unit, and thin pelletic packstone-grainstone layers (MFT3), bottom part of the middle sub-unit of the carbonate unit of the area are the typical of low energy deposit of lagoon type. According to Tucker and Wright(1990) the coastal lagoons are protected environment from strong wave action behind barriers to ward land, in broad interiors of rimmed shelves or behind inner ramp shoal belts. Lagoons are typically shallow water depositional environments (<10m deep) they are sites for depositions of fine grained sediments forming mudstone to packstone and pellets formed by molluscs and algae are abundant in lagoon sediments(Reading, 1996)(for which the present observed layers can be particular example). The inner most platform areas are commonly restricted or hypersaline and support only a low diversity biota. Rare fossils like molusks, algae, brachiopods and forams are occuring in this facies from the present observations(as shown in plate 3 and 9).

6.3.3. Platform margin carbonate sand bodies

The oolitic microfacies (MFT4) and some top part of bioclastic peloidal grainstone facies (MFT3) layers of lower subunit of the carbonate unit of the area, those comprises large size ooids (reaching sand sizes) and rare amounts of skeletal within sparite cements, with some grains surrounded with micritic envelops (as shown in plate 4), are the typical facies of platform margin carbonate sands/ oolitic sand barrier deposits. The grains in these facies are well sorted, well-rounded, tangential ooids, lithified forming horizontal beds of grainstone, which is the result of reworking by wave and tidal currents at these margins. 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. They occur in shallow, high energy areas and typically develop in inner ramp settings and along high energy inner shelves (Burchette and Wright, 1992). Their formation shows that the presence of barrier/ islands at this margins. The carbonate sand bodies on the windward and leeward margins exhibit different geometries and sediment compositions. The oolitic sand bodies dominate windward, open margins where sediment transport is mostly on to the shelf, on leeward

margins net sediment movement is off-shelf so that much of the material is derived from platform interior, largely micritized peloidal, skeletal and oolitic grains. Such difference is used to identify the windward from leeward sides.

6.3.4. Carbonate Foreshoal environment/ slope deposits

The middle part of carbonate unit of the area which has the coarser grained deposits of resedimented wackestone- packstone- grainstone facies (MFT5-8, given in plate 5-8) those are dominantly intraclastic (mainly micro-breccias'), various sized peloidal grains, some skeletal (like mollusks, echinoderms, ostracods, corals, foraminifers, etc) and with rare amount patches of colonial organisms within micritic layers at bottom part, from military section, are the typical of platform margins away from the barrier sea ward and slope deposits or transitional slope facies . In this facies there are no indications of major shelf angle break, the intraclast rich layers are passing simply to the micritic dominating fine grained wackestone to mud stone layers of upper sub-units. They show the accretionary slope (low angle) type deposits (Reading, 1996). In the accretionary slope the major site of deposition is the lower slope apron or basin margin. These deposits have alternative layers of mudstone, wackestone, packstone and grainstone layers with varying thickness. The sediment supply toward the platform slope may be from number of sources (Walker, 1992): The fine grained carbonate may be supplied from shallow platform and from planktonic fall out to produce hemipelagic oozes. The coarser shallow water grains are supplied from platform top and margin and mix with material eroded from the slope and redeposit in the deeper water.

6.3.5. Offshore carbonate deposits

After passing the middle intraclastic, skeletal and peloidal dominating deposits, the upper sub unit of carbonate successions of the area are mainly fine grained thin-thick black micritic layers dominating with some intermixing of clastic shale and silicified layers. They show generally the deposition under low energy conditions. 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). For which the present shale dominated layers will be the most typical example of carbonate deposits of low energy condition of outer shelf/ramp setting, at basin margins or open sea conditions.

6.4. Facies model for the carbonate units of the area

Any facies models are a general summary of a given depositional environment or depositional system (Walker, 1992; Reading, 1996). According to the present field investigations and microfacies analysis results, the general successive facies and facies belts of the carbonate units of the Dire Dawa area show the carbonate **ramp facies model** settings. The ramp was recognized by Ahr (1973) as a major type of depositional setting for carbonate rocks and was put forward as an alternative to the carbonate shelf. A carbonate ramp is a gently sloping surface with a slope of less than 1°, i.e. ramps slope gently from intertidal to basinal depths, with no major change in gradient. On a ramp, shallow-water carbonates pass gradually offshore into deeper and deeper water and then into basinal sediments. The major depositional processes are seaward progradation of the inner sand belt and storm transport of shoreface sand out to the deep ramp. On a ramp, wave energy is not as intense as along a shelf margin where oceanic swell and storm waves are suddenly confronted with a shallow steep slope. Nevertheless, the gradual shoaling of a ramp does result in relatively strong wave action in the shoreface-intertidal and this permits the formation of shoreline carbonate sand bodies. Storm events are generally very important on through shoreward movement of sand. Offshore storm surges are important in transporting shoreface sands to the outer, deeper ramp. Shoreward of the inner ramp sand belt, smaller lagoons and tidal flats may develop, if the ramp continues into the supratidal. But, if the ramp leads up to a platform, then a very extensive lagoon-tidal flat supratidal area will occur behind the beach barrier.

On the basis of dominating processes the ramp profile can be: Inner, mid and outer ramps zones (Burchette and Wright, 1992). The **inner ramp** is the zone above fair weather wave base where wave and current activities are almost continuous, above 60m water depth, or it's between upper shoreface (beach or lagoon shoreline) and fair weather wave base. In this zone tidal flat, lagoon and barrier environments are common. The **mid-ramp** zone lies between fair weather wave base and storm wave base, between 60 and 140m water depth, so the storm processes is dominating. In this zone the bottom sediment is frequently reworked by storm waves and swells. The **outer ramp** zone extend from below normal storm wave base to the basin floor, between 140 and 200m water depth, storm generated currents can lead to the depositions of graded units or the local erosion or reworking of a sediments. Deeper parts of the ramps predominantly low energy setting. While shallow water reefs are scarce in the ramp, small isolated biological build-ups are common, mainly in mid -outer ramp setting.

As described in depositional environment section, the overall facies associations of carbonate deposits of the area are showing a low gradient of depositional dip from inner-ramp domains (tidal flat, lagoon and shoreline high-energy shoals deposits) to mid-outer ramp areas of slope – offshore low energy deposits, as given in (fig. 5.1).

6.4.1. Inner ramp facies

These include the carbonate sands formed in the agitated shallow subtidal shoreface zone (above fair-weather wave base) and low intertidal, including: tidal flat deposits, lagoon deposits and barrier/island area deposits (Burchette and Wright, 1992). From the present study area, the lower sub-unit carbonate layers, which comprises: the low energy deposit of tidal flat and lagoonal facies; having the marginal, dolomitized mudstone, bioclastic wackestone and peloidal packstone-grainstone microfacies (represented by MFT 1, 2, 9 & 3, respectively); and high energy carbonate bar deposit of oolitic grainstone microfacies (MFT4) and some upper layers of peloidal grainstone are the particular representative of inner ramp deposits.

6.4.2. Mid ramp facies

Includes the carbonate deposit formed between fair weather wave base and storm wave base in which the storm processes is dominating. Due to this, the bottom sediment is frequently reworked by storm waves and swells (Tucker and Wright, 1990; Burchette and Wright, 1992).

The middle sub-unit carbonate layers of the area, those containing some bioclastic mudstone-wackestone microfacies (MFT10) at bottom part of military section/ bottom of middle sub-unit, intraclastic wackestone layers, and dolomitized micritic facies layers, bioclasts, peloidal, and intraclast dominating packstone to grainstone microfacies (MFT5-8) of slope area/foreshoal deposits, having so many reworked and redeposit carbonate sediments are generally the mid ramp deposits facies of the area.

6.4.3. Outer ramp facies

On the outer parts of ramp carbonate sedimentation is dominated by fine-grained deposits (Tucker and Wright, 1990; Burchette and Wright, 1992). In this study the dominance of fine grained dark-gray micritic layers with clastic shale and silicified layers intermixing, in the carbonate upper subunit of the area, from which the bioclastic wackestone (MFT9) facies and

micritic facies (MFT10) obtained, mainly logged at top of military camp and Dachatu River sections, shows the outer ramp deposits. They contain some fine grained fossils like fragments of mollusks, forams, echinoderms, sponges and etc.

The colonial organism dominated micritic layers and carbonate buildup bearing layers observed in the field at Dachatu section of the area are also the typical deposits of basin margin /outer ramp deposits.

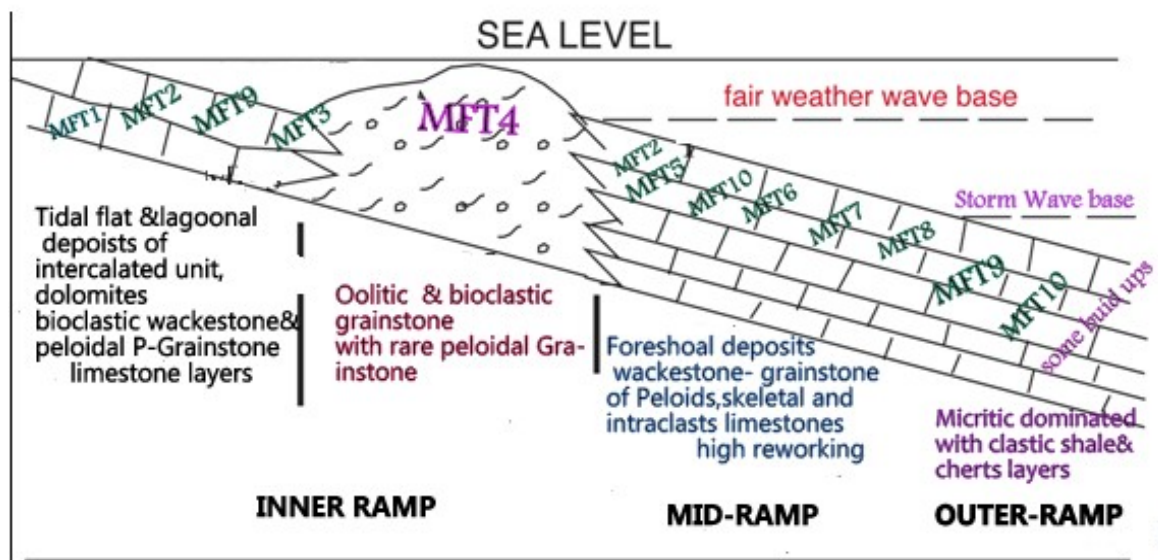


Figure 6.1. The distributions of carbonate facies of the study area on the ramp morphology.

MFT1-10, shows the major microfacies types. This picture left to right represents the move from NW to SE direction in the study area, from the bottom to top of the unit. This picture is not scaled and used only to show the facies distribution patterns.

6.5. Composite stratigraphy of the area

From the present field investigations and data analysis, in Dire Dawa area, about (~306m) total thick Bathonian-Kimmeridgian carbonate successions are sandwiched between Lower, Adigrat Sandstone (Triassic-Bajocian (Bosselini, 1989)) and Upper sandstone unit (Aptian-Albian (Atnafu and Kidane, 2012)), giving the overall composite Mesozoic stratigraphy of the area, as given in (fig.6.2).

The carbonate units of this area, are again subdivided into Lower, Middle and Upper sub-units, from older to younger, according to their facies contents. The detail field description for these three sub-units was given in chapter three of this paper. But under this section, the overall distinctions among these sub-units, based on the results obtained from the microfacies analysis, diagenetic descriptions, depositional interpretations and biostratigraphic interpretations will be elaborated in detail.

The lower sub-unit: conformably overlies the Adigrat Sandstone Formation and this sub-unit consists of intercalation unit, peloidal packstone to grainstone type limestone beds and oolitic grainstone layers, from bottom to top, with total thicknesses of(~119 m). This sub-unit is generally deposited in inner ramp setting, in which the low energy tidal flat and lagoonal deposits consist of the intercalation units and peloidal limestone part of this subunit and high energy deposit oolitic grainstone beds at its top part.

The lower intercalation part of this sub-unit of about 100m thick, has various beds of fine grained sandstones, sandy limestones, calcareous sands, dolomite layers, clastic mudstone layers and thin micritic limestone layers in ascending order and they are topped by the peloidal layers and oolitic layers of high energy deposits(around carbonate shoals/ barriers of platform margins) at top. The intercalated layers show the cyclicity of the components up wards, which show most probably the local sea level fluctuations during depositions. There are very rare fossils remains (like molluscs, foraminifers, and algae) in this unit. The sedimentary structures dominating in these units are bioturbations, bedding, some laminations, horizontal stratifications and post depositional structures like smaller cavernous, small karstifications and hollows.

Petrographically the collected samples from this unit show the calcareous sandstone in which the various sized detrital quartz grains are imbedded in calcite cements (as shown in plate 1) and other samples from this unit also shows extensive dolomitization (L2, L3, as shown in plate 2), peloidal and oolitic rich grainstone textures from sample K1-K4 (as shown in plate 3 and 4).

Microfacies analysis from this lower sub-unit also shows successive facies of inner ramp facies , which comprises: marginal facies, tidal flat facies, lagoonal facies and carbonate shoals facies successively. The marginal facies (MFT1) contains detrital quartz grains within calcite cements; tidal flat facies (MFT2) comprises the dolomitized fine grained carbonate materials; lagoonal facies of thin bioclastic wackestone microfacies (MFT9) and peloidal packstone-grainstone microfacies (MFT3) and the carbonate shoal facies which contains dominantly oolitic grainstone facies (MFT4). The age of this subunit is Bathonian to Callovian, as given above. This lower subunit is generally showing the shallow marine marginal facies to tidal flat and lagoon to carbonate shoals/ barriers of platform margins depositional environments, from bottom to top, this lower unit is overlaid conformably by thick fine grained micritic and dolomitized limestone layers of the bottom parts of middle sub-unit above it.

The Middle sub-unit: is characterized by dominance of various carbonate allochems embedded within sparry calcite cements and/ or micrite. This unit has about (~84m) total thickness. It's conformably overlay the lower unit, with gradational type of contact and it

contains micritic layers, thin peloidal wackestone layers, intraclastic wackestone layers, and dolomitized cavernous micritic layers with some patches of colonial organisms, peloidal, bioclasts and intraclastic rich packstone to grainstone thick layers(those are described in chapter 3) according to their ascending order. This middle unit is differentiated from the lower and upper unit by the absence of clastic layers, its fossil contents and by the dominance of carbonate allochems thoroughly within this unit.

The micritic, dolomitized mudstones and cavernous micritic layers, those containing patches of colonial organisms, dominating at the lower part of this unit, shows that locally agitated low energy shallow water conditions during depositions. The peloidal, bioclastic and intraclastic packstone to grainstone thick layers at upper part of this sub-unit show the reworking of sediments and depositions around unstable high energy depositional site like that of the slope area, behind the carbonate barriers toward the sea.

According to petrographic and microfacies analysis this unit contains the carbonate facies those deposited at low energy of mid-outer ramp microfacies types (MFT 2, MFT5,MFT 9 and MFT10) at places and high-energy deposits of the slope area containing (MFT6-8). The facies of this middle unit shows the cyclic deposits, alternating lower energy deposits of mudstone and wackestone with intermediate to high energy deposits of packstone and grainstone layers, with varying thicknesses at different level throughout the unit. Generally they produce deepening up facies patterns throughout the unit, which is most probably correlable with that of Urandab sequence type of deposits indicated by many authors in South Eastern and Ogaden basins of Ethiopia. This subunit is deposit in Foreshoal environments.

The sedimentary structures throughout this sub- unit are laminations, thin-thick bedding, stratifications and post depositional structures like smaller cavernous, minor karistifications and hollows.

The dominant fauna obtained from this unit are bivalves, echinoderms, brachiopods, gastropods, varieties of foraminifers (like *Kurnubia palastiniensis*), ostracods and etc. According to these fauna, the age of this middle unit is Oxfordian- lower Kimmeridgian. Diagenetically this unit shows extensive marine to meteoric cementations; and some micritization, compactions, dolomitization and silicification (as discussed in chapter 5).

The upper sub-unit: has a total thickness of about (~103m). This unit overlies the middle unit conformably and truncated disconformably by the upper clastic unit (Upper Sandstone Formation) above it. This unit consists of black-dark gray micritic layers, alternating layers of mudstone and shale unit, massively bedded bioclasts, intraclasts and peloids bearing wackestone-packstone layers, massively bedded micritic layers, mudstone layers with colonial organisms, carbonate build up bearing mudstone layers and mudstone layers(those are described in chapter 3) according to their ascending order. This unit has dominance fine grained micritic layers, clastic shale layers, nodular and lenses of cherts. The general pattern of facies in this upper unit shows deepening-up facies pattern (except the colonial organism bearing thin layers, those may be the results of the local tectonic uplift), which is the

characteristics of the Urandab sequence throughout South East and Ogaden basin of Ethiopia. This deepening up facies shows the increments of the depth of sea level during its depositions. The sedimentary structures throughout this sub-unit are laminations, thin-thick bedding and massive bedding (mainly in colonial organism bearing layers).

Petrographically this upper unit shows the dominance of micritic and bioclastic wackestone textures (MFT9, 10) of outer ramp, which contains small amounts of skeletal like ostracods, echinoderms, foraminifers, bivalves, sponges and etc. Diagenetically most of the samples collected from this sub-unit show the compactions features, silicification, and marine and burial cementations. The colonial and carbonate buildup bearing parts are most probably deposited under local shallow marine part, which may be formed as a result of local uplift within this basin. The age of this upper sub-unit is Kimmeridgian.

6.6. Correlation

Presently studied Dire Dawa area carbonate units (Antalo Limestone) have been correlated with some of the chronostratigraphic equivalents and lithologically similar deposits, identified by many workers from some proximal area of SE Ethiopia plateau and within other basins (like; Mekele basin, Blue Nile basin and Ogaden basin (of Ethiopia) and Sana'a basin (of Yemen)). These correlation pictures are given in (fig.6.3 and 6.4 respectively).

6.6.1. Correlations with some studied sections of SE Ethiopia

Mesozoic deposits in the SE parts of Ethiopia, in some local area and sections like Harar, Sof Omer, Kuni and Gara Muleta are correlable with the present studied units (fig. 6.3.). These all area is located to South east of the present study area, at different distances, within Hararge region of Ethiopia, the same as that of present study area.

According to Greitzer(1970) the Mesozoic deposits of Harar region from bottom to top includes: Lower Sandstone(Bajocian), lower limestone and upper limestone(Bathonian-Oxfordian), Brown limestone and Dogou limestone(Kimmeridgian age) and upper sandstone(Aptian-Albian age). From these deposits, the Lower and upper limestones are equivalent to Lower and middle subunit of the present study area, whereas, the Brown limestone and Dogou limestone are equivalents to upper subunit of the present studied carbonate unit. The lower and the upper sandstone layers are equivalents of Adigrat and upper sandstones of our area respectively.

From the microfacies analysis study of Turi et al. (1980) on Sof Omer, Kuni, Hirna and Gara Mullata sections, we get the lithology and age information's of carbonate units of these sections. The correlation was made for each of this section with respect to age and lithology, with the present study area carbonates as follow:

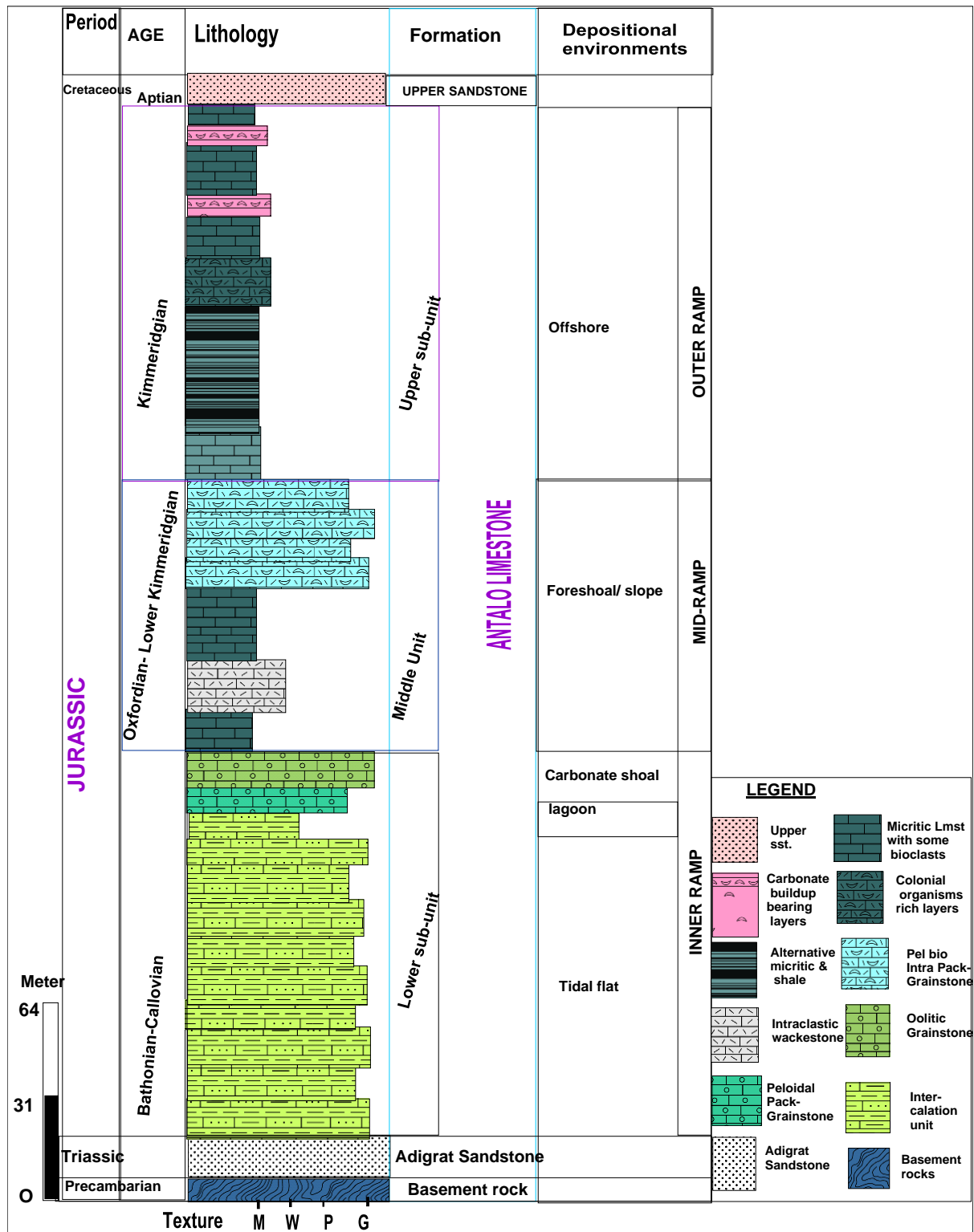


Figure 6.2. Composite stratigraphy of Dire Dawa area rock units, with detail age, lithology and depositional environments for the Carbonate units of the area.

