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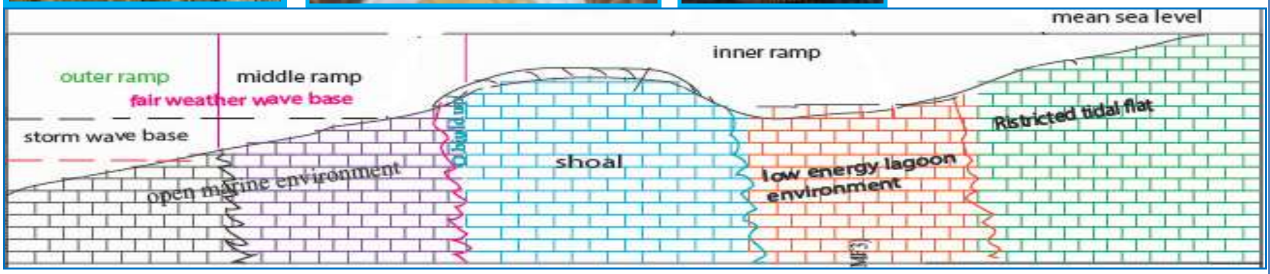
FACIES ANALYSIS AND PALEONTOLOGY OF CARBONATE SEDIMENTARY ROCKS IN HAGERE-SELAM, MESSOBO AND WUKRO STRATIGRAPHIC SECTIONS; NORTHERN ETHIOPIA, TIGRAI: IMPLICATION FOR DEPOSITIONAL ENVIRONMENT RECONSTRUCTION AND AGE DETERMINATION.



BY

WEREDE GIRMAY TESFASILASIA

A Thesis Submitted to the School of Earth Science, Addis Ababa University in partial fulfillment of the requirement for the Degree Master of Science (Stratigraphy and Sedimentology Program).

May 2018, Addis Ababa, Ethiopia

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DECLARATION OF ORIGINALITY

I hereby declare that the thesis entitled **“Facies Analysis and Paleontology of carbonate sedimentary rock in Hagere-Selam, Messobo and Wukro stratigraphic sections, Northern Ethiopia: Implication for Depositional Environment Reconstruction and Age Determination”** has been carried out by me under the supervision of Dr. Balemwal Atnafu, School of Earth Science, Addis Ababa University, Addis Ababa, Ethiopia during the year 2017-18 as part of Masters of Science program in Stratigraphy and Sedimentology. I Furthermore, declare that this thesis is my original master degree work and has not been submitted to any university or institution in the past for the award of any degree or diploma at any other university. All sources and materials used for this thesis work have been well referenced and duly acknowledged.

Werede Girmay Tesfasilasia ______________ ________________

Signature Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Balemwal Atnafu (Advisor) ______________ ________________

Signature Date

ABSTRACT

There is carbonate unit deposited in the Mekelle Outlier during the Upper Jurassic Period as a result of flooding of the area by Paleotethys Ocean toward the southeast direction. The Mekelle Outlier is situated in the northern most part of Northwestern Plateau (NWP) and the study carbonate successions are aligned along the western (Hagere-Selam), southeastern (Messsobo) and northeastern (Wukro section) margin of the Mekelle Outlier. This study focused on detailed investigation of facies analysis and paleontology of the Upper Jurassic carbonate units in order to obtain a detailed picture of depositional environment, age determination and correlation. Three main methods were implemented in order to accomplish the stated research problem and objective of the present study. These are pre-fieldwork, a detailed main fieldwork and laboratory analysis (petrographic analysis, micro and macro fossil description and systematics and microfacies analysis). A total of 65 rocks and 26 productive dry marl sediment samples are collected from the study sections and examined under petrographic microscope. Lithostratigraphically, the carbonate succession has a total thickness about 400m, which is characterized by thin-thick bedded limestone, mudstone, fossiliferous, coquinoidal, oolitic and sandy limestone with different skeletal components and different sedimentary structures. Based on a detailed field investigation, paleontological and petrographical information, 19 microfacies type are recognized. These are grouped into four microfacies association including tidal flat (MFT1-3), lagoon (MFL1-2), shoal (MFS1-6) and open marine environment (MFO1-8). Therefore, the depositional system of the carbonate succession represents a homoclinal ramp setting because of thier wide lateral and vertical distribution of facies. Additionally, the carbonate units of the study area are affected by different diagenetic features including compaction, cementation, dissolusion, micrtization, dolomitization, neomorphism, and silicification. The carbonate rock units are correlated within different measured sections in the Mekelle Outlier and regionally correlated with the Antalo Limestone of Blue Nile, the Urandab Formation of Ogaden, the Antalo Limestone of Eretria and other Arabian platforms based on biostratigraphy and lithostratigraphy.

Keywords: *Stratigraphy, Microfacies analysis, Age, Paleontology, Depositional environment, diagenesis, Mekelle Outlier*.

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LIST OF ACRONYMS

E	East	ml	milliliter
FWWB	Fair Weather Wave Base	MMS	Messobo marl sample
FZ	Facies Zone	MS	Messobo rock sample
GPS	Global Positioning System	N	North
H	Hagere-Selam	NWP	Northwestern Plateau
Hcl	Hydrochloric acid	PPL	Plane polarized light
HMS	Hagere-Selam marl sample	S	Sample
H_2O_2	Hydrogen peroxide	SEP	Southeastern Plateau
HS	Hagere-Selam rock sample	SMF	Standard Microfacies Type
ICONS	Intracontinental Sag	SWB	Storm Wave Base
		sp	Spices
M	Messobo	W	Wukro
MERV	Main Ethiopian Rift Valley	WMS	Wukro marl sample
M	meter	UTM	Universal Transversal Mercator
MFL	Microfacies Lagoon	USA	United State of America
MFO	Microfacies open marine	W	West
MFS	Microfacies Shoal	WS	Wukro rock sample
MFT	Microfacies Tidal	XPL	Cross polarized light

CHAPTER ONE

1. **INTRODUCTION**

1.1. **Background and Justification**

Sedimentary basins are regions of depression due to prolonged crustal subsidence, in which sediments are accumulated (Philip and John, 2005). Excluding the thin Quaternary and unconsolidated sediments, which are deposited in the main Ethiopian rift valley, sedimentary regions of Ethiopia covers a major part of the country and mainly exposed in five distinct basins which are located in different part of the country (Ethiopian Ministry of Mines, 2011) (Figure 2.1).

The Mekelle Outlier is one of the major Mesozoic sedimentary basin in Ethiopia, which is situated in Northern Ethiopia that exposed from Amba-Alage mountain in the southern part up to Wukro town towards the north and Abi-Adi on the western part, it also extend to the east up to the western escarpment of the Ethiopian rift valley.

In terms of structural evolution, Beyth (1972b) proposed that it is an intramontane origin that was formed by the rise of two east-west trending structural highs around 13^0N and other one 14^0N latitudes between Wukro fault belt and Precambrian rock. Later on, Bosellini et al. (1989; 1997); Russo et al. (1994), and Merla et al. (1979) postulated as intracontinental rift related basin formed as a result of extensional stresses induced by the break-up of Gondwanaland since the Late Paleozoic to Tertiary Period similar to the Blue Nile and Ogaden basins; however, recently the structural evolution of the Mekelle Outlier suggested as sag basin (ICONS) with the help of geological field, remote sensing and geophysical gravity data (Tadesse et al., 2018).

The Mekelle Outlier is filled with a thick succession of carbonate sedimentary rock, which is conformably underlain and overlain by continental to shallow marine clastic Adigrat Sandstone and regressive related Agula Shale or unconformably by Amba Aradom Formation respectively and it forms a nearly circular outlier of 8000 km^2 in the area around Mekelle (Beyth, 1972a and Bosellini et al., 1997). These Upper Jurassic carbonate rocks are a type of chemical biochemical sedimentary rock deposited in marine environment that contain carbonate ion ($CO3^{2-}$), important various textures, sedimentary structures, skeletal and non-skeletal grains that yield important information about ancient depositional environments, paleoecological conditions, biostratigraphic position and paleoenvironmental interpretation (Boggos,2009). Also, they are significant economic importance because, they act as reservoir rocks for petroleum, as aquifer for ground water and can be useful for agricultural and industrial purposes, since they form good soils and good building stones and cement.

Many researchers have studied the Upper Jurassic carbonate rock in the Mekelle Outlier from stratigraphic, sedimentologic, geochemical and paleontological point of view, among these are: Beyth (1972); Bosellini et al. (1997); Worash and Valera (2002) and Kiessling et al. (2011). Four different facies are identified from bottom to top as: **A**. A cross-bedded sandy oolitic and coquina with minor marl and few chert beds, **B**. Interbedding of marl and limestone with abundant brachiopods and some algal, **C**. Cliffs of coral and algal reef limestone interbedded with marl and biostromes and **D**. Finally black to grey microcrystalline limestone interbedded with marl Beyth (1972a; b). Also, Bosellini et al. (1997) attempted to subdivide the carbonate unit into four depositional sequences (A1 to A4), which are composed of thickening and shallowing up cycles.

Additionally, the carbonate unit was assigned into different age by different authors on the base of different index fossils. For example, based on benthic foraminifera Bosellini et al. (1997) assigned the age of the Antalo Limestone to Late Callovian(?)-Kimmeridgian; however, Martire et al. (2000) attempted to assign as Oxfordian-Kimmeridgian age based on ammonite macrofossil. In addition to this controversial idea relative to age of the carbonate succession, the study area was roughly investigated in terms of facies analysis, paleontology especially micropaleontology, depositional environment interpretation hence, this is the first detailed study.

To get all such interesting information and resources of carbonates deposits, a detail studies was carried out with the help of different methods and concepts. Among them, facies analysis and paleontology are the most powerful methods for detail investigations of carbonate sedimentary rocks. Facies analysis refers to a method of characterizing bodies of rocks with unique lithological, physical and biological attributes relative to all adjacent deposits that indicate a particular depositional environment. Therefore, the main objective of the present work is to provide a detailed investigation of facies analysis and paleontology of carbonate succession in order to obtain a detailed picture of depositional environment interpretation, a detailed microfacies analysis, stratigraphic position and to see their lateral and vertical relationship among the carbonate successions.

1.2. General setting of the study area

1.2.1. Location of the study area

As part of East Africa there are three main geomorphologic features of Ethiopia, namely Northwestern Plateau (NWP) and the Southeastern Plateau (SEP) that is separated by the Main Ethiopian Rift Valley (MERV) (Figure 1.1E). The study area under investigation situated in the Mekelle Outlier, Tigrai region part of Northwestern Plateau (NWP) around 783 km far from Addis Ababa the capital city of Ethiopia to Mekelle town capital of the Tigrai province.

The present studies were undertaken on three locally selected stratigraphic sections throughout the Mekelle Outlier. These sections are: **1**) Hagere-Selam section: Which is located 35 km northwest of the Mekelle town between Ale-Asa and Tanka Avergale villages, along the main road Mekelle-Abi Adi, **2**) Messobo section: Located near the Mekelle town at about 5 km far to the northeast, along the main road Mekelle-Wukro and **3**) Wukro section: Located near Wukro town at 25 km distance from Mekelle toward north along the main road Mekelle-Wukro-Adigrat and Further, bifurcate to northwest of Wukro-Hawzen by gravel road about 2.5 km (Figure 1.1 A, B, C, D, and E).

Geographically, the measured sections are bounded between 523033 to 524826 m E, 1509836 to 1505936 m N, 554988 to 557002 m E, 1499022 to1473984 m N and 560557 to 563074 m E and 1527034 to 1523343 m N in UTM and found in the Abi Adi, Agula and Wukro separate sheet respectively.

1.2.2. Accessibility of the study area

The study area can be accessed from Addis Ababa through main highways passed via Dessie-Woldiya-Almata-Mekelle (783 km) and they are other important asphalt road, which are significant to reach the study area. There are two main asphalt and gravel roads that bifurcate from Mekelle-Hagere-Selam, Mekelle-Maimekden and Mekelle-Wukro-Hawzen respectively (Figure 1.1 A, B, C). Most of the areas between these main asphalt and gravel roads are inaccessible to four-wheel drive vehicles; however, numerous interweaved footpaths and stream provide additional access during the field work.

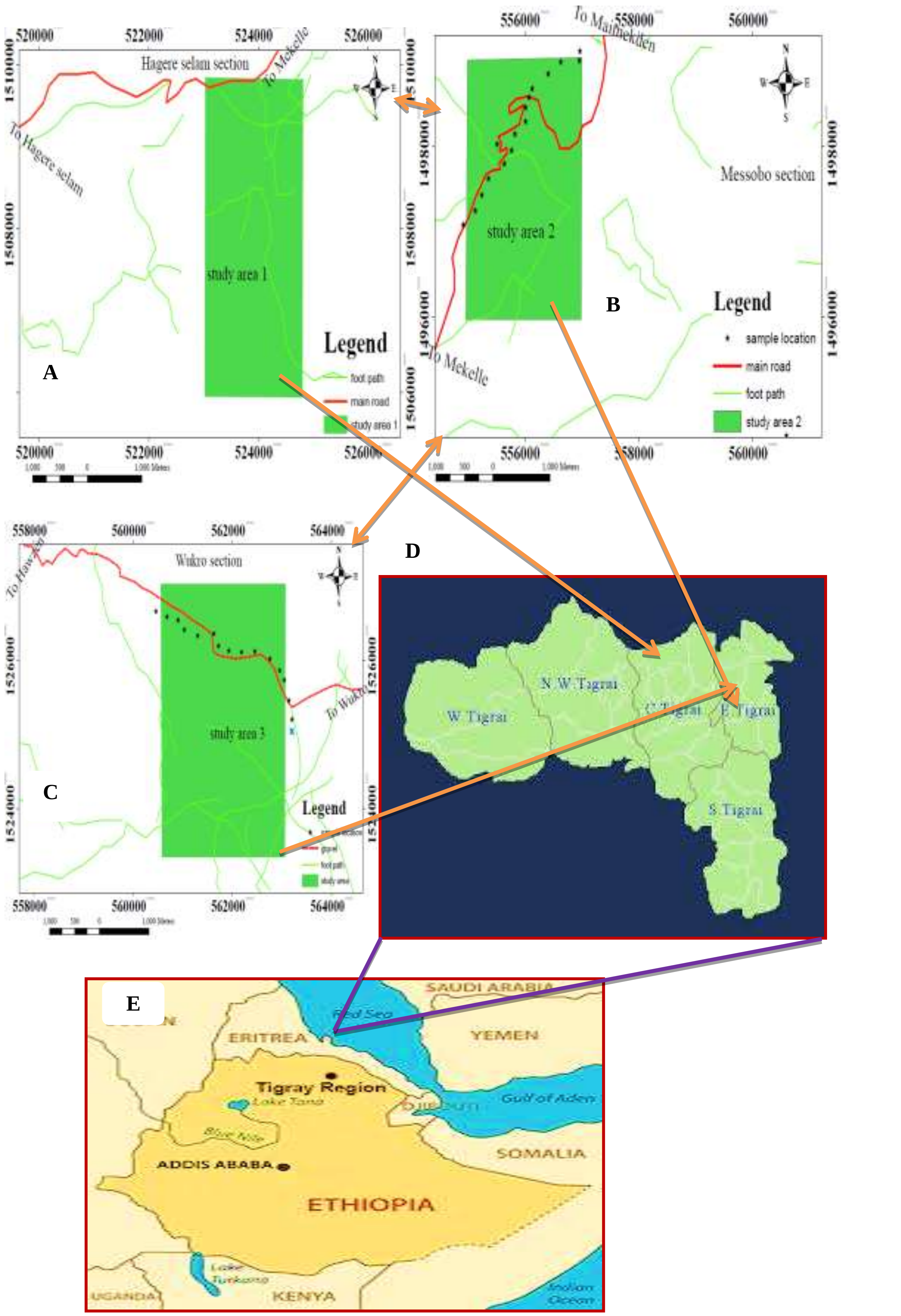


Figure 1.1: *Location and accessibility map of the study area* (**A**) *Hagere - Selam* (**B**) *Messobo* (**C**) *Wukro* (**D**) *Tigrai and* (**E**) *Ethiopia map.*

1.2.3. Physiography of the study area

The Mekelle Outlier is part of Northwestern Plateau (NWP) which is bounded in the east by the western escarpment of the Danakil Depression, in the west, north and south by Tigrai Plateau (Beyth, 1972b). Therefore, the study area is characterized by different topographic features including hills, ridges, deep gorge, rugged terrains, plateaus and flat lands. The hill and ridge of the area is deposited by massive, bedded limestone unit and upper sandstone whereas, the flat surface consisted by marl and shale rock unit. The present landform of the study area is result of tectonic activities of Wukro, Mekelle, Chelekot fault and different diorite dike.

1.2.4. Drainage pattern of the study area

The study area is drained with the Genfel (Wukro), Ilala (Messobo) and Menzegzeg (Hagere-Selam) main rivers and other small tributaries that drained into the main river valley including Menketket and Tiliku Arato (Wukro) and Arkeka, Medhani Alem (Hagere-Selam) section (Figure 1.2). Most of the streams flow seasonally and joining with the main river flowing together towards the northwestern and western direction of the study area into Giva finally to Tekeze river. The drainage pattern of the stream and Main River shows variation in density of water flow due to seasonal variation. Most of the measured stratigraphic section especially in the Wukro and Hagere-Selam area, the carbonate rocks are exposed due to river and stream cut. Therefore, sampling and lithological description were conducted following the river and stream cut. Generally the study area is characterized by dendritic to trill drainage pattern.

1.2.5. Climate and vegetation of the study area

1.2.5A. Climate

Sub-tropical (Woina Dega) to hot semi-arid climate conditions with bimodal rain fall are the main climatic conditions of the study area. Based on rainfall and climate, the study area can be categorized into two broad seasons. These are the dry season (winter), which covers the period from October to May and wet season (summer) extends from June to September, with slightly rainfall during autumn and spring. The most highly rainy season was from end of June up to September. The annual mean temperature of the study area is 18.9^0C in the Messobo and Wukro section with 590 mm annual precipitation whereas, in the high land of the Hagere-Selam section, the annual temperature is about 15.1^0C with annual precipitation 689 mm (Tigrai meteorological agency, 2001).

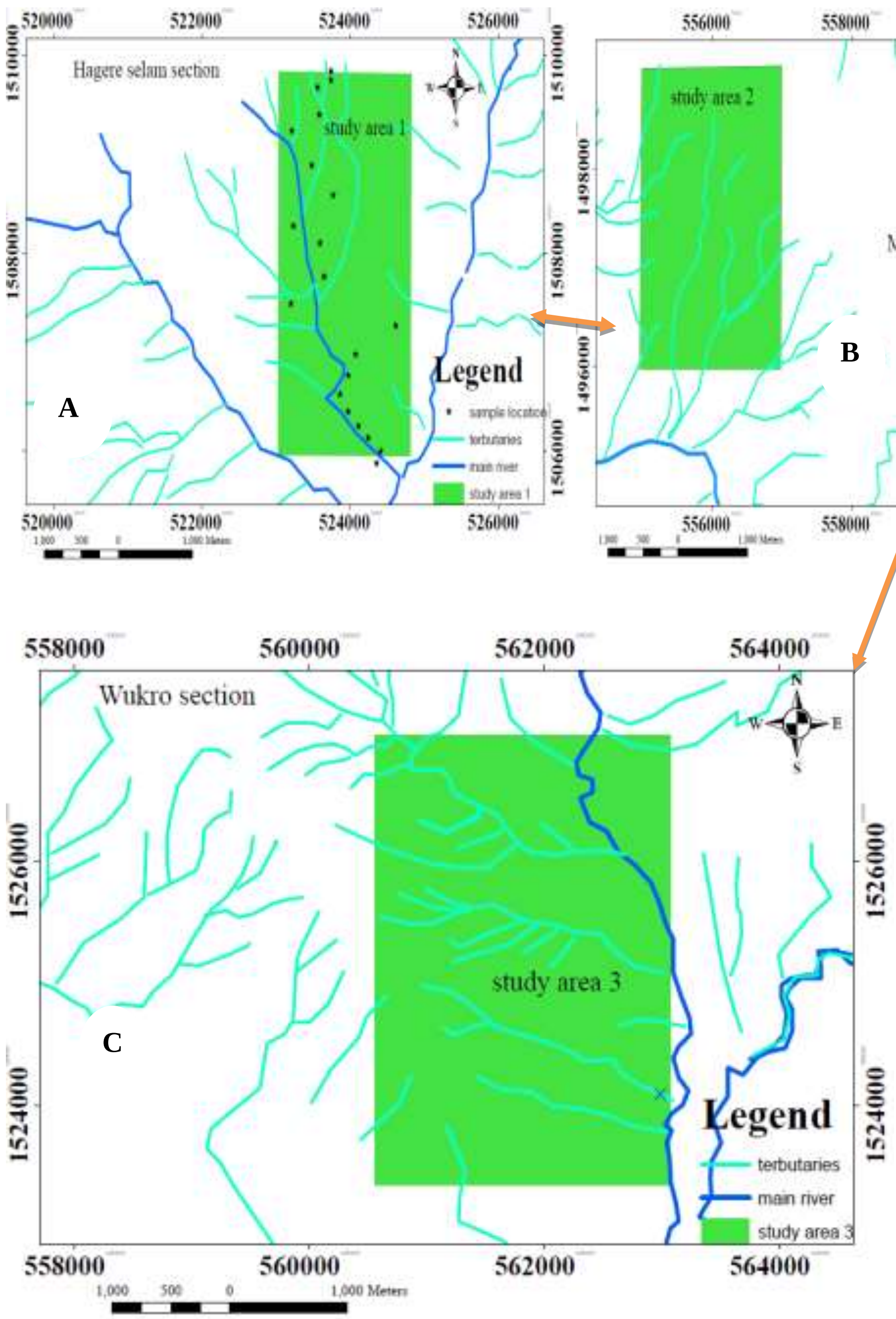


Figure 1.2: *Drainage map of the study area* (**A**) *Hagere - Selam.* (**B**) *Messobo and* (**C**) *Wukro section.*

1.2.5B. Vegetation coverage

Vegetation type and its distribution in the study area vary with soil type, elevation and humidity and/or rainfall. Accordingly, there are areas of slightly forest, woodland and grassland coverage. Forest coverage mostly occurs along the main river valley, its tributaries and black fertile marl sediment deposit. The grassland region occurs on the lowland of black marl fertile soil and along the river valley and its tributaries. The plateau is mostly covered with scarce shrub vegetation.

1.2.6. Population and settlement

The study area is mainly inhabited by Tigrai nationalities, who speaking Tigrina language. They are dominated by Christians with some Muslim religious. Different ethnic groups live in the neighboring town including Shao, Afar, Tigrai, Amhara etc. The rural area is randomly distributed, due to the differences in the suitability of environmental conditions for settlement and also due to socio-economic factors. Among the major environmental factors that influence population distribution in the area are the geomorphic characteristics (relief) and the suitability of the land for farming, livestock and animal breeding. Most of the people of the area live in the lowland and on the plateau due to suitability for domestic animal breeding and farming. They participate in agricultural practices, cultivating different kinds of crops such as wheat, maize, barley, sorghum and teff. In addition, most of the rural residents participate also in breeding of all domestic animals such as cattle, sheep, goat and donkeys commonly.

1.3. Review of previous works of the carbonate succession

The study of sedimentary rocks in Ethiopia has been started since the middle of the nineteenth century (Blandford, 1870; Dainelli, 1943; Mohr, 1962 and Kazmin, 1973). Mainly, the Mesozoic sediments in the southeastern Ethiopia (Ogaden basin) were more studied relative to other sedimentary basins by foreign petroleum exploration companies for its petroleum potential.

The Mekelle Outlier contains a wide variety of Paleozoic to Mesozoic sedimentary rocks, which are unconformably underlain and overlain by Precambrian basement and Tertiary continental flood basalt respectively (Beyth, 1972a and Bosellini et al., 1997). Many published and unpublished regional sedimentological, stratigraphical, geochemical and paleontological studies were undertaken by different researchers at different times after a type section located first near the Antalo village (Blandford, 1869; 1870). Among these are Beyth (1972); Bosellini et al. (1995; 1997); Worash and Valera, (2002), and Kiessling et al., 2011) etc.