At Sof Omer section, they identified about 120m thick limestone layers which has lower thick part of whitish dolomitic layers (followed by calcarenite, calcisiltite and calcilutite) and middle yellowish dolomitic limestone with some microfossils (Callovian-oxfordian) and an

upper part dominated with pale brown calcareous dolomite(Kimmeridgian-Tithonian). From these, the lower and Middle parts are correlable with Middle unit of the present study area and the upper part is with the upper unit. At Kuni section, Antalo lime stone overlies Adigrat Sandstone(which is correlable with the same formation of the present area)and its mainly made up of calcarenites with less amounts of calcisiltite and calcilutite, often extensively dolomitized and its age is Bathonian to oxfordian which is correlable with Lower and Middle unit from my study area. At Hirna section, Antalo limestone of about 270m thick, which is made up of calcarenites, calcisiltite and calcilutite, sometimes dolomitized are overlain by calcareous sandstone,wich in turn overlain by volcanites are Callovian to Kimmeridgian age. Accordingly the lower and upper parts of this area are correlable with middle and upper unit of my study area.

At Gara Mullata section, Antalo limestone overlies Adigrat sand stone, the lower part of Antalo limestone is made up of alternating layers of limestone, dolomitic limestone, calcareous dolomite and dolomite, at times marly. The middle and upper part of the unit consists of calcarenites, calcisiltite and calcilutite and overlain by upper sandstone. The age of this Antalo Limestone Formation ranges from Bathonian to lower Kimmeridgian. Accordingly these all Antalo limestone parts are correlable with lower, middle and upper carbonate subunits of our present study area.

6.6.2. Correlation with sections of other basins

Early Jurassic – Oxfordian time major transgressions, probably 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 in different basins (Bosellini, 1989; Russo et al. 1994,). Among these, carbonate deposits in Ethiopia can be best examples.

Particularly, extensive carbonate deposits are exposed in three regions in Ethiopia: the Mekelle Outlier in the North (Tigris), the Blue Nile Basin in central Ethiopia and the Ogaden Basin (including Western Hararge region and Dire Dawa area) in the Southeast. But there are scarcity of detail carbonate microfacies works on these carbonate rocks to do detail microfacies correlations throughout all these basins. Now, only the general chronological and lithological correlation among Jurassic deposits within those major basins of Ethiopia (Mekele basin, Blue Nile basin and Ogaden basin) and the Sana'a basin of Yemen(due to its proximity and easily correlable) with the present study area carbonate deposits were attempted in this work, as given in (fig.6.4), and described in the following sections.

In the Mekele basin of Ethiopia, the carbonate deposits known by the name 'Antalo Limestone' were described in detail by Levitte(1970), Beyth (1972a, b), and Bosellini et al. (1997). The thickness of the succession ranges from 300 m in the West to 800 m in the East. Beyth (1972a, b) identified four facies for this unit. Those are (i) a cross-bedded sandy oolite and coquina with minor amount of marl and a few chert beds, with microfauna including mainly corals, gastropods, and echinoids, (ii) interbedding of marl and lithographic limestone with abundant brachiopods and some algal and chert beds, (iii) cliffs of coral and algal reef limestones interbedded with marl and biostromes, and (iv) black to grey microcrystalline

limestone interbedded with marl. Bosellini et al. (1997) attempted to subdivide the same limestone unit into four depositional sequences (A1 to A4), which are composed of thickening and shallowing up cycles and also he noted that the limestone succession was deposited in a homoclinal ramp or on a wide cratonic margin gently dipping to the southeast and they assigned the age of this Antalo limestone to be Late Callovian to Kimmeridgian age. Accordingly, the Antalo limestone of the Mekele basin is correlable more with the middle and upper subunit of the present studied carbonate unit of Dire Dawa area. There is no correlable limestone unit for the Lower subunit of the present studies in Mekele basin, i.e. during the Bathonian time the flooding was not reached the Mekele area of Ethiopia. .

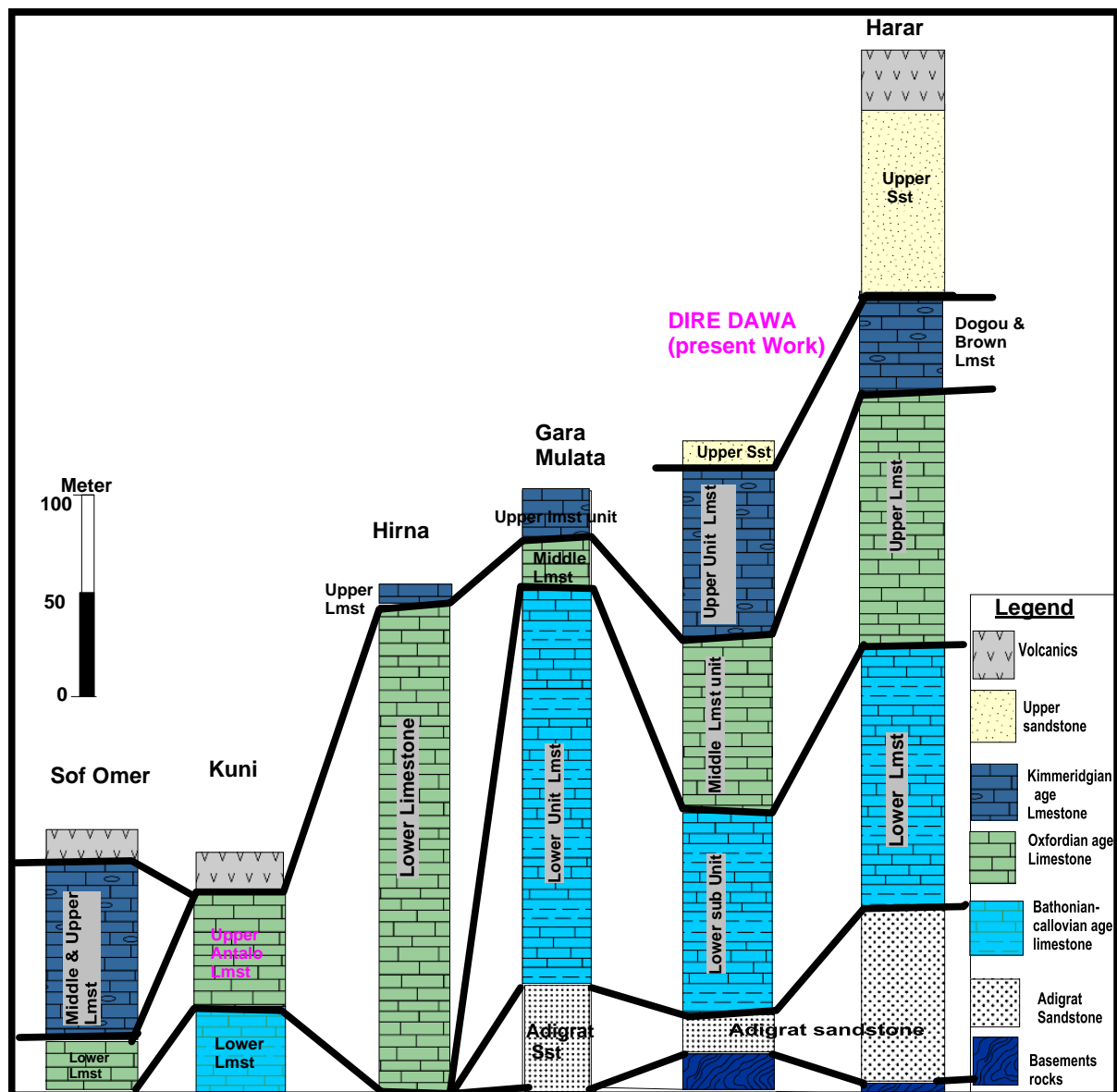


Figure 6.3. Mesozoic stratigraphy correlation between some areas from SE Ethiopian plateau. Sources: Sof Omer, Kuni, Hirna and Gara Mulata (from Turi et al., 1980), Dire Dawa area (from present work) and Harar from Greitzer (1970).

In Blue Nile (Abay) basin of Ethiopia, about 420 m thick carbonate succession, also called 'Antalo Limestone' are described by Russo et al. (1994). This succession is found conformably overlying the Gohatsion Formation and it can be generally subdivided into three parts; lower, middle and upper limestone/Antalo. 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 interbedding of marly limestone, marls and silty limestone. A shelf to open marine environment was inferred based on the presence of some ammonites, Terebratuline associated with *Nanogyra*, rhynchonellid brachiopods and infaunal siphon-feeders (by the same author). The upper part reaches a thickness of 50m. 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 (*Pfenderina sp.* and *Nautiloculina oolithica*) at the base of the Antalo Limestone suggests Callovian age (Russo et al. 1994). While the occurrence of *Kurnubia palestiniensis*, *Parurgonina caelinensis*, *Conikurnubia sp.* and *Salpingoporella annulata* at the top of the unit indicates a Kimmeridgian age.

Based on the age concern and the facies successions described above the lower and middle part of this Abay basin limestone is more or less correlable with the middle subunit of our study area, while as the upper part is probably correlable with the upper sub unit of the present area by the age concern, but there is no oolitic and observable reefal limestone layers are identified from our area during the current work, those are identified from that of Abay, which make this upper to upper correlation questionable. But in other ways, even though there are no feasible reefal units, there are undifferentiated carbonate buildup bearing limestone layers observed at Dachatu river section (in upper subunit), during the present study that may support this correlations of upper part upper subunit in other way.

In Ogaden basin, as pointed out by Abbate et al. (1974) a threefold Jurassic partition is present overlying the Adigrat sand stone (from below) : Lower, Middle and Upper Hamanlei Formations represent an Early Jurassic to Callovian syn-rift marine sequence, and consist of the following lithologies: limestone with intercalated shales (in the lowermost section); anhydrite, dolomite and limestones with local oolitic and stromatolitic beds (in the middle section); and bioclastic oolitic limestones (in the uppermost section). The Uarandab Formation corresponds to the maximum flooding sequence deposited during the break-up transgression (Callovian- Oxfordian), and is composed of dark, laminated marls and limestones containing a pelagic marine fauna. The Gabredarre Formation (Upper Jurassic) represents a passive-margin sequence comprising bioclastic, locally oolitic and reefal limestones; these limestones were deposited in offshore bars and small reefal build-ups. Based on various fossils obtained from them the age of lower Hamanlei (Hettangian- Pliensbachian), middle Hamanlei (Pliensbachian-Bajocian), upper Hamanlei (Bajocian-callovian), Urandab Formation (Oxfordian), Gabre Darre (Kimmeridgian- Tithonian) and

Gorrahei formation (Berrisian-Albain) were assigned respectively by Shigut(1998). From these sequences, there is no carbonate correlative for lower and middle Hamanlei Formation; they are most probably correlable with the Adigrat sandstone Formation of our study area. These shows that the first flooding the Ogaden basin before that of Dire Dawa area. The upper Hamanlei Formations is correlable with the lower subunit of carbonate of the Dire Dawa area , Urandab Formations are correlable with the middle unit of the present area and the Gabre Darre Formation are more correlable with the upper subunit of the carbonates of the present study. Overlying all this limestone unit the Main Gypsum (lower cretaceous) and Gumburo Group (Mustahil Limestone, Ferfer Gypsum, Belet Uen Formation and Yesomma sandstone all upper cretaceous in age) unconformably follow, as well as the Dire Dawa area carbonates are also truncated by Upper Sand Stone Formation unconformably. In Ethiopia, overall regression was thought to prevail during latest Jurassic (Tithonian) and Berriasian times (Assefa, 1991, Schimidt and Werner 1998) which terminate carbonate deposits. Throughout most part of Ethiopia clastic deposits overlies carbonate units starting from this time. Siliciclastic deposits in the central Ethiopia (Blue Nile Basin) were interpreted to be deposited in a fluvial environment during this time and also coeval sandstone deposits have been described from Danakil and Mekelle area, Northeast Ethiopia.

In the **Sana'a basin of Yemen**, which found at North direction from Ethiopia country , according to the work of Al-Thour(1997), the Jurassic carbonate deposits known by 'Amran Group' are conformably overlaying the lower clastic deposits known by the name 'Kohlan Formation' and unconformably underlies the upper clastic deposits called Tawilah Group. These Jurassic carbonates, Amran Group, are varying between 410-520m in thickness and subdivided into three formations. From the base to tops are: 1)Al- Khothally Formation(late Callovian-oxfordian age): it consists of sandy, oolitic, oncolitic, peloidal, partly dolomitic, massive, thick limestones and at base overlies either disconformably on the Kohlan Formation or unconformably on the Precambrian basement rocks. 2)Raydah Formation(Early Kimmeridgian age): shows varies lithologies like: massive, cherty, fossiliferous, bituminous grainstone, packstone, wackestone, mudstone, marly fossiliferous and at top massive mudstone with echinoids, stromatoporoids and corals.3) Wadi Al-Ahjur Formation(late Kimmeridgian age): consists of several carbonate intervals which are mudstone, wackestone, packstone, grainstones intercalated with sandy dolomitic marly shale, fossiliferous and partly silty limestones. This formation is unconformably overlain by cretaceous Tawilag Group.

Even though they shows some difference in the age extensions, the overall Mesozoic deposits of this Sana'a area are highly correlable with that of the present study area, in which the Precambrian basement rocks are unconformably overlaid by Adigrat Sandstone Formation (equivalent to the Kohlan Formation of Yemen), which in turn conformably overlaid by the carbonate deposits of Antalo Limestone Formation (equivalent to the Amran Group) topped unconformably by the cretaceous deposit of Upper Sandstone(equivalent to Tawilah Group of Yemen). In detail correlations, from the Amran Group of Sana'a area, the Al- Khothally Formation (late Callovian-oxfordian age) is correlable with the Lower and middle carbonate sub-units of our study area in both age and lithologies, with little variations.

Whereas, the Raydah Formation (Early Kimmeridgian) and Wadi Al-Ahjur Formation (late Kimmeridgian age) are equivalents to our Upper sub unit in terms of age.

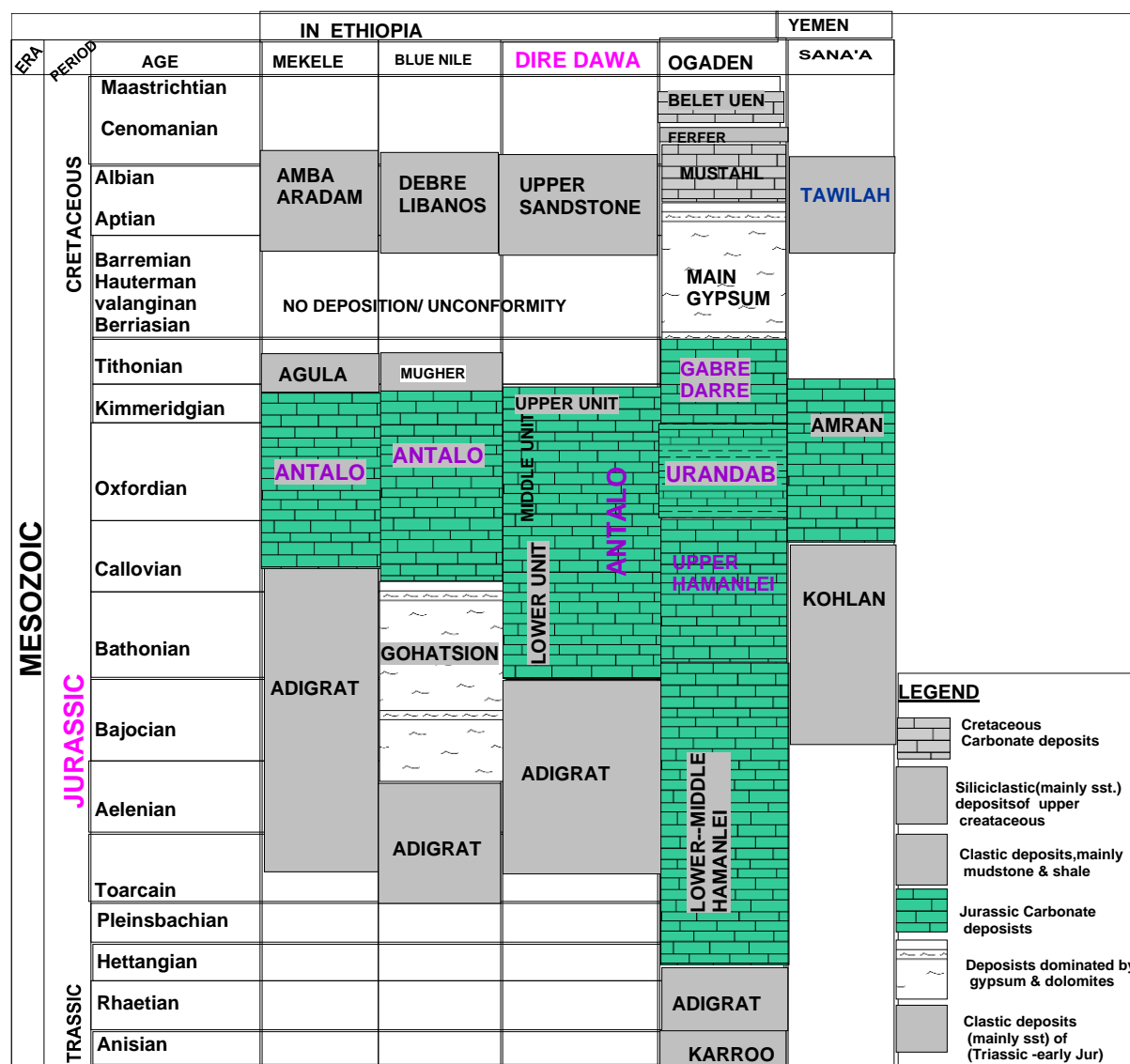


Figure 6.4. Mesozoic stratigraphy correlation throughout Mekele, Blue Nile, Dire Dawa area and Ogaden (from Ethiopia) and Sana'a (from Yemen) basins. Sources: Mekele (Levitte, 1970; Beyth, 1972a & b; Bosellini et al., 1997), Blue Nile (Russo et al., 1994), Dire Dawa area (from present work for Antalo limestones and other workers cited in texts for the Adigrat and Upper Sandstones ages), Ogaden (Abbate et al., 1974; Shigut, 1998) and Sana'a (Al-Thour, 1997).

6.7. Sea level fluctuations and paleogeographic setting

There are two overriding controls on carbonate sedimentations: (1) geotectonics and (2) climate. The geo-tectonic context is of paramount importance. It controls one of the prime requisites for carbonate sedimentation, the lack of siliciclastic material inputs, by determining hinterland topography and drainage. Geotectonics controls the orientation of shorelines and platform-shelf margins, rates of subsidence and uplifts, which also affect sea-level transgressions and regressions, and the location of positive and negative areas.

Climate determines the energy level and direction of wind-waves, storm and tidal currents, as well as the circulation pattern and location of upwelling, nutrient-rich zones. Both geotectonics and climate control the position and fluctuations of sea-level. This is of great significance to the production of carbonate sediment and the resulting facies mosaic.

From the present field investigations and data analysis, the Mesozoic deposits of Dire Dawa area start at its base with clastic units (of Triassic age), which pass gradationally to the thick carbonate successions overlying it. These carbonate deposits shows some deepening of facies toward East/South East throughout the area, this shows that, the Mesozoic sedimentation in the area started with the marine transgression in Triassic from South-Eastern side of the area or of Ethiopia in general. This match with the idea of other workers those saying, due to eustatic sea-level rise in the Mesozoic, Indian Ocean transgressed over gently sloping platform (Somalia, Ethiopia and part of Sudan). There was an abundant clastic supply in Triassic, when sea-level was rising, as well as in Early Cretaceous, when sea-level was falling, which produced two sandy successions, identified throughout Ethiopia and neighbouring countries(Bosellini,1989). These clastic deposits are also observed from the present study area as Adigrat Sandstone Formation, from lower and Upper Sandstone Formation from upper respectively. Whereas during Jurassic, time ,when sea-level was at its acme, clastic supply became negligible (as it was restricted in coastal area), a carbonate dominating succession, sandwiched between these two sandy successions, formed, those can be represent thick carbonate units from our study area.

The carbonate unit of the Dire Dawa area documents the flooding of the East Africa craton. The Jurassic sea reached Dire Dawa area in late Bathonian, which is age of lower sub-unit of carbonate unit of this area, producing thin layers of cyclic limestone and sandstone at its base, indicating continuation of relatively limited accommodation space and repeated withdrawals of the sea during this initial stage of the marine flooding.

The lower and middle sub-units of Dire Dawa area carbonate represent second order cycle (mega sequence), involving a longer time span, from late Bathonian to late Oxfordian, possibly related to the separation of India from Africa and the contemporaneous subsidence of East Africa. These units composed of several cycles of shallowing-up carbonate facies at bases, which shows small scale change in sea levels.

In the upper unit of carbonate of the area major flooding and associated deepening was documented by the thin bedded and cherty black micritic limestone layers, at bottom of this upper sub-unit. The clastic shale and black dark micritic layers of this upper part represents maximum sea level achievements during their depositions (at lower Kimmeridgian time), this stage may correspond to the eustatic sea level-rise related to the separation of Madagascar from Africa.

The colonial organisms and carbonate buildup bearing limestone layers at top part of this upper subunit are most probably the result of local tectonic uplift, favouring their depositions, under shallow water conditions, and also there are some reefal carbonate units reported from

outer ramp deposits by many workers, for which these undifferentiated carbonate buildup layers can represent such example in our area, even though they are not clear enough to say reefal layers.

After all the carbonate deposits of Dire Dawa is truncated by fluvial clastic deposits (Upper Sandstone units) at top, and showing that major tectonic events uplifting of Ethiopian and neighbouring regions to subaerial conditions starting early Cretaceous and sea retreated away.

Palaeographic setting

In general for the paleogeographic setting, when we look at the major carbonate deposits throughout NE-Africa and neighbouring areas, carbonate deposits 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 composed of parts of Africa, Madagascar, India and Arabia (Bosellini et al., 1997; Bosellini, 1989) and according to the general stratigraphic relationship it seems very likely that carbonate deposits was deposited on a homoclinal ramp (Bosellini 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 dissecting 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 (the beginning of carbonate deposition) 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.

For indicating paleogeographic setting for the carbonate deposits of the study area, the time between middle Jurassic (Late Bathonian, the age of lower sub-unit of the present studied carbonate units) to late Jurassic, Kimmeridgian (the age of upper sub-unit) will be essential times, since there is no unconformity throughout the unit, these both end times can help to show the whole unit depositional conditions. Based on the available previous works on the paleogeography of the NE-Africa we have selected the early – middle Jurassic (Toarcian-Callovian) and late Jurassic (Kimmeridgian) times intervals between which our study area carbonate deposits were formed. The paleogeographic maps of NE-Africa and Arabian platforms during the early Jurassic (Toarcian time) and late Jurassic times were given in (figure 6.5 and 6.6) respectively, those can show the palaeographic conditions in Ethiopia and some surrounding areas, during the depositions of this carbonate units.

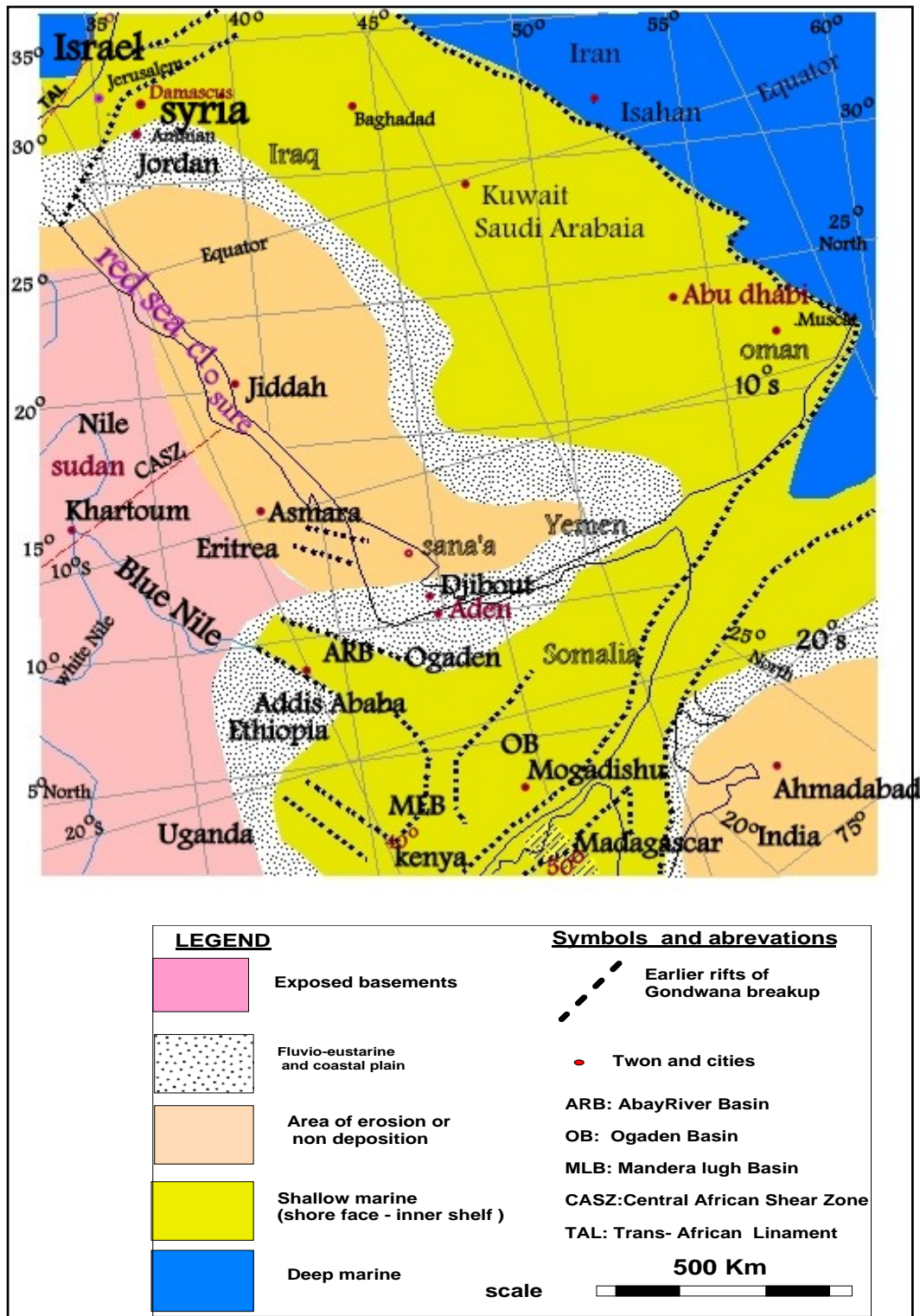


Figure 6.5. Early Jurassic (Toarcian) time palaeogeographic map of NE- Africa and the SE part of the Arabian platform (modified after Reynolds et al. 1997).

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 encroached from the Northeast onto wide areas of the Arabian platform and propagated as far

Southeast as central Ethiopia. During which shallow marine clastic of Adigrat sandstone formation deposit formed, in Ethiopia and other neighbouring country.

Along the East African margin rifting occurred again during the early Jurassic superimposed on the older Karoo structures, heralding this time 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. Furthermore, the NE-inclined depositional dip was inverted towards the southeast, i.e. towards the developing rift between East and West Gondwana. Active rift subsidence enhanced by eustasy resulted in a marine transgression, which flooded wide areas of East Africa and the Arabian platform.

The lower part of present studied Dire Dawa area carbonate deposits of Bathonian to Callovian age, which showing some shallow marine depositional conditions and shallowing up facies are most probably indicate that as the middle Jurassic sea reached the Dire Dawa area during this time. Also deposits of the same age are reported from other area like, the Blue Nile Basin Antalo limestone Formation; middle Hamanlei carbonate deposits of Ogaden basins and Amran Group of Sana'a (Yemen) are most probably the result of these transgressions.

During the Late Jurassic (Kimmeridgian) time, the northeast propagation sea to the Arabian platform was largely complete. On the regional scale platform was still a shelf, showing weak structural differentiation that was predominantly covered by a very shallow sea.

Initial formation of Indian Ocean occurred between middle and late Jurassic. Following a long period of crustal extension and rifting, break-up of Gondwana commenced in late Jurassic and a seaway began to open contemporaneously in southern Gondwana between south America-Africa and Antarctica. In northern Gondwana a seaway opened up and extends from the Tethys towards the south where its shoreline reached southern Madagascar. It's also time-transgressive and corresponds to an abrupt deepening of East Africa and Southern Arabia shallow water ramps and carbonate platforms, a collapse most probably related to the separation of Madagascar from Africa, a major tectonic event occurred in early Cretaceous from northern Ethiopia to Yemen and Southern Ethiopia and Somalia.

This propagated sea on the horn Africa during late Jurassic is also recognized by the different carbonate units, throughout the continents in various basins. From these, the upper sub-unit of the present studied Dire Dawa area carbonate, which are Kimmeridgian age, are showing that during late Jurassic the area was covered by the sea. The equivalent carbonate units are also reported from Ogaden basin, Mekele basin, Blue Nile basins of Ethiopia and Sana'a basins of Yemen as the workers are cited above in the correlation sections. The total paleogeographic map showing the extent of the sea on NE-Africa during late Jurassic is given in (figure 6.6).

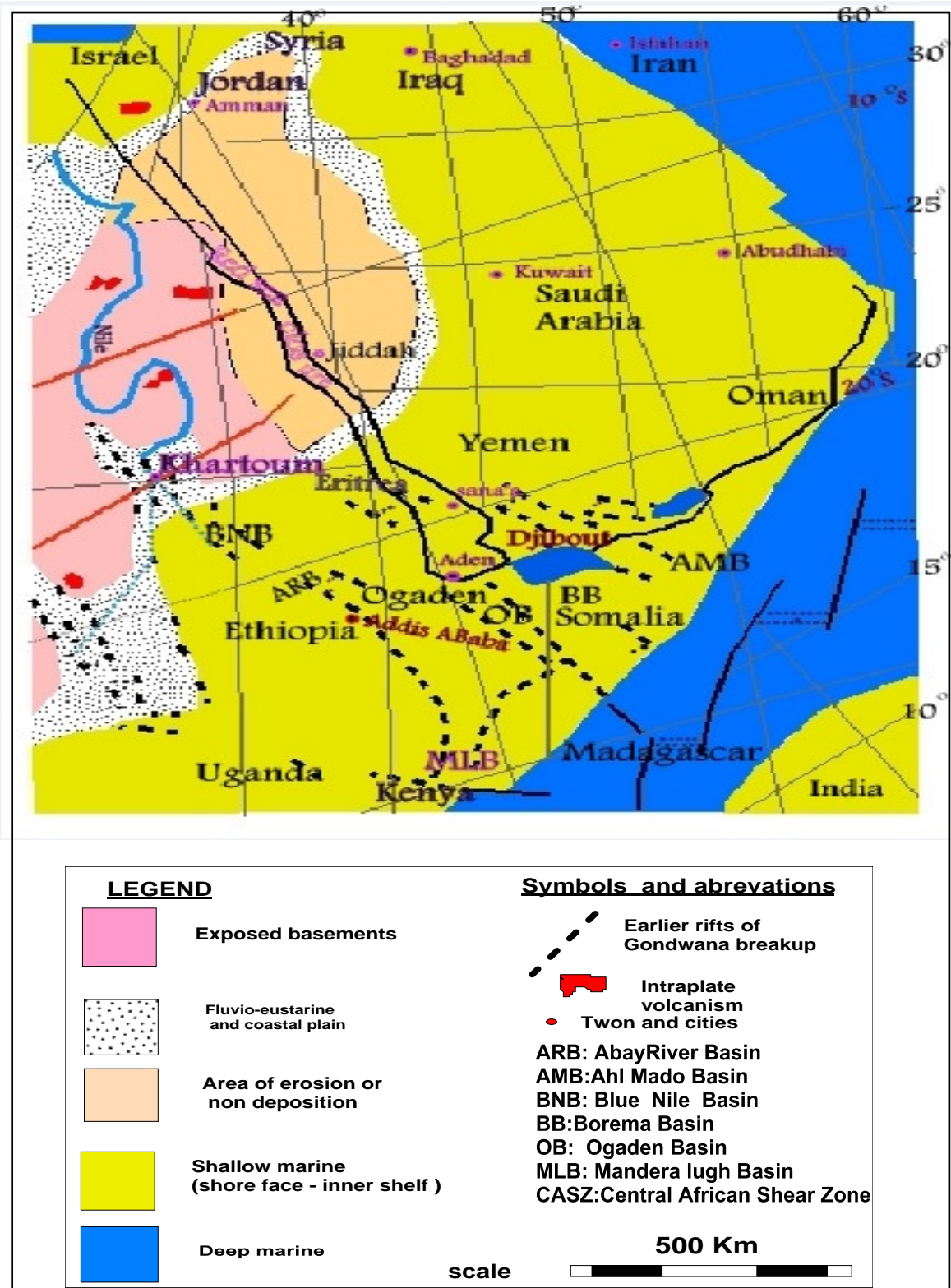


Figure 6.6. Late Jurassic (Kimmeridgian) time palaeogeographic map of NE-Africa and the SE part of the Arabian platform (modified after Reynolds et al. 1997).

Chapter 7: Conclusions and Recommendations

7.1. Conclusions

Based on the present field investigations; stratigraphic, petrographic and microfacies analysis on the Jurassic carbonate succession of Dire Dawa area, SE Ethiopia, the following conclusions were adopted:

Stratigraphically, about (~306m) thick 'Bathonian-Kimmeridgian; age carbonate successions (Antalo Limestone Formation) are overlying the lower Adigrat Sandstone Formation conformably and topped by Upper Sandstone Formation unconformably throughout the area. These carbonate successions are again subdivided into lower, middle and upper sub-units, from bottom to top, based on their lithological characteristics, faunal and floral contents, facies patterns and stratigraphic positions. Lower sub-unit: is about (~119 m) thick, conformably overlies the Adigrat Sandstone Formation below it and consists of mixed carbonate and siliciclastic facies at bottom, and, peloids and coarser oolitic rich grainstone massive beds of limestone at top part. It has rare fossils of bivalves, gastropods and aged to be Bathonian-Callovian by occurrence of *Pfenderina trochoidea-salernitana*. Middle sub-unit: about (~84m) thick unit, conformably overlies the lower unit and consists of dolomitized and cavernous micritic facies with rare patches of colonial organisms; intraclastic wackestone facies; and, skeletal, peloidal and intraclastic dominated packstone-grainstone limestone beds of varying thickness. This unit has various fossils like; Molluscs, echinoderms, forams and dated to be Oxfordian-lower Kimmeridgian by occurrence of *Kurnubia palastiniensis*. Upper sub-unit: under lied by the middle unit conformably and overlaid by Upper Sandstone unconformably. It consist of thick beds of dark micritic limestones, with intermixing of clastic shale and silicified layers at bottom part and, silicified remains of colonial organisms and carbonate buildup bearing limestone layers at top part. It's Kimmeridgian in age, according to its stratigraphic position.

As revealed from the petrographic analysis diagenetically these thick carbonate successions of the area are affected by various diagenetic processes with varying intensities and occurrence throughout the area. The diagenetic sequence are as follow: micritization dissolutions, dolomitization, early marine cementations, meteoric calcite cementation, mechanical and chemical compactions those followed by fractures and stylolitization, silicification and burial cementation, when listed from early stage to the late stage of diagenesis.

From the detail microfacies analysis of the representative rocks samples collected from the carbonate succession of the area, about 10 major microfacies types (MFT 1-10) were identified, those are designated as : MFT(1) mixed siliciclastic and carbonate microfacies, 2) Dolomitized micritic microfacies, 3) peloidal grainstone microfacies, 4) Oolitic microfacies, 5) peloidal wackestone microfacies, 6) bioclastic intraclast grainstone microfacies, 7) bioclastic intraclast packstone microfacies, 8) bioclastic peloidal grainstone microfacies, 9) bioclastic wackestone microfacies, and 10) micritic microfacies. Each of this

microfacies were described, interpreted and also compared with SMFT and FBs of Wilson (1975). For generalization these 10 microfacies were compared with facies belts of Wilson (1975), ranging from open sea to restricted platform (2-8, except 5) from top to bottom, as their detail respective matching were given in microfacies analysis sections.

Based on the various skeletal and non-skeletal sediment obtained and the dominating depositional processes, the carbonate deposits of the study area shows the depositions under shallow marine conditions for the lower and middle sub-units and some offshore (marginal basin to open sea) depositional conditions for the upper sub-units.

Generally the carbonate microfacies and facies successions of the area shows deposition on ramp carbonate depositional setting, under which various sub-depositional environments ranging from shore line carbonate deposits (including low energy platform interiors (of tidal flat and lagoon) and high energy platform margin carbonate sand bodies) of inner ramp, foreshoal/ slope deposits of mid-ramp to the offshore deposits (basin margins/ open sea) of outer ramp deposits, from bottom to top.

The presence of intermixed clastic layers, peloids, skeletal grains with micritic envelop and ooids grains facies, obtained from lower subunit of carbonate deposits of the area indicates the shallow marine depositional conditions of inner ramp. The facies successions in this inner ramp also shows the shoreline tidal flat and lagoonal sub-depositional environments of low energy in platform interior and the existence of oolitic sand bars of high energy environments at carbonate platform margin respectively at this lower part.

The dominances of various larger skeletal grains and non-skeletal grains (like peloids, intraclasts and rare ooids) within wackestone to grainstone microfacies, reworked carbonate sediments, smaller breccias and some local smaller patches of colonial organisms identified throughout the middle sub unit of the carbonate deposits of area indicates the depositions under shallow marine conditions in Foreshoal/slope area of mid ramp depositional environments.

The dominance of fine-grained dark micritic carbonates grains with some skeletal grains within bioclastic wackestone and micritic microfacies, and presence of intermixing layers of clastic shale and cherts with the micritic limestone beds throughout the upper subunit of the carbonate deposit of the area indicates the deposition under low energy offshore conditions of outer ramp for this upper sub-unit. Except the existing of the local undifferentiated colonial organisms and carbonate buildup bearing layers at top part of this upper subunit, those shows shallow marine conditions, again those deposits of outer ramp.

Carbonate deposits of the area 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 outer ramp carbonate facies of upper parts are overlying the more shallower marine carbonate facies deposits of middle and lower units, those in turn the overlies fluvatile deposit of Adigrat sandstone units below them. These transgression pattern is interpreted as, most probably the results of the breakup of Gondwanaland starting from the

early Mesozoic time , which produce wide spread transgressions and extensional deformation on all horn of Africa and Early Jurassic – Oxfordian time major transgressions, probably 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 in different basins, for which the present carbonate rocks can be an example.

The Lower and Middle sub units of Dire Dawa area carbonate represent second order cycle (mega sequence), involving a longer time span, from late Bathonian to late Oxfordian, possibly related to the separation of India from Africa and the contemporaneous subsidence of East Africa. These units composed of several cycles of shallowing-up carbonate facies, which shows small scale change in sea levels. In the upper unit of carbonate of the area major flooding and associated deepening was documented by the thin bedded and cherty black micritic limestone layers, at bottom of this upper this subunit. The clastic shale and black dark micritic layers of this upper part represents maximum sea level achievements during their depositions (at lower Kimmeridgian time), this stage may correspond to the eustatic sea level-rise related to the separation of Madagascar from Africa.

Lastly the Dire Dawa area carbonate deposits are correlable with some of the chronostratigraphic equivalents and lithologically similar deposits of some proximal area of SE Ethiopia plateau (Harar, Sof Omer, Kuni and Gara Muleta), and within other basins (like Mekele, Blue Nile and Ogaden (of Ethiopia) and Sana'a basin (of Yemen).

7.2. Recommendations

The present study more or less tried to cover and reveal Dire Dawa areas' carbonate rocks microfacies analysis, depositional environment interpretations and age, based on the selected stratigraphic sections. But, the following recommendations were given for further works beyond the present works, for additional values:

Since the carbonate successions of the area are very extensive laterally, even so many kilometres out of the present study area, they may contains more interesting information's to give overall lateral and vertical facies associations, facies models and facies geometries and age for these deposits, and may contain natural resources like hydrocarbons, so detail works on numbers of lateral and vertical stratigraphic sections surrounding the present study area is recommended.

The carbonate deposits of the area comprises so many varieties of skeletal grains; those can reveals so many interesting information's for Palaeoclimate and paleoenvironmental studies . Due to this the detail biostratigraphy and paleontological works over there area will be more than worthy.

According to the present field observations, the tectonic disturbance throughout the area was paramount. Therefore, the detail structural analysis works in the area will be useful.

8. References

- Abate, E., Ficarelli, G., Pirini Radrizzana, C., Salvietti, A., Torre, D. & Turi, A. (1974). Jurassic sequence from Somalia east of the Gulf of Aden. *Riv. Ital. paleont. stratigr.* **80**, 409-478, Milano
- Adams, A.E. and Mackenzie, W.S. (1998). *A colour atlas of carbonate sediments and rocks under microscope*. Manson publishing, London, 179 pp.
- Ahr, W. M. (1973). The carbonate ramp; an alternative to the shelf model. *Trans. Gulf-Cst Ass. geol. Socs* **23**, 221-25.
- Ahr, W. M. (2008). *Geology of carbonate reservoirs: the identification, description, and characterization of hydrocarbon reservoirs in carbonate rocks*. John Wiley & Sons, Inc., Hoboken, New Jersey, 296pp.
- Al-Thour, K. A. (1997). Facies sequences of the Middle – Upper Jurassic carbonate platform (Amran Group) in the Sana's region, Republic of Yemen. *Marine and Petroleum Geology*, Vol. **14**, No. **6**: 643 – 660 pp.
- Assefa, G. (1988). Potential hydrocarbon-generating rock units within the Phanerozoic sequence of the Ogaden Basin, Ethiopia: a preliminary assessment using the Lopatin model. *J. Petrol. Geol.* **11**: 461–472.
- Assefa, G., (1991). Lithostratigraphy and environment of deposition of the Late Jurassic–Early Cretaceous sequences of the central part of the Northwestern Plateau, Ethiopia. *N. Jb. Geol. Paläont. Mh.* **182**: 255–284, Stuttgart.
- Asrat A. , Baker A., Leng M.J., Gunn J. and Umer M. (2008). Environmental Monitoring in the Mechara caves, South-eastern Ethiopia: Implications for Speleothem Palaeoclimate Studies. *International Journal of Speleology*, **37** (3), 207-220. Bologna (Italy). ISSN 0392-6672.
- Atnafu, B. & Kidane, T. (2012). Age estimation of the deposition of the Cretaceous Upper Sandstones and a later remagnetization event, from Hirna area, SE Ethiopia. *Phy. Earth. Pla. Int.* **190-191**: 15–24 pp.
- Ayers, F.M. (1952). Geology of the Wajir-Mandera district. Geological survey Kenya, unpublished report 25. Kenya.
- Berhe S.M. (1985). Geological map of Dire Dawa sheet at the scale of 1:250,000, Ethiopian institute of Geological survey; ministry of mines, unpub. report, Addis Ababa.
- Beyth, M. (1972a). To the Geology of Central-Western Tigre. Ph.D. thesis, Friedrichs Wilhelms Universität, Bonn.
- Beyth, M. (1972b). Paleozoic–Mesozoic sedimentary basin of Mekele Outlier, Northern Ethiopia. *AAPG Bull.* **56**: 2426–2439.
- Beyth, M. (1973). Correlation of Palaeozoic–Mesozoic sediments in Northern Yemen and Tigre, Northern Ethiopia. *AAPG Bull.* **57**: 2440–2443.
- Blanford, W.T. (1869). On the Geology of a portion of Abyssinia. *J. Geol. Soc. Lond.* **25**: 401–406.
- Blanford, W.T. (1870). Observations on the Geology and Zoology of Abyssinia made during the British Expedition to that country in 1867-68. With Illustrations and a Geological Map. London: Macmillan & Co.
- Bosellini, A. (1989). The continental margins of Somalia: their structural evolution and sequence stratigraphy. *Mem. Sci. Geol.* **41**: 373–458. Ferrara, Italy.
- Bosellini, A. (1992). The continental margins of Somalia. Structural evolution and sequence stratigraphy. *American Association of Petroleum Geologists, Memoir* **53**,
- Bosellini, A. (1999). Stratigraphic evidence for an Early Aptian sea-level fluctuation: the Graua Limestone of southeastern Ethiopia. *Cretaceous Res.* **20**: 783–791.