These carbonate units were well described and studied by Levitte (1970); Beyth (1972b) and Bosellini et al. (1997). According to Beyth (1972a; b) the thickness of the carbonate succession ranges from 300 m in the west to 800 m in the east and he identified four different facies. Later on, Bosellini et al. (1997) attempted to subdivide the Antalo Limestone units into four depositional sequences (A1 to A4), which are composed of thickening and shallowing up cycles. Additionally, age of the carbonate units were determined on the base of different index fossil according to Bosellini et al. (1997) and Martire et al. (2000). Geochemistry and paleontology of the Antalo Supersequences were studied by (Worash and Valera, 2002 and

Kiessling et al., 2011) respectively. Recently the structural evolution of the Mekelle Outlier explained as Sag (ICONS) using different methods (Taddesse et al., 2018).

1.4. Statement of the research problem

The carbonate succession of the Mekelle Outlier was studied by different scholars, who have different fields of specialization. Most of the previous works on carbonate units in the Mekelle Outlier are regional and focused on sedimentological, stratigraphical, geochemical and paleontological of the Antalo Supersequence by combining both the Antalo Limestone and Agula Shale; however, these two rock formations have different in mode of formation, age and thier depositional environment (Beyth, 1972a; Bosellini et al., 1997; Martire et al., 1998; Worash and Valera, 2002 and Kiessling et al., 2011).

Additionally, the Antalo Limestone was assigned into different age by different scientists using different index fossils. For example, Bosellini et al. (1997) assigned the age of Antalo Limestone using benthic foraminifera fossil to Late Callovian(?)-Kimmeridgian whereas, Martire et al. (2000) attempted to assign as Oxfordian to Kimmeridgian age based on ammonite macrofossil.

Besides, the carbonate rock unit in the Mekelle Outlier is the least investigated interms of a detailed facies analysis, depositional environment interpretation and paleontology, especially in micropaleontology. Therefore, this is the first detailed study focused on facies analysis and paleontology of carbonate rock unit.

1.5. Objectives of the research

1.5.1 General objectives

The general objective of this research study is to provide a detailed investigation of facies analysis and paleontology of carbonate succession in order to obtain a detailed picture of depositional environment interpretation, age determination and to see the lateral and vertical relationships of the carbonate succession in the Hagere-Selam, Messobo and Wukro stratigraphic sections.

1.5.2. Specific objectives

The main specific objectives of this research are as follows:-

- ✓ To study paleontology of carbonate succession.
- ✓ To describe and interpret a detailed microfacies analysis.
- ✓ To reconstruct the depositional environment.
- ✓ To elucidate the age of a carbonate unit.
- ✓ To construct a detailed stratigraphic log.
- ✓ To correlate the carbonate rock unit intrabasinally and regionally.

1.6 Expected output of the research

Finally, the wealth of information about paleoenvironment reconstruction, biostratigraphic position, microfacies analysis, stratigraphic relationship and correlation of carbonate rocks of the study area helps us to understand by studying a detailed facies analysis and paleontology of carbonate rocks unit.

1.8. Limitation of the study

The main limitation of this thesis work is lack of published and unpublished data conducted on the carbonate units of Mekelle Outlier especially, related to facies analysis, depositional environment and micropaleontology for comparison and correlation.

CHAPTER TWO

2. REGIONAL GEOLOGICAL SETTING OF THE MESOZOIC SEDIMENTARY BASIN AND THEIR STRATIGRAPHIC SUCCESSION OF THE MEKELLE OUTLIER.

2.1. Introduction

Sedimentary basins are regions of depression due to prolonged crustal subsidence, in which sediments are accumulated (Philip and John, 2005). These are originated due to crustal subsidence relative to their surroundings, often uplifted areas. Sedimentary basins exist in a diverse geological setting usually environment of active plate motions. Therefore, the essential concept is being the tectonic creation of place of high to provide both as a source of sediment due to erosion and a relatively low place for the accumulation and/or deposition of these eroded sediments.

2.2. Geodynamic setting and sedimentation in Ethiopian sedimentary basins

Excluding the thin Quaternary, unconsolidated sediment deposits, the sedimentary basins of Ethiopia cover a significant portion of the country, which are mainly exposed in five distinct basins that located in different part of the country (Ethiopian Ministry of Mines, 2011) (Figure 2.1). These are: In Southeastern Ethiopia the Ogaden, Central Ethiopia the Blue Nile, Northern Ethiopia the Mekelle, Western Ethiopia the Gambela and Southern part of the Southern rift basins.

Figure 2.1: *Sedimentary Basins of Ethiopia (source: Ethiopian Ministry of Mine, 2011).*

Tectonic evolutions throughout Northeastern Africa of the country and sea level fluctuations through geologic time in general have the great roles for the formation of these basins and thick Mesozoic sedimentary sediments accumulation within them.

In terms of structural evolution, most of these sedimentary basins are related to the extensional tectonic events that have taken place intermittently since, the Late Paleozoic and continued up to Tertiary Period. The Ogaden, Blue Nile and Mekelle Outlier are presumed to be an intracontinental rift related basins formed as a result of extensional stresses induced by the break-up of Gondwanaland starting from the Upper Paleozoic up to Tertiary Period (Mohr, 1962 and Blandford, 1970). However, the Mekelle Outlier was explained as an intramontane origin that was formed by the rise of two east-west trending structural highs, around 13^0N and other one 14^0N latitudes between Wukro fault belt and the Precambrian rock (Beyth, 1972b). Recently according to Tadesse et al. (2018), the structural evolution of the Mekelle outlier attempted to describe as sag basin (ICONS) using geological field, remote sensing and geophysical gravity data.

In addition to this tectonically controlled formations of the Ethiopian sedimentary 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 these basins and to serve for different resources including gypsum, limestone for cement and construction materials etc.

In general the Late Paleozoic to Mesozoic sedimentary basins of Ethiopia is the result of a complex history of suturing and rifting during cyclical assembly and dispersal of supercontinents Dawit Lebenie (2010). This complex evolution of general Late Paleozoic to Cenozoic succession involves: Tectonic quiescence and associated peneplanation of the Precambrian rock during the Early to Middle-Paleozoic Period and severe regional glaciation and subsequent marine incursions from the Paleotethys in the Late Paleozoic times, which serve for deposition of Late Paleozoic sedimentary sediment in different part of the region. Then a large scale down warping of the entire East African continents took place during the Upper Triassic to Lower Jurassic time and consequently fluvio-deltaic sediments (Adigrat Sandstone) deposited over a large area, extending up to the western and northern regions of Ethiopia(Dawit Lebenie, 2010). Furthermore, rifting and subsidence of the region including the Saudi Arabia and Yemen areas led to the transgression of the sea from the east and southeast, flooding an extensive area and lead to deposit the marine carbonate unit (the main focus of present study) as depth of the water body increases (Dainelli,1943). Then as the result of arching and doming of the Arabian-Somalian massif regression of the sea from Ethiopia began in the Late Jurassic and sediments of varying facies including restricted marine, lagoonal and supratidal to inter-tidal were deposited in structurally controlled domains. The deposited sediments after withdrawal of the sea are Agula Shale in the Mekelle Outlier, Gebredare in the Ogaden and Muger Mudstone in the Blue Nile basin (Ethiopian ministry of mine, 2011).

2.3. Jurassic carbonates Formations within Ethiopian sedimentary basins

According to Beyth (1972b), Assefa (1988; 1991) and Asrat et al. (2008) thick carbonate successions are found with different thickness and exposure mainly in three different regions of Ethiopia: In Northern Ethiopia, the Mekelle Outlier and Danakil Depression, Central Ethiopia, the Blue Nile and Southeastern Ethiopia, the Ogaden basin including western Hararghe region (Figure 2.2). Depending on geographical name of their deposit different name have given for the Upper Jurassic limestone. For example, Antalo Limestone Formation (in the Mekelle Outlier and Blue Nile) after a type section located first in the Antalo village, Hamanlei Formation and Urandab Formation in the Ogaden basin.

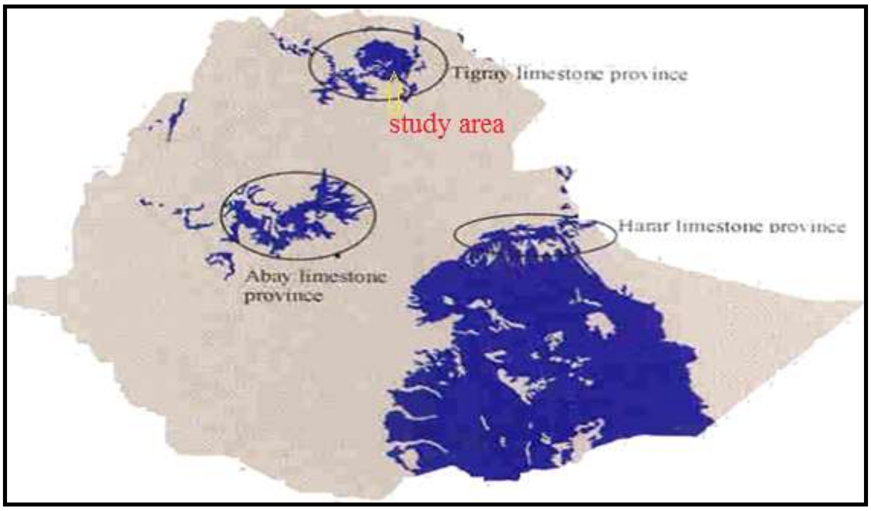


Figure 2.2: *The major sedimentary rock of Ethiopia (source: Ethiopian ministry of mine, 2011).*

2.4. Stratigraphy of the Mekelle Outlier

Rocks ranging in age from Precambrian basement to recent constitute the geology of the region. These are the Precambrian rocks, the Paleozoic to Mesozoic sedimentary rocks, the Tertiary flood basalt and Quaternary unconsolidated sediments. Therefore, the general stratigraphy of Northern Ethiopia is characterized by the Precambrian basement, the Late Palaeozoic and Mesozoic sedimentary successions, the Tertiary continental flood basalts (Trap series) and Quaternary sediments from the older to younger in age respectively (Figure 2.4). Their detailed stratigraphies are discussed as follows:

2.4.1. The Precambrian basement

The Precambrian basement of Northern Ethiopia is the oldest rock of the Upper Proterozoic age. This contains low-grade volcano-sedimentary succession and mafic-ultramafic complexes of the Arabian Nubian Shield with their associated syn to post-tectonic intrusions (granites, granodiorites, diorites and aplitic dikes) (Kazmin et al., 1978).

The geology of Northern Ethiopia was easily interpreted or understood by previous workers in isolation of much more detailed information and crustal evolutionary concepts as a single major stratigraphic unit, Tsalit group (Beyth, 1972b). Moreover, the entire region was grouped as the upper complex and considered to be the youngest of the metamorphic basement of Ethiopia (Kazmin et al., 1978). The Precambrian basement of the Northern Ethiopia is underlain by low-grade metavolcano sedimentary and plutonic rocks of the Pan-African Arabian Nubian Shield assemblage and is a juvenile (Mantle-derived) domain formed by subduction-related arc accretions (Tadesse, 2000 and Asrat, 2001).

2.4.2. Palaeozoic to Mesozoic sedimentary successions of Northern Ethiopia

According to a researchers of Blandford (1869; 1870); Dow et al. (1971); Beyth (1972a; b), and Merla and Minucci (1938) the Late Paleozoic-Mesozoic sedimentary rocks of the region attempted to subdivided into six units. These are: Enticho Sandstone, Edaga Arbi Glacials, Adigrat Sandstone, Antalo Limestone, Agula Shale and upper sandstone (Amba Aradom Formation) (Shumburo, 1968) from older to younger which are unconformably overlain and underlain by Tertiary continental flood basalt and basement rock respectively.

2.4.2A. Enticho Sandstone

The Enticho Sandstone was named first by Dow et al. (1971) after its type section located first near the Enticho town on the Axum-Adigrat road with geographic location (N 14°16′/E 39°09′) in Northern Ethiopia, Tigrai province. This rock unit is unconformably overlain the Precambrian basement rocks, with maximum thickness about 160-200 m. It is characterized by white, coarse grained and friable sandstone. Additionally, it contains calcareous, ferruginous coating materials, bed of siltstone, grit and polymict conglomerate, quartz arenites, large scale cross bedding and at places contains erratic boulder of granite and part of metamorphic rock.

According to Dow et al. (1971); Beyth (1972 a; b) and Garland (1980) the rock unit is characterize as arenaceous facies of the Edaga Arbi Glacials. However, recently Bussert & Dawit (2009b) and Dawit & Bussert (2009) recognized the rock unit as bimodal formation at the lower subunit of glaciomarine origin and an upper subunit deposited in a shallow-marine environment.

Based on fossil siphonoromid impressions, Saxena & Assefa (1983) assigned as Ordovician age for the Enticho Sandstone in general. Later on, Bussert & Dawit (2009) assigned to Late Ordovician (Hirnantian) age for the glacigenic lower part because of their similarity with other Hirnantian glacigenic sediments widespread in North Africa and on the Arabian Peninsula.

2.4.2B. Edaga Arbi Glacials

Dow et al. (1971) first recognized the glacigenic character of the sediments in the lower part of the basal siliciclastic deposits, in which they termed as Edaga Arbi Tillite after locating a type section near the Edaga Arbi village (N 14°02′/E 39°04′) in Tigrai province. This rock unit is unconformably underlain by Precambrian basement rock with maximum thickness about 150-180 m. It is characterized by conglomerates, sandstone, grey, black and/or purple clay and siltstone that often contain dispersed pebbles or boulders up to 6 m in diameter (similar to Enticho Sandstone). The siltstone are characterized by variegated color, massive or thinly bedded, contain thin band of shale. Presence of erratic boulders of granite, metavolcanics and other basement rocks most of are striated and/or grooved indicating glacial transportation. This glacigenic sediments are named according to Beyth (1972 a; b, and 1973) as Edaga Arbi Glacials. Bussert & Dawit (2009a) subdivided the Edaga Arbi Glacials into two laterally interfingering subunits: (**A**). A fine-grained lithofacies association contain silt and claystone as varve-like or with dispersed clasts (dropstones) that interpreted as glacilacustrine environment. The intercalated massive to crudely stratified clast-rich diamictites represent a meltout and (**B**). Coarse-grained lithofacies association composed lenses of clast-supported massive to crudely horizontally bedded conglomerates with clasts of up to 30 cm in diameter and trough cross-bedded sandstones.

The Late Carboniferous to Early Permian age has been assigned to the Edaga Arbi Glacials (Bussert & Schrank, 2007) on the base of palynological data. This rock unit in the Northern Ethiopia seems to be correlative with similar glacigenic sediments in many parts of Gondwanaland deposited during the well-known Permo-Carboniferous Gondwana glaciation, Saudi Arabia (McClure, 1980; 1988) and in Yemen (Kruck & Thiele, 1983, El-Nakhal et al., 2002) as well as in Egypt and Sudan (Klitzsch, 1983).

2.4.2C. Adigrat Sandstone

The continental to shallow marine clastic Adigrat Sandstone was named after the type section located for the first time in Adigrat town (N 14°16′/E 39°28′) by Blandford (1869). Later on, the rock unit is redefined by Levitte (1970); Dow et al. (1971) and Beyth (1972a; b) to include only the upper part of the previous Adigrat Sandstone with its type section near the town of Abi-Adi. The succession is described below according to the information given by these researchers. The thickness reaches up to 670 m thinning westward over a short distance to about 80 m above the Tekeze River and disappearing north of the Adigrat-Axum road, also the continuation towards the Danakil Depression is not yet clear. Dawit Lebenie (2010) divided the Adigrat succession into four members as fellow: Unit 1 forms a gentle slope at the base of the section and units 2-4 forms a cliff above the slope. Unit 1 is composed of white and yellow to brown, well-sorted, fine to medium-grained sandstones with bed thickness 1-15 m and the sandstones contain abundant quartz pebbles with cross-bedding. Unit 2 is composed of poorly sorted medium to fine-grained reddish sandstones with abundant quartz pebbles, cross-bedding and ferruginous wood fragments. Unit 3 is made up of friable, medium to coarse-grained, cross-bedded white quartz sandstones with well-distributed lenses of ferruginous silt that show turbidity structures. Unit 4 consists of fine to medium-grained yellow to red sandstones interbedded with variegated silt and claystones.

The rock unit has been deposited either in the estuarine, lacustrine-deltaic due to absence of any trace fauna, abundance of ferruginous or lateritic beds and presence of fossil wood fragments (Beyth, 1972a; b). Also, Garland (1980) and Bosellini et al. (1997) suggested as continental depositional environment in a piedmont area or in an intramontane basin. In contrast, Dainelli (1943), Merla & Minucci (1938) and Merla et al. (1979) proposed as shallow marine origin. However, recently Dawit Lebenie (2010) attempted to assign as continental to shallow marine depositional environment and Late Triassic to Middle Jurassic in age on the base of pollen microfossil.

2.4.2D. Transition Beds

This rock unit is found between the boundary of underlain clastic Adigrat Sandstone and overlain Antalo Limestone with maximum thickness of a 20-30 m. It is characterized by shale, some calcarenite and sandstone intercalations (Bosellini et al., 1997). The sandstone is very rich in quartz, with rare feldspars, micas, reddish and highly bioturbated, calcite cement and has also some scattered small shell fragments. Presence of some oolite layers and common shells of echinoids, brachiopods and bivalve indicate the transitional bed deposited in shallow marine environment. In addition to this, presence of some laterite soils and ferruginous hard grounds spotted with vertical borings indicates to repeated local withdrawals of the sea during the initial stage of the Upper Jurassic transgression. The age of this unit is Late Callovian (?) and/or Early Oxfordian based on some benthic foraminifera fossils such as: *Nautiloculina oolithica*, *praekurnubia crusei*, *Valvilina* gr.*negeoni*, *Kurnubia palestniensis*, *Trocholina* sp, *cylindroporella* sp (Besollini et al., 1997).

2.4.2E. Antalo Limestone

The Antalo Limestone in the Mekelle Outlier is the main focus of present study, which is conformably underlain and overlain by the Adigrat Sandstone and Agula Shale and/or unconformably by Amba Aradom Formation respectively. The Antalo Limestone was first named by Blandford (1869;1870) after a type section was located first near the Antalo village (N 13°18′/E 39°19′) in Northern Ethiopia. Many researchers investigated the carbonate succession; eventhough, most of the study was together with all Mesozoic sediments and

Agula Shale as Antalo Supersequence. Among, these are Levitte (1970); Beyth (1972a; b); Meral et al. (1979); Bosellini et al. (1997); Martire et al. (2000); Worash and Valera (2002) and Kiessling et al. (2011). These most studies were focused on sedimentological, stratigraphical, geochemical and paleontological point of view. Four different facies and different thickness of the Antalo successions ranging from 300 m in the west to 800 m in the east are identified according to Beyth (1972a; b). The four facies are described as:- A cross-bedded sandy oolite and coquina with minor of marl and a few chert beds, intrbedding of marl and limestone, coral and algal reef limestone and black to gray microcrystalline limestone that showing fining (deepening) upward from bottom to top. Later on, Bosellini et al. (1997) attempts to divide the Antalo Limestone into four depositional sequences as A1, A2, A3 and A4 each are having a number of parasequences with a typical thickening and shallowing upward pattern (Figure 2.4). **A1** is the first well developed thickening and shallowing up cycle of the Antalo Supersequences and it is the most widespread carbonate unit in Tigrai and can be followed from the vicinity of the Mekelle to Abi-Adi area with 20-30m lies on shale, limestone or sandstone of the transition beds. It is characterized by basal nearshore facies consisting of grainstones, wackestones and some marl layers. Its upper part (5-10 m) characterized by silicified and rusted coral-stromatoporids with any relief bioconstructed framework. The top of this unit particularly in the western side of the basin is marked by reddish and ferruginous surface, bored and encrusted by small ostriedia (hard ground), documenting withdrawal of the sea and subaerial exposure before subsequent flooding. **A2** consists of arinaceous limestone deposited in a storm-controlled estuarine environment. **A3** is a relatively deep-water facies made up of micritic limestone. It shows some intercalation of wackestone and coquina beds within. A3 is generally considered to be a sub-tidal facies affected by storms as documented by storm layers (coquina beds). **A4** is a marl-limestone sequence, whose basal part is represented by cherty limestone.

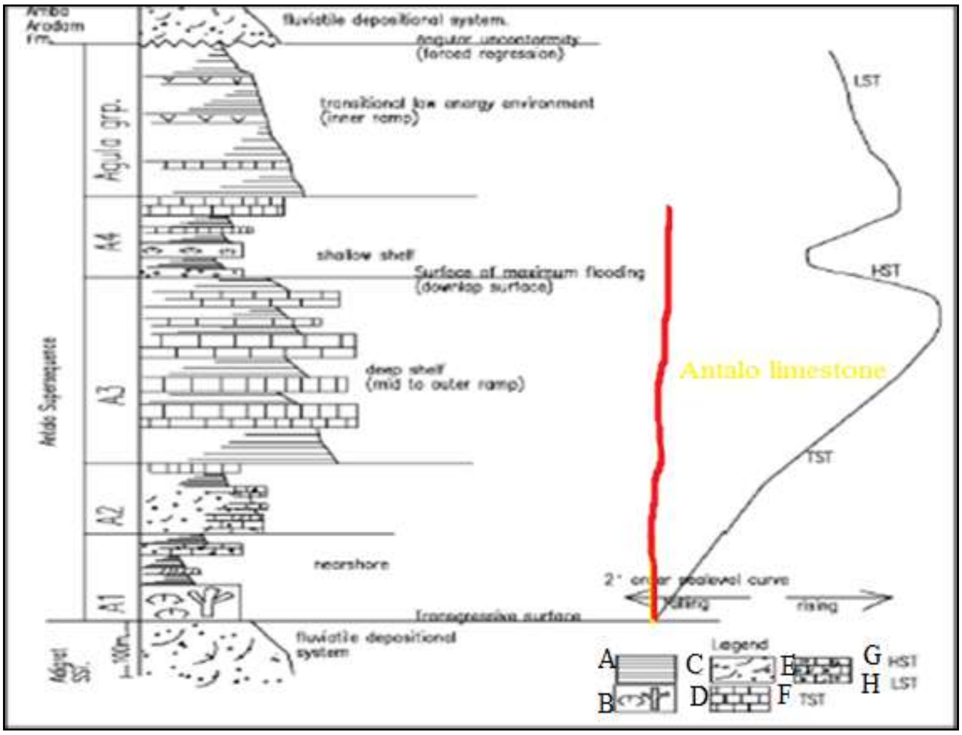


Figure 2.3: *Composite stratigraphy of the Antalo Supersequence in the Mekelle Outlier (modified from Bosellini et al., 1997):* (**A**) *marl,* (**B**) *coral-stromatoporoid rich limestone,* (**C**) *cross-bedded sandstone,* (**D**) *limestone,* (**E**) *cross-bedded oolitic limestone,* (**F**) *transgressive system tract,* (**G**) *high-stand system tract, and* (**H**) *low-stand system tract.*

Based on benthic foraminifera fossils, Bosellini et al. (1997) assigned the Antalo Limestone as Late Callovian(?) to Kimmeridgian age; however, Martire et al. (2000) proposed as Oxfordian to Kimmeridgian age based on ammonite macrofossil.

Geochemistry and marine benthic invertebrates (brachiopoda, corals and bivalvia) of carbonate Supersequences were investigated according to Worash and Valera (2002) and Kiessling et al. (2011) respectively.