- Bosellini, A., Russo, A., Fantozzi, P. L., Assefa, G. & Solomon, T. (1997). The Mesozoic succession of the Mekele outlier (Tigre Province, Ethiopia). *Memorie di Scienze Geologiche* **49**, 95–116.
- Bosellini, A., Russo, A. and Assefa, G., (2001). The Mesozoic succession of Dire Dawa, Harar province, Ethiopia. *Journal of African earth science*, **32**, no 3, pp. 403-417.
- Brain, J. and Andre, D. (1992). Shallow platform carbonates .In Walker R.G & James, N.P. (eds.), *Facies Models: Response to Sea Level Change*: 219–238. St John's: Geological Association of Canada, Canada.
- Burchette ,T.P. and Wright, V.P.(1992). Carbonate ramp depositional systems. In B.W. Sellwood(ed), *Ramps and Reefs. Sediment.Geol.*,**79**: 3-57, Elsevier Science publishers B.V.,Amsterdam.
- Chiocchini, M. and Mancinelli, A., (2001). Sivasella monolateralis SIREL and GÜNDÜZ, 1978 (Foraminiferida) in the Maastrichtian of Latium (Italy). *Revue de Micropaléontologie*, **44**: 267-277
- Coffin, M.F. & Rabinowitz, P.D. (1988). Evolution of the conjugate East African Madagascan margins and the western Somali Basin. *Geol. Soc. Am. Spec. Paper.* **226**: 1-78.
- Dawit E. and Bussert R., (2009).Stratigraphy and Facies architecture of Adigrat sandstone, Blue Nile basin,central Ethiopia. *Zbl.Geol.Palaont.Teill heft3/4*,217-232pp, Stuttgart.
- Dawit L. (2010). Late Triassic – Middle Jurassic Siliciclastic Sediments (‘Adigrat Sandstone’) in Northern and Central Ethiopia: Stratigraphy, Facies, Depositional Environments and Palynology. Technische Universität Berlin, PHD. Thesis,162p.
- De castro, P.(1987). Le facies di piattaforma carbonatica del Giurassico italiano: diffusione areale e lineamenti biostratigrafici. *Bollettino Societa Paleontologica Italiana*, **26**: 309-25.
- Dunham, R.J. (1962). Classification of rocks according to their depositional texture. IN (W.D.Ham. (ed).) *Proceedings of Classification of carbonate rocks. Amer.Assoc.Petrol.Geol.Mem.*, 1: p. 108-121.
- Ethiopian Ministry of mine, (2009). Report on investment opportunities in limestone resources development of Ethiopia by promotion team. unpublished report. Addis Ababa.
- Ethiopian Ministry of mines, (2011a).Mining journal special publication-Ethiopia. Un-published report, Addis Ababa.
- Ethiopian Ministry of mines, (2011b). Petroleum potential of Ethiopia. Un-published report. Addis Ababa.
- Ficcarelli,G.,Pirini Raddrizzani,C., Turi,A.(1975). Analysis of the microfacies of Antalo limestone in Dire Dawa area, Ethiopia. *Bolletini societa Geologica Italiana* **94**:759-770
- Flugel, E., (2004). *‘Microfacies of Carbonate Rocks Analysis, Interpretation and Application’*,Germany, Springer-verlag, Berlin Heidelberg, pp.996.
- Folk, R. L. (1962): Spectral subdivision of limestone types, in Ham, W.E., ed., *Classification of Carbonate Rocks-A Symposium: American Association of Petroleum Geologists Memoir 1*, p. 62-84. Forman, M
- Gani, N. DS. , Abdelsalam, M. G., Gera, S. and Gani, M. R. (2008). Stratigraphic and structural evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau.,*Geol. J. ,* Published online in Wiley InterScience, (www.interscience.wiley.com)
- Gani, N.D.S., Abdelsalam, M.G., Gera, S., Gani, M.R., (2009). Stratigraphic and structural Evolution of the Blue Nile Basin, North-western Ethiopian Plateau. *Geological Journal*, **44**: 30–56.

- Gortani, M. and Bianchi, A. (1937). Osservazioni geologiche e petrografiche nella regione di Harar (Africa orientale Italiana). *Bollettino Societa Geologica Italiana* 56, 499-516.
- Greitzer, Y. (1970). Stratigraphy, hydrogeology and Jurassic ammonites of the Harar and Dire Dawa area, Ethiopia. PhD thesis, Hebrew University, Tel Aviv, 205 pp.
- Haq, B.U., Hardenbol, J. & Vail, P.R. (1987). Chronology of the fluctuating sea level since the Triassic. *Science* 235: 1156–1167.
- Hunegnaw, A., Sage, L. & Gonnard, R. (1998). Hydrocarbon potential of the intracratonic Ogaden Basin, SE Ethiopia. *J. Petrol. Geol.* 21: 401-425.
- Kazmin, V. (1973). Geology of Ethiopia (explanatory note to the geological map of Ethiopia 1:200000 scale), unpublished report ministry of mine, geological survey of Ethiopia. Addis Ababa.
- Kemal T., Demir A., Hayati K. and Muhsin E., (2008): Benthic foraminiferal biostratigraphy of the Jurassic platform carbonate succession, Bolkar Mountains (Southern Turkey). *Micropaleontology*, vol. 54, no. 5, pp. 425-444.
- Lamare, P. (1930). Nature et extension des depots secondaires dans l'Arabie l'Ethiopia et les pays Somalis. *Memoir Societe Geologique France* 6, 49-68.
- Levitte, D. (1970). On the geology of the central part of the Mekele sheet, 1:250,000: Ethiopia Geol. Survey, unpub. report. Addis Ababa.
- Longman, M.W. (1980). Carbonate diagenetic textures from nearshore diagenetic environments. *Bull. Am. Ass. Petrol. Geol.* 64, 461-487.
- McIlreath, I. A. and Morrow, D. W. (1990). *Diagenesis*. Geoscience Canada Reprint Series No. 4, 338 pp.
- Mohr, P.A. (1962). *The geology of Ethiopia*. Addis Ababa University Press, Addis Ababa.
- Peter A. S. and Dana S. U. (2003). A Color Guide to the Petrography of Carbonate Rocks: Grains, textures, porosity, diagenesis. *AAPG Memoir* 77, Tulsa, Oklahoma, U.S.A.
- Philip A. and John R. (2005). *Basin analysis: principles and applications*, 2nd ed, Blackwell publishing, UK, 562 pp.
- Reading, H. G. (ed) (1996). *Sedimentary Environments: Processes, Facies and stratigraphy*. Third edition. Blackwell, Oxford, p688.
- Reynolds, P.O., Schandelmeier, H. & Semtner, A.K. (1997). Chapter 9 and 10. Early Jurassic (Toarcian, ca. 180 Ma) and the Late Jurassic (Kimmeridgian, 153 Ma) respectively. In H. Schandelmeier & P.O. Reynolds (eds.), *Palaeogeographic-Palaeotectonic Atlas of Northeastern Africa, Arabia, and Adjacent Areas: 57–64*. Rotterdam: Balkema.
- Riccardi, A.C. (1991). Jurassic and Cretaceous marine connections between the southeast Pacific and Tethys. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 87: 155–189.
- Russo, A.; Getaneh Aseffa. and Balemwal Atnafu (1994): Sedimentary evolution of Abay (Blue Nile) Basin, Ethiopia. *N. Jb. Geol. Palaont. Mh.* 1994 (5): 291-308; Stuttgart.
- Sartoni, S. and Crescenti, U. (192). Ricerche biostratigrafiche nel mesozoico dell'Appennino Meridionale. *Giornale di Geologia, Ann. Mus. Geol. Bologna, ser. 2, vol. xxxix*.
- Sartorio, D. and Venturini, S., 1988. Southern Tethys Biofacies. Agip S.p.A., S. Donato Milanese, 235 pp.
- Saxena, G.N., Assefa, G., 1983. New evidence on the age of the glacial rocks of northern Ethiopia. *Geological Magazine* 120: 549-554. printed in Great Britain.
- Schmidt, D. & Werner, C. (1998). Early Cretaceous coastal plain sediments of the Muger Mudstone Formation, Abay River Basin, Ethiopia. *Zbt. Geol. Palaont.* 1: 293–309.
- Selley, R.C. (2000). *Applied Sedimentology*, 2nd ed, Academic press, A Harcourt science and technology company, California, USA, 543 pp.
- Septfontaine, M., 1980. Les Foraminifères imperforés des milieux de plate-forme au

- Mésozoïque: détermination pratique, interprétation phylogénétique et utilisation biostratigraphique. *Revue de Micropaléontologie*, **23**: 169-203.
- Shigut G.(1998), Biostratigraphy, depositional environment, basin evolution and hydrocarbon potential of the late Triassic to late Jurassic succession, Ogaden Basin, Ethiopia. Institute und Museum fur Geologie und palontologie, Tubingen, Germany
- Shumburo, M.M. (1968). The Amba Aradam Formation (formerly the Upper Sandstone). *Mobile Petroleum Ethiopia Inc.*, Unpublished report. Ethiopia.
- Stern, R.J. (1994). Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for the consolidation of Gondwanaland. *Ann. Rev. Earth Planet. Sci.* **22**: 319–351.
- Tadesse T., Hoshino M. and Sawada Y. (1999); Geochemistry of low-grade metavolcanic rocks from the Pan-African of the Axum area, Northern Ethiopia, *Precambrian Research* **99** (1999) 101–124.
- Worku, T. and Astin, T. R. (1992); The Karoo sediments (Late Palaeozoic to Early Jurassic) of the Ogaden Basin, Ethiopia. *Sedimentary Geology*, **76** (1992) 7-21 7 , Elsevier Science Publishers B.V., Amsterdam.
- Tefera, M., Tewodros Chernet and Haro, W.(1996). *Geological Map of Ethiopia, 1: 2000000*. 2nd ed, Ethiopian Institute of Geological Survey, Addis Ababa, 1p.
- Tilahun Mammo,(2010). Delineation of sub-basalt sedimentary basins in hydrocarbon exploration in North Ethiopia; *Marine and Petroleum Geology* ,**27** (2010) : 895–908
- Tilahun Mammo,(2012). Analysis of gravity field to reconstruct the structure of Omo basin in SW Ethiopia and implications for hydrocarbon potential, *Marine and Petroleum Geology* ,**29** (2012):104-114.
- Tucker, M. E. and Wright V. P. (1990). *Carbonate Sedimentology*, Blackwell, Oxford London, 496pp.
- Tucker, M.E. (2001). *Sedimentary Petrology, an Introduction to the Origin of Sedimentary Rocks*, 3rd ed, Blackwell Scientific publication, Oxford London.
- Tucker,M.E. (2003). *Sedimentary Rocks in the Field: the geological field guide series*, 3rd ed, John Wiley and Sons, UK, 250 pp.
- Turi A, Bigi L, Pirini Radrizzani C (1980.) Microfacies of the Antalo Limestone (Middle to Upper Jurassic) in some sections of East – Central Ethiopia. *Bollettino Societa Geologica Italiana* 99: 437- 454
- Velic, I. (1977). Jurassic and Lower Cretaceous assemblage-zones in Mt. Velika Kapela, Central Croatia. *Acta Geologica* 9: 15-37.
- Walker R.G. (1992).Facies, facies models and modern stratigraphic concepts (In Walker R.G & James, N.P. (eds.), *Facies Models: Response to Sea Level Change*: Geological Association of Canada, Canada.
- Walker, R.G. & Plint, A.G. (1992). Wave and storm-dominated shallow marine systems. In R.G. Walker & N.P. James (eds.), *Facies Models: Response to Sea Level Change*: 219–238. St John’s: Geological Association of Canada.
- Wilson, J.L. (1975). *Carbonate facies in geologic history*. 456pp.Springer-Verlag, Berlin.
- Wolela A. (2007). Source rocks potential of Blue Nile (Abay) basin, Ethiopia. *Journal of Petroleum Geology*, **30(4)**: 389-402
- Wright, V.P. (1984).Peritidal carbonate facies models: A review. *Geol.J.*, **19**,309-325.

Plates

Under this subtitle, 15 plates containing the photomicrographs of some collected carbonate rocks samples from Dire Dawa area are given. These microphotos are used for supporting the descriptions and interpretations given throughout this paper, as cited in the body. Each plates are given with the photomicrographs, descriptions of the photos, sample from which it's taken, types of light used for viewing (Cross-Polarized Light (XPL) or Plane Polarized Light (PPL)) and amount of magnifications used in number with 'times'(X) sign respectively.

Plate 1: Microphotographs of mixed siliciclastic - carbonate microfacies

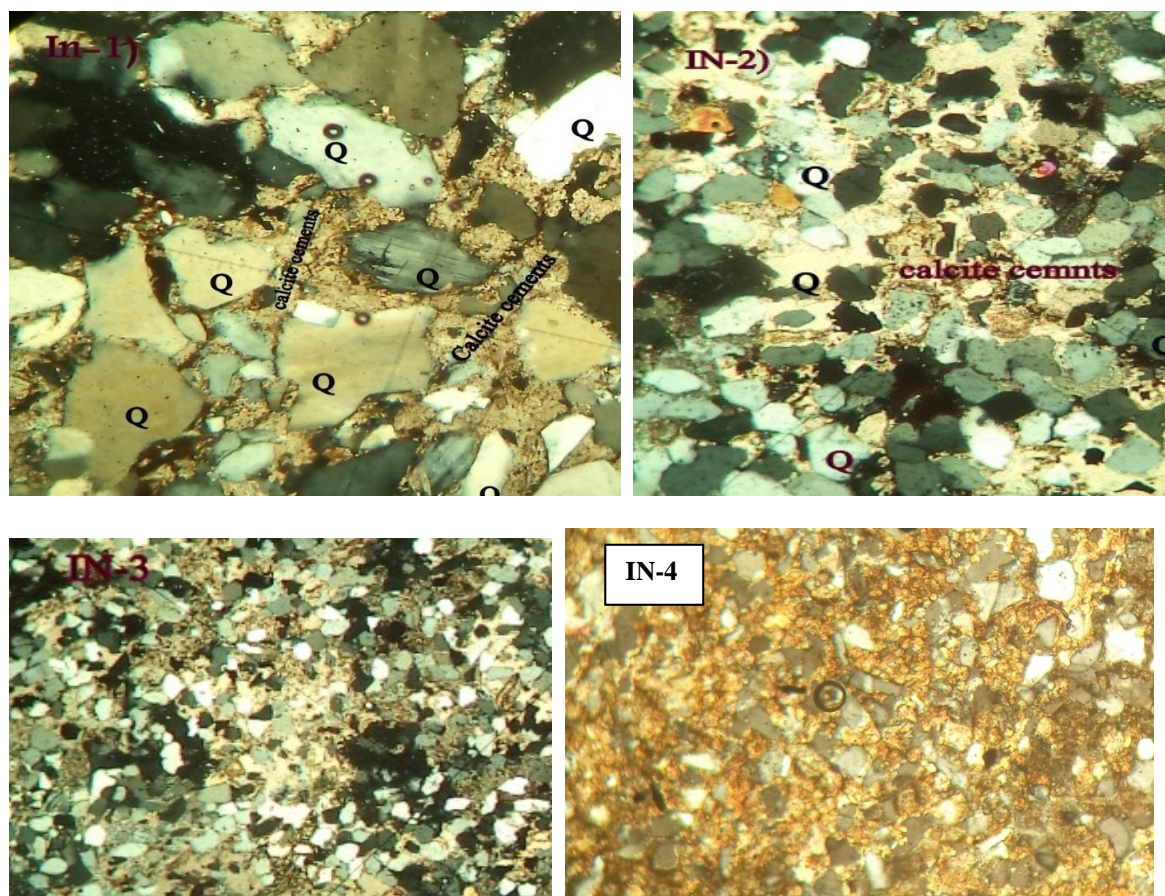


Plate 1: **IN-1)** The larger and angular quartz grains (Q) imbedded in the sparry calcite cements, calcite cemented quartz arenite (sample no: IN-1, taken from lower part of intercalation unit at Lange section, Dire Dawa area). **IN-2)** Medium sized and sub-rounded quartz grains (Q) imbedded in the sparry calcite cements (photomicrography of IN-2 sample taken from the middle part of intercalation unit at Lange section. **IN-3)** Photomicrography of smaller and sub-rounded detrital quartz grains imbedded within calcite cementing materials, IN-3 sample taken from the top part of the intercalation unit at Lange section. **IN-4)** The fragmented quartz grains with more dominant calcite crystals (of IN-3 sample taken from top end of this intercalation unit). Note: All photomicrographs in this plate are under **XPL**, with **40X** magnifications.

Plate 2: Microphotos of dolomitized micritic microfacies

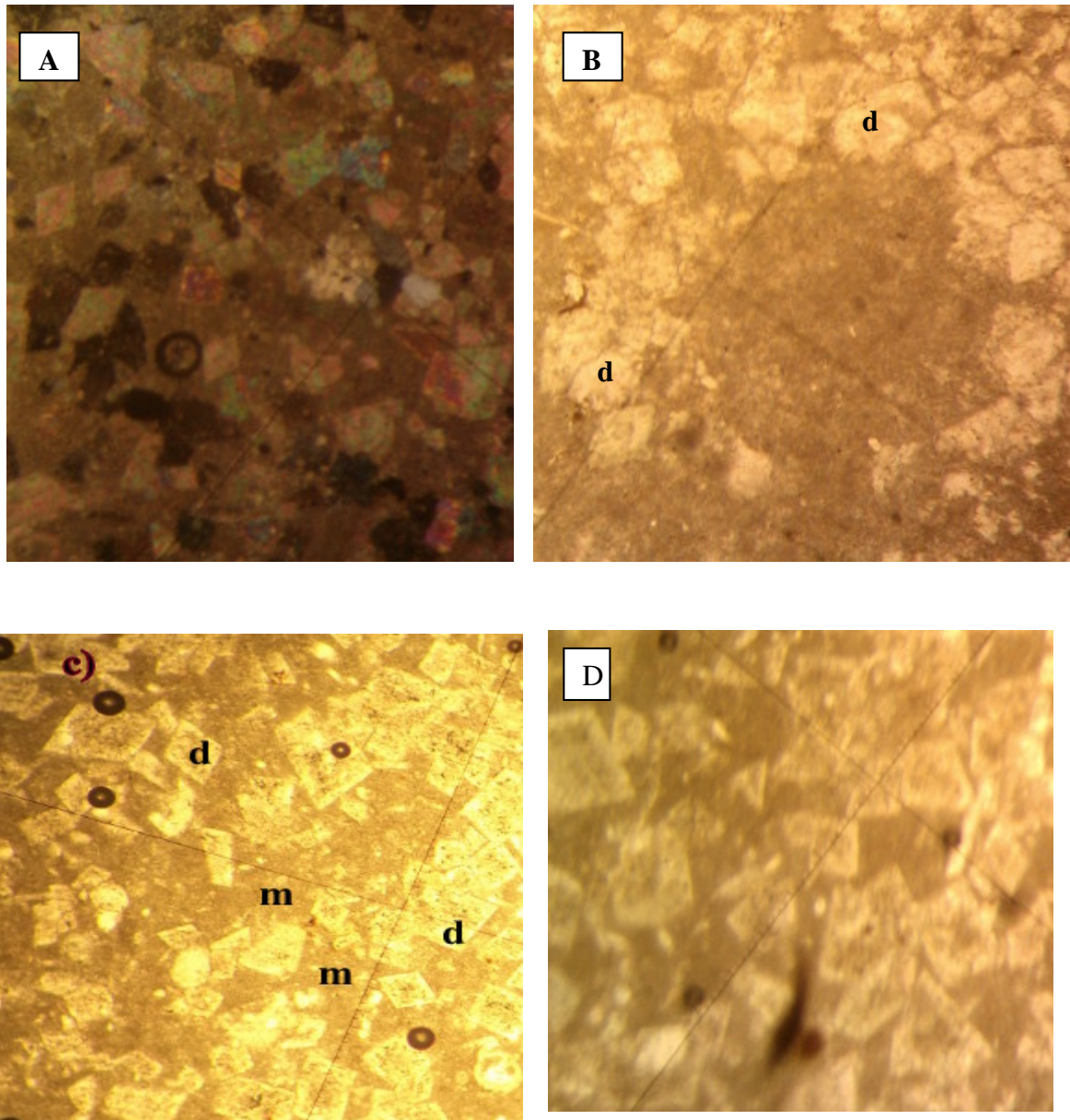


Plate 2: A- B) The partially dolomitized micritic limestone, in which micrites are replaced by some smaller dolomite crystals (sample R4 and R3 respectively, collected from lower of military section).

C -D) show highly dolomitized micritic limestone of sample L2 and H2; collected from lower Lange section and lower military section respectively. The calcite micrites (m) are replaced by the planar-e (euhedral) coarser dolomite crystals (d). The dolomite crystals obtained are mostly planar euhedral and coarser. There are some finer inclusions within dolomite crystals; those are most probably the remains of undigested calcite precursors. All photographs in this plate are under XPL, with 40X magnification).

Plate 3: Microphotos of Peloidal grainstone microfacies

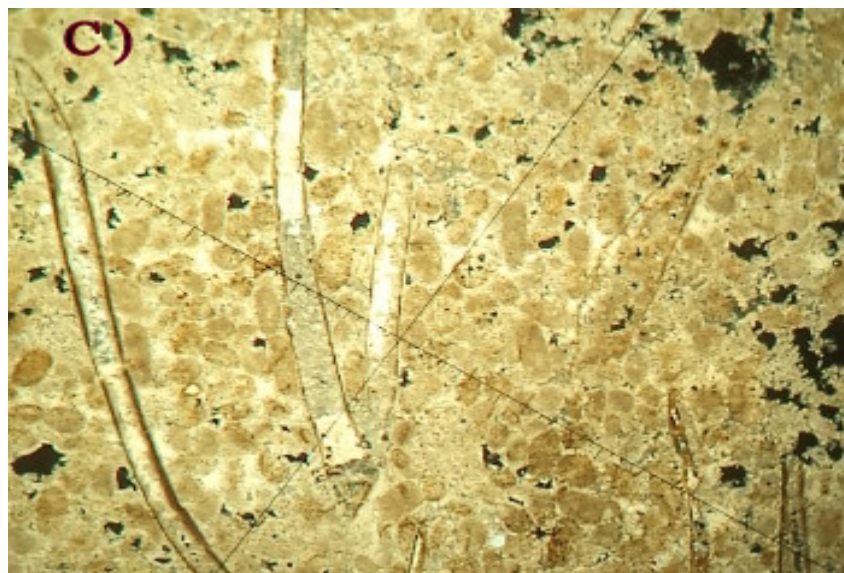
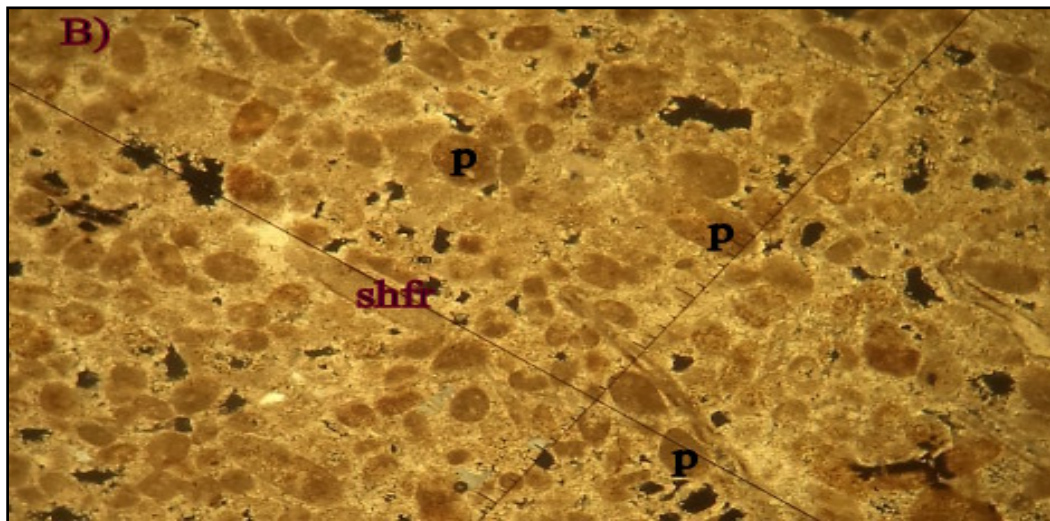
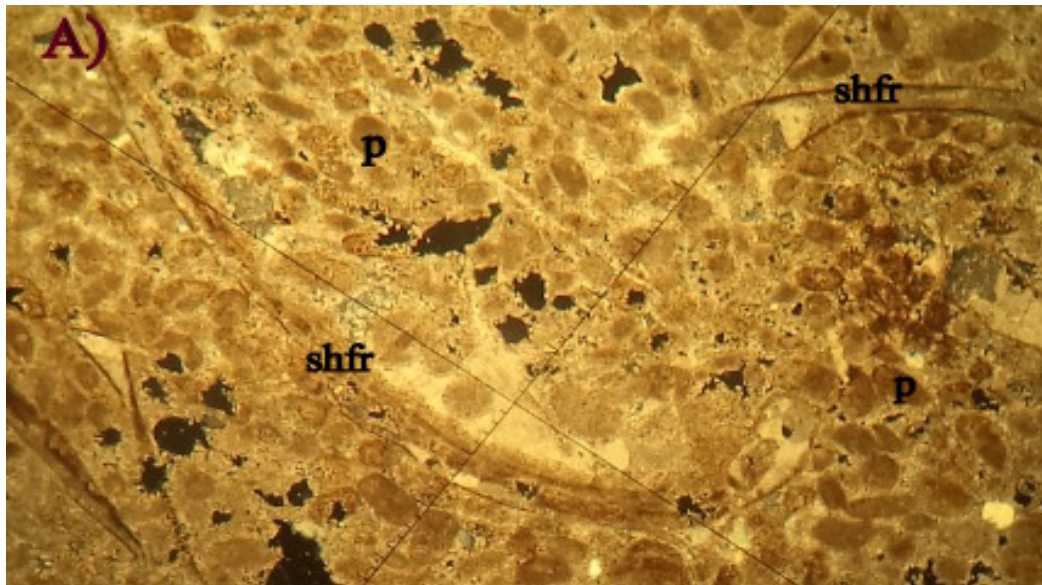
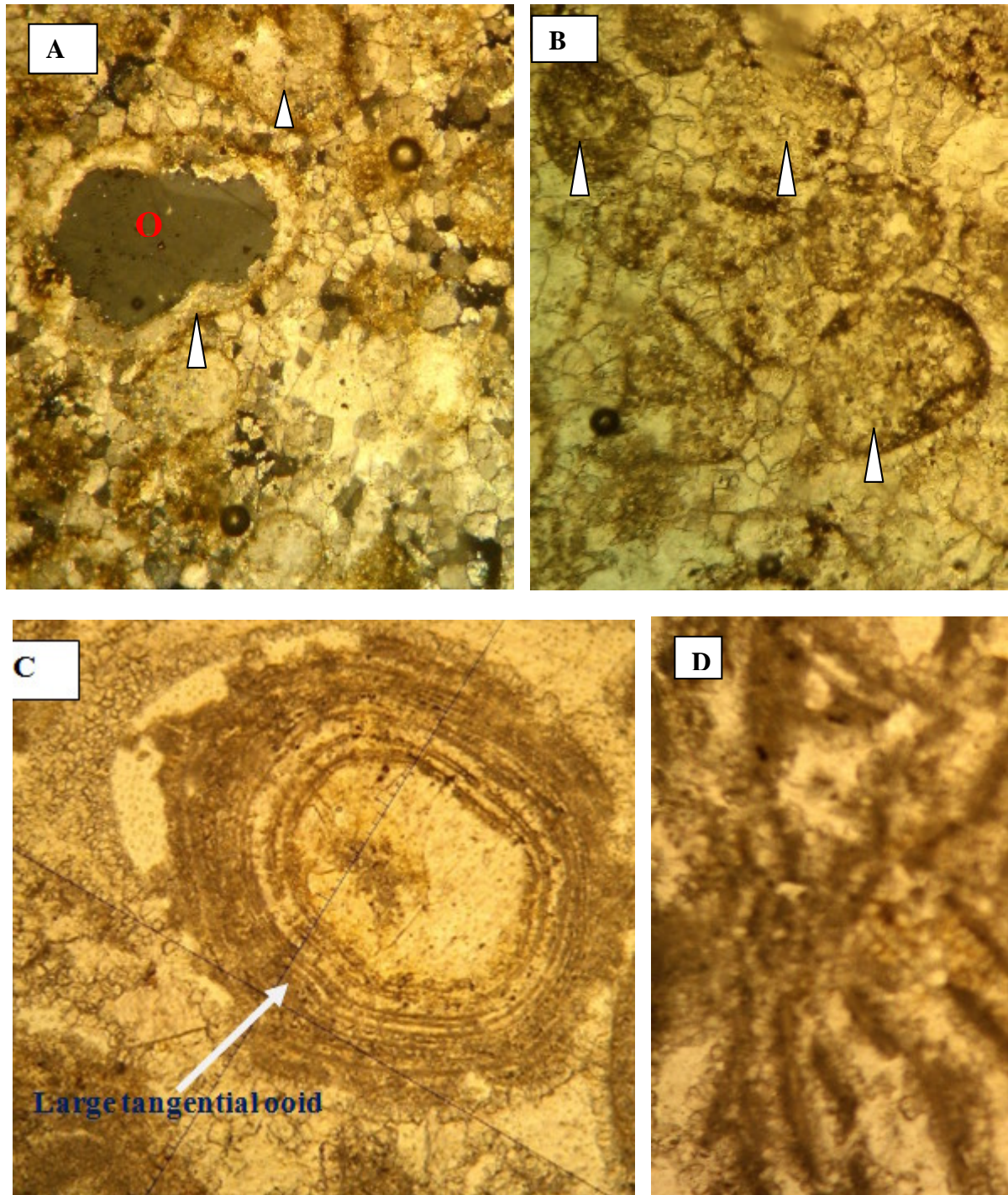


Plate 4: Microphotos of oolitic microfacies



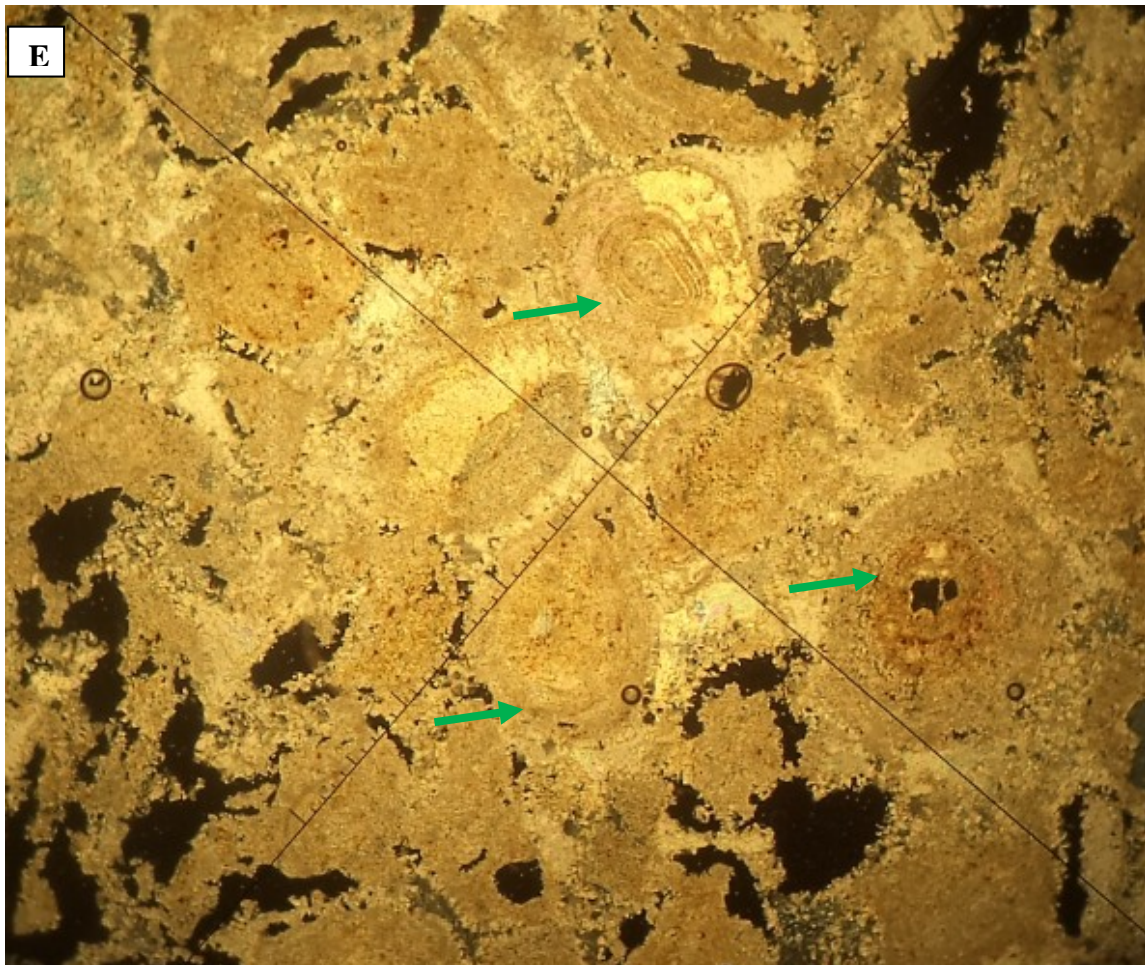


Plate 3: A) photomicrography showing peloidal grainstone facies in which concentrated numbers of smaller size peloids grains (P), with some amounts of shell fragments (**Shfr**) are imbedded in the sparry calcite cements (whitish color between grains). There are also pore spaces (black color) between the grains and within the grains (photomicrography under XPL, X40, of sample N_o K1).

B - C) Another views of the same sample (K1) under XPL and, PPL respectively with 100 X magnifications, those showing the smaller peloid grains imbedded in sparite and some micritic envelope (shown by arrows) and void spaces (black spaces).

Plate 4: A & B) Photomicrography showing the oolitic grainstone microfacies in which ooid grains (spherical shaped with internal nucleus, arrowed) with rare amounts of quartz grains are imbedded within the sparite cements, quartz grains (Q) as the nucleus of ooid grain are observed. Ooid grains are coarser in size and moderately sorted, the ooid grains in B are surrounded by micritic envelope (sample K2, XPL and PPL respectively, with magnifications of 40X for both).

C) Showing the larger tangential ooid (high energy environment product) surrounded by calcite cements. Sample K4, XPL, 100X.

D) Micritized skeletal fragments cemented together forming carbonate sands, most of the grains are compacted and broken. Sample K4, PPL, X40.

E) Concentrated numbers of coarser ooid grains (arrowed) in oolitic microfacies; those are mainly dissolved, forming secondary pores (black colors) and fitted together due to compactions. Sample K2, XPL, 40X.

Plate 5: Microphotos showing the peloidal wackestone microfacies.

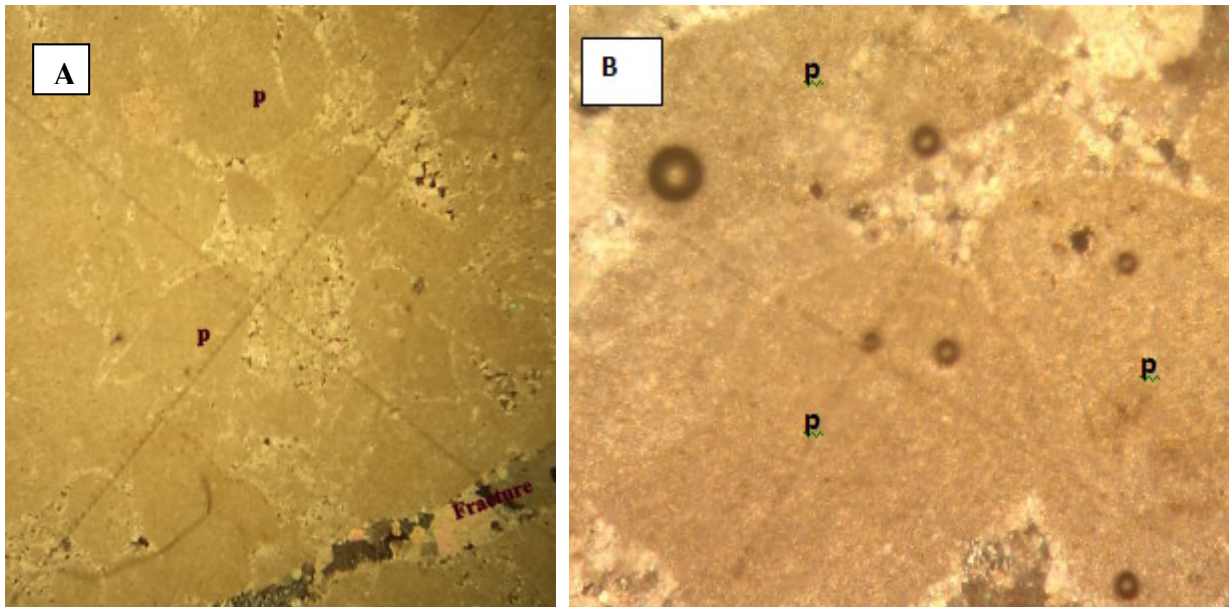


Plate 5(above): A - B) The mud peloidal grains (p) imbedded in the micrite background and also long fracture filled with sparite cements on the bottom part of A. The peloids grains in this sample are not well developed and they are poorly sorted. In **B**, the peloid grains are coarser and there is compaction among grains (Sample no. R1, under XPL for both, X40, for A and 100X for B).

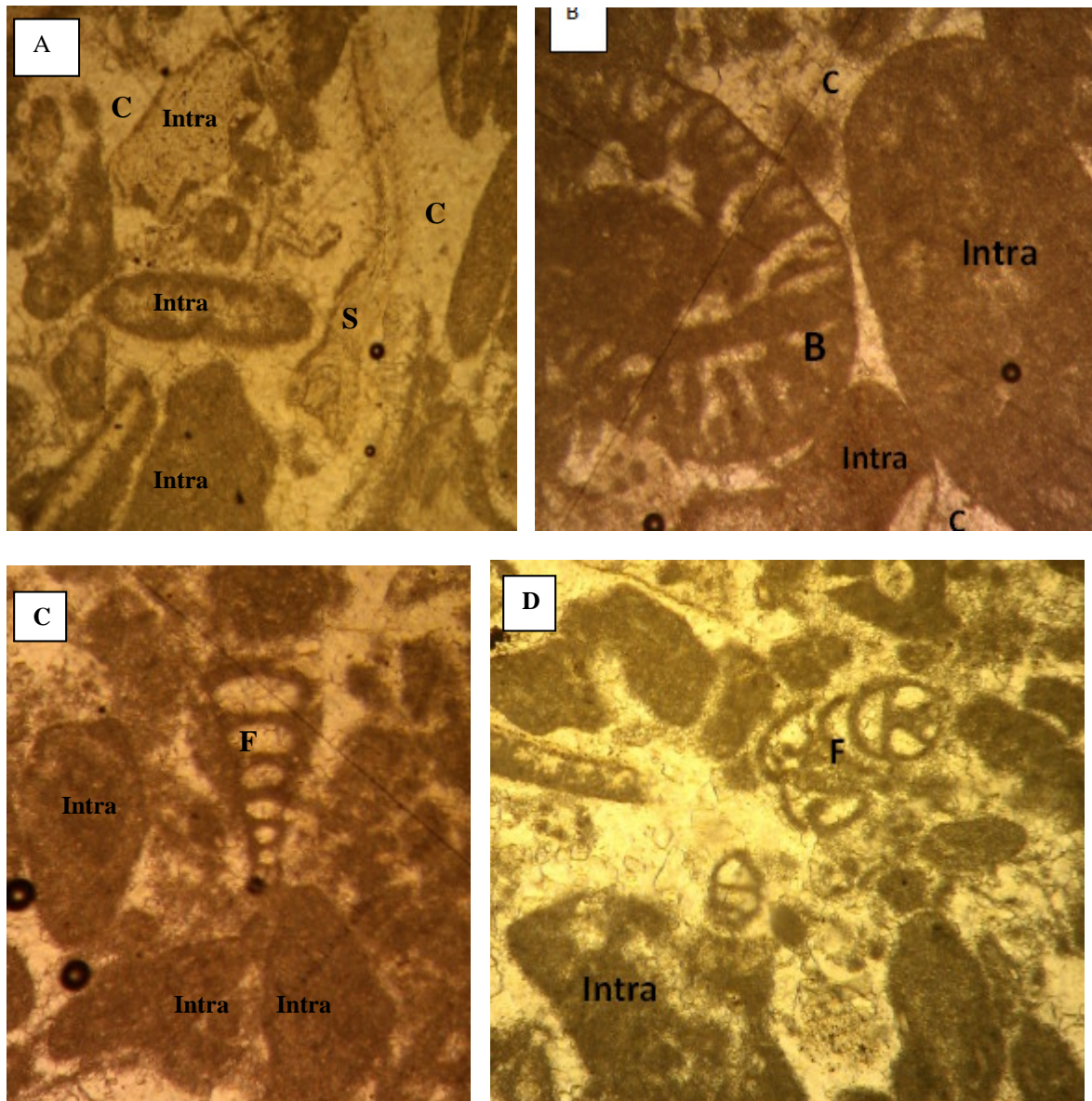
Plate 6(below): A) Grainstone microfacies which contain intraclasts (Intra) and shell fragments(S) cemented together by calcite cements(C). The grains are poorly sorted and irregular in shapes. Sample R8, PPL, X40.

B) The bioclastic intraclast rudstone, in which the larger foraminifera(B) and larger intraclastic grains(Intra) are cemented together by sparry calcite cements(C). Sample R10, under XPL by 40X.

C & D) Photomicrography showing various size intraclast grains(Intra), fossils (F) and other skeletal fragments within spar calcite cements and rare micrite. Sample R11, under PPL by 40X magnify..

E) Photomicrography of sample No R6 under XPL, with 40X magnification, showing the larger carbonate clasts (lcls) and fossils ((f) imbedded in the sparry calcite cements(C). The grains are irregular in shape and somewhat rounded.

Plate 6: Microphotos of bioclastic intraclast grainstone microfacies



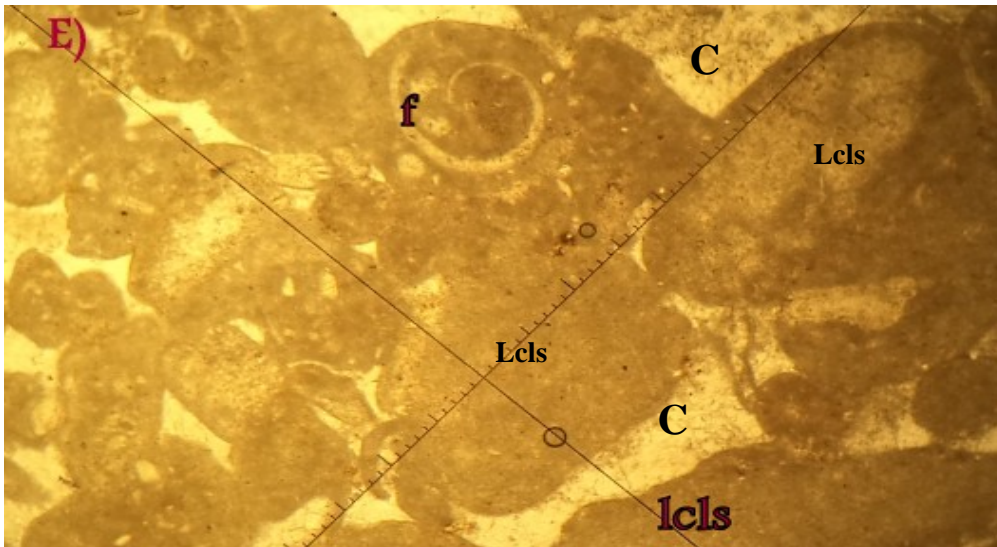
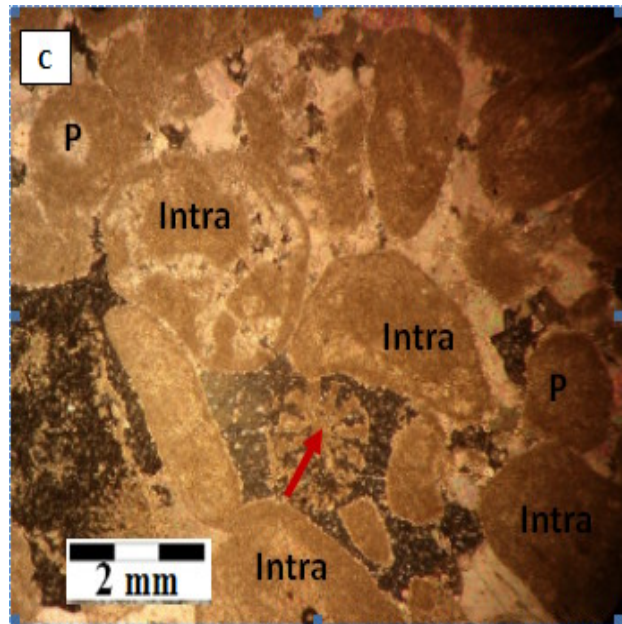
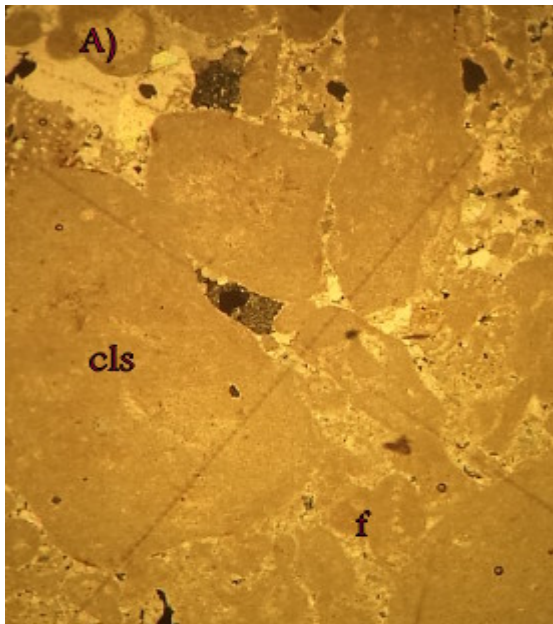