2.4.2F. Agula Shale succession

The Agula Shale also named after the type section found for the first time near the town Agula (N 13°41′/E 39°35′) in northern Ethiopia; however, most of the worker describes this unit together with lower unit of the Antalo Limestone as Antalo Supersequence. This indicates separate study is not conducted related to Agula Shale. Beyth (1972a) identified a shaly unit at the upper part of the Antalo Limestone; however, later Bosellini et al. (1997) and Kiessling et al. (2011) included the shale unit of Agula Shale with Antalo Limestone and named as Antalo Supersequence. The thickness of the rock unit reaches up to 300 m in Agula and 400 m east of Hagere-Selam particularly near the Ale-Asa village. It is characterized by well-sorted, festoon cross-bedded, fine quartz arenites, laminated black shale, mudstones, dolomites and gypsum beds with nodular, chickenwire structure. Additionally, oolitic or coquinoid limestone with small gastropods and pelecypods macrofossils are the main component of this rock unit.

According to Beyth (1972a; b) and Bosellini et al. (1997) the facies association of this unit is interpreted as peritidal, lagoonal and sabkha environments. Further, with the help of various fossils including *Modiolus* cfr. *Intricatus*, *Palaeonucula*, *Corbulomima* and *Placunopsis* a Late Kimmeridgian age are assigning for the Agula Shale succession in Northern Ethiopia. Additionally, Bosellini (1989) explains the mode of formation for this rock unit is related with the last regression of the Jurassic sea toward southeast from Northern Ethiopia, and most probably from the entire East Africa.

2.4.2G. Amba Aradam Formation

This rock unit is the youngest of all the Mesozoic sedimentary rock of the Northern Ethiopia found with angular unconformably overlain the Upper Jurassic Agula Shale and/or upper part of Antalo Limestone with maximum thickness about 200m (Bosellini et al., 1997). The Amba Aradom Formation was named after its type section was located near the Amba Aradam town (N 13°20′/E 39°34′) in Northern Ethiopia by (Shumburo, 1968). It is characterized by white or red sandstones with interbedded purple to violet silt and mudstones, lateritic paleosoils and lenses of conglomerates. The sandstones are often cross-bedded and form fining-upward sequences, which are interpreted by Bosellini et al. (1997) as point bar sequences deposited in a fluvial meandering river system. The lower and uppermost parts of the successions are intensively lateralised. The same upper sandstone occur in the Blue Nile Basin called Debre Libanos Sandstone (Assefa, 1991), southeast Ethiopia (Harar plateau, DireDawa and Chercher Mountains), (Gortan, 1973) and Ertirea (Hutchinson and Engels, 1970). Therefore, this Formation is correlated with the Debre Libanos Sandstone in the Blue Nile Basin (Assefa, 1991) and the Aptian-Albian Upper Sandstone unit in the Harar region of southeastern Ethiopia (Assefa, 1991, and Bosellini et al., 1997). It also seems to correlate in part with the Yesomma Sandstone in western Somalia (Bosellini, 1989), with the lower part of the Tisje Formation in Northern Somalia (Luger et al., 1994) and with the Tawilah Sandstone (Kruck et al., 1996) or Ghiras Formation (Al Subbary et al., 1993) in Yemen.

2.4.3. Dolerite

Geologically, the youngest rocks of the region are the Mekelle dolerites, which are intruded the Antalo Limestone and Agula Shale rock units. The dolerites are believed to be comagmatic with the Trap volcanic that overly the Amba Aradom Formation. This Trap volcanic is Oligoccne-Miocene extrusive that covers most of the north-western plateau of Ethiopia (Hofmann et al., 1997).

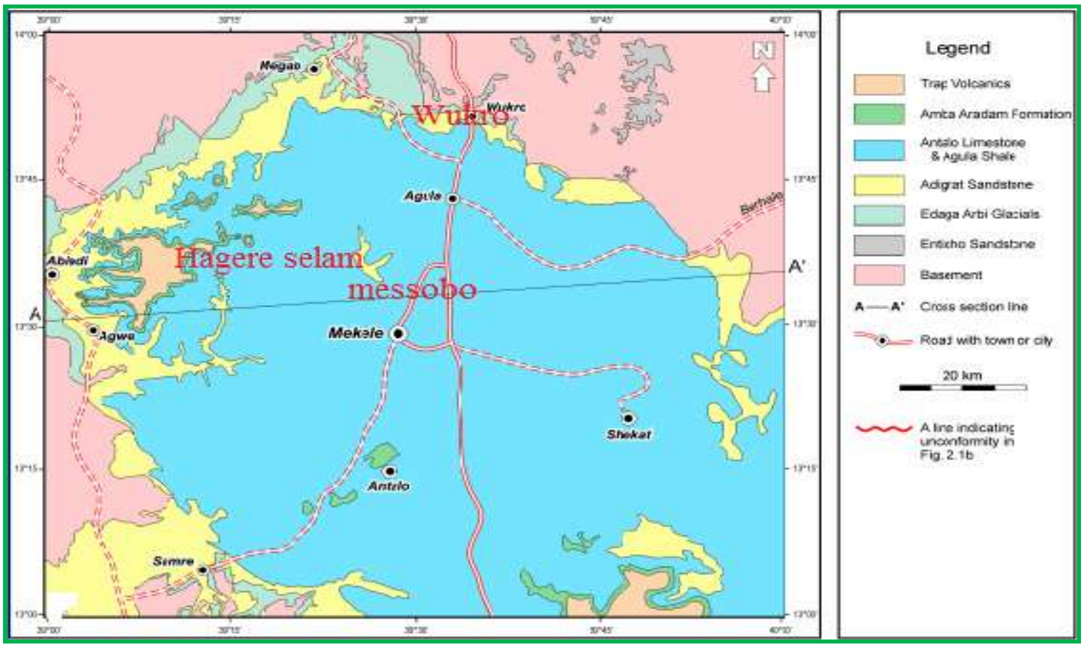


Figure 2.4: *Geological map of the Mekelle Outlier (source: Dawit Lebenie, 2010).*

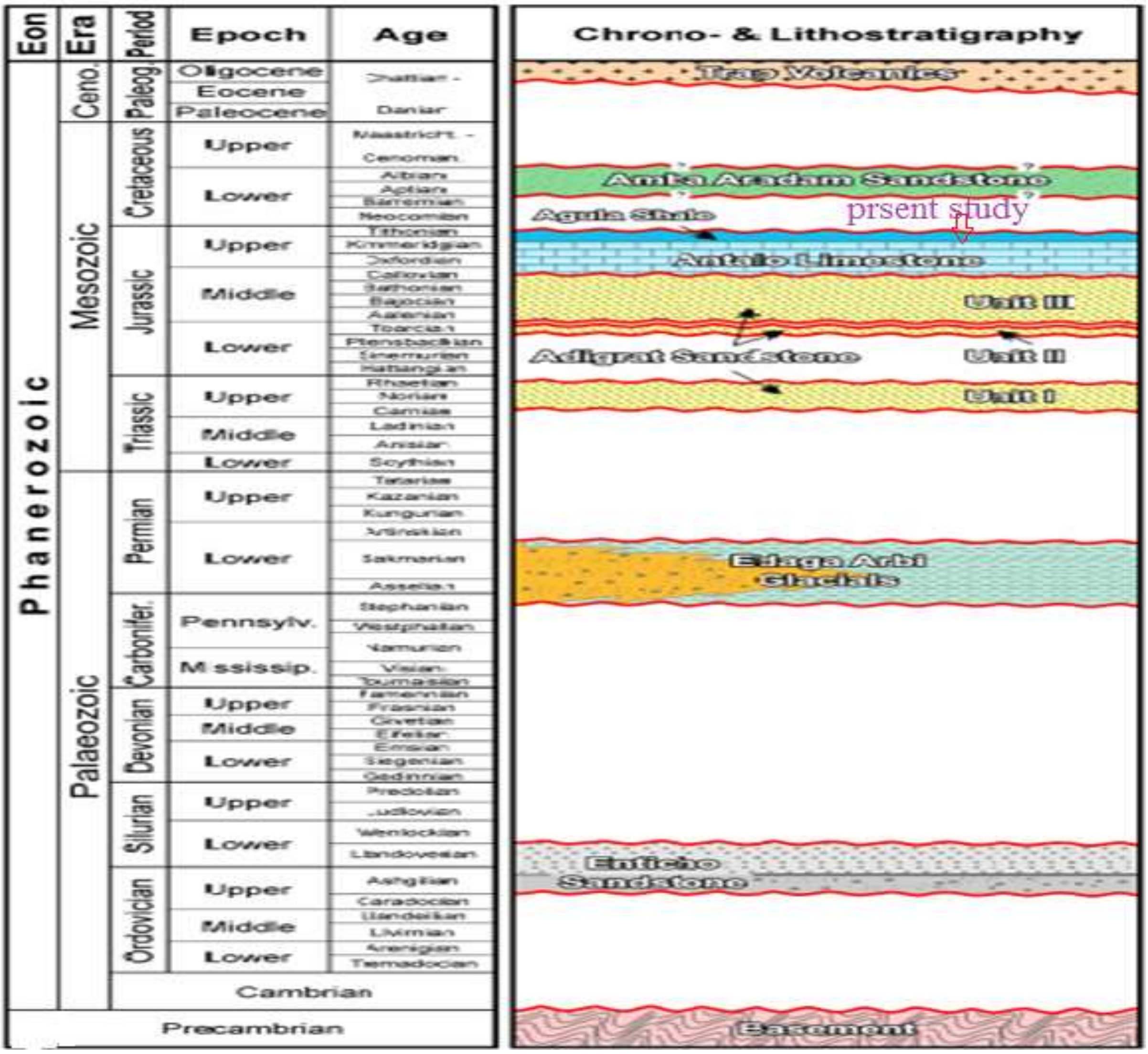


Figure 2.5: *Composite stratigraphy of Northern Ethiopia, Mekelle Outlier (Dawit Lebenie, 2010)*

CHAPTER THREE

3. MATERIALS AND METHODOLOGY

3.1. Materials

3.1.1. Field instrument

Different materials and equipment were used for field data collection and laboratory analysis to accomplish the stated research problem, the general and specific objectives of this research study. The different field instruments that exist at the applied geology department of Mekelle University were used to perform field data collection, rock sample and dry marl sediment collection in the study sections. These are Brunton compass, geological hammer, dilute 10% Hcl, GPS, sample bag, plastic sample bag, marker, pen, note book, meter stick, hand lenses, three base maps with scale of 1:50,000 (Abi Adi, Agula and Wukro sheet) and one 1:250,000 Mekelle topographic sheet and digital camera.

Figure 3.1: *Photograph shows the different instrument used during fieldwork.* (**A**) *Geologic hammer.* (**B**) *Sample bag.* (**C**) *Brunton compass* (**D**) *Standard scale* (**E**) *Note book.* (F) *GPS* (**G**) *Ruler.* (**H**) *Marker pen.*

3.1.2. Laboratory instruments

The most basic type of paleontological and petrographical instrument involved in extracting and identification of both macrofossil and microfossils found in the sedimentology and paleontology laboratory of Addis Ababa University were used. These are precision balance, 50 ml graduated cylinder, 100, 150 and 250 ml standard beaker, funnel, set of USA (United States of America) standard sieve number 35, 45, 60,120 and 450, which have 0.5 mm, 0.375

mm, 0.25 mm, 0.123 mm and 0.032 mm mesh sieves sizes, wash bottle with distilled water, 250 ml plastic containers, labels, petrographic microscope, light reflected binocular microscope, 30% H_2O_2, distal water, paint brush, splitter and different software including Arc GIS, Strater, Adobe Illustrator, Sedlog and Corel DRAW.

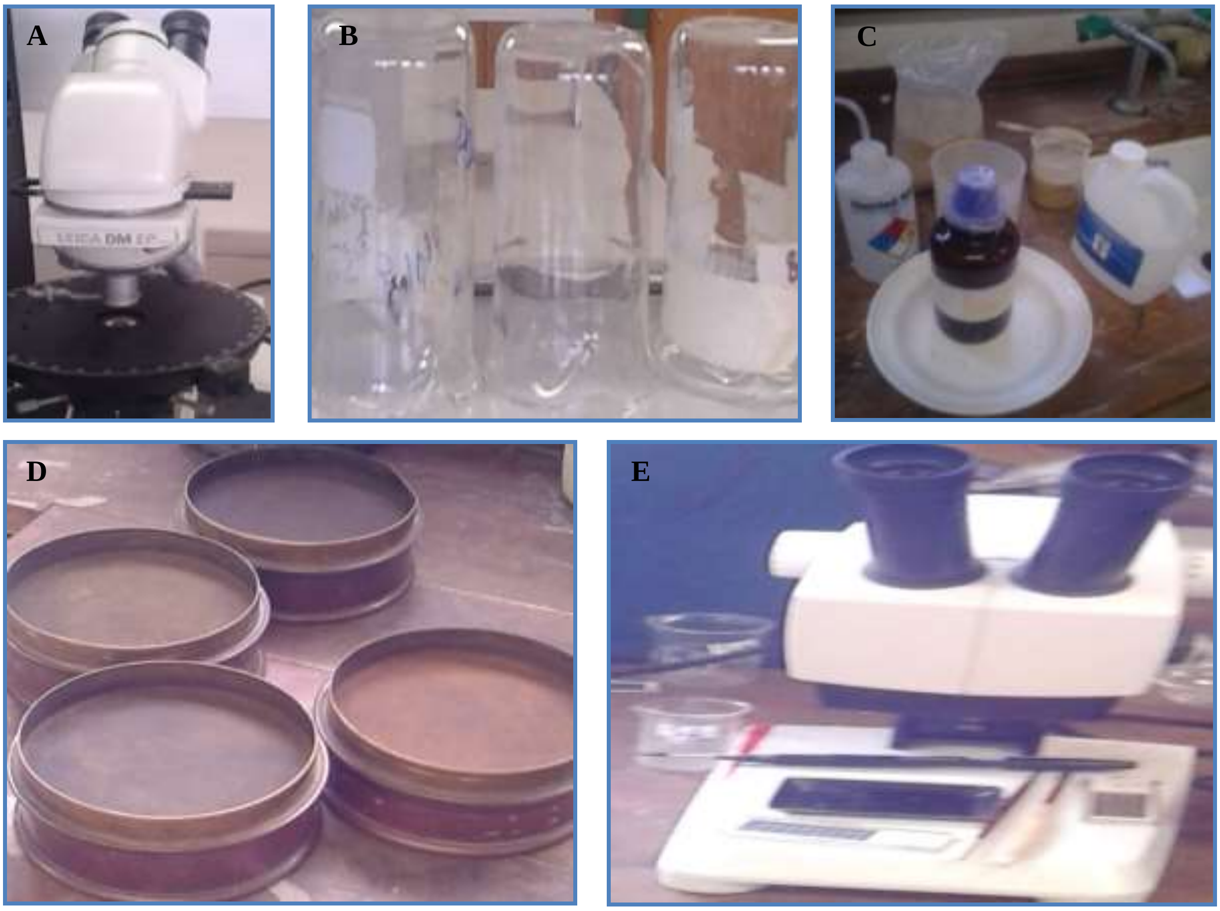


Figure 3.2: *Instrument used during laboratory data analysis existed at the sedimentology laboratory, Addis Ababa University,* (**A**) *Petrographic Microscope,* (**B**) *Standard beakers,* (**C**) *Distill water, spoon, and H2O2, (***D***) Standard set of sieves and* (**E**) *Binocular microscope, splitter, paint brush, marker pen and slide.*

3.2. Methodology

Three main methods were implemented to investigate a detailed picture of depositional environment, a detailed microfacies analysis and age determination of the carbonate rock unit in the study area. Each method was followed by its own detailed activities.

3.2.1. Pre-Fieldwork

Before the main fieldwork, office preparation has been undertaken. These includes review of previous work and available base maps, previous geological map in order to have an overview about the geology of the study area and their surrounding region, collecting of secondary data including meteorological data and published geological map, preparation of working plan and scheduling the various research activities, finalization of the methodology to be adopted for the proposed study and preparation for the fieldwork (equipment, base map, transport and personal preparation).

3.2.2. Field data collection (Main Fieldwork)

Two field trips were carried out during the study to investigate facies analysis and paleontology of carbonate succession in the Mekelle Outlier particularly in the Hagere-Selam, Messobo and Wukro stratigraphic sections. The first trip was conducted in June 2009 for 5 days in order to observe and select well exposed stratigraphic section of the study. During the first trip simple observation was conducted on 5 different sections namely, in the Hagere-Selam, Messobo, Sheket, Maimekden and Wukro in terms of their exposure, stratigraphy, fossil content, accessibility and their field relation with overlain and underlain rock unit. Then, the three sections Hagere-Selam in the west, Messobo in the southeast and Wukro in the northeast of the Mekelle Outlier margin were selected for a detailed facies analysis and paleontological study of a carbonate rock unit.

The second trip was conducted from mid of November-mid of December 2010 for a detailed fieldwork. During this field campaigns, different carbonate rock unit and their stratigraphic relationship to other rock units were identified, description of all the lithological variation in color, textures, sedimentary structures, mineral composition, macrofossils based on size and morphology, trace fossil identification, and degree of bioturbation identification were done. Palaeocurrent directions were recorded using a geologic Brunton compass, discriminating of limestone from dolomite rock unit using 10% diluted Hcl acid, carbonate rocks were classified and named using Dunham (1962) and modified Embry and Klovan (1972) carbonate classification scheme and measuring bed thickness by meter stick. Three detailed sedimentological stratigraphic sections were logged bed-by-bed depending on the lithology variation to document thier microfacies architecture, paleontology and to see thier lateral and vertical relationship of the carbonate unit among the measured three stratigraphic sections, to construct their depositional model and finally to correlate intrabasinally and regionally with time equivalent carbonate rock unit. At each section facies was described based on rock color, physical and biogenic sedimentary structures, ichnofacies associations, skeletal and non-skeletal grains, degree of bioturbation and rock texture.

3.2.3. Sample collection and sampling techniques

A total of 65 representative hard carbonate rocks (25 from Hagere-Selam, 13 from Messobo, and 27 from Wukro sections) and 26 dry marl sediment sample (6 from Hagere-Selam, 8 from Messobo and 12 from Wukro sections) for petrographic and micropaleontologic laboratory descriptions and analyses were collected from the various carbonate units. Sampling intervals were varying depending on variations of the lithology. 10-25 m sampling interval was taken for carbonate succession with little or no lithological changes and for rapid lithological change sampling interval was as narrow as 0.3-0.6 m. Sample selection is done aiming at having complete carbonate succession of these sections. The annotation of sample site, rock sample and marl samples names were given as follows. That annotation follows the format of section name, sample type and sample number respectively as **HS1**, **HMS1**, **WS1**, **WMS1** and **MS1**, **MMS1**. **H**, **W** and **M** refer to the sections name and **S** to the sample name. **M** refers to the marl sample and the number refers to the number of the samples. Section selection and geological traverses in the field was supported by topographic maps of 1:50,000 and 1:250,000 scales produced by the Ethiopian Mapping Agency. Photographs were taken at each layer to document sedimentary structures, lithologies, macrofossils, textures, trace fossil associations and their stratigraphic relationships and in the laboratory by digital camera with standard scale inorder to facilitate the whole data after returned from the field.

3.2.4. Laboratory data analysis (Post Fieldwork)

Laboratory data analyses were conducted on collected samples from the measured stratigraphic sections to support the macroscopic analysis of field data. These include a petrographical, macrofossil and micropalaeontological description and analysis.

3.2.4A. Petrographic analysis

Like other sedimentary rocks carbonate rocks are difficult to describe all the properties including textures, sedimentary structures, mineralogical components, skeletal and non-skeletal grains using field observation alone in order to determine their facies analysis, age determination and interpretation of their depositional environment hence, a detailed studies were revealed through studies of thin-sections.

The petrographic analyses were performed on 65 representative carbonate rock sample collected from the three sections for microfacies analyses and fossil identifications in Ethiopian Geological Survey central laboratory Addis Ababa. Their petrographic studies of these 65 thin sections were done under petrographic plane polarizing microscope in Addis Ababa university petrology laboratory center. For each sample the textures including grain-size, degree of sorting, roundness, mineralogical compositions, degree of bioturbations, varieties of skeletal and non-skeletal grains, various biogenic sedimentary structures, common diagenetic type, microcrystalline micrite, sparite identifications and descriptions were done. The carbonate rocks were classified following the common classification schemes of Dunham (1962) and modified classification schemes of Embry and Klovan (1971).

3.3. Microfacies Analysis of the carbonate successions

Identification of the sedimentological facies was based on field observations in addition to thin-section analysis. Analysis of carbonate rocks using the hand lens in the field were combined with a detailed microfacies study in the laboratory in order to obtained a complete picture of the measured sections. The sixty five thin-sections were investigated their compositional variation of limestone and mixed carbonate rock unit in all sections with some sandy limestone. Each sample was viewed under optical light microscope. The classification used to characterize the microfacies following the guidelines of Dunham (1962) classification of carbonate rocks, standard microfacies classification schemes of Wilson (1975) and Flugel (1982; 2004) and ramp microfacies type of Flugel (2004) were applied. Depositional settings and paleoenvironmental reconstructions of carbonate unit were interpreted based on compositional, textural, fabrics, sedimentary data and by comparison with modern carbonate environments (Tucker and Wright, 1990).

3.4. Constructing a detailed stratigraphic log of the measured sections

Stratigraphic log are a graphical method for representing a series of beds of sediments or sedimentary rocks using all information collected from field and laboratory data. These includes bed thickness in vertical axis, texture in horizontal axis, lithology, sedimentary structures, fossils both body and trace, contacts between different rock units, stratigraphic position (age), sample number, microfacies type, depositional system using detailed scale of 1:5. The stratigraphic logs were constructed for the three stratigraphic measured sections (Hagere-Selam, Messobo, and Wukro sections) and for correlation with 420 m total thick carbonate successions (see Appendix one, Plate I, Figure B-D). Finally intrabasinally and regional rock correlation were done.

3.5. Schematic flow diagram of the methodology

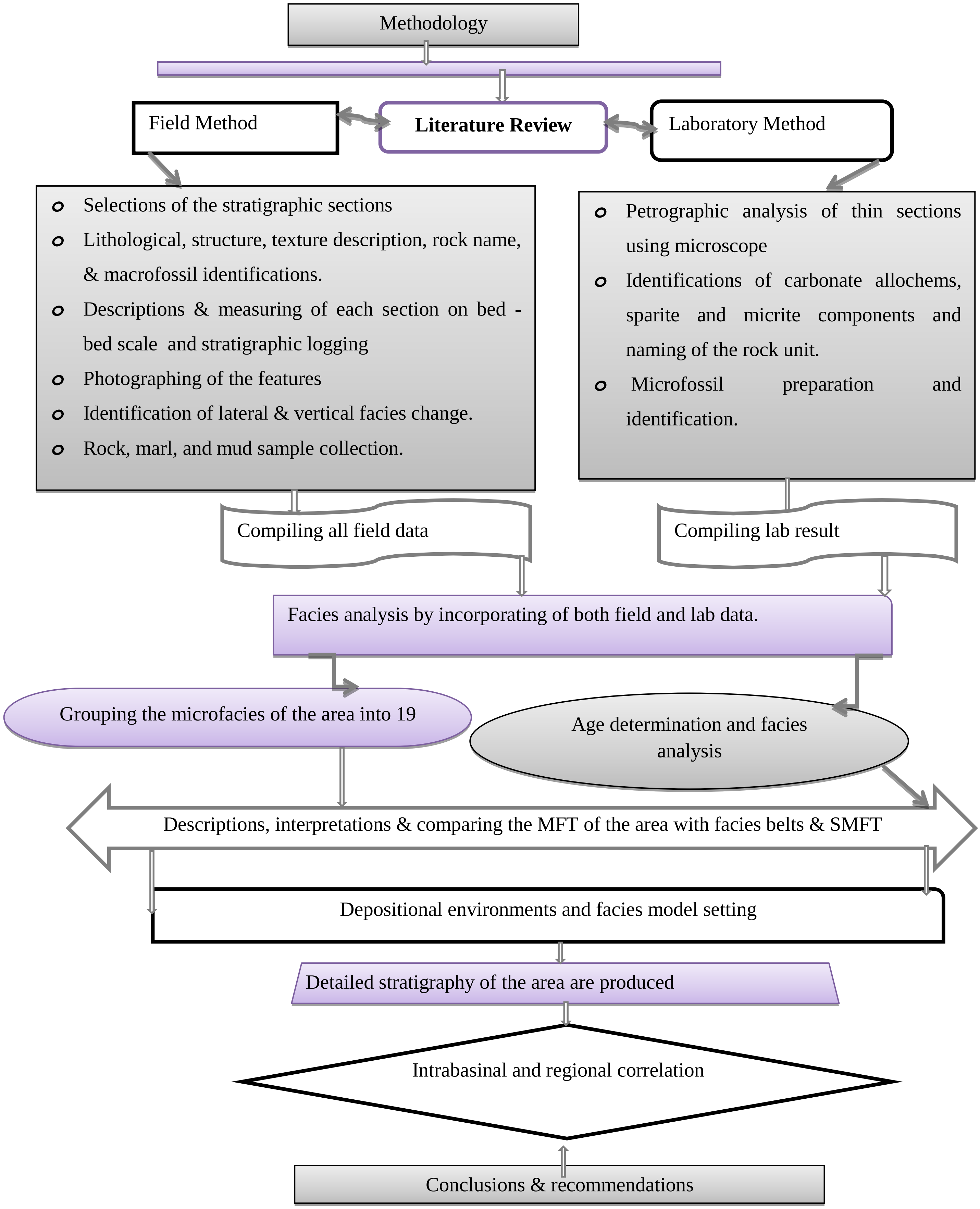


Figure 3.3: *Schematic Flow Diagram of Office, field data collection and Laboratory data analysis applied on the present study.*

CHAPTER FOUR

4. STRATIGRAPHY

4.1. Introduction

In the study area a thick carbonate successions are exposed in several localities around Mekelle with a total thickness about 400m, which are deposited in different part of the study sections with different degree of exposures, depositional environments and fossil content. In order to elucidate the lithofacies analysis, depositional environment interpretation, age determination, to see thier lateral and vertical relationship of the carbonate rock unit and correlation, a detailed facies analysis and paleontology of a carbonate unit were investigated on the measured three stratigraphic sections.