Plate7: Microphotos showing the bioclastic packstone microfacies



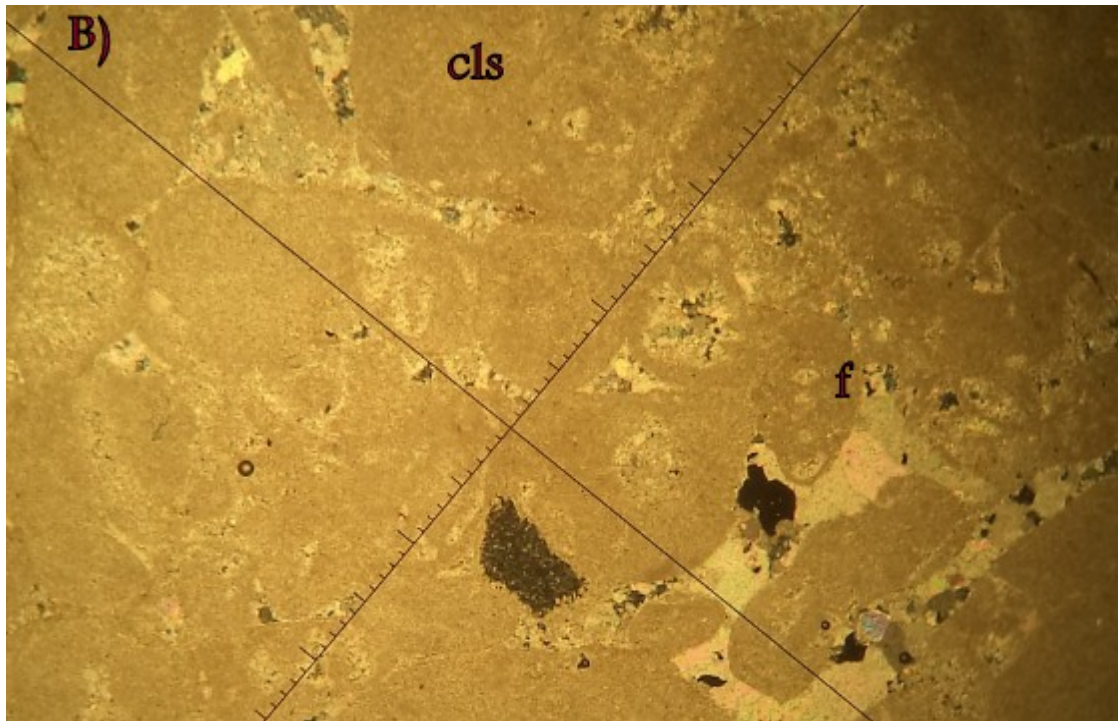
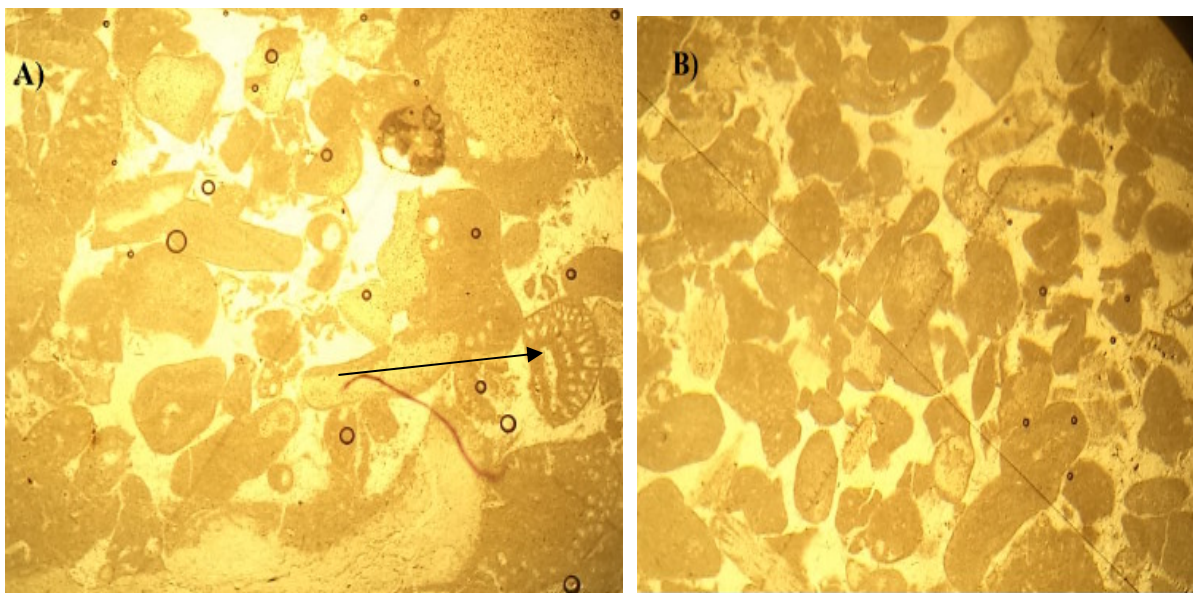


Plate 7: A & B)Photomicrography of sample R12 and R13 respectively, showing the packstone in which the some *Naulithica oolithica* (f) and various shaped carbonate clasts (cls) are imbedded in the sparry calcite cements and some micrite. The grains are poorly sorted and irregular in shape. (Under XPL, 40X).

C) Bioclastic intraclast packstone in which the irregular shaped intraclast grains (**Intra**), peloids (**P**) and echinoderms (arrowed) are imbedded in sparry calcite(whitish space between grains) and with rare micrite background materials. Sample R12, XPL, 40X.

Plate 8: Microphotos of bioclastic peloidal grainstone microfacies.



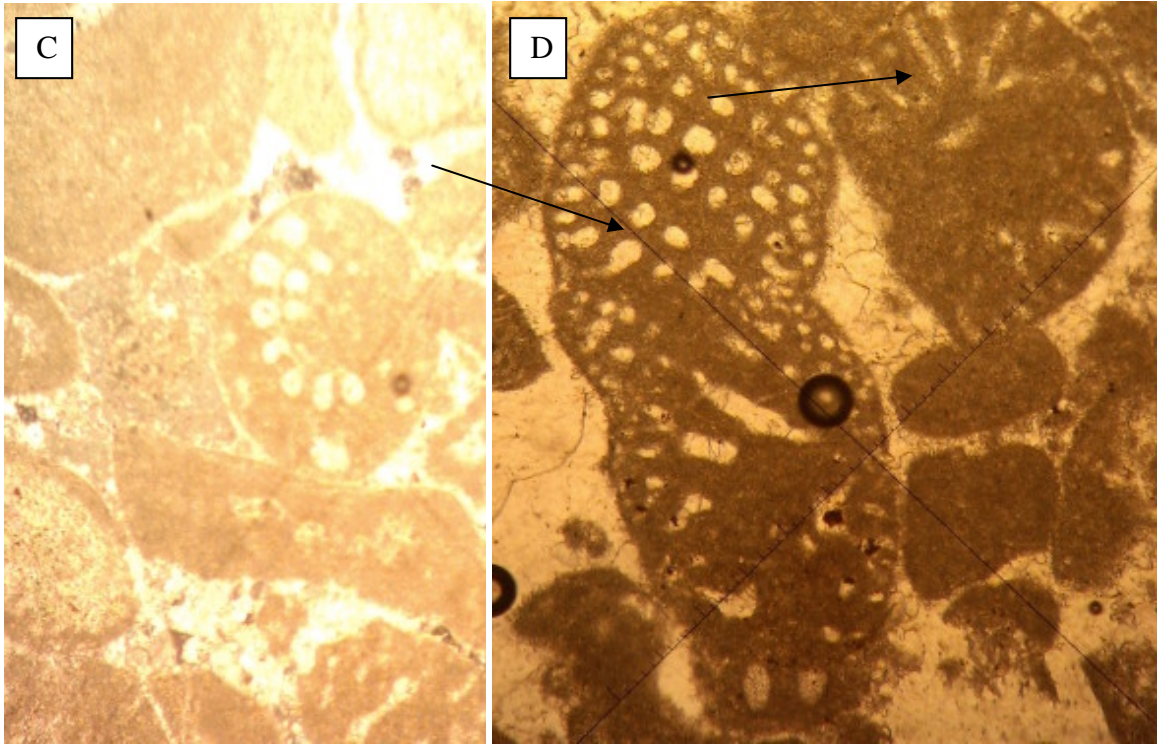


Plate 8: A - B) micrographs of bioclastic Peloidal grainstone facies in which the various sized Peloidal grains (P) and rare amounts of smaller skeletal grains such as **codiaceae algae** and forams (black arrowed), and other fragmented skeletal grains are imbedded in the sparite (c). From sample No 15, under PPL, 40X.

C) Photo showing larger fossils and irregular shaped peloid under PPL with 100X magnification. Sample R15.

D) Grainstone microfacies in which the larger foraminifers (*Kurnubia palastiniensis*) (arrowed) and peloid (P) grains are cemented together by sparry calcite cements (C). Sample R15, under XPL, 100X.

Plate 9: Bioclastic wackestone microfacies photomicrography

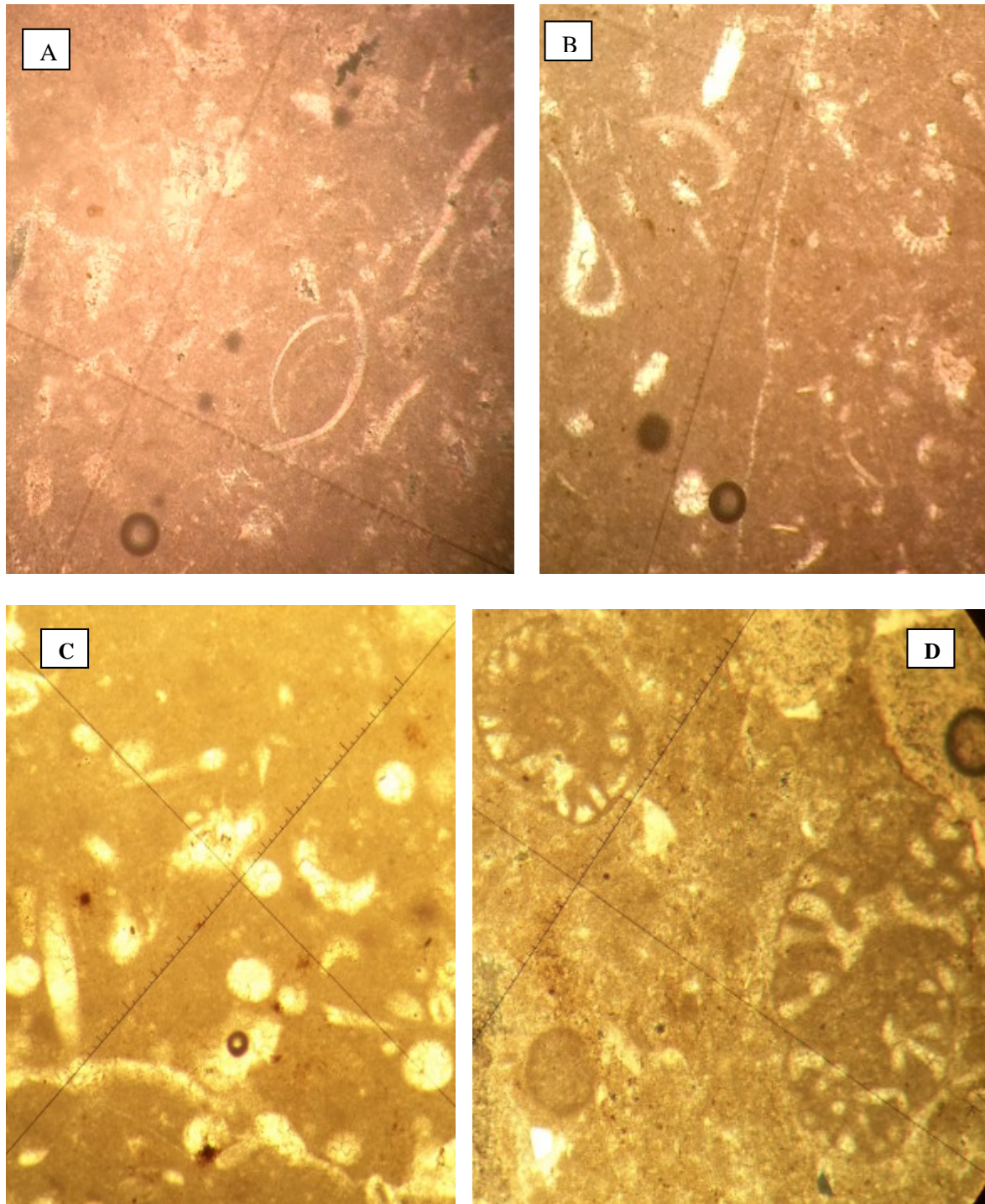


Plate 9: **A- B)** Bioclastic wackestone microfacies bearing various shell fragments within the micrite fine materials. Sample M1 and H1 respectively.

C) Bioclastic wackestone microfacies containing sponges dispersed in micrite. Sample M1. **D)** Bioclastic wackestone containing *Paleopfenderina trochoidea-salernitana*. Sample L7. All photos in this plate are under XPL with 40x magnifications.

Plate 10: Microphotos of micritic microfacies

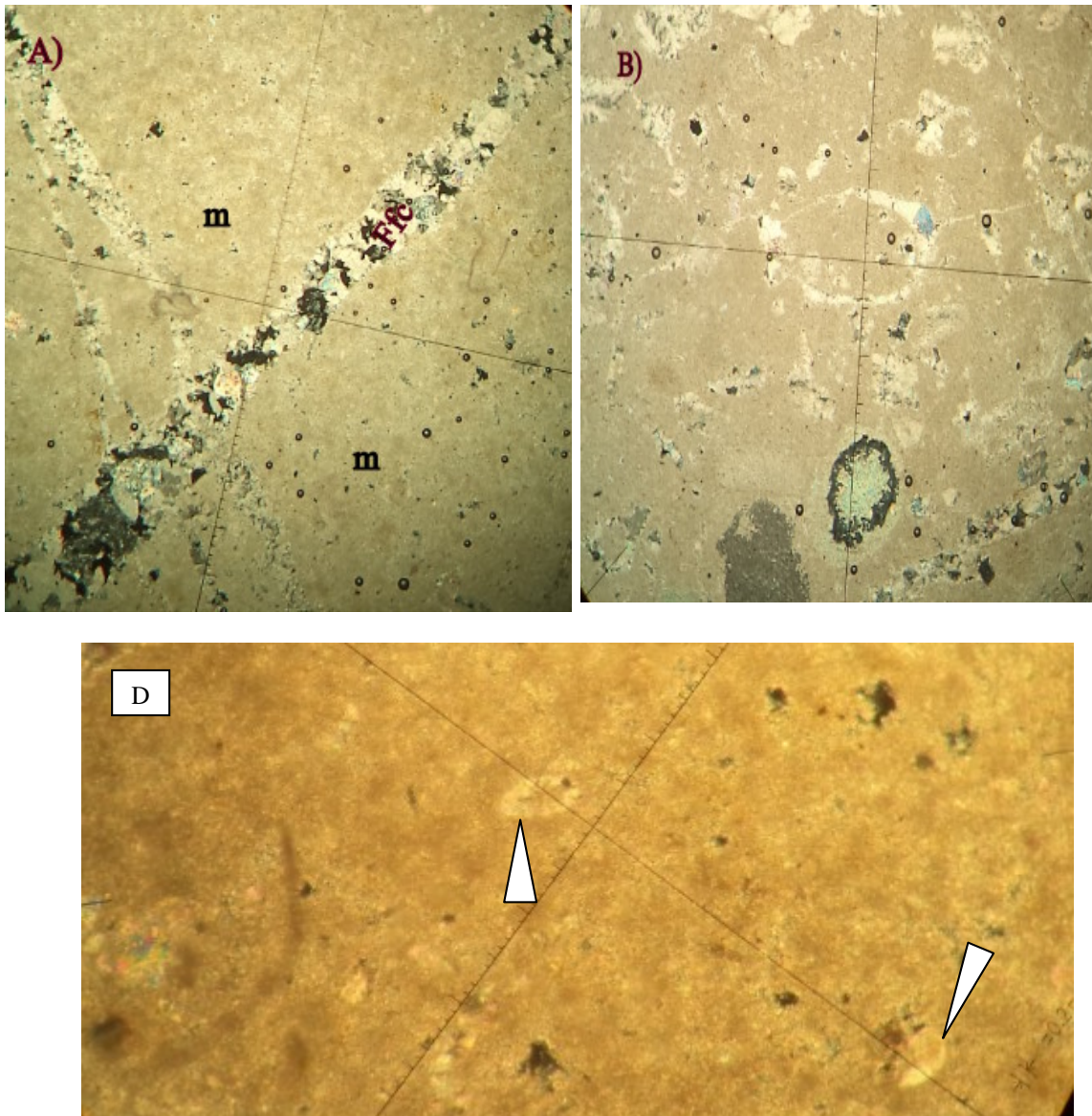


Plate 10: A) Micritic limestone photomicrography showing the fractured micrite layers in filled by the secondary calcite cements (Ffc) between the micritic (m) layers, the two fractures cut across each other. Photo taken from sample no. MM3, B) Photomicrography of micritic layers, it shows bioturbated, dissolved and the boring of micritic layers by organisms (Sample DR4, which taken from upper part of Dachatu section).

D) Shows the micritic limestone photomicrography taken from sample MM4 in which ostracods grains (arrowed) are dispersed in micrite. All photos in this plate are under XPL, with 40X magnifications.

Plate 11: Microphotos showing compactions and its effects

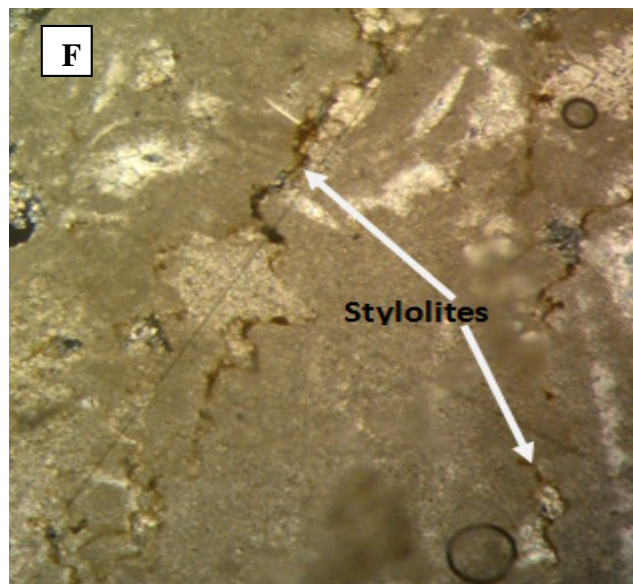
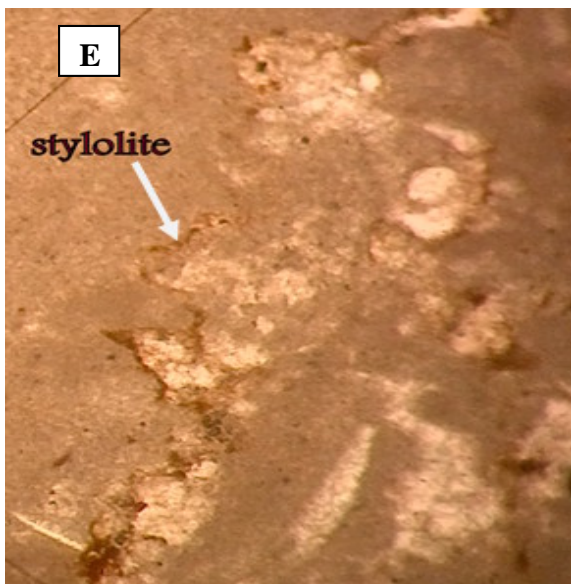
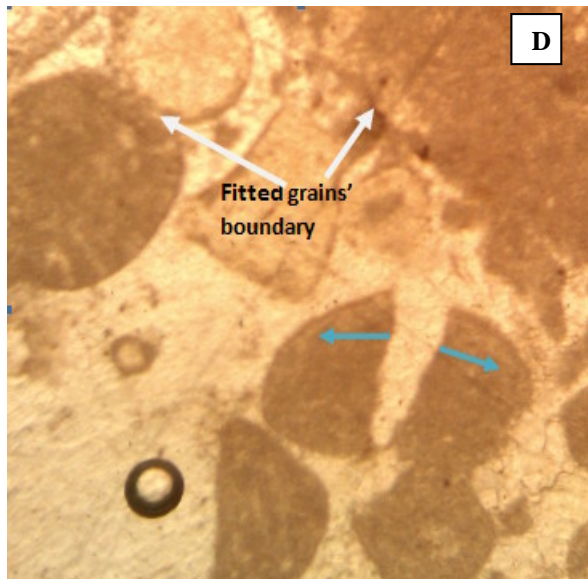
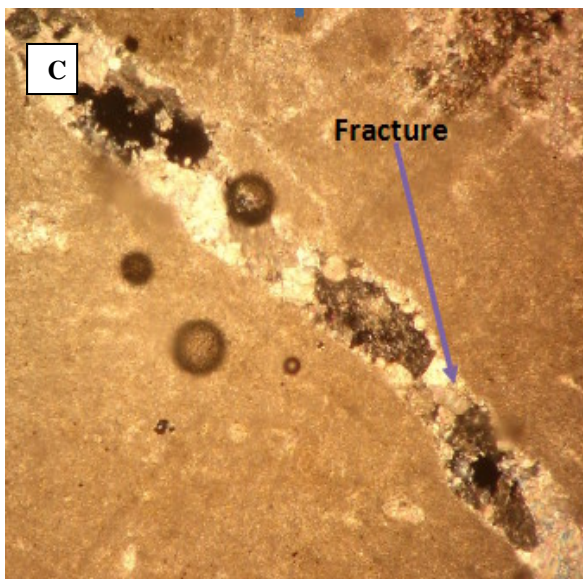
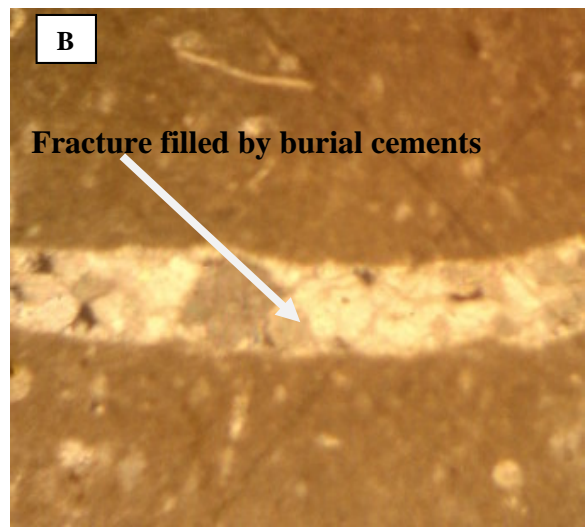
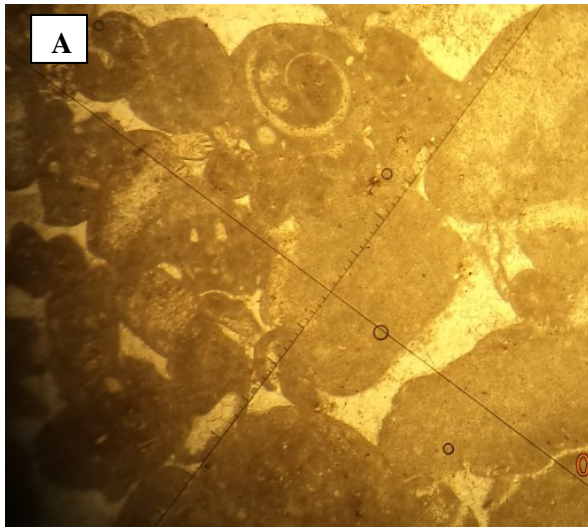


Plate 11: A) The embayed grain contact among various sized carbonate grains due to the compaction processes and the space between them are later filled by burial cements. Sample R6, under XPL, X40.

B and C) The long fracture filled partially with calcite cements, which are the results of burial compaction processes. Photomicrography of sample L6 and R10 respectively under XPL, X40.

D) Photomicrography showing the mechanical breakdown of peloidal grain (shown by blue arrows) and also other fitted grain boundaries by mechanical compactions. As indicated by arrows the peloidal grain is broken away from each other by the compaction effect and later on the space between is filled by calcite cements. Sample R12, PPL, x40.

E and F) Photomicrography showing stylolites (shown by arrow) in the lime mudstone and bioturbated wackestone of sample: L4 and H1 respectively, under XPL, X40.

Plate 12: A) photomicrography showing peloidal packstone in which, thin micrite envelop around skeletal grains (**ME**) and skeletal grain altered with micritization totally(**TM**). Sample K1, XPL,40X.

B) Photomicrography showing micrite envelopes (the thin dark envelopes shown by arrows) showing the dissolved aragonitic ooid grains morphology. The micritized ooids grains (**DO**) were first dissolved which in turn filled by precipitated calcite cements; these cements are most probably burial stage. Sample K2, XPL, 40X magnifications.

C) Photomicrography showing secondary pore spaces(black spaces and arrowed) formed by the dissolutions of micritized gastropd shell(**MGstp**) and peloids grains .Sample K1,under XPL by maginification 40X magniofications.

D) The dissoloved boundary (black color)of large ooid grain. Sample K4, XPL, 40X magnification.

Plate 12: Microphotos showing some micritic envelopes and dissolutions

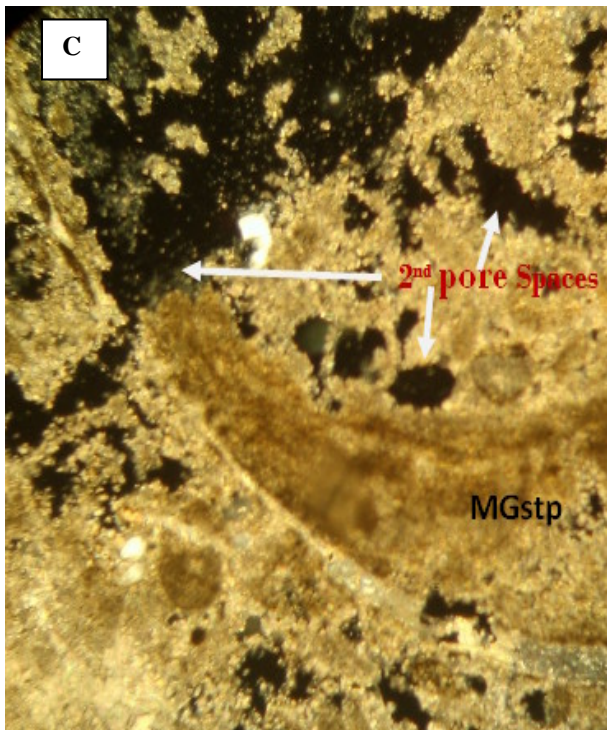
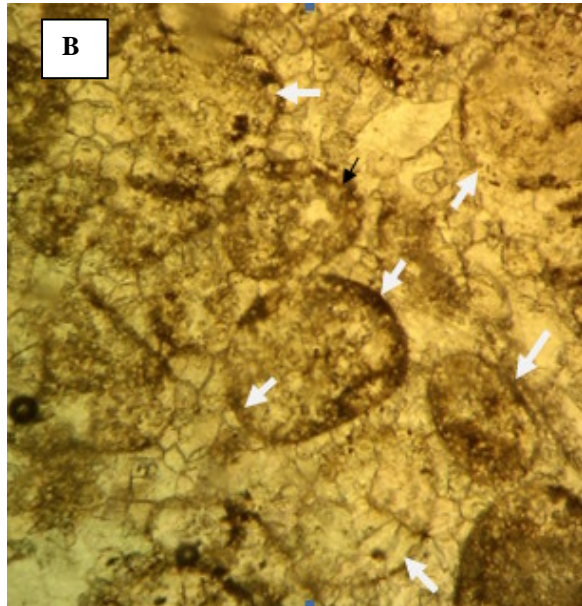
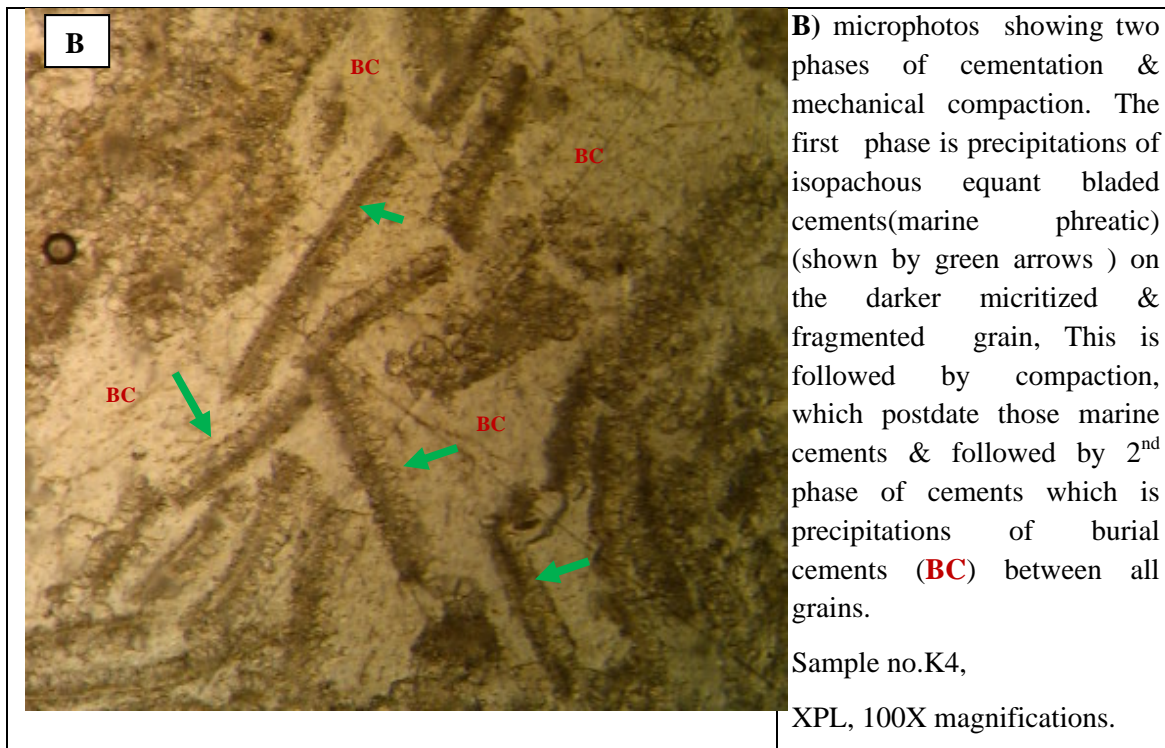
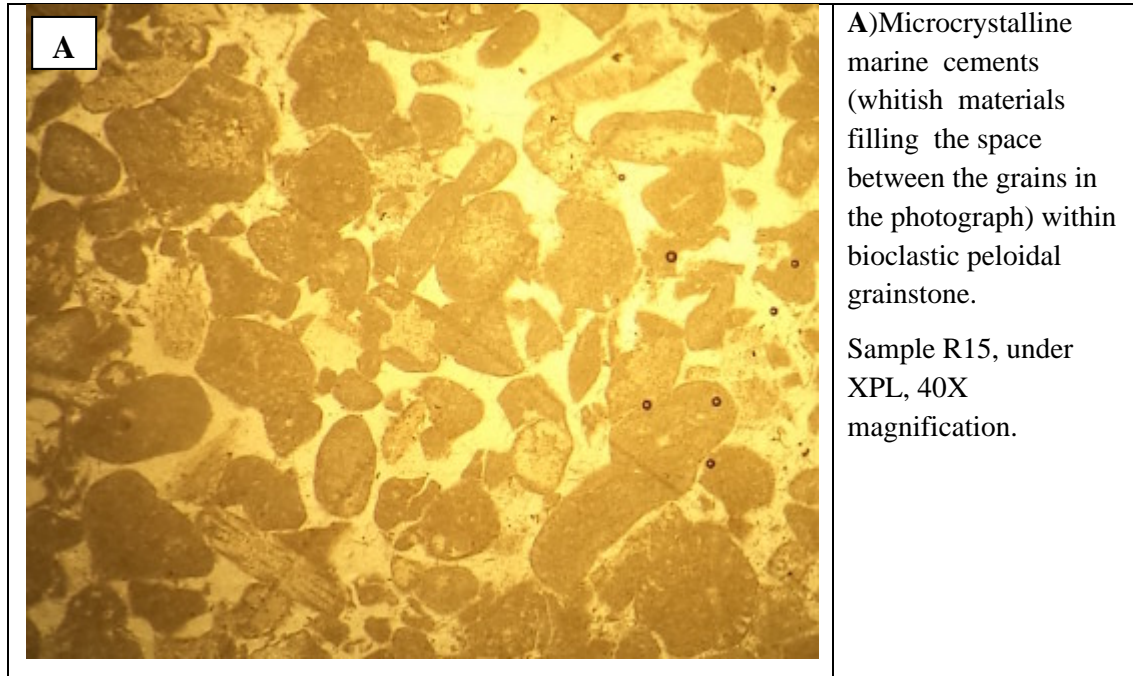
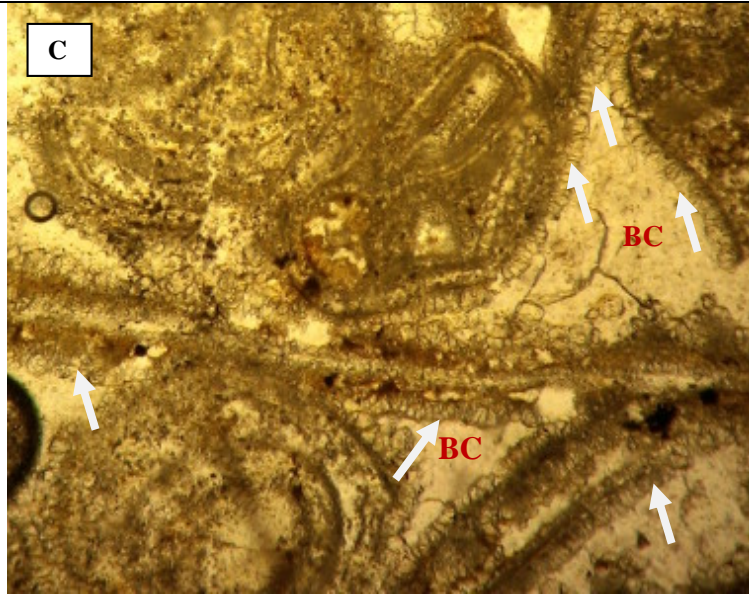
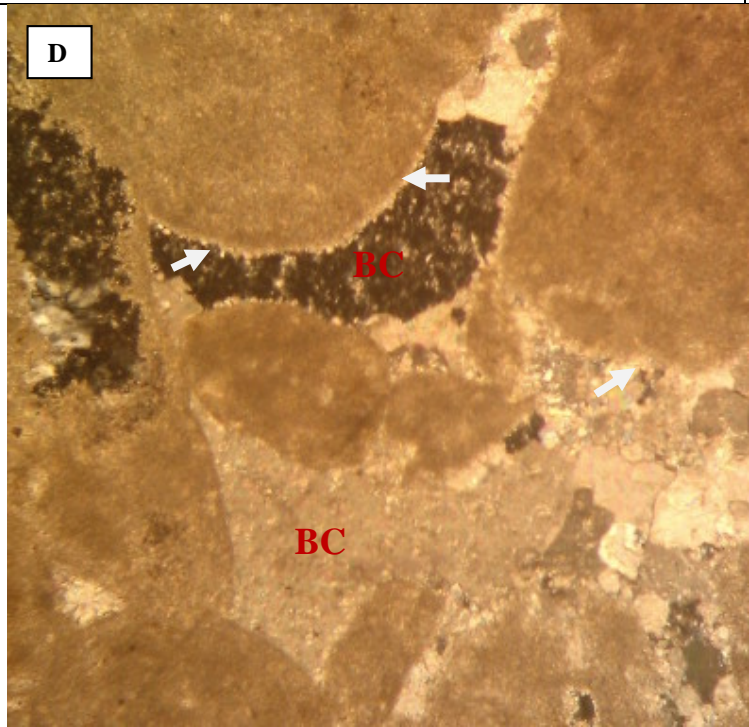


Plate 13: Microphotos of various types of cements



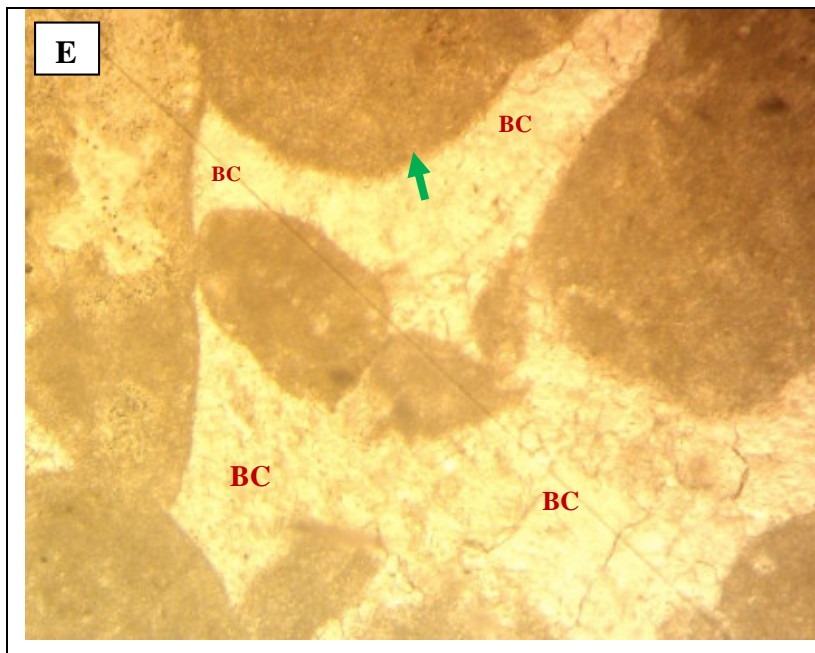


C) Two phases of cementation: First isopachous rims of equant crystal (arrowed) around the ooids and other grains (marine phreatic), followed by some sort of compactions that deformed original grains & these early cements & later the 2nd phase cementations; clear, coarser space filling burial cements (BC), formed. Also shows iron cement, reddish. **Sample** other view of K4, XPL, 100X magnifications.

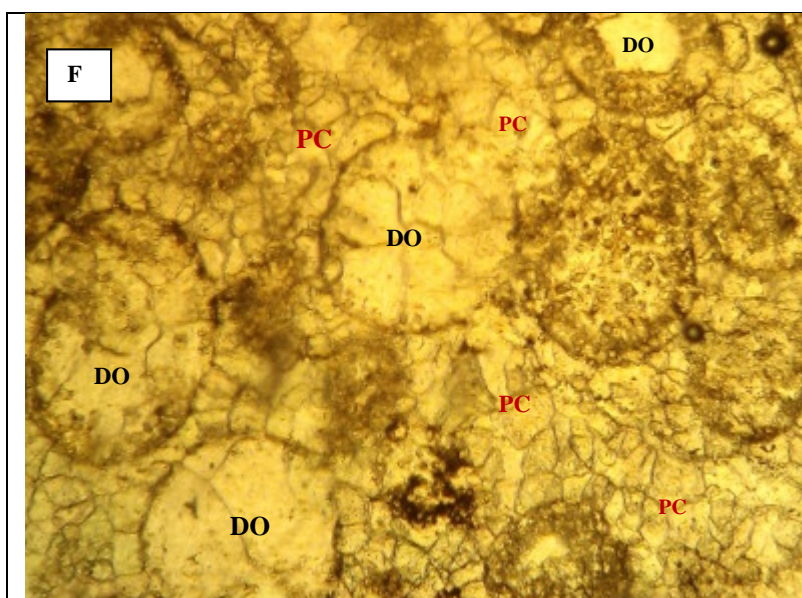


D) Microphotos showing two phases of cementations. First phase is precipitations of very fine circum-granular (phreatic origin), thin layers cements around the grains (arrowed) followed by 2nd phase precipitations of burial stage coarse grained cements (BC) in the void left between grains. The 2 phase of cements show different extinctions under rotations of stages, black and whitish.

Sample **R6**, XPL, and 100X magnification.



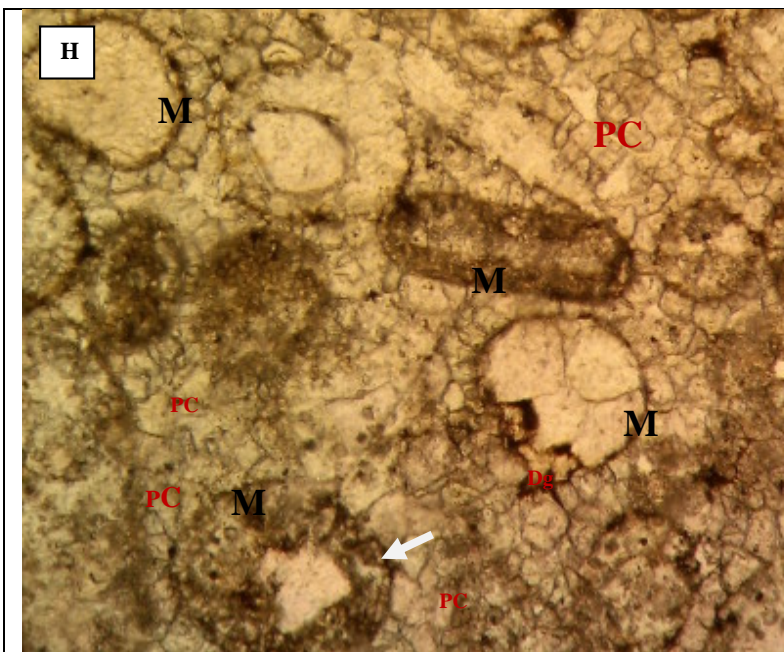
E) The same R6 sample above under PPL, also showing two phases of cements are rarely observed, the first phreatic cements (shown by green arrows) and the late coarser burial cements (**BC**).



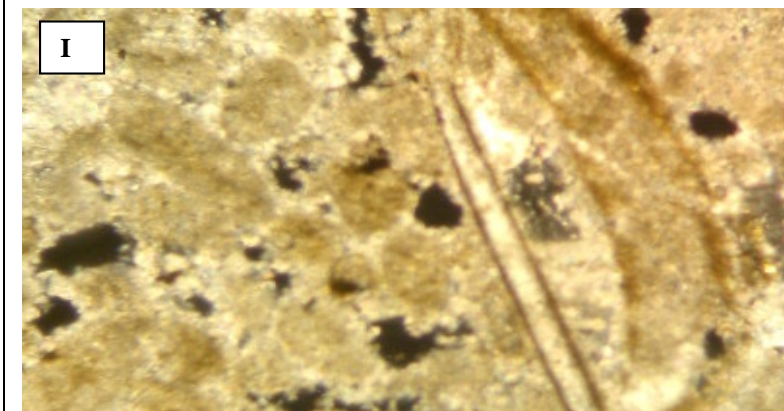
F) 1st metastable Ooid grains are covered by micritic envelopes, preserving ooid shapes & then they are cemented by blocky meteoric-phreatic cements (**PC**) & later on, these ooids are dissolved out (**DO**) losing their internal structure and again late stage cements are filling the dissolved places of those grains. Sample K2, PPL, 100X.



G)The same K2 sample above under XPL. Showing ooids and phreatic cements, but the phreatic cements are not easily separated under this views.



H) Other views of sample K2 under PPL, in which more than 3 phases of diagenesis are observed. 1ststage original grains are micritized(M), 2nd all spaces between grains are filled by phreatic blocky cements (PC),3rd compactions, 4th dissolutions of original grains, mostly ooids (Dg),5th those spaces in turn infilled by the late stage burial cements, coarser and whitish within micritic envelopes.



I) Meniscus type cements between the peloid grains which are meteoric vadose zone, precipitating mainly at grain boundary by reducing and rounding pore spaces(black color) between grains.

Sample K1, XPL, 100X.