The carbonate successions of the study sections are conformably overlain and underlain by Agula Shale and Adigrat Sandstone in the Wukro section, sandwiched between Agula Shale in the Messobo section, overlain and underlain by Amba Aradom Formation and Adigrat Sandstone in the Hagere-Selam sections respectively. Moreover, the study areas constitutes of different normal faults including Wukro, Mekelle, Chelekot fault and diorite dyke, that makes the stratigraphic relationship of the carbonate rock with underlain and overlain rock units different in different sections and protect from erosion. The physical nature of each lithological unit is investigated and described, the name of lithological unit is given and facies analysis based on the textural, paleontological, sedimentary structures and mineralogical constituent of the rocks observed during field investigation and petrographic analysis. The study areas are characterized by different carbonate rock units with various lithologies, nature of exposure, fossil content, depositional environment, trace fossil association, textures and sedimentary structures.

Lithostratigraphically, the carbonate succession in these sections ranges from mudstone to grainstone including sandy limestone and chert bed, with dominated fibrous chalcedony mineral. The thickness of carbonate units of the area are varying laterally and vertically from one section to other and reveal a complex arrangement of facies units due to the sea level fluctuation and varying depositional environment ranging from low to high energy shallow homoclinal ramp setting. Therefore, this section presents a brief explanation of the description and interpretation of the main carbonate rock unit, stratigraphy, facies analysis and their depositional systems that have predominantly bearing on carbonate sedimentary successions on the three stratigraphic sections, based on the field observations and petrographic studies.

4.2. Hagere-Selam stratigraphic section

The study section in the Hagere-Selam area is located 35 km northwest of Mekelle town between Ale-Asa and Tanka Avergale villages, along the main road of Mekelle-Abi Adi.

Geographically, the area is bounded between 523033 to 524826 m E and 1509836 to 1505936 m N. The carbonate successions are conformably underlain by clastic Adigrat Sandstone and overlain by angular unconformity of the Amba Aradam Formation with maximum thickness up to 300 m. This stratigraphic section includes cross bedded reddish sandstone, thin-thick bedded bioturbated bioclastic grayish wackstone, chalcedony rich chert bed, tabular and branched coral rich limestone, bioclastic sandy limestone, stromatoporidal rich mudstone, cross bedded oolitic-peloidal grainstone, tabular cross bedded-reddish-bioclastic sandy limestone, fossiliferous limestone, coquiniod limestone, marl and marl intercalated bioclastic bedded limestone, bioturbated *Thalassiniodes* wackstone, coral-stromatoporoids mudstone, crinoidal packstone-grainstone, karastified micritic limestone and Upper Sandstone Formation from bottom to top (see Appendix one, plate I, Figure B). A detailed lithological and stratigraphical description and interpretation of this stratigraphic section are discussed as follows:

4.2.1. Cross bedded-reddish sandstone

Description: This clastic sandstone rock unit is exposed by river cut in the lower part of the Hagere-Selam section, which is conformably overlain by carbonate rock unit. It is characterized by reddish and white in fresh color, fine to medium grain size and moderately sorted grains. This rock unit consists of a tabular cross bedded structure, massive, bedded, lamination and normal graded bedding sedimentary structure.

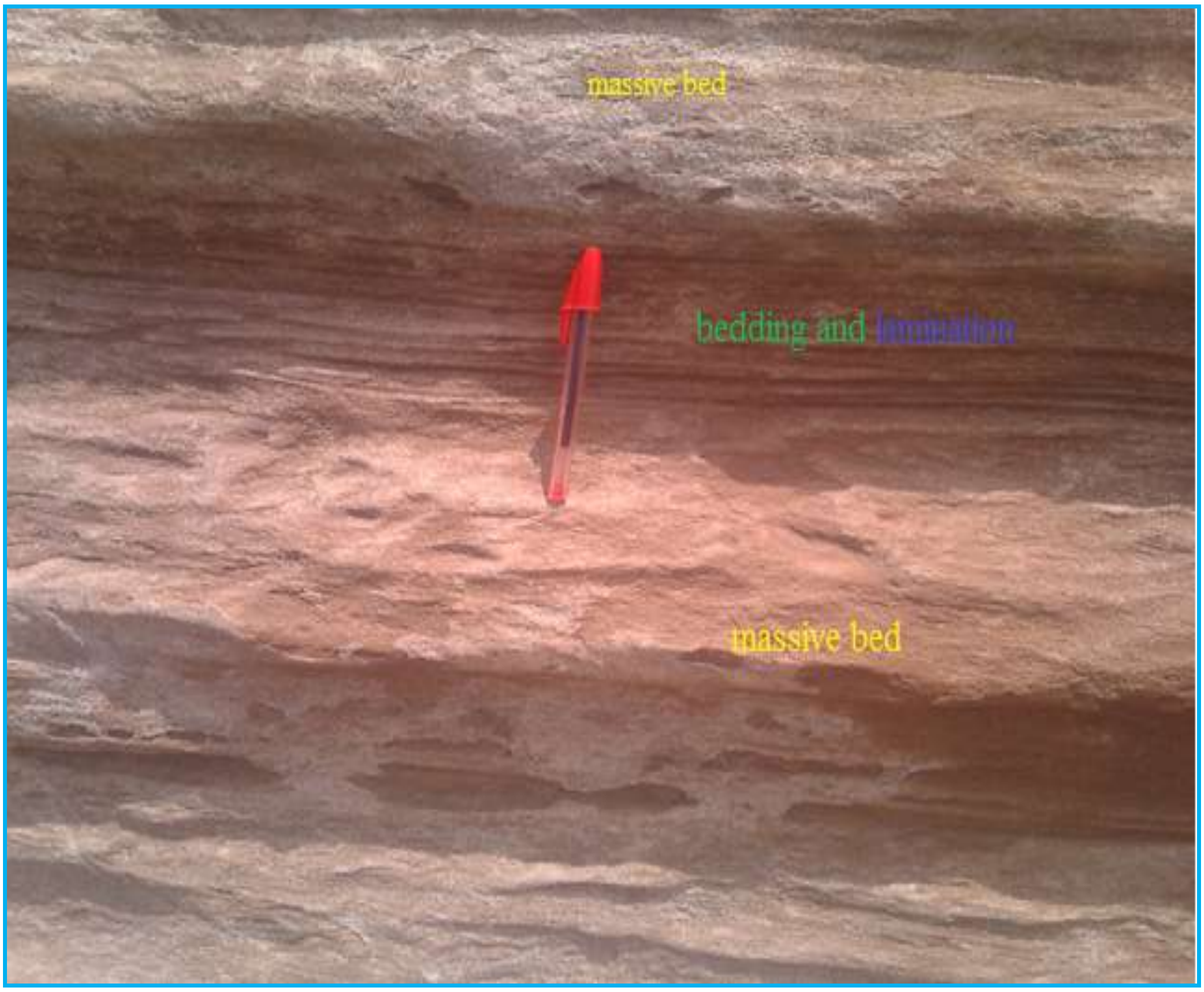


Figure 4.1: *Field outcrop of the cross bedded reddish sandstone. Characterize by lamination, bedding and massive bed, lower part of Hagere-Selam section.*

4.2.2. Thin-thick bedded bioturbated-bioclastic wackstone

Description: This rock unit is mainly exposed by river cut in the lower and middle part of Hagere-Selam section with maximum thickness range of 20-50 m, which forms cliff in place. It is characterized by fine to medium grain, brownish, light gray to reddish in color, compacted, horizontal bedded and have some dissolved cavern structure, bioturbated bed and simple to complex parallel microstylolite structure. Additionally, some silicified coral, benthic foraminifera and chalcedony mineral especially in the lower section and macrofauna of brachiopod and bivalve with some *Thalassiniodes* isp in the middle section is the main characteristics of this rock unit (Figure 4.2). Individual bed thickness of the bedded limestone varies from 0.5 to 1m.

Interpretation: Due to presence of *Thalassiniodes* isp trace fossil, macrofossil, some benthic foraminifera, having of very fine grain and bedded black color the rock unit, simple to extensive bioturbation indicate this rock unit deposited in low energy, open marine depositional environment between FWWB and SWB.

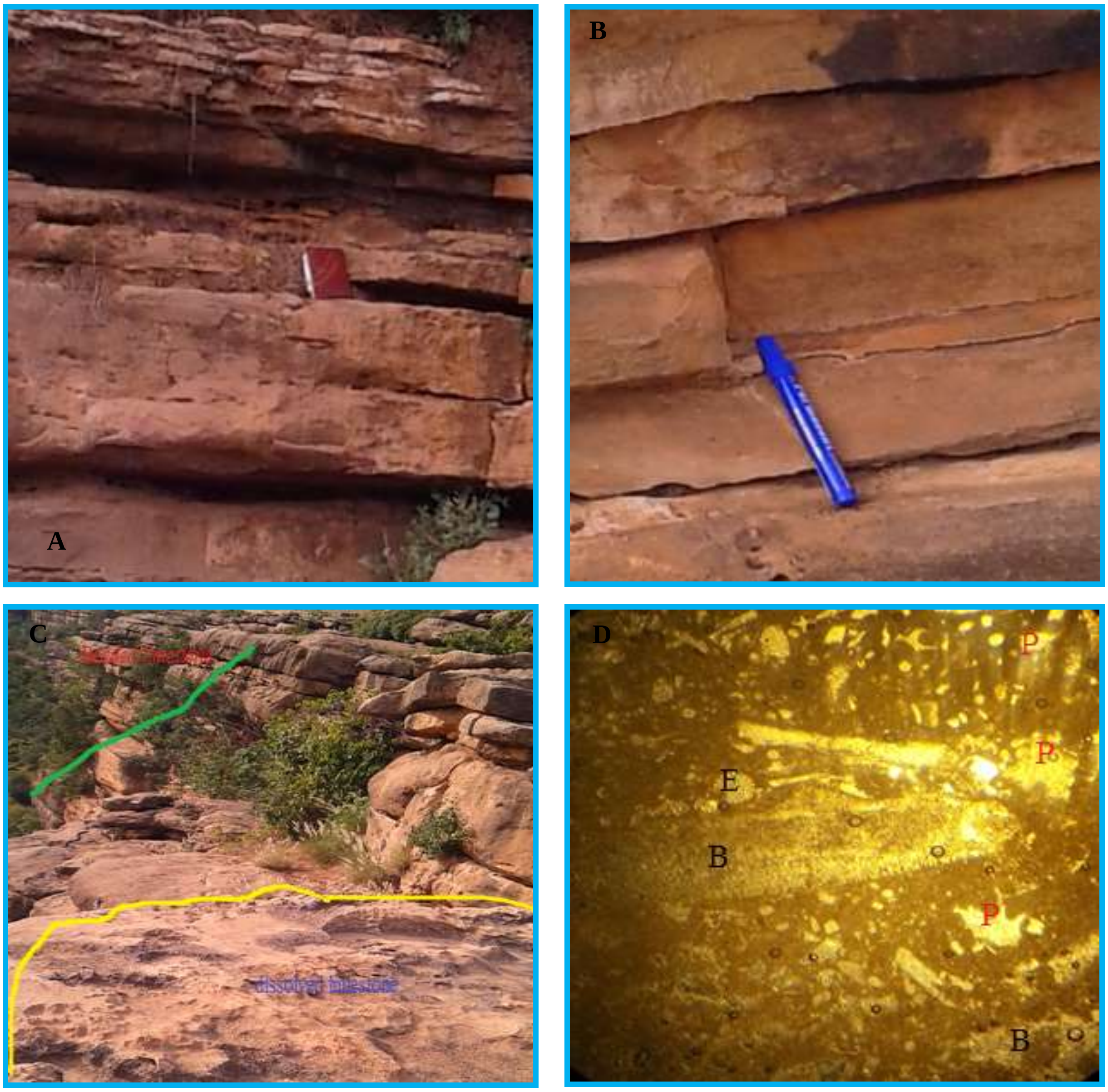


Figure 4.2: *Field outcrop and photomicrograph of the bedded limestone, Hagere-Selam section,* (**A** &**B**) *Bedded limestone middle section,* (**C**) *Bedded and dissolved limestone lower section,* (**D**) *Photomicrograph of bioturbated bedded limestone, Echinoderms and (***E**) *Bivalve shell* (*B*) *and fenestrae pore filling (P) 4X, PPL field of view, lower part of Hagere-Selam section sample HS1.*

4.2.3. Chalcedony chert

Description: The chert rock unit is exposed conformably overlain and underlain by coral rich mudstone in the lower part of Hagere-Selam stratigraphic section with maximum thickness of 15 m. It is characterized by dark, rusty red, white, brown and grayish brown in color, very fine grain, hard, and massive structure (Figure 4.3). This rock unit contains some silicified coral fossil, fibrous chalcedony mineral with some nodular structure in place.

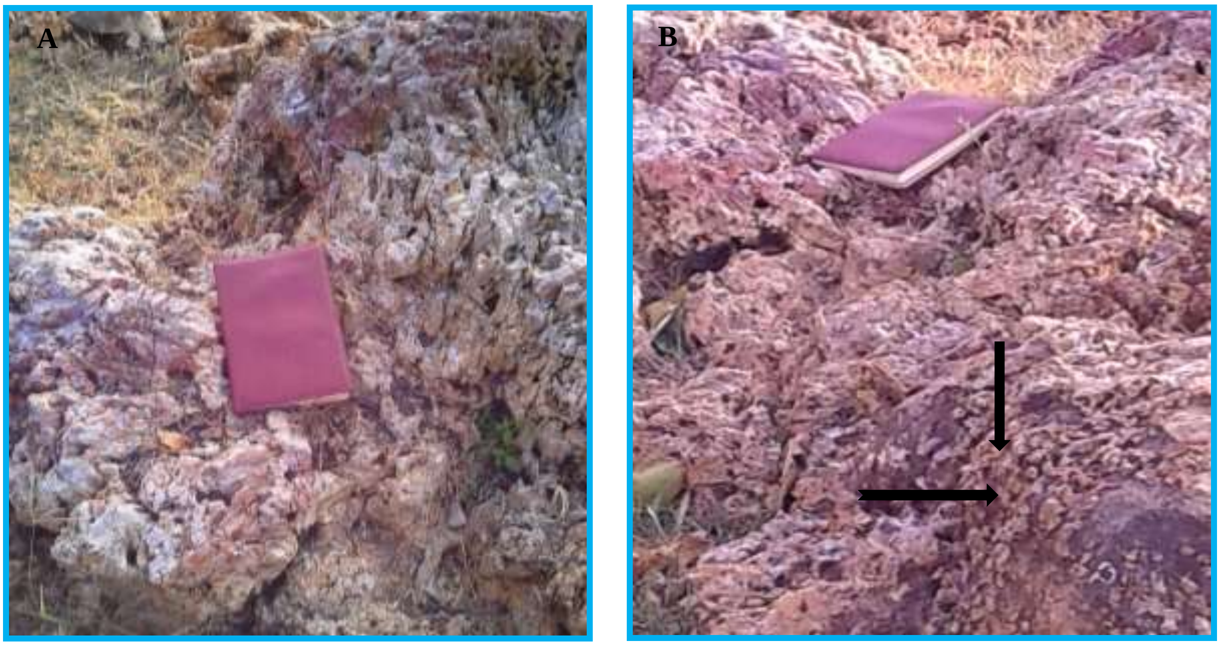


Figure 4.3: *Field outcrop of chalcedony chert lower part of Hagere-Selam section, (***A***) Massive chert, and* (**B**) *Massive rusted chert with some nodular structure, the black arrow.*

4.2.4. Massive to branched coral-stromatoporoid-rich mudstone

Description: Massive to branched corals and stromatoporoids rich of the carbonate rock unit is exposed in the lower and upper part of Hagere-Selam section, which forms bioherms stratigraphic reefs with maximum thickness up to 20-30 m. The rock unit is characterized by fine grain, light gray in fresh color; bioherms massive, poorly bedded and branched with individual thickness range of 1.5-5 m. The stromatoporoids are abundant, tabular, branched with silicified or rusted and fresh color whereas, most of the corals are highly silicified (rusted) and found associated with the stromatoporoid (Figure 4.4). These bioherms are predominantly characterized by in-situ isolated coral and stromatoporoid heads with a micritic matrix and may have microbial and stromatoporoid encrustation. Based on the extensive description of the carbonate rock unit in this section, the corals have hexagonal or pentagonal colonial forms and tabular solitary forms. Some of the identified coral species includes *Isastrea bernensis* and *Actinastrea crassoramosa* (Figure 4.4A-B and C-D) and branched and tabular stromatoporoid (Figure 4.4E and F) respectively.

Interpretation: The depositional environment of the stromatoporoid-coral bioherms is assigned to the proximal lower shoreface as they are generally overlain by the cross bedded-bioclastic-oolitic grainstone facies in upper shoreface succession and underlain by the bioclastic wackstone, which indicate the lower shoreface (proximal open marine environment) for the stromatoporoid rich limestone and high energy shoal environment for the coral framestone rich limestone. Such a high to low energy environment is interpreted based on the coral and low frequency of storm deposits of stromatoporoids. Therefore, the stromatoporoid-coral bioherms are interpreted to have been deposited in the proximal lower shoreface environment above FWWB.

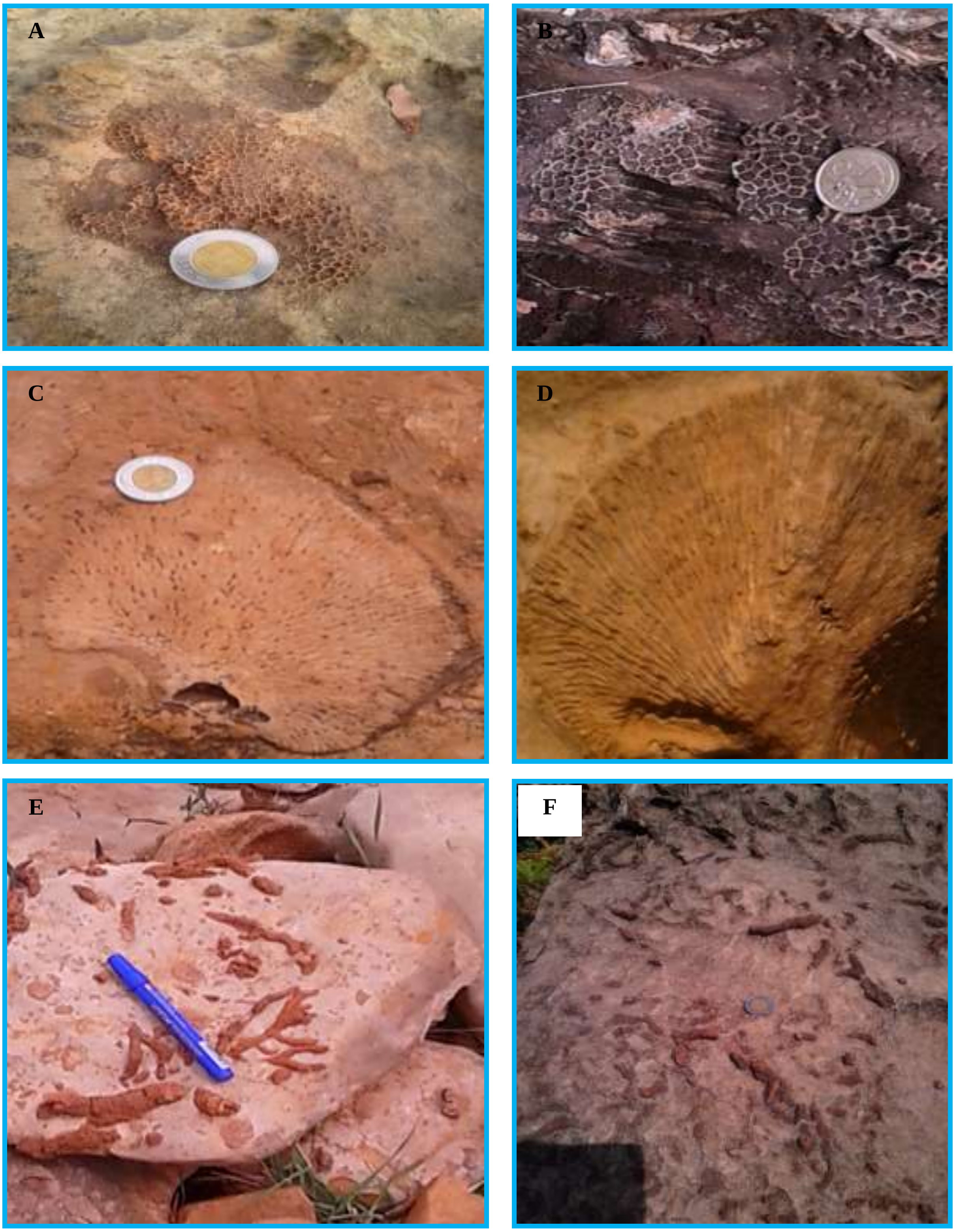


Figure 4.4: *Field outcrop of the coral and stromatoporoid rich limestone.* (**A**) *Isastrea bernensis rich limestone.* (**B**) *Silicified Isastrea bernensis lower part of Hagere-Selam section.* (**C- D**) *Actinastrea crassoramosa rich limestone, upper part of Hagere-Selam section* (**E**) *Branched and tabular stromatoporoid limestone.* (**F**) *Tabular silicified stromatoporoid lower part of Hagere-Selam section.*

4.2.5. Cross-bedded skeletal-oolitic-peloidal grainstone

Description: This rock unit is mainly exposed in the lower part of Hagere-Selam section with maximum thickness up to 75 m, which is conformably overlain and underlain the stromatoporoid-coral mudstone and sandy limestone. It is characterized compositionally by well-sorted medium to coarse grained ooid, peloids, gray to reddish fresh color, abundant brachiopod and bivalve, echinoderms macrofossil with scarce coral and stromatoporoids. The most prominent features of the cross bedded skeletal-oolitic grainstone facies are presence of large cross-bed sets (Figure 4.5 B & D) and current ripple mark (Figure 4.5C). Individual beds are thin to medium bedded (5-10 cm), whereas, a bed set can be as thick as 2 m. Moreover, peloids, benthic foraminifera and the calcareous algae are sparsely present.

Interpretation: The well-developed cross-bedding, ripple mark, abundant skeletal oolitic-peloidal grainstone indicates an upper shoreface depositional setting above fair-weather wave base (FWWB) (Clifton, 2006). This interpretation is supported by the grainy and relatively well-sorted fabric. Also, this facies is found overlain the stromatoporoid-coral mudstone facies and underlain the sandy limestone.

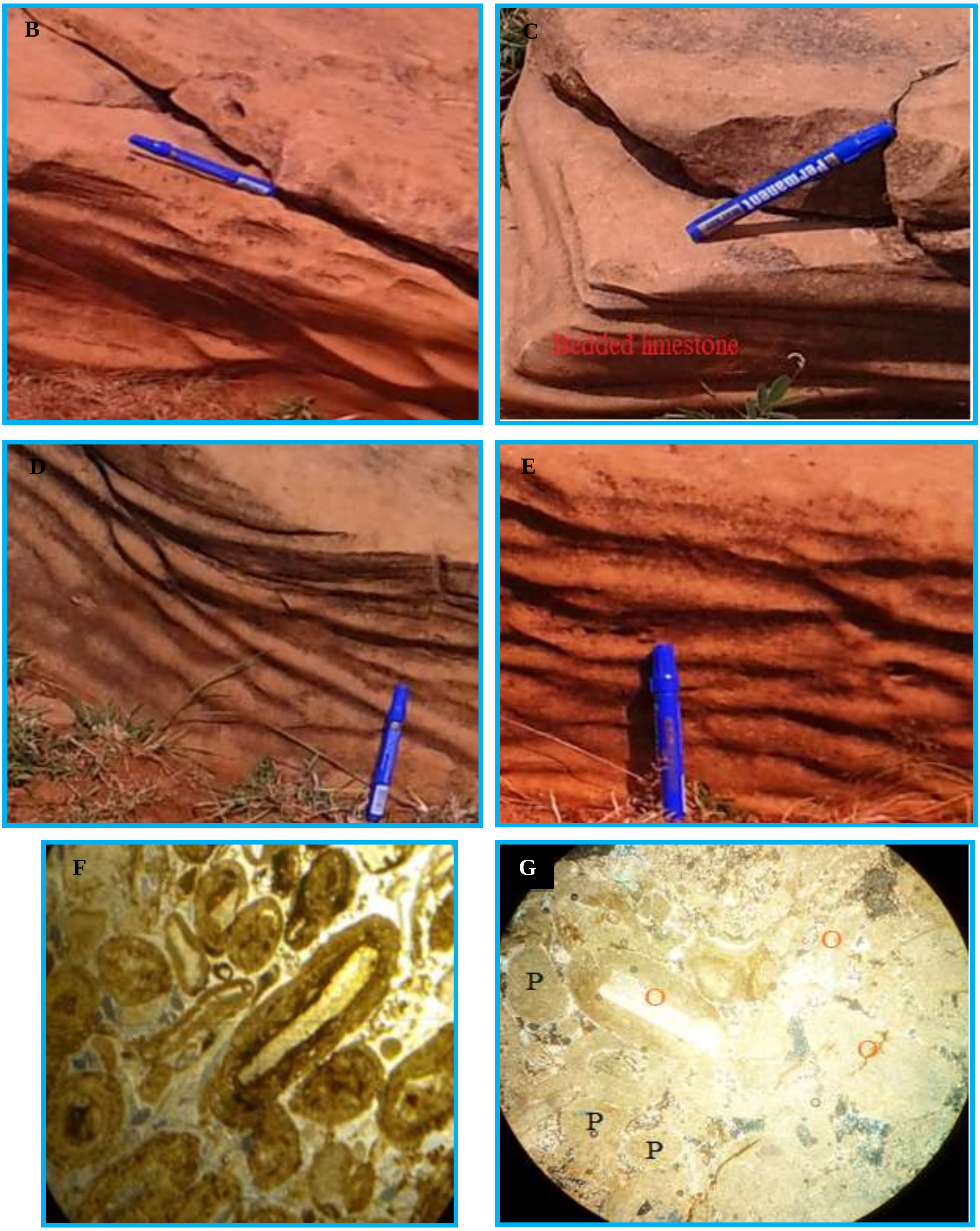


Figure 4.5: *Field outcrop and photomicrograph of the cross bedded-bioclastic-oolitic grainstone, Hagere-Selam section* (**A**) *rounded to spherical oolitic-peloids grainstone.* (**B**) *Bedded structure.* (**C**) *Bedded oolitic-peloidal grainstone.* (**D**) *Crosses bedded structures.* (**E**) *Symmetrical ripples mark. (F) Photomicrograph of Spherical to rounded Oolitic limestone sampleHS6, PPL, 4X and* (**G**) *spherical ooilitic (O) and peloid (P) grain stone with some quartz grain sample HS17, XPL, 4 X.*

4.2.6. Tabular cross bedded-reddish-bioclastic sandy limestone

Description: This reddish sandy limestone rock unit is exposed in the lower part of the Hagere-Selam section underlain by gradational contact from cross bedded oolitic grainstone and overlain by the coral-stromatoporoid rich mudstone with maximum thickness variation from 10-12 m. It is characterized by medium to coarse grained sandy limestone, reddish, dark, and brown in color. Sandy limestone bedding surface exhibit different types of physical and biological sedimentary structure such as various form of current ripple mark, normal gradded bedding, lamination, tabular cross bedding, erosional sedimentary structure, bioturbation, some trace fossils (e.g. *Diplocraterion parallelum*) with abundant quartz and calcite cementing mineral. Body fossil are also abundant within the sandy limestone bed including brachiopods and bivalve in the lower part of Hagere-Selam section (Figure 4.6.D).

Interpretation: This rock unit indicates a high-energy nearshore environment, possibly a beach and upper shoreface. The brown or red colors result from impregnation with iron oxide minerals. Therefore, a high energy shoreface environment is the main depositional environment for this rock unit.

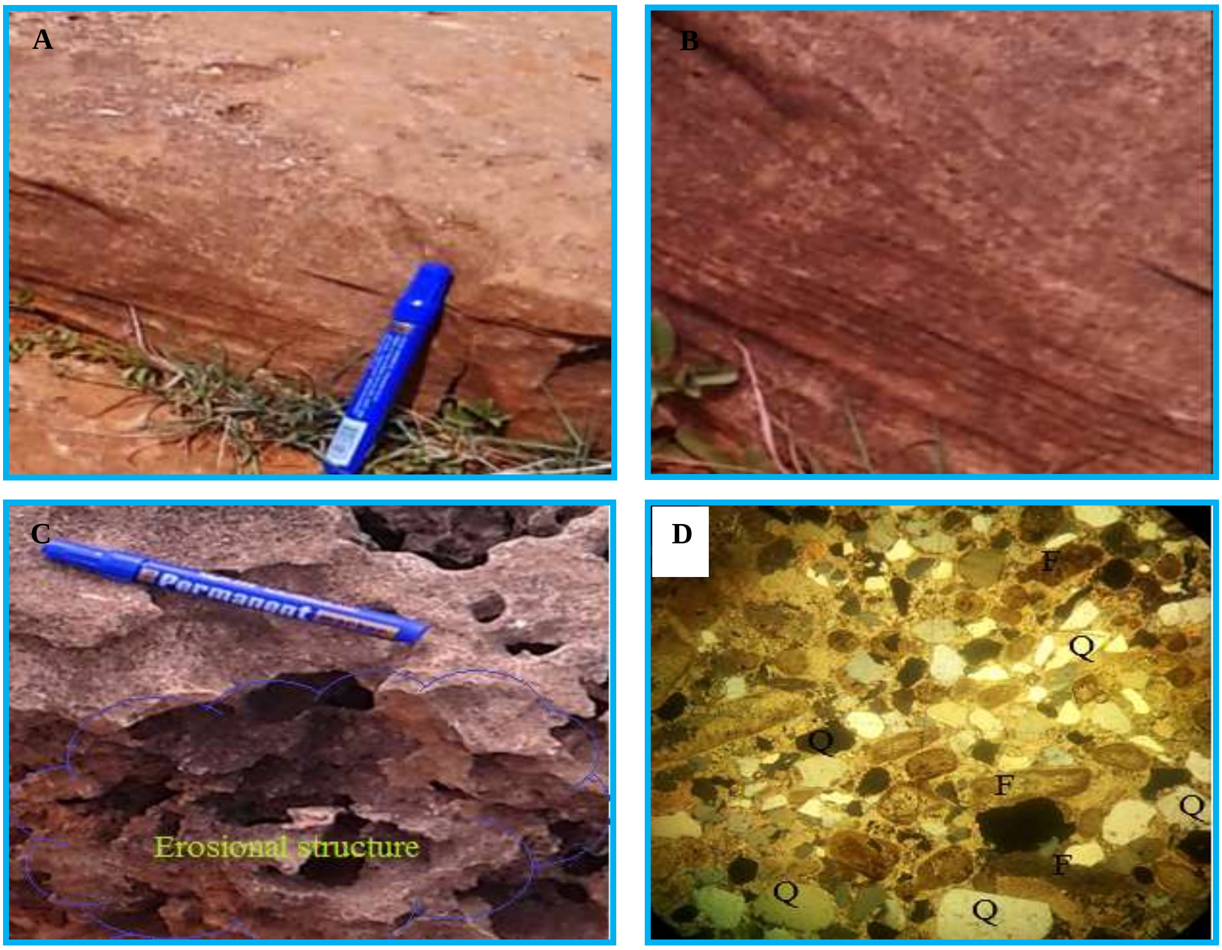


Figure 4.6: *Field outcrop and photo micrograph of the sandy Limestone lower part of Hagere-Selam section.* (**A** &**B**) *Cross bedded and bedded sandy limestone with abundant fossil and bioturbation, B is*

close view of A. (**C**) *Erosional Structure of sandy limestone.* (**D**) *Photo micrograph of sandy limestone of sample HS4, and HS9) Q-quartz, F-fossil cemented by calcite mineral, XPL.*

4.2.7. Fossiliferous limestone

Description: The fossiliferous limestone rock unit is found dominantly in the lower, middle and upper part of Hagere-Selam section, which is exposed by stream, road and quarry site with maximum thickness variation of 3-15 m. It is characterized by yellow, brown, reddish, light gray to dark in fresh color, coarse grain, with abundant body fossils including, crinoids, brachiopods and bivalve and *Thalassinoides* isp traces fossil association (Figure 4.7 A-C) respectively.

Figure 4.7: *Field photographs of fossiliferous limestone Hagere-Selam section.* (**A**) *Crinoid rich fossilferous limestone, upper part.* (**B**) *Bivalve and brachipods rich limestone lower part.* (**C**) *Bedding plane of view Thalassinoides (**Th**) trace fossil, middle part.*

4.2.8. Coquinoid limestone

Description: This coquinoid rock unit is exposed in the middle part of Hagere-Selam section with a total thickness variation from 3 m-12 m. It is exposed by the stream and hill cut overlain and underlain the fossiliferous limestone and marly limestone respectively. This rock unit is characterized by dark, reddish in color, coarse skeletal grain, well sorted, compositionally and texturally matures and consists dominantly of bivalves, brachiopods and some bryozoan marine benthic invertebrate fossil (Figure 4.8A and B).

Interpretation: The well sorted skeletal grain, compositionally and texturally mature, presences of coquinoid bivalve, brachiopods and bryozoan indicate deposition in upper shore face (storm) environment under high agitated energy.

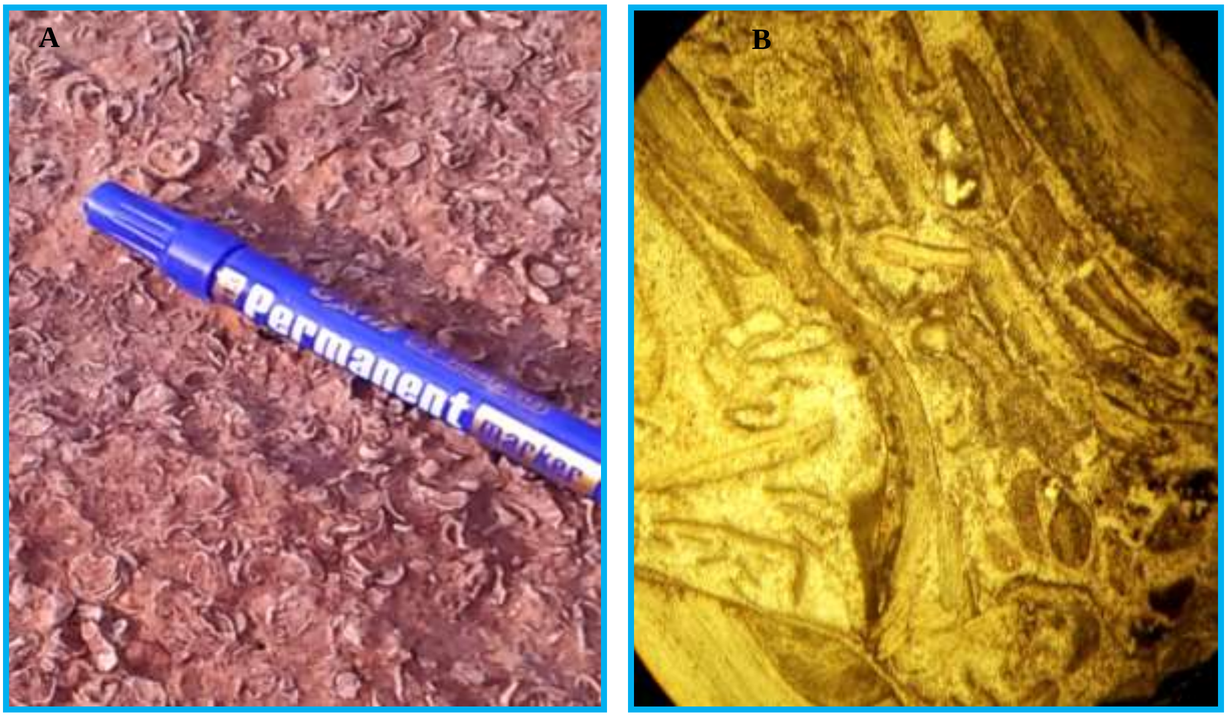


Figure 4.8: *Field and photomicrographs of coquinoid limestone, Hagere-Selam section.* (**A**) *Coquinoid limestone* and (**B**) *Photomicrograph of coquinoids limestone sample HS18, PPL veiw 4X.*

4.2.9. Marly and marl intercalation with bedded bioclastic limestone

Description: This rock unit is recorded in whole section alternating with the limestone rock unit with thickness variation from 0.3 m-30 m. It is characterized by very fine grained, light gray, white, brownish and dark in color, soft to hard grain, with some bedded of sedimentary structures of limestone rock unit (Figure 4. 9). These rock units vary from place to place in terms of fossil content, which consist fossiliferous in some locality and lack of fossil.

Interpretation: This rock unit is deposited under low energy environment. The presence of large bivalve shell (oyster) and *Alveosepta jaccardi* benthic foraminifera indicate low energy of open marine environment and presence of unfossiliferous mudstone and marl unit represent restricted low energy subtidal environment.

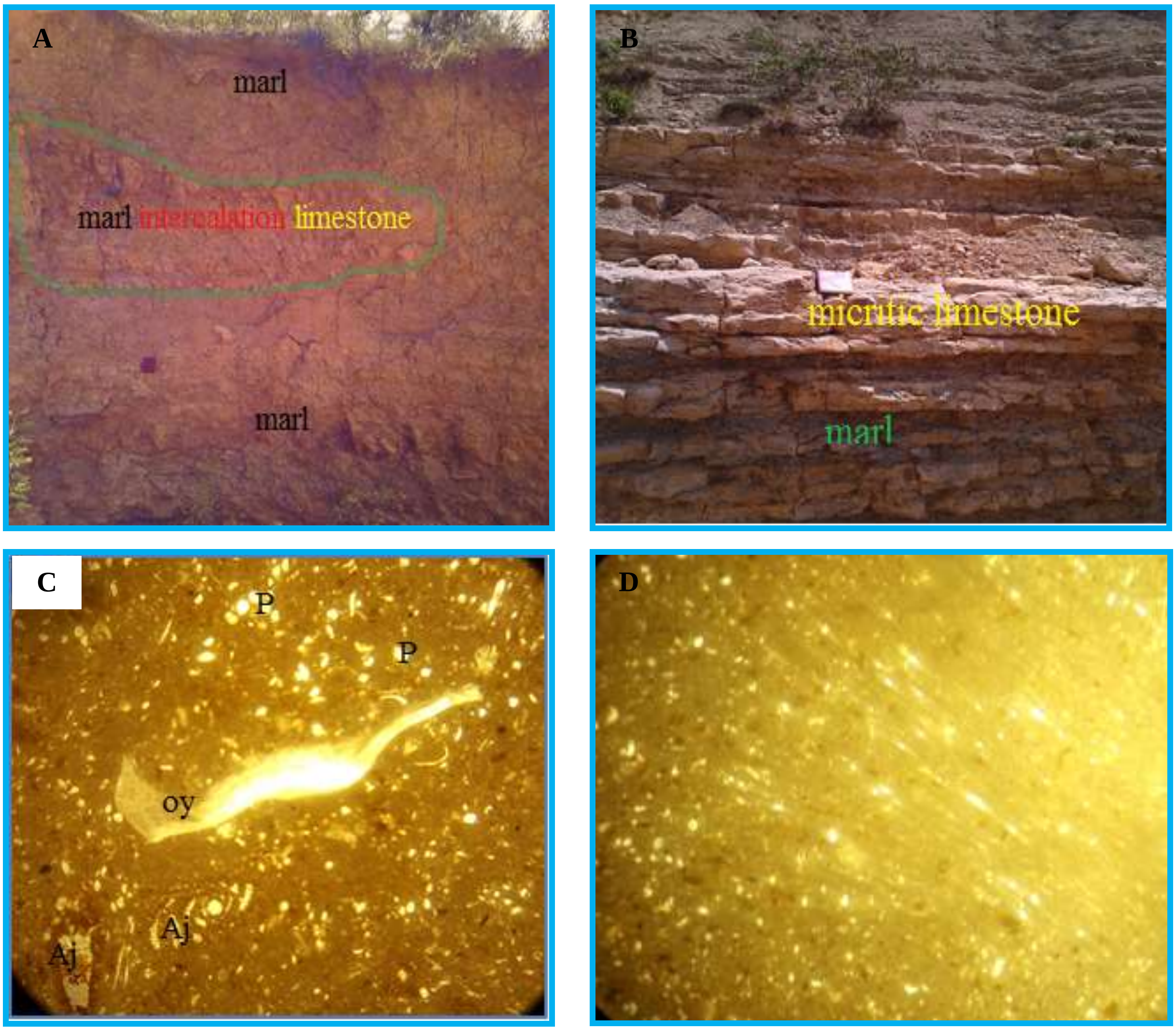


Figure 4 .9: *Field outcrop and photomicrograph of the Marly and Marl intercalation with Bedded Bioclastic Limestone. Middle part of Hagere-Selam section.* (**A**) *Marl limestone with marl intercalation limestone*. (**B**) *Marl intercalated with bedded bioclastic limestone*. (**C**) *Bioclastic mudstone consist of Alveosepta jaccardi(Aj) and bivalve oyster shell(oy) and* (**D**) *Fenestrae pore filling (P)sample HS19, PPL field of Veiw,4X.*

4.2.10. Bioturbated *Thalassiniodes* wackstone-mudstone

Description: *Thalassiniodes* isp is the dominant constituent grains for the bioturbated Thalassiniodal wackestone or mud-dominated facies whereas, brachiopods species are rarely present (Figure 4. 10A-B). This rock unit is exposed by river cut in the upper part of Hagere-Selam section, overlain and underlain by marl intercalation to limestone and coral rich mudstone with maximum thickness about 20 m. It is characterized by fine grain to medium grain, light gray in color, bedded limestone, dominated by *Thalassiniodes* trace fossil with some brachiopod fauna and other non-skeletal grain.

Interpretation: This interpretation is supported by the intensive bioturbation that moderate to high bioturbation by *Cruziana* ichnofacies, which is *Thalassinoides* belong to indicate a shallow-marine depositional environment between FWWB and storm wave base (SWB).

Additionally, the higher degree of bioturbation in the upper Hagere-Selam is indicative of shallow low energy setting. In a shallowing-upward succession, the coral and crinoidal grainstone facies overlies this facies.

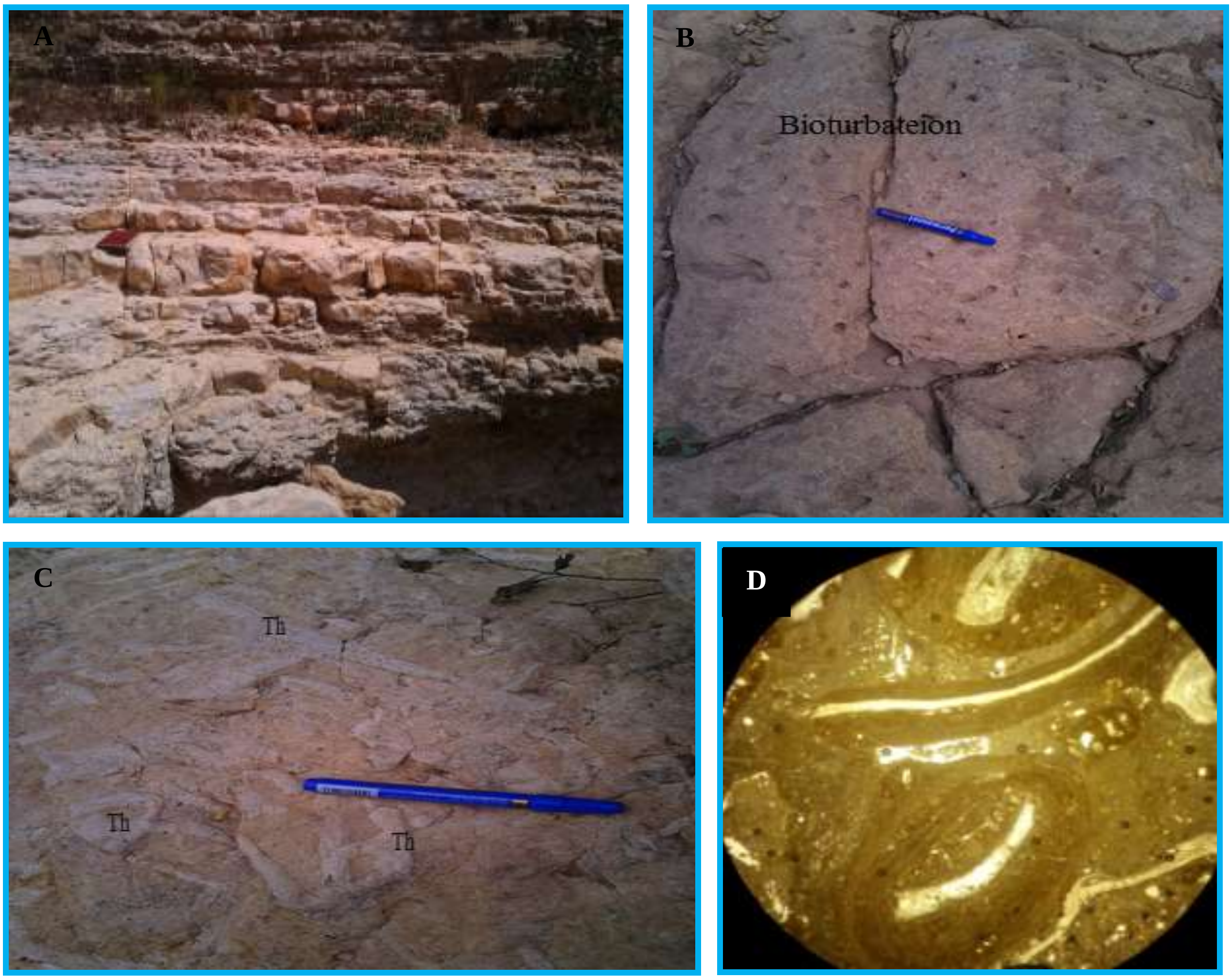


Figure 4.10: *Field outcrop and photomicrograph of the Bioturbated Thalassinoides (**Th**) Wackstone/mudstone .upper part of Hagere - Selam section*. (**A**) *Bedded and bioturbated limestone with coarse skeletal and non-skeletal grain at the bottom,* (**B**) *Highly bioturbated limestone.* (**C**) *Thalassinoides rich limestone*. (**D**) *Photomicrograph of bioturbated Thalassinoides consist of oncoids and fenestrae with dense micrite.*

4.2.11. Crinoidal packstone to grainstone limestone

Description: This rock unit is mainly exposed in the upper part of Hagere-Selam section, which is overlain and underlain by coral-stromatoporoidal mudstone and cavern mudstone respectively and it exposed by hill cut with maximum thickness range from 10-15 m in the Hagere-Selam section. It is characterized by light gray in fresh color, and well preserved crinoid rich limestone (Figure 4.11A).

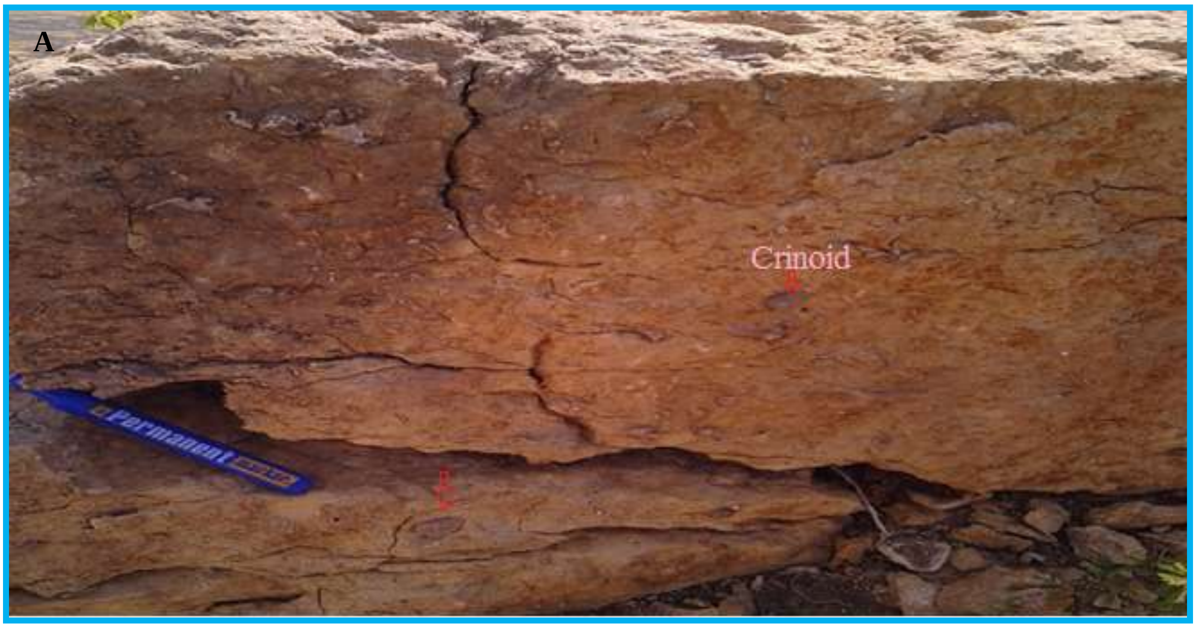


Figure 4.11*: ***A***. Field outcrop of crinoidal grainstone, which dominated by well-preserved crinoid macrofossil, upper part of Hagere-Selam section.*

4.2.12. Karastified micritic limestone

Karastified micritic limestone is exposed in the upper part of Hagere-Selam section, which is exposed by hill cut with maximum thickness variation from 10-25 m. This rock unit is conformably underlain by crinoidal rich grainstone and overlain by thick fossiliferous marly limestone. It is characterized by very fine to fine grain, light gray in fresh color, brownish and dark in weathered color. This rock unit has unique features of medium to highly karastified limestone with nodular chalcedony rich chert in place (Figure 4.12A and B).

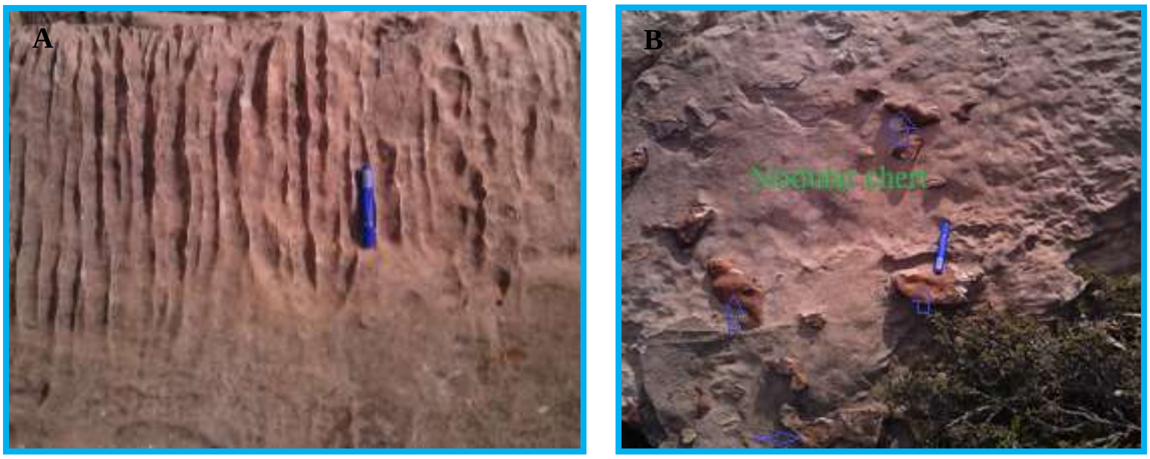


Figure 4.12*: (***A***) Field outcrop of karastified micritic limestone, and (***B***) Micritic limestone with nodular chert structure, upper part of Hagere-Selam section.*

4.2.13. Upper sandstone

The upper sandstone unit, also called Amba Aradam Formation is the youngest of the Mesozoic sedimentary succession exposed by road cut in the Hagere-Selam section with maximum thickness about 40 m. This rock unit is underlain by the marl and overlain by the trap basalt in place. It is mainly characterized by variegated (with white, purple, red and yellow) in colors, medium to coarse grained, some friable, shale and have some laterite bed in the lower and upper part of the section. It also contains bedding, massive bed and cross bedding sedimentary structure.

Previous studies assign the age of this rock unit to Late Jurassic age of the upper sandstone found at Harar plateau (Merla and Minucci, 1938 and Dainelli, 1943) to suggest an Early Cretaceous age for the upper sandstone in Tigrai province. This is based on the stratigraphic continuity between the upper sandstone and the underlying Antalo succession and the angular unconformity observed.

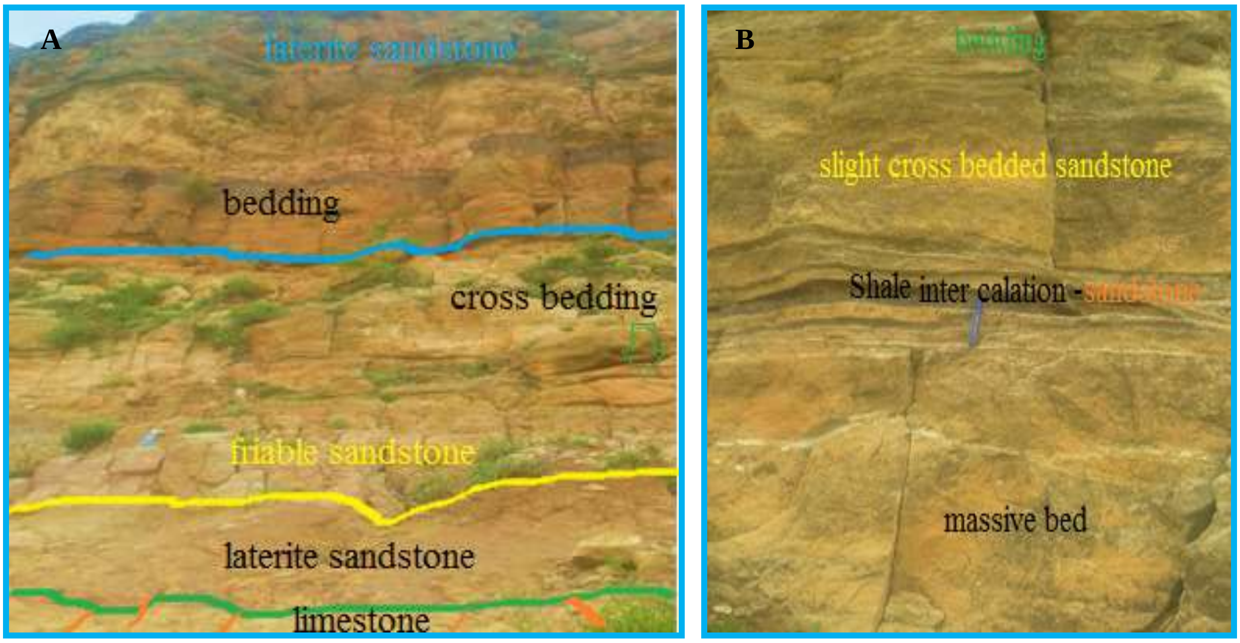


Figure 4.12*: Field outcrop of Upper Sandstone Formation, upper part of Hagere-Selam section.* (**A**) *Show angular unconformity with underlain carbonate rock unit and characterized by friable, laterite and bedded sandstone.* (**B**) *Massive bed intercalated of sha le- sandstone and bedded sandstone rock unit.*

4.3. Messobo stratigraphic section

The study section in the Messobo area is located on the southeastern direction of the Mekelle Outlier at 554988 to 557002 m E longitude and 1499022 to1495984 m N latitude along the Mekelle-Adigrat main asphalted road. The carbonate successions are conformably overlain and underlian by Agula Shale respectively with maximum thickness up to 230 m (see appendix one Plate I. Figure C). This section includes unfossiliferous micritic limestone, bioclastic sandy oolitic limestone, bioclastic wackstone to packstone limestone and bedded micritic limestone rock unit from the bottom to top with younger alluvial and diorite dyke in the middle part of the section. A detailed lithological and stratigraphical description and interpretation of this section was discussed as follows:

4.3.1. Unfossiliferous micritic limestone

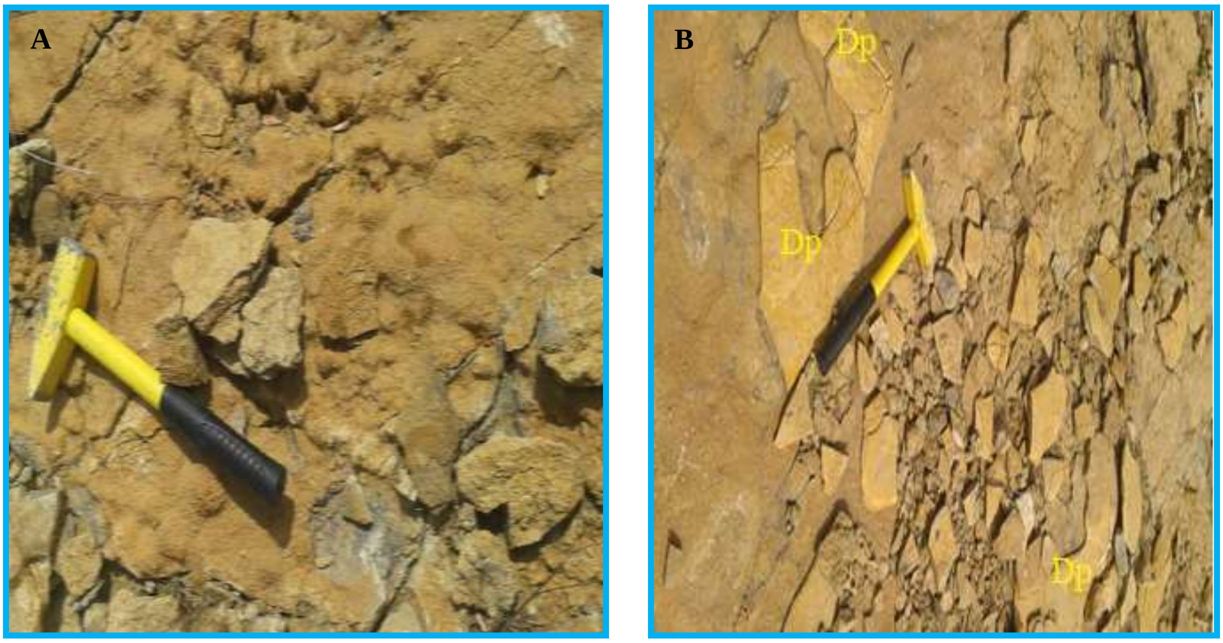
Descriptions: This unfossiliferous limestone facies exposed by road cut, which is overlain by fossiliferous limestone and underlain by shale unit with maximum thickness about 5 m. It is characterized by light gray to dark in color, very fine grain with thinly bedded. This facies have no skeletal grains.

Interpretation: Absence of skeletal grain, presence of fine grain texture, thin bedding and lamination with fenestrae pore space filling calcite mineral indicate the rock unit is deposited under clam, low and no agitated energy on shallow intertidal environment.

4.3.2. Bioclastic sandy oolitic limestone

Description: The oolitic limestone rock unit is found dominantly in the lower part of Messobo section, which is exposed by road cut and quarry site with maximum thickness up to 20 m. It is characterized by yellow, brown, light gray to dark in fresh color, well sorted, well rounded coarse ooid grain, with abundant fossils including brachiopods and bivalve. Additionally, abundant *Diplocraterion parallelum* traces fossil and flute cast structure (Figure 4.13A) are common.

Interpretion: The well sorted skeletal grain, presences of coquinoid bivalve, brachiopods and presence of abundant trace fossil association indicate deposition in upper shore face (storm) environment under high agitated energy.



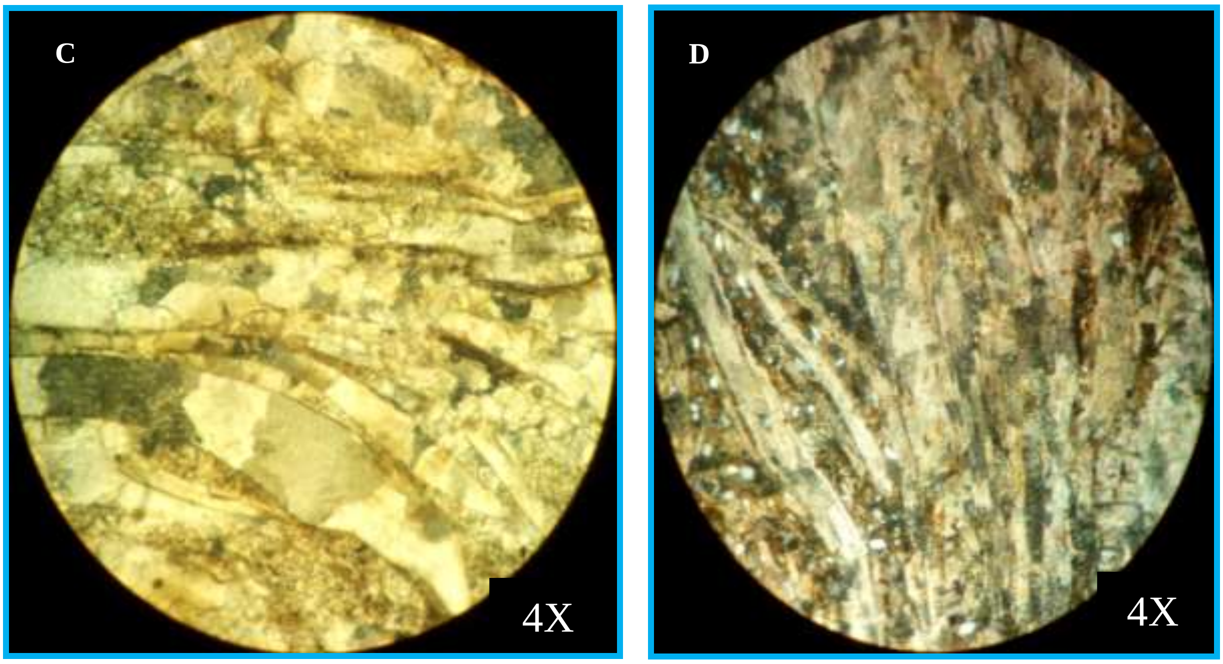


Figure 4.13: *Field Outcrop and photomicrograph of the fossiliferous limestone, Messobo section.* (A) *Fossil rich limestone and flute cast structure upper part of the picture* (**B**) *Deplocraterian trace fossil*(C) *Calcitized bivalve shell rich limestone sample MS2 and* (**D**) *Calcitized bivalve shell rich grainstone with scattered fine grain quartz grain sample MS3,XPL field of view.*

4.3.3. Alluvial sediment

Alluvial sediments are the youngest unconsolidated sediment that exposed in the middle part of the Messobo section with maximum thickness up to 30 m. These sediments are overlain and underlain conformably by wackstone and fossiliferous limestone respectively and composed of fluvial sediments ranging from poorly-sorted, angular pebbles and boulders with abundant mixtures of clay, silt, sand and pebbles (Figure 4.14B).

4.3.4. Bioclastic wackstone-packstone limestone

Description: This wackstone rock unit is mainly exposed by road cut in the middle part of Messobo section with maximum thickness about 50 m and overlain by diorite dyke and underlain by alluvial sediment. It is characterized by brownish weather and light gray to black in fresh color, fine to medium grain with some secondary filling calcite material (Figure 4.3.4A). In place it is massive and forming cliff.

Interpretation: This dark to black in color, fine to medium grain and bioclastic wackstone rock unit indicated the rock unit deposited in non-agitated, low energy environment.

Figure 4.14: *Field outcrop of the wackstone and alluvial sediment, Messobo section*. (**A**) *Dark wackstone/packstone limestone*. (**B**) *Alluvial sediment*.

4.3.5. Dolerite

This rock unit is exposed by road cut on the Mekelle-Adigrat asphalt road at the middle part of Messobo section with a total 15 m maximum thickness. The diorite in this area is exposed as intruded small stocks following the main Mekelle normal fault and it is characterized by dark green to gray in color, fine to medium grained, crystalline, dykes and show spheroidal weathering.

4.3.6. Bedded micritic limestone

Description: This rock unit is mainly exposed by road cut along the main asphalt road of Mekelle-Adigrat at the Messobo stratigraphic section with maximum thickness about 100 m and conformable overlain and underlain by black shale and black wackstone rock unit respectively. It is characterized by fine grain, brownish, light gray to dark color, compacted, bedded in horizontally to sub-horizontally bedded, intercalation of bedded limestone, marl, lack of macrofossil and trace fossil association with little non skeletal grain (Figure 4.15). Individual bed thickness of the bedded micritic limestone varies from 0.56 to 1 m.

Interpretation: Due to absence of trace fossil association, macrofossil, having of very fine grain and bedded black color, the rock unit is deposited in deep, low energy depositional environment.

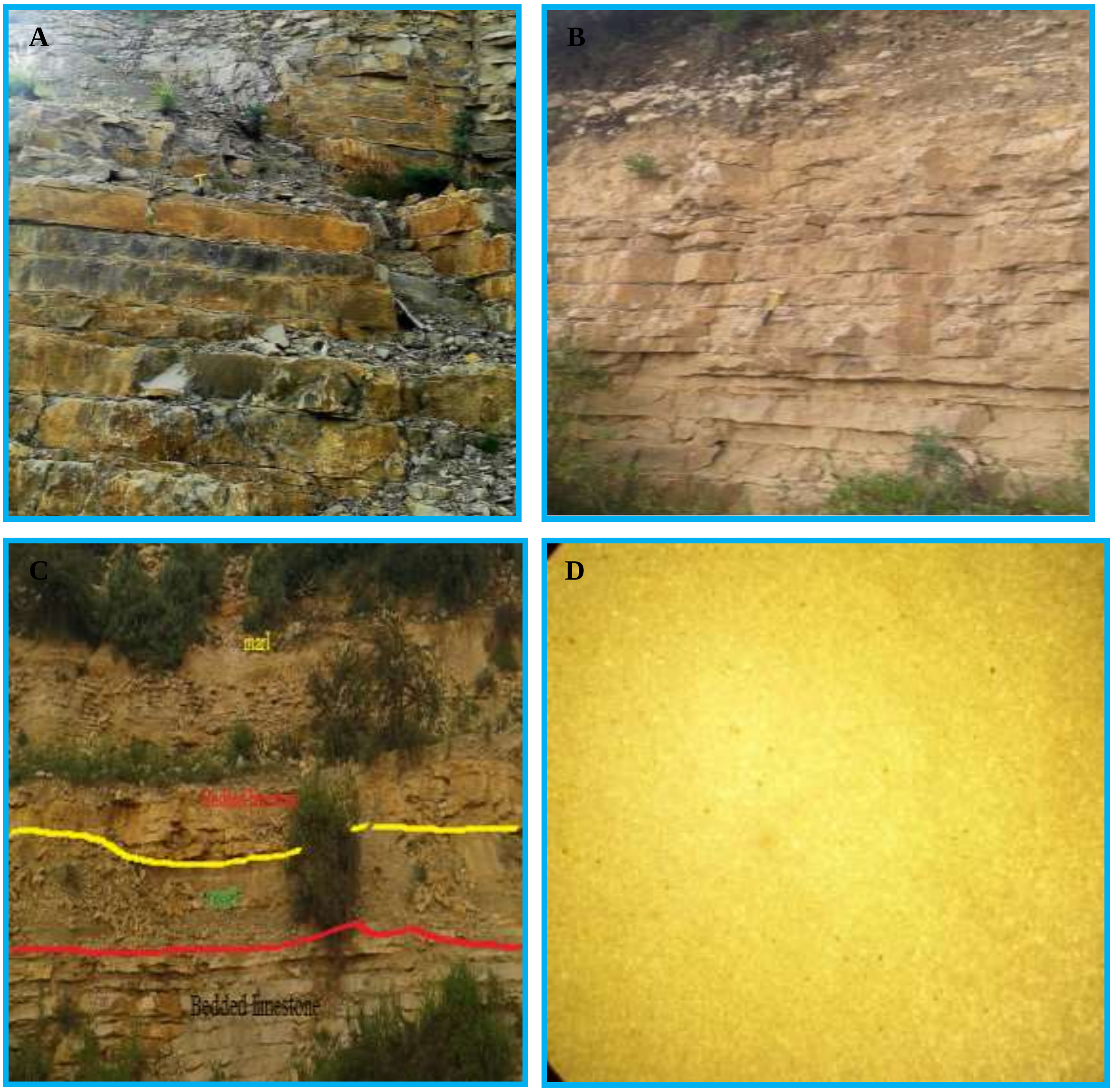


Figure 4.15: *Field outcrop and photo micrograph of the bedded micritic limestone*. (**A**) *Slightly tilted bedded black limestone*. (**B**) *Bedded limestone* (**C**) *bedded limestone intercalated with marl and* (**D**) *Unfossiliferous micritic limestone, sample MS17, PPL field of view,* 4X. *Upper part of Messobo section.*

4.4. Wukro stratigraphic section

The study section in Wukro area is located on the northeastern margin of the Mekelle Outlier at 560557 to 563074 m E longitude and 152734 to 1523343 m N latitude along the Wukro-Hawzen gravel road. The carbonate successions are conformably overlain and underlian by Agula Shale and clastic Adigrat Sandstone respectively with maximum thickness up to 420 m. This section includes marly limestone, wackstone to packstone, fossiliferous limestone, oolitic limestone, coquinoid limestone, sandy limestone, bedded limestone, karastified mudstone and marly limestone rock unit from bottom to top with highly intercalation (see appendix one, Plate I, Figure D). A detailed lithological and stratigraphical description and interpretation of this section are discussed as follows:

4.4.1. Bioclastic wackstone to packstone limestone

Description: This rock unit is mainly exposed by river cut in the lower part of Wukro section with maximum thickness about 10 m. This carbonate unit is overlain by fossiliferous limestone and underlain by marly limestone. It is characterized by brownish weather and light gray to dark-black fresh color, fine to medium grain size with some invertebrate macrofossil. In place it is massive; forming cliff and it contains bedded chert dominated with chalcedony mineral of fibrous structure and nodular structure (Figure 4.16).

Interpretation: This dark to black in color, fine to medium grain, lack of trace fossils and presence of chert bed indicate the rock unit, deposit in low energy environment.

Figure 4.16: *Field outcrop of the bioclastic wackstone to packstone limestone, Wukro section* (**A**) *Nodular structure.* (**B**) *Nodular and bedded chert red rectangle.*

4.4.2. Sandy oolitic limestone

Description: This rock unit is recorded in the lower, middle and upper part of Wukro section with thickness variation from 1-90 m. It is characterized by fine to sand sized carbonate grains, light gray to reddish, brownish and dark in color with abundant of sedimentary structure including cross bedding and bedding. Another distinctive feature is presence of ferruginous hard ground, spotted in vertical column and trace fossil at distinct interval (Figure 4.17). Moreover, this rock unit contains of abundant body fossil including bivalve and brachiopods and some *Thalassiniodes* trace fossil.

Interpretation: Due to presence of these features of the ferruginous hard ground, oolitic rock units and trace fossil are deposited under high energy, agitated nearshore environment of upper shore face or inner ramp.

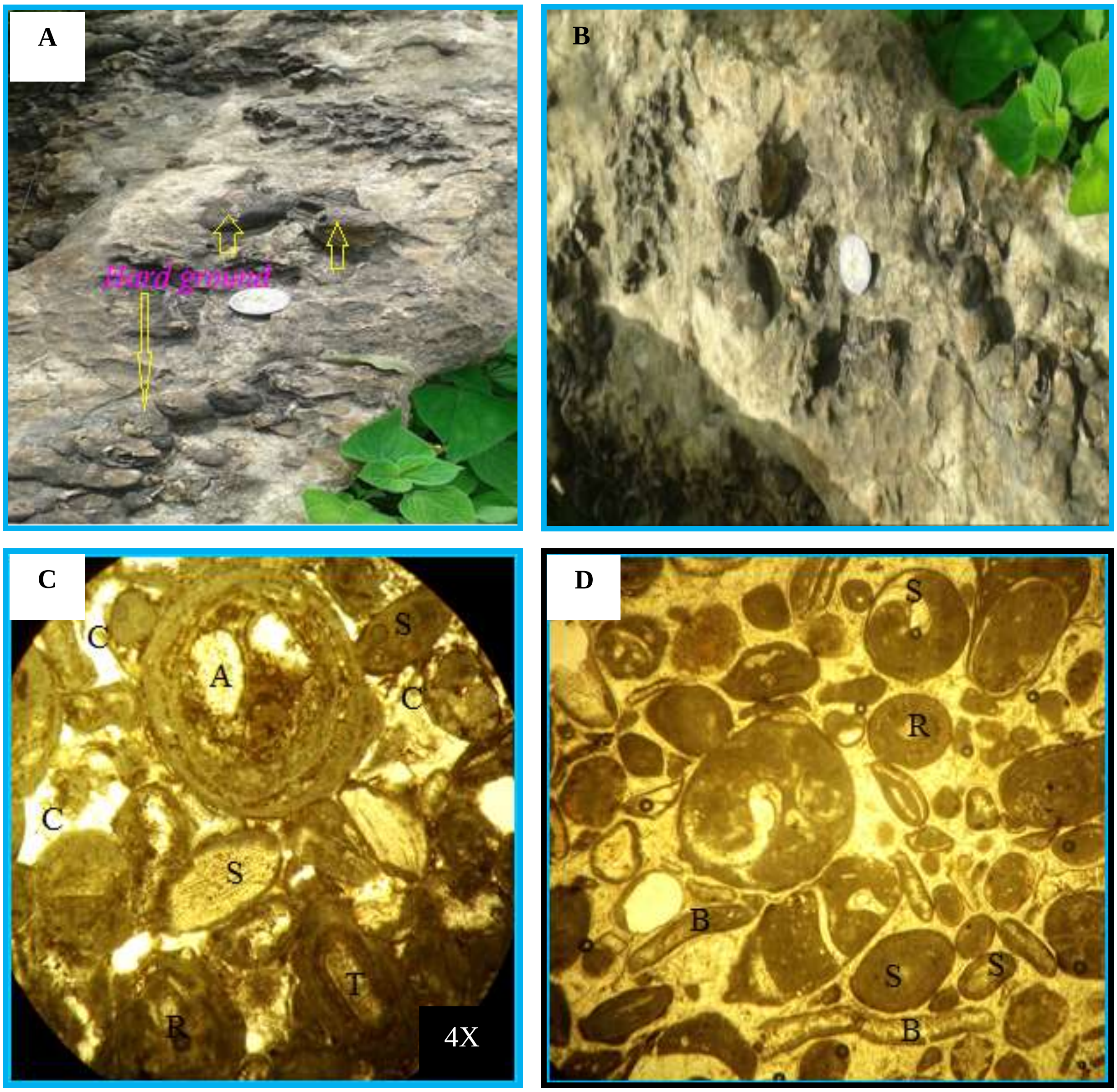


Figure 4.17: *Field outcrop and photomicrograph of the sandy oolitic limestone, Wukro section*. (**A-B**) *Abundant sub rounded to well-rounded hard ground lower part of Wukro section*. (**C**) *Well sorted spherical to well-rounded oolitic grain stone consist of superficial(S),radial(R),tangential ooids with calcareous algae(A) as nucleus cemented by sparry calcite* (C) *sample* WS36, *upper part of Wukro section and* (**D**) *Well-rounded ooids with some bivalve and brachiopods shell fragment, sample* WS5,*4X,PPL field of View, lower part of Wukro section*

4.4.3. Fossiliferous limestone

Description: The fossiliferous limestone rock unit is found dominantly in the lower and middle part of Wukro section, which is exposed by stream, road and hill cut with maximum thickness variation from 5-18 m. It is characterized by yellow, brown, reddish, light gray to dark in fresh color and coarse grain. Abundant fossils including brachiopods, bivalve and *Diplocraterion parallelum* traces fossil are common in this rock unit.

Figure 4.18: *Field photographs of fossiliferous limestone, Wukro section*. (**A**) *Light grayin color and* (**B**) *Reddish fossil rich limestone* (**C**) *Brachiopods rich limestone*.

4.4.4. Coquinoid limestone

Description: This coquina rich rock unit is exposed in the lower part of Wukro section with a maximum thickness variation from 3 m-12 m. It is exposed by the stream and hill cut. This rock unit is characterized by light gray, dark in color, coarse skeletal grain, well sorted, compositionally, texturally matures and consists fully of brachiopods and/or bivalves marine benthic invertebrate fossils (Figure 4.19).

Interpretation: The well sorted skeletal grain, compos, presences of coquinoid brachiopods and/or bivalve indicate deposition in the upper shore face (storm) environment under high energy.

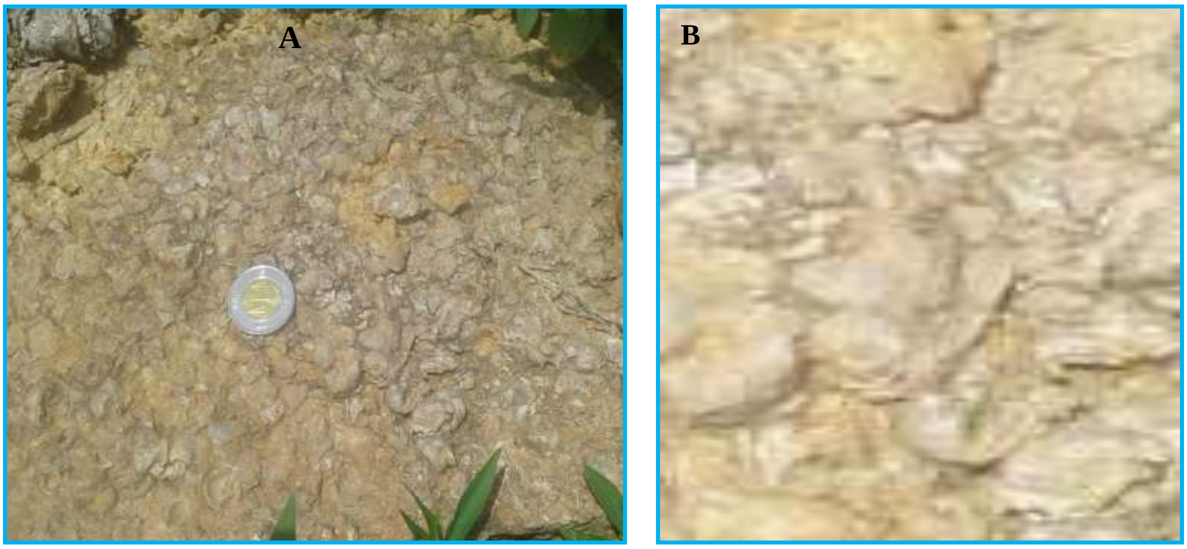


Figure 4.19: **A**) *Field photographs of coquinoid limestone, Wukro section and* (**B**) *close veiw of* **A**.

4.4.5. Sandy limestone

Description: This sandy limestone rock unit is exposed in the lower part of Wukro section with maximum thickness variation from 0.5-1.6 m, which is exposed by river cut. It is characterized by fine to medium grained, angular to sub angular sandstone, white, yellow and brown in color. It is friable with abundant quartz and calcite cementing mineral. This rock unit is overlain by oolitic limestone and underlain by marl sediment (Figure 4.20).

Interpretation: The deposition of this rock unit occurred during a period of steady sediment supply to the beach by a drainage system originated under moderate to high tidal range within the restricted platform in areas of large supply of detritus and high tidal current. Therefore, a well oxygenated shallow environment with normal marine salinity is proposed.

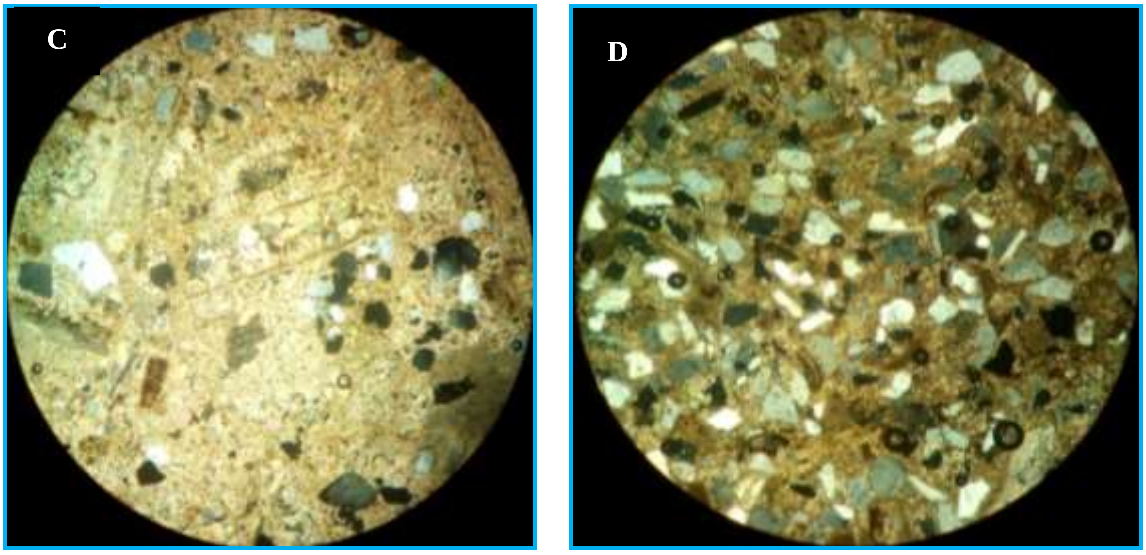


Figure 4.20: *Field Outcrop and photo micrograph of the sandy Limestone, Wukro section*. (**A**) *Friable fine to medium grained sandy limestone overlain and underlain by oolitic limestone and marl*. (**B**) *Photo micrograph of fine grain to medium grain quartz arenite (Q) cemented by calcite(C) sample WS10, XPL field of view, 10X. (***C***) Sandy limestone consist of some quartz grain with some bivalve shell, sample WS12,XPL field of view,10X and (***D***) Sandy limestone consist abundant detrital grain with scattered mollusk shell impeded by micrite, sample WS14, XPL field of view, 10X, lower part of Wukro section.*

4.4.6 Karastified limestone

Description: Karastified limestone is exposed in the lower, middle and upper part of Wukro sections, which is exposed by river and hill cut with thickness variation from 10-25 m. This rock unit is characterized by fine to coarse grain, light gray in fresh color, brownish and dark in weathered color and medium to highly karastified limestone (Figure 4.21A-B).

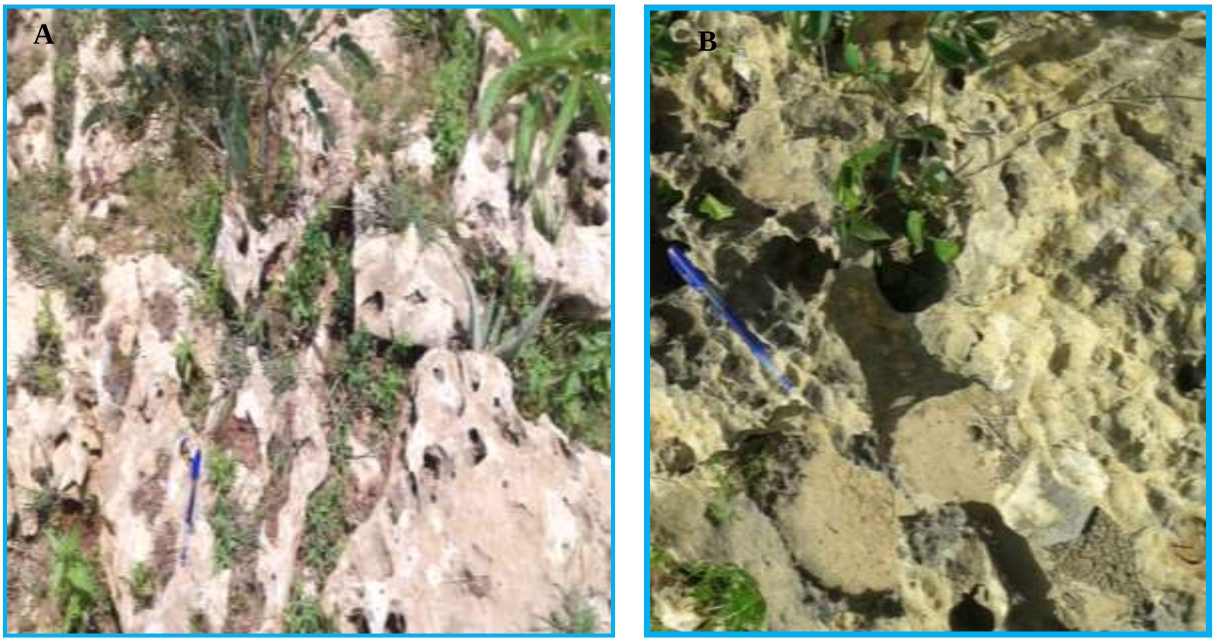


Figure 4.21: *Field outcrop of highly karastified limestone* (**A-B**). *Upper part of Wukro section*.

4.4.7. Marly limestone

Description: This rock unit is recorded in whole section alternating within the limestone rock unit with thickness variation from 0.3 m-30 m. It is characterized by very fine grain, light gray, white, brownish and dark in color, soft to hard grain, with lack of sedimentary structure except it shows some lamination to bedding and some cross bedding structure in some locality (Figure 4.22). This rock unit varies from place to place in terms of fossil content, which consist a fossiliferous in some locality and lack of fossil in other places and degree of exposure.

Interpretation: This rock unit is deposited under low energy, shallow marine environment.

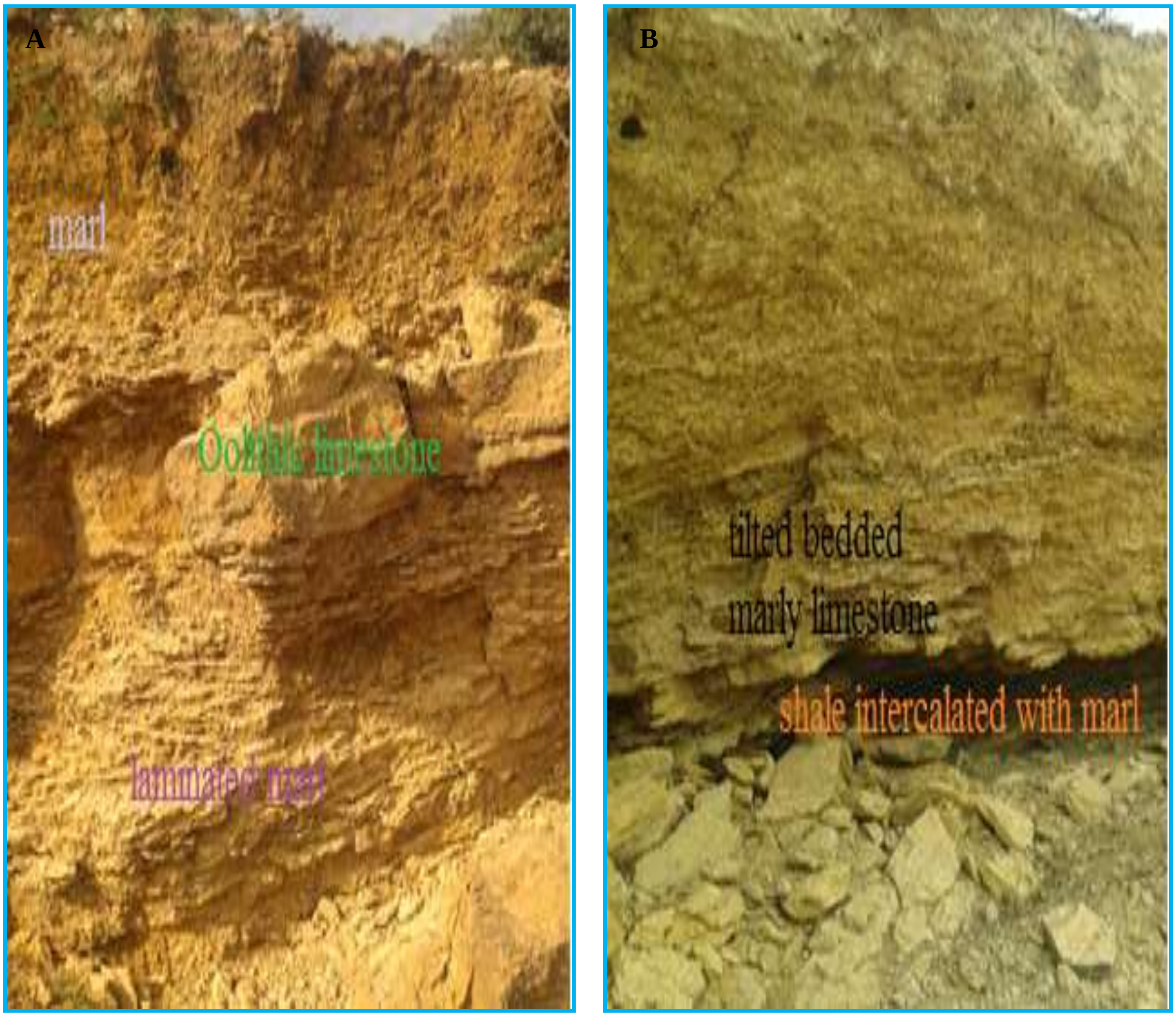


Figure 4.22: *Field outcrop of the marly limestone, Wukro section*. (**A**) *Show lamination with some limestone bed middle part*, (**B**) *Bedded, laminated and slightly tilted cross bedded marly limestone with some fissile shale upper part of Wukro section.*

4.4.8.Bioclastic bedded limestone

***Description*:** The bedded limestone is exposed in the middle and upper part of the wukro section,which is exposed by river cut with maximum thickness varation from 10-15 m. It is characterised by horizontal beddeing with slightly tilted bed especially in the middle part of the study section. It also cantain some fossil in the upper part of wukro section.

Interpretion: Deu to presence of aboundant foraminifera fossils including *Alveosepta jaccard*i, *Pseudocyclammina lituus*, *Nautiloculina oolithic* embedded with dense micrite indicate the bioclastic bedded limestone deposited in open marine environment, which indicate low, non agitated depostional environment.

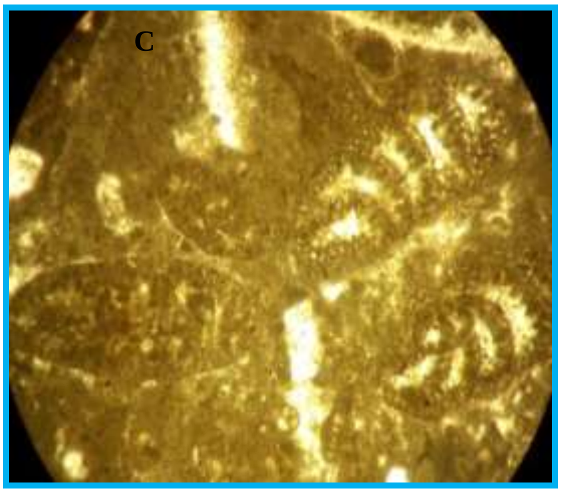


Figure 4.23: *Field outcrop and photomicrograph of the bioclastic bedded limestone, Wukro section*. (**A**) *Show bedded limestone upper part*; (**B**) *Slightly tilted bedded limestone middle part of Wukro section.* (**C**) *Alveosepta jaccardi rich bedded limestone upper p part of Wukro section.*

CHAPTER FIVE

5. PETROGRAPHIC DESCRIPTION, MICROFACIES ANALYSIS AND INTERPRETION OF CARBONATE ROCK UNIT.

5.1. Petrographic descriptions

Like other sedimentary rocks, carbonate rocks can be classified based on the hand specimens description with the help of hand lens and naked eye; however, field description alone is not enough for carbonate description and classification. Therefore, in addition to a detailed field observations and description made in the Hagere-Selam, Messobo and Wukro stratigraphic sections, a detail descriptions and classification on 65 representative carbonate rocks thin-section were made under petrographic microscope in Addis Ababa university petrology laboratory. These detailed thin section description and classification were conducted on the base of Dunham (1962) and modified Embry and Klovan (1971) carbonate rock classification scheme. According to the petrographic analysis various major carbonate components such as skeletal and non-skeletal component, terrigenous constituents, microcrystalline calcite matrix (micrites), sparry calcite (spar) and the most common diagentic features are recognized. Texturally, the collected rock samples display various carbonate textures ranging from mudstone (22 of total sample), wackestone (11 of total), packstone (5 of total) and grainstones (26 of total) with grain sorting range from poorly sorted to well-sorted. Therefore, this petrographic description shows that the carbonate unit of the three sections contains: Mudstone, wackstone-grainstone of peloids, ooids, oncoids, aggregate, dolomite, skeletal grains and detrital quartz grains. All these petrographic properties with their depositional environment interpretation, microfacies analysis, stratigraphic position (age) and some diagenetic features were discussed. Also, representative photomicrographs of some thin section with their detailed petrographic descriptions were given.

5.2. Microfacies analysis

Microfacies are a sedimentary facies that can be studied and characterized in thin sections of a rock sample using polarizing light microscope. The name is generally applied to characteristics that can be determined by study of rock thin sections and micropaleontology on the base of petrographic and light reflected binocular microscope respectively. Therefore, microfacies are defined as the sum of all sedimentological and paleontological information, which are defined and classified on the basis of petrographic microscope.

The purpose of microfacies analysis is to provide a detailed record of carbonate rock characteristics of relative abundance of the main constituents (allochem grains, matrix and cements), shapes, sizes, sorting and other characteristics of the carbonate grains, including types of fossil, nature of the matrix, kinds of cements and nature of the fabric (grain-support, mud-support and bioturbation) that can subsequently be related to a particular depositional conditions, which are significant to ancient depositional environmental interpretation.

Studying of microfacies analysis begins in the field with collection of rock and dry marl sediment samples from three measured sections for detailed study under light microscope. Flugel (1982; 2004) and Wilson (1975) have advocated use of carbonate microfacies data to establish a restricted number of major microfacies types that serve as standard models for all carbonate microfacies of the carbonate rock unit. These microfacies are referred to as a standard microfacies type and they can be grouped into facies "belts" or zones, which are finally used to reconstruct a generalized depositional environment for carbonate sedimentary rock.

24 Standard microfacies (SMF) types were identified on the basis of major kinds of carbonate grains, paleontological data, micrite to sparite abundance and carbonate fabrics using the textural classification of Dunham (1962), modified Embry and Klovan (1971) and Wilson (1975) (see appendix three, plate I). Based on petrographic analysis, sedimentological characteristic of the 65 thin sections, 26 productive marl samples and detailed field information obtained from the carbonate succession of the study sections, 19 microfacies types can be defined, which are grouped into four facies association. They includes the restricted intertidal, tidal flat system (3 facies type), lagoon (2 facies type), high energy shoals and patch reef (6 facies type) and open marine (8 facies type), which range from inner ramp to middle-outer ramp environment. Their detailed facies association and their microfacies are discussed as bellows:

5.3. Facies Association A (Tidal flat system)

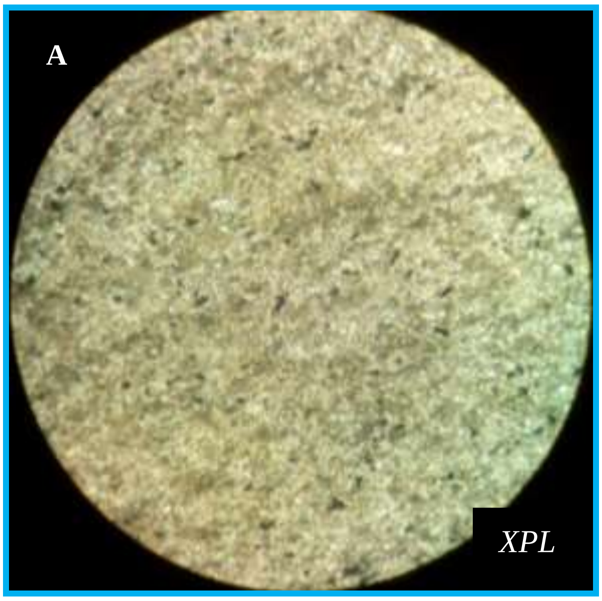
Carbonate tidal flat occur in settings, which are protected from open Ocean waves by wide shelf lagoons, which dampening the incoming waves by its position behind barrier land that separate back shoal lagoons from open Ocean (Walker, 1992; Reading, 1996). These tidal flat are partly sea and partly land,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

5.3.1. Very fine-crystalline-dolomudstone microfacies (MFT1)

Description: This very fine crystalline dolomite microfacies is not widespread throughout the measured sections; however, it records from the middle part of Messobo stratigraphic section from sample MS10 which is overlain by unfossiliferous mudstone and underlain by siliciclastic mudstone to wackstone microfacies type. The fine crystalline dolomite consists of subhedral to euhedral crystal fabric (Figure 5.1A-B). This type of microfacies forms dense, clear to dark mosaics of interlocking crystal with fine detrital quartz grains, devoid of any skeletal and non-skeletal grains and forming planar layers.

Interpretation: The very fine crystalline dolomite crystal restricts to pertidal depositional environment (Amthor&Friedman, 1991). The fine crystal size represents a result of early dolomitization of precursor on peritidal lime mudstone or neomorphism of a pen contemporaneous or early diagenetic dolomite (Zenger, 1983; Amthor&Friedmon, 1991).

However, the dolomite is not indicating their depositional facies, which indicate diagenetic facies. But, due to presence of the fine grain size, presence of quartz grains, lack of fauna, fenestral fabric & vertical changes suggest that deposition occurred in a low-energy, restricted intertidal & supratidal environment (Wilson & Evans, 2002). Therefore, this microfacies is deposited in shallow subtidal to lower intertidal environments, which is corresponding to SMF-23 of Wilson (1975) and Flugel (2010) of facies belt 8.



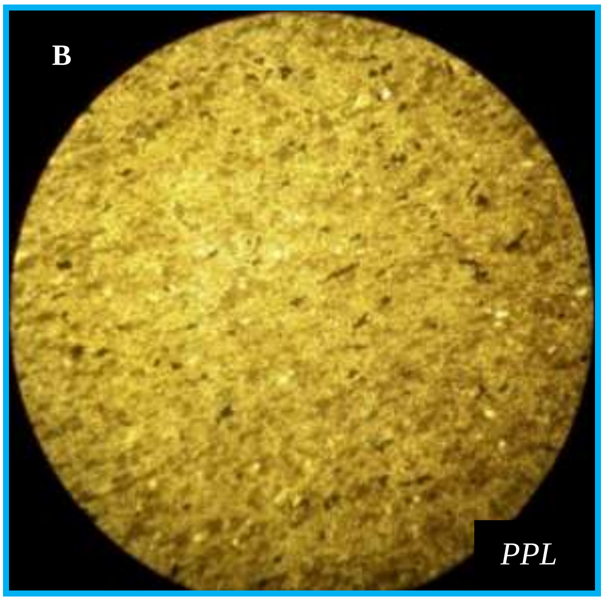


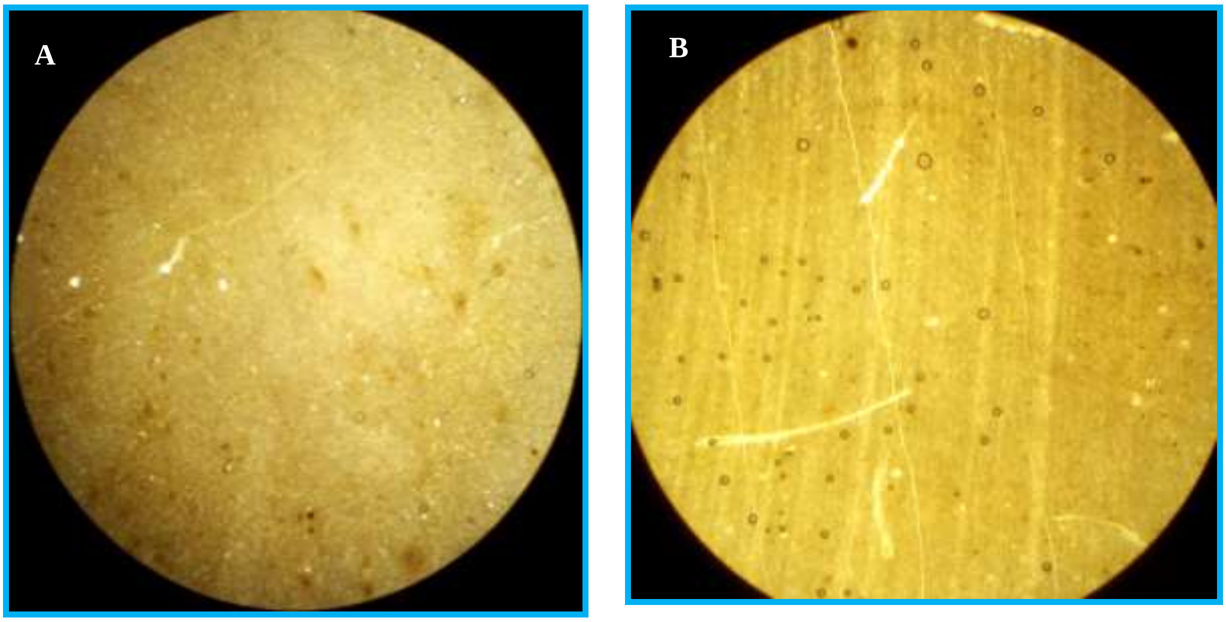
Figure 5.1: *Photomicrograph of very fine crystalline dolomite microfacies middle part of Messobo section, sample MS10, XPL and PPL view, 10X*. (**A-B**) *Very fine crystalline dolomite with scattered detrital quartz grain with some opaque or organic mineral the black color indicates*

5.3.2. Unfossiliferous lime-mudstone (MFT2)

Description: This microfacies is recorded from the lower, middle and upper part of Messobo stratigraphic section from sample MS1, MS4, MS11, MS13, MS17 and upper part of Hagere-Selam section from sample HS21 and HS26. It is characterized by fine textured, thin and medium to thick-bedded homogenous lime mudstone, which is dark to light grey, brown in color, cavern and partly bioturbated. Texturally, non-skeletal lime mudstone is formed as cloudy fine-crystalline calcite crystals, which have partially suffered from aggrading neomorphism into pseudospar. It contains many cavities filled with granular sparry calcite.

This rock unit consists of scattered bivalve shell and sponge spicules with fine grain, sparse detrital quartz grain and fenestrae fabric. Some lime mudstone beds are partly recrystallized into microsparite.

Interpretation: The unfossiliferous lime-mudstone facies has been deposited in a low-energy, poorly fossiliferous environments, which are common in shallow restricted intertidal areas of clam conditions which have no water circulation (Flugel,1982) that reduce the normal wave or current energy on shallow marine carbonate shelf. They represent deposition in shallow tidal. The restricted conditions are achieved by the low diversity of the faunal content. The relative absence of microfauna strongly advocates deposition in nearshore domain at water depth less than 5m, where a nearshore ebb and tide condition is common. This microfacies correspond to facies SMF-23 of Wilson (1975) and Flugel (2010). Thus, the fine grain size, the presence of scattered detrital small quartz grains, lack of skeletal grains, the fenestral fabric and vertical change at the Messobo stratigraphic section indicate that deposition occurred in low-energy, restricted intertidal and supratidal environment (Wilson and Evans, 2002). The flat lamination and diagnostic structures of arid upper intertidal flat is indicative that the lime mudstone was of lower intertidal origin.



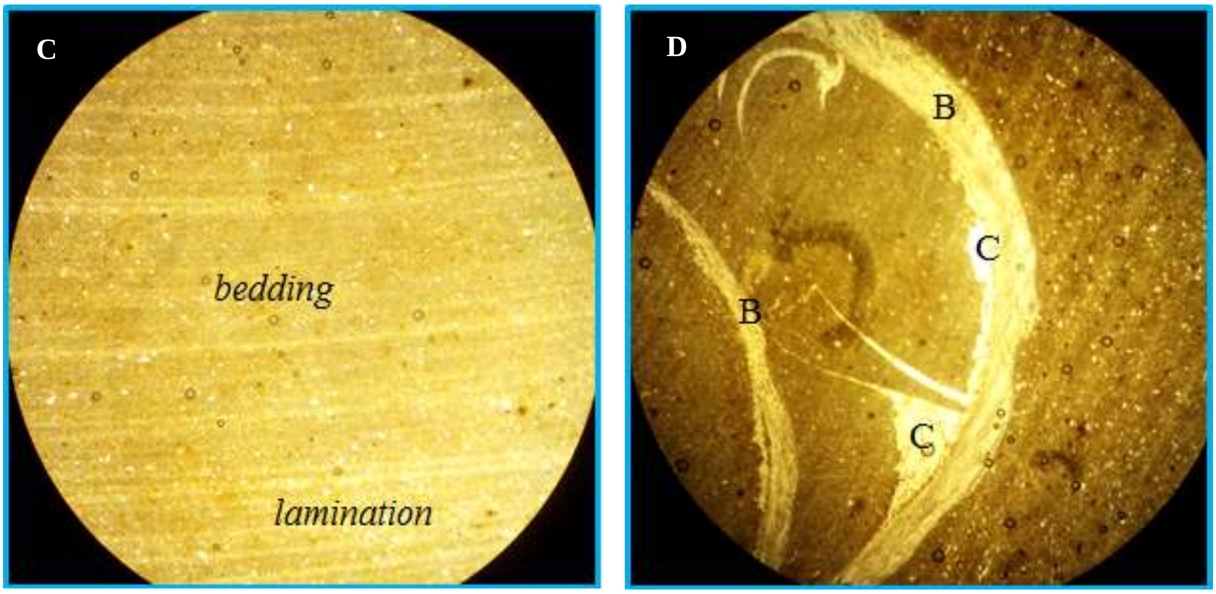


Figure 5.2: *Photomicrograph of unfossiliferous mudstone upper part of Hagere-Selam and lower, middle and upper part of Messobo stratigraphic section indicate laminated, bedded (C), have scattered mollusk shell(B) and fenestrae fabric(C), PPL field of view, 4X.*

5.3.3. Siliciclastic mudstone microfacies (MFT3)

Description: This siliciclastic mudstone microfacies is recorded in the middle part of Messobo stratigraphic section from sample MS8, which is overlain by very fine-crystalline dolomudstone and underlain by bioclastic wackstone respectively. It is characterized by dark grey color with abundant detrital material and some crystalline calcite associated with dense micrite (Figure 5.3A-D). The most striking character of this facies is the alternation of the thin beds of mudstone and clay rich beds.

Interpretation: This microfacies type can be deposited in a shallow, restricted platform environment with low-energy conditions. The lack of fauna and dark grey color reflects deposition under low-oxygen water condition and/or high fine argillaceous input during deposition from their nearby continent. Additionally, presence of dolomite and unfossiliferous lime mudstone overlain this rock unit indicate restricted low energy shallow environment. The depositional setting for the argillaceous limestone is interpreted to be the restricted shallow intertidal environment. The dominance of carbonate mud and argillaceous materials with lack of skeletal grain supports this interpretation. Therefore, this facies is similar with facies zone of FZ8 of Wilson (1975).

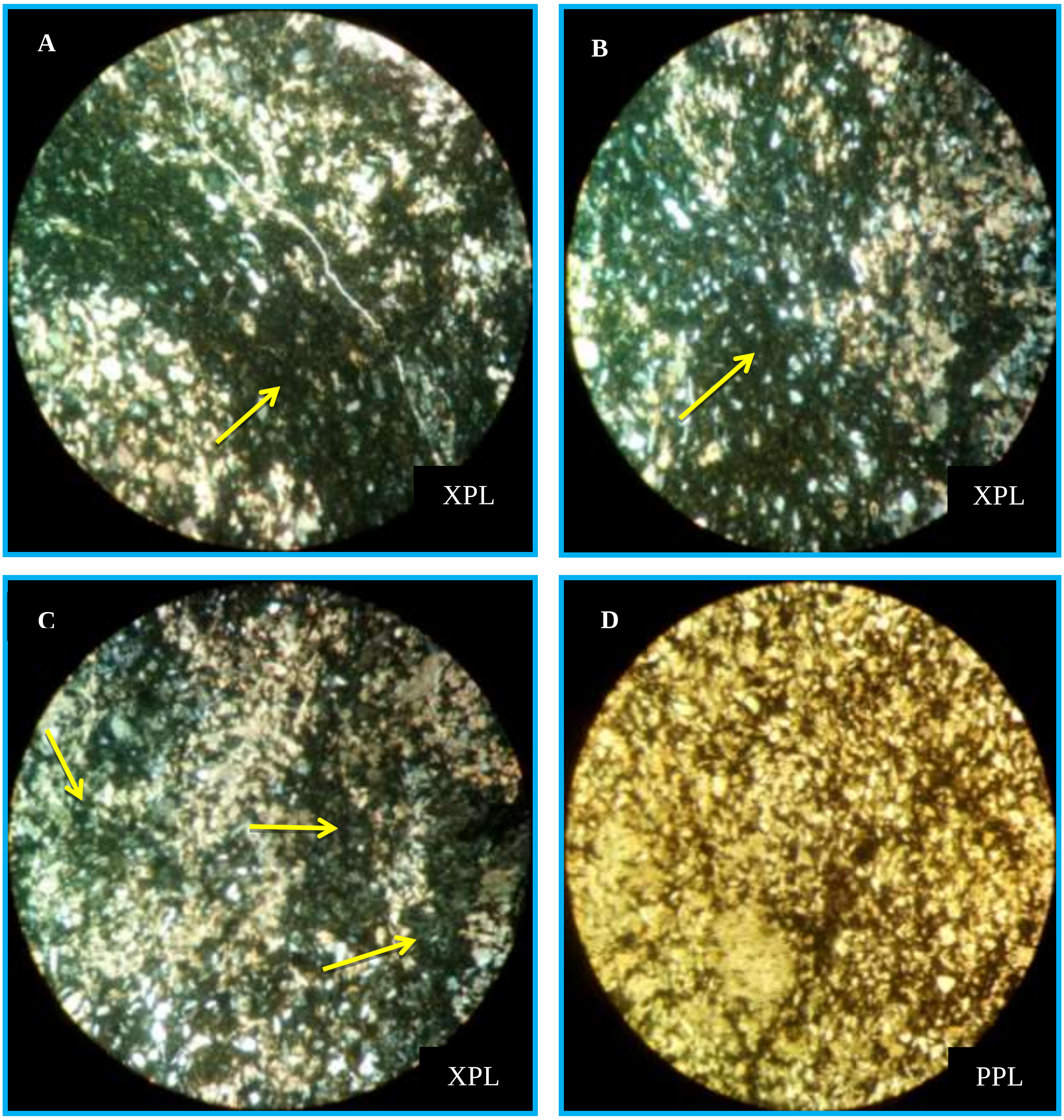


Figure 5.3: *Photomicrograph of siliciclastic mudstone microfacies type composed of extensive, fine grain argillaceous clastic material yellow arrow indicate, abundant detrital quartz grain and dense micrite obtained from middle part of Messobo section, sample MS8, XPL and PPL field of view,10X.*

5.4. Facies Association B (Lagoon Facies)

Lagoons form along carbonate coastlines, where a beach barrier wholly or partly encloses an area of shallow water, which have very limited connection to the open ocean. Seawater reaches a lagoon directly through a channel to the sea or via seepage through a barrier (Nichols, 2009). Carbonate lagoons are sites of fine-grained sediment forming layers of carbonate mudstone and wackestone with scattered carbonate packstone and grainstone deposited as washover near the beach barrier. This facies association contains two facies type as follows:

5.4.1. Dolomitized bioclastic mudstone microfacies (MFL1)

Descriptions: This microfacies type is composed of abundant medium size crystalline dolomite rhombohedra within the dense micrite. This microfacies is obtained from samples collected from middle and upper part of Wukro and lower part of Hager-Selam stratigraphic sections from sample WS20, WS27 and HS12 respectively. At some places the micrites are partially dolomitized and bioturbated (with dolomite >45%) and at places the micrites are slightly dolomitized (dolomite crystal up to 20%) forming dolomite-bioclastic mudstone rocks unit. The dolomite crystals are characterized by medium to coarse crystalline grains and planar euhedral in shape (Figure 5.4 A). Additionally, this microfacies is dominated by abundant skeletal mollusks including brachiopods, partially to complete dolomitized bivalve shell fragment, gastropods, calcareous algae and *Lenticulina* sp. with extensive fenestrae pore felling fabric and scattered peloids (Figure 5.4C-F). This facies consist of simple to moderate parallel sedimentary pressure solution (stylolite) (Figure 5.4A-B)

Interpretations: This dolomitized skeletal mudstone microfacies is deposited under low energy conditions of restricted environments, shallower part of lagoons or tidal flat environments. Owing to their very shallow water origin of peritidal carbonates are liable to freshwater invasion, leading to early diagenetic alterations by meteoric processes and dolomitization (Wright, 1984). In the field observation of this microfacies is difficult to distinguish from associated limestone rock unit using field methods. The abundance of the horizontal stylolite seams in this microfacies strongly suggests dissolution and chemical compaction that probably took place during the diagenetic process of the preexisting carbonates. Therefore, this dolomitized-skeletal mudstone is compared to SMF-23, facies belt 7/8 of Wilson (1975) and Flugel (2010) which is deposited in restricted platform depositional environment. The dolomite indicates it is diagenetic microfacies, which formed after dolomitization. However, presence of fine grained peloids, calcareous algae, dense micrite and field relationship, which is overlain by oncolitic grainstone and underlain by sandy limestone indicate deposited under intertidal environment. Therefore, this microfacies is crossponding to facies zone of FZ7or 8 (Wilson, 1975) deposited in low energy lagoon shelf or tidal environment.

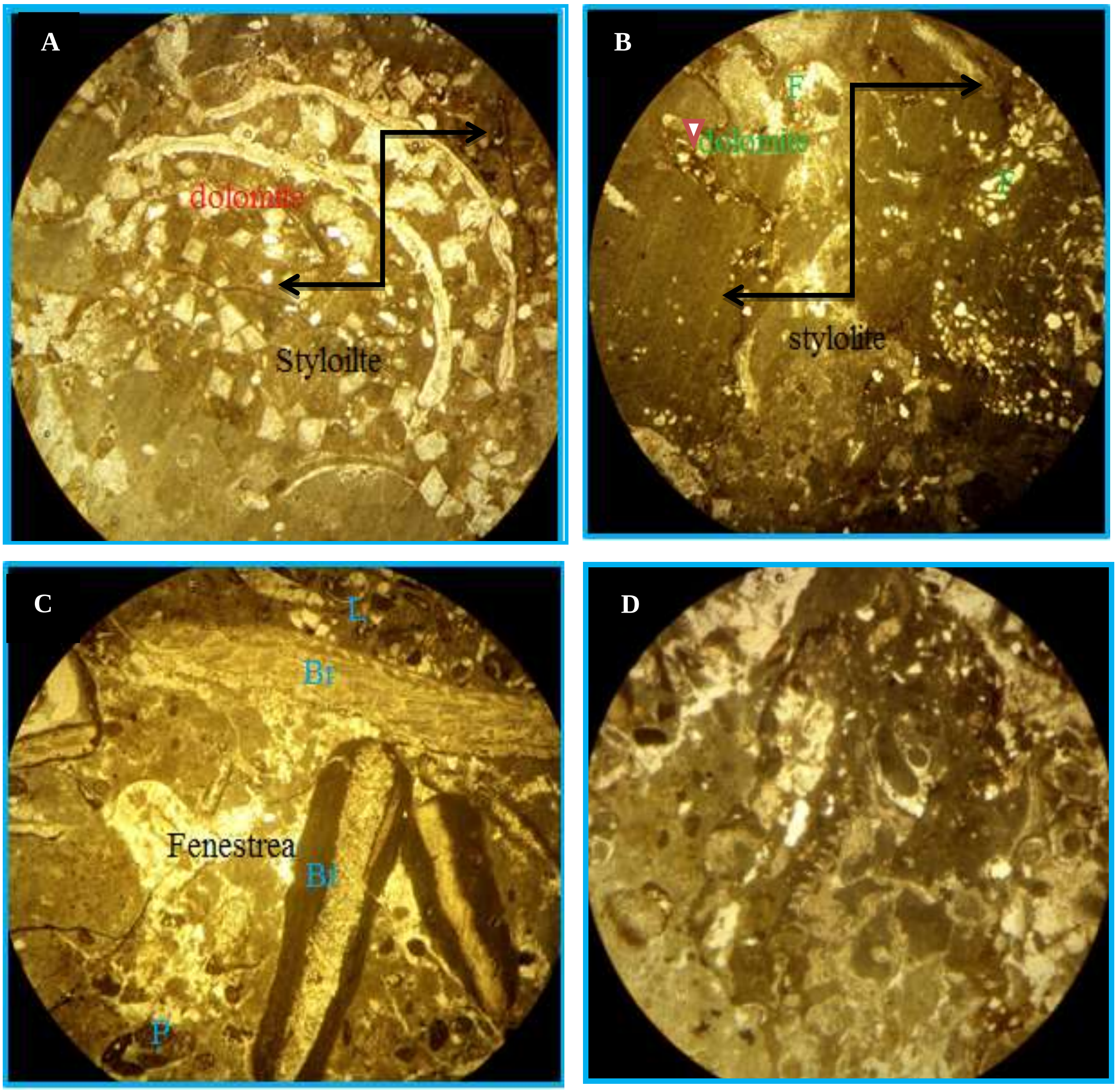