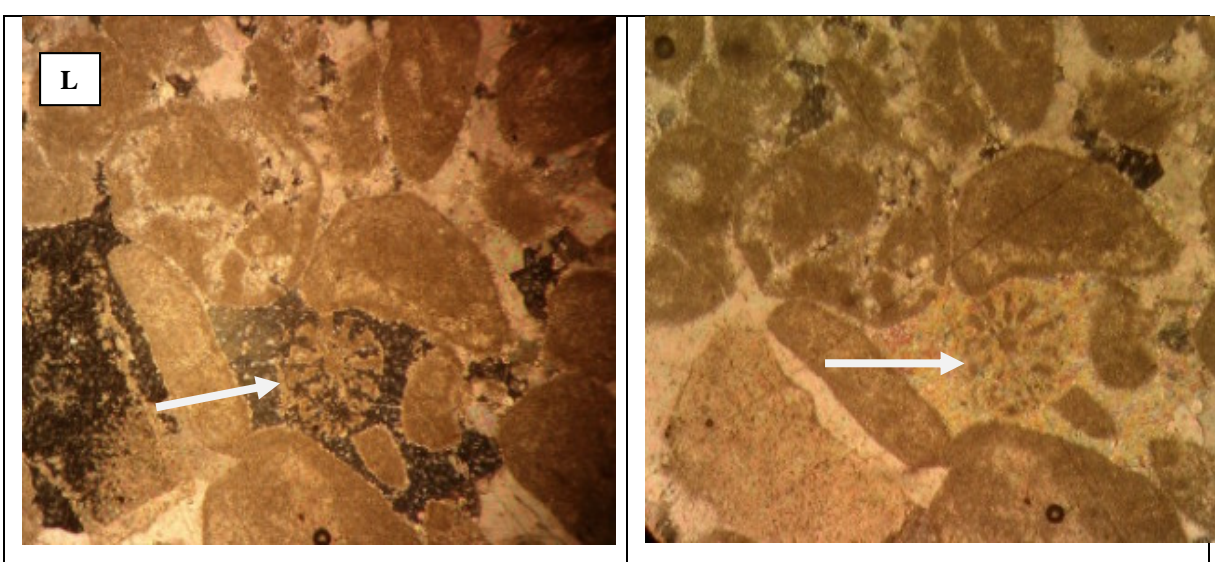
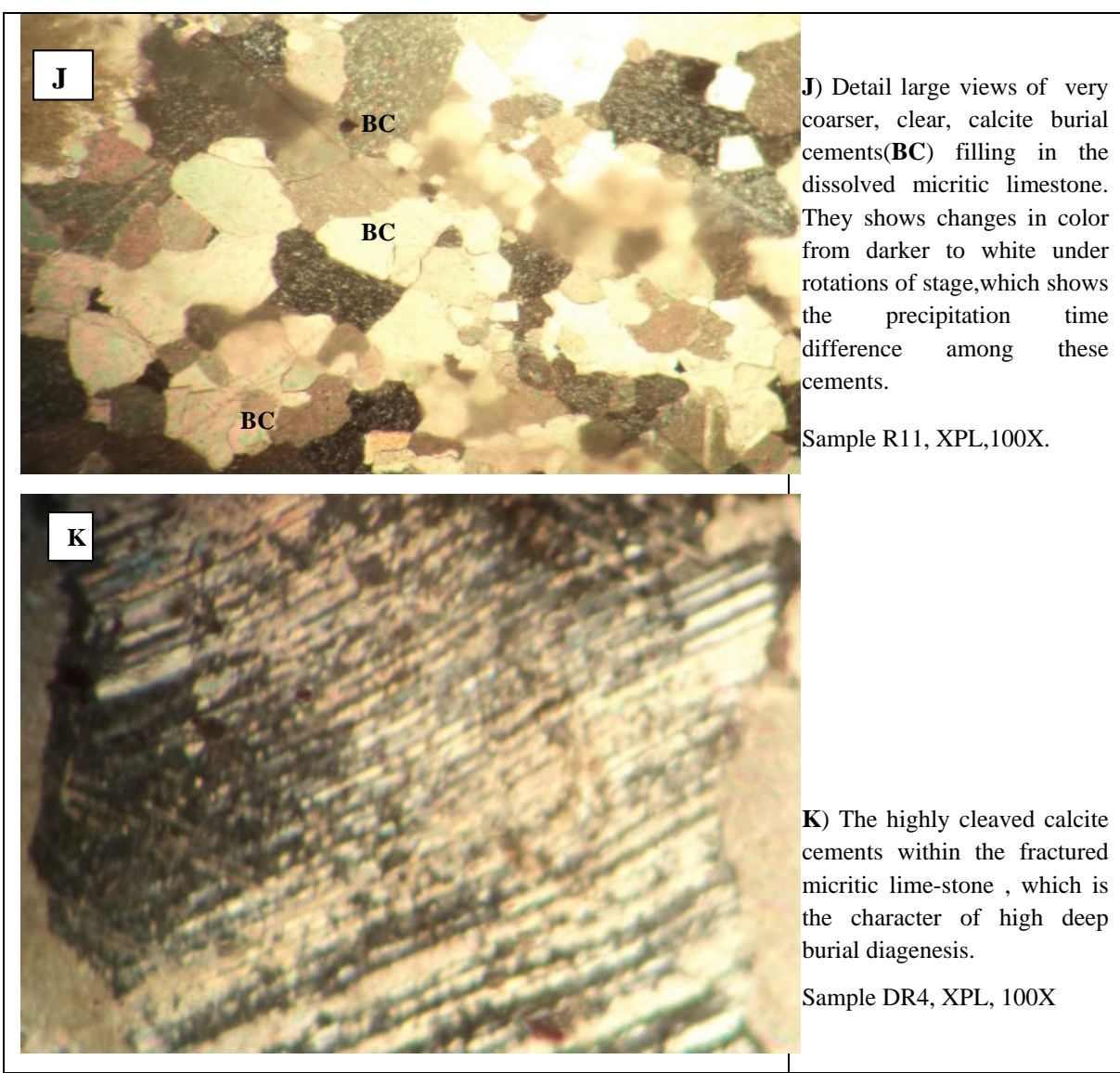


Plate 14: Microphotos of some replacements (dolomitization and silicifications)

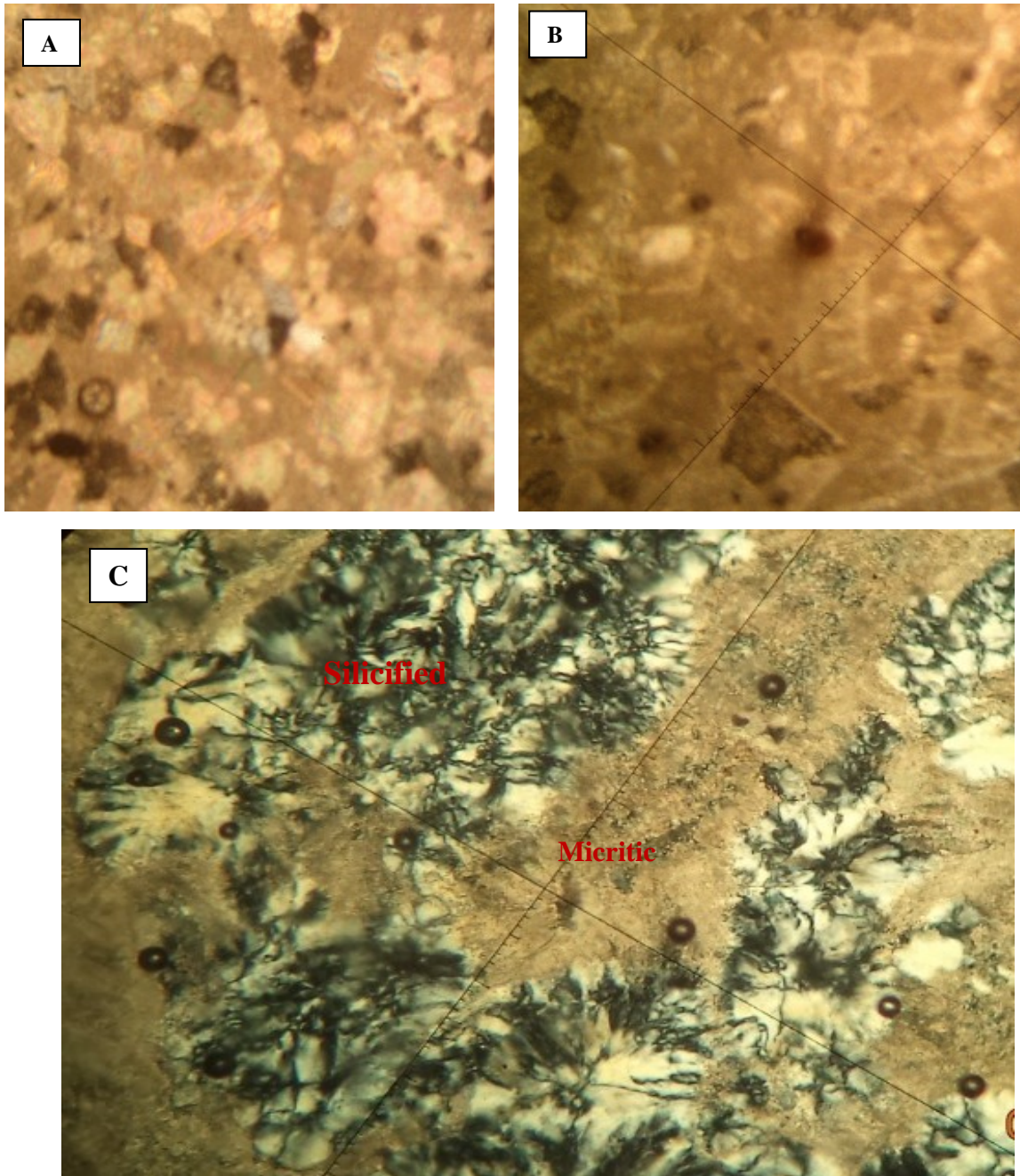


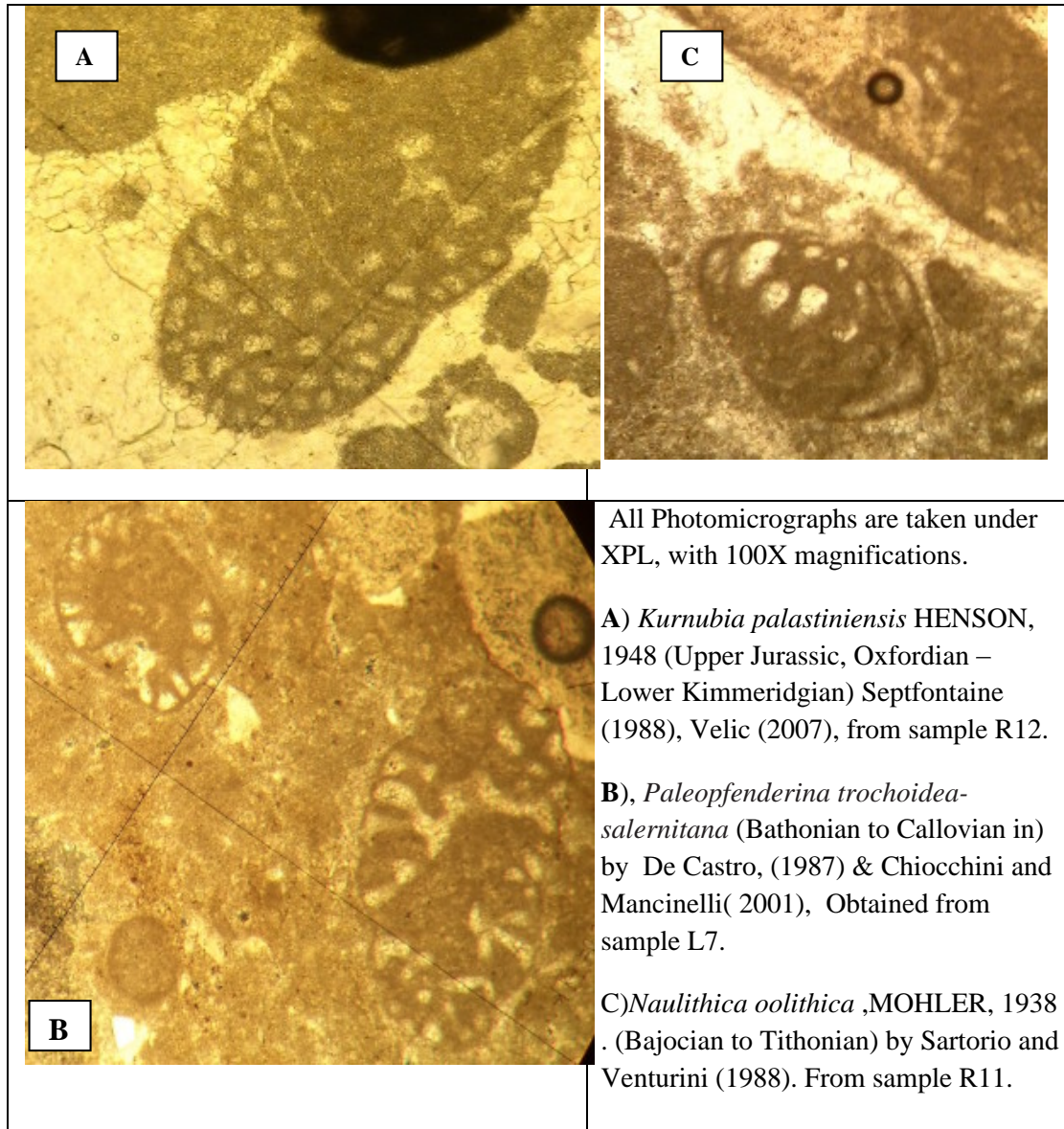
Plate 13: L) showing the syntaxial overgrowth cements in which the cements are overgrowth on a single echinoderm spines with optical continuities (arrowed). The left picture under XPL and the right one under PPL of sample R15. There are larger intraclasts imbedded within sparites

Plate 14: A) Microphotograph showing replacement process, partially dolomitized micritic limestone, showing some dolomoldic types of pore spaces(black colors in the photo graph). Sample R3, XPL, X40.

B) Dolomitized sample which also showing some dedolomitization processes, in which darker micritic sediments are filling and replacing the coarser dolomite rhombic shape crystals. Specifically at lower center of the picture. Sample H2, under XPL, 40X.

C) Silicified micritic limestone photomicrography of sample DR4 in which the Fibrous microcrystalline quartz (silicified) (consisting of zoning) replaced the micritic calcite minerals.

Plate 15: The Microphotos of fossils used for Age determination.



Appendixes

Under this appendix these tables are attached. Table 1 containing meteorological data of the area, obtained from Ethiopian meteorological agency office, table 2 containing detail petrographic analysis results for the representative rock samples collected from the study area during field works and the third table shows the distributions of SMFT and Facies belts on the generalized carbonate platform morphology taken from Wilson(1975).

Appendix 1: Meteorological data of Dire Dawa.

It consists mean monthly, seasonally and annual values of Dire Dawa Meteorological elements (temperature and rainfall)

	Parameters	Rainfall (mm)	Temp (⁰ c)
Month	Ja	21.7	21.8
	Feb	32.6	23.1
	Mar	71.1	25.3
	Apr	102.8	26.3
	May	46.8	27.7
	Jun	22.8	28.7
	Jul	92.6	27.1
	Aug	126.6	26.5
	Sep	68.2	26.7
	oct	25.5	25.6
	Nov	15.6	23.1
	Dec	9.6	21.7
Season	Winter	72.4	25.6
	Spring	253.3	21.6
	Summer	310.2	27.3
	Annual	636.0	25.3

❖ Data from Ethiopian meteorological agency office, 2013

Appendix 2: Petrographic description of carbonate rocks samples collected from Dire Dawa area.

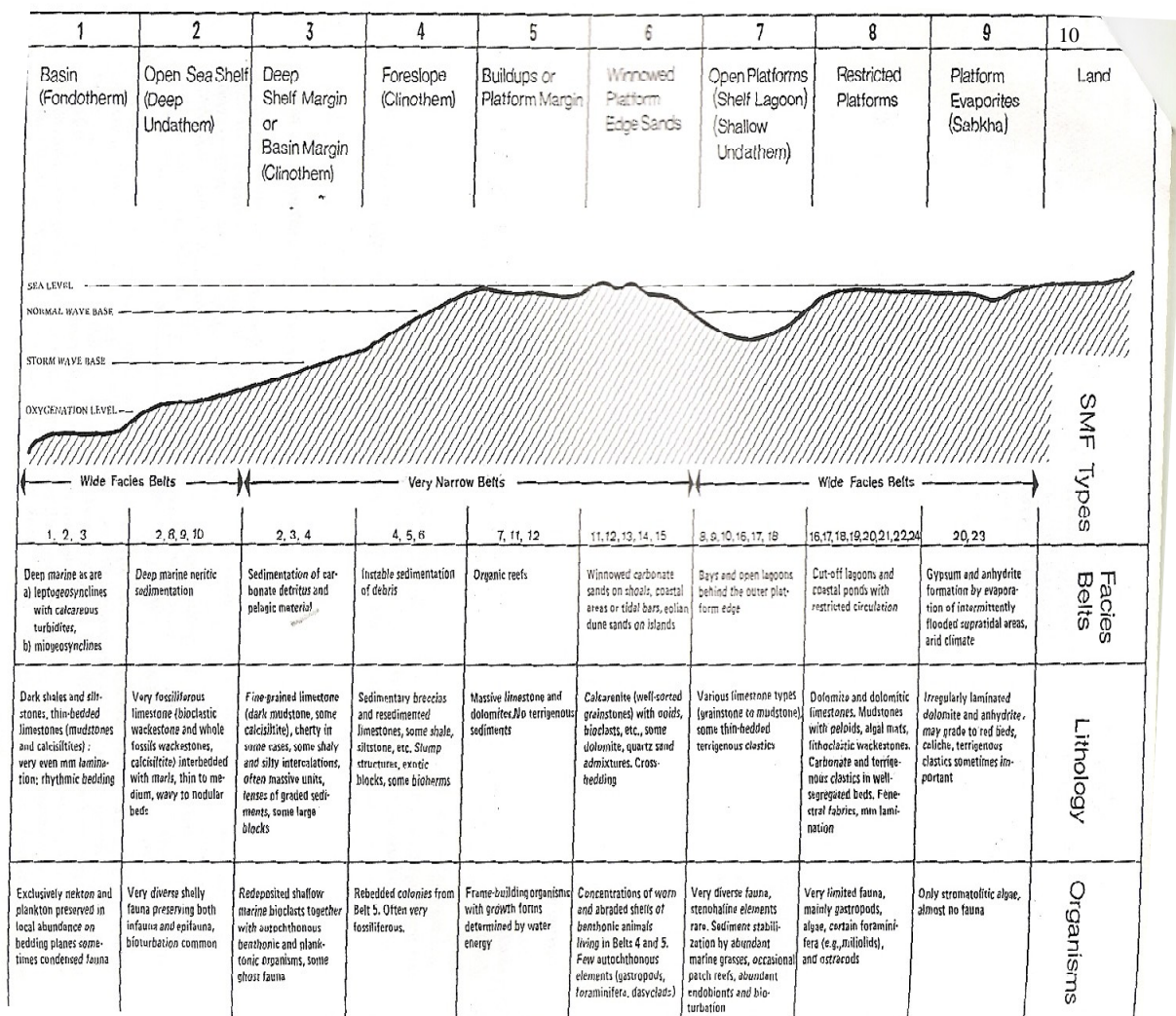
s e c t i o n	Sam ple No	Rock's major components (%)								Rock name
		Allochems				Interstitial materials		voids	Other	According to Dunham/Folk
		fos sil	ooi ds	pel oid	Intr a	Micr ite	Spar ite			
	IN1	-	-	-	-	-	25	1	74	Calcareous sandstone
	IN2	-	-	-	-	-	35	3	62	Calcareous sandstone
	IN3	-	-	-	-	2	40		58	Calcareous sandstone
	IN4	-	-	-	-	4	75	1	20	Calcareous sandstone
	L2					45	15	5	20	Dolomitic mudstone/micritic
	L3					70	10	2	2	Mudstone / Micritic
	L7	30		2	3	55	10			Wackestone/ Biomicrite
	K1	14		53		5	20	6	2	Grainstone/Biopelsparite
	K2	10	37	5			40	3	5	Oolitic grainstone/Oosparite
	K3	10	44				40	2	4	Oolitic grainstone/Oosparite
	K4	11	50			5	26	6	2	Grainstone/Bioosparite
Military Camp	M3					70	22	5	3	Mudstone/Micritic
	R1	2		30	5	35	20	4	4	Wackestone/Pelmicrite
	R3					35	5	7	53	Dolomitic mudstone/micritic
	R4					40	20	4		Dolomiticmudstone/micritic
	R6	20	1	10	35	6	25	2	1	Grainstone/Pelbiointrasparite
	R8	30	1	15	19	5	25	3	2	Grainstone/Biosparite
	R10	20		10	40	8	23	4		Grainstone/ Intrasparite
	R11	50		15	20	5	10	2		Grainstone/Biosparite
	R12	23	1	12	40	4	15	1	3	Grainstone/Intrasparite
	R13	21	1	10	35	20	10	2	2	Packstone/Biointra micrite
	R15	35		30	10	5	15	1	2	Grainstone/Pelbiosparite
R21	15	1	25	28	10	17	2	2	Packstone/ Biopelintrasparite	

Continuation of appendix 2...

	Samp. No.	Rock s' components (%)								Rock Name
		fossils	oids	peloid	Intra	Micrite	Sparite	voids	Other	
Dac hatu										According to Dunham/Folk
	DR1	15		4		60	20	1		Wackestone /Biomicrite
	DR2						75	6	10	Mudstone/Micritic
	DR4	3				65	25	5	2	Mudstone/Micritic
Late ral	M1	20				65	15			Wackestone/Biomicrite
	M4	5				73	20	2		Mudstone/Micritic
	H1	11				70	14	1	4	Wackestone/ Biomicrite
	H2					80	12			Dolomitic mudstone/micritic
	L1					52	15	2	6	Mudstone /Micritic
	L4	25				70	5			Wackestone/Biomicrite
	L5	15			2	70	9	2		Wackestone/Biomicrite
	L6	20				70	9	1		Wackestone/Biomicrite

Note: These tables shows the petrographic analysis results for collected samples from the study area. All samples were collected during field works from the three local stratigraphic sections sequentially from bottom to top, except those given in 'lateral' section, those collected randomly throughout the area laterally. Components given in the 'other' column includes other summations of other components rather than major carbonate components like quartz grains, cherts, dolomite minerals and other minerals, even though their amounts are varying from sample to samples. After giving proportions for all major components, the rock name were given according to the Dunham (1962) and Folk (1962) carbonate classification schemes.

Appendix 3: Facies schemes and sequences of standard microfacies types after Wilson (1975).



This 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.

DECLARATION

I, the undersigned, declare that, this thesis is my original work, has not been presented for a degree in any other university and that all source of material used for the thesis have been duly acknowledged.

Geramu Fufa Negari

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Approved by: Dr. Balemwal Atnafu (Advisor)

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May, 2014

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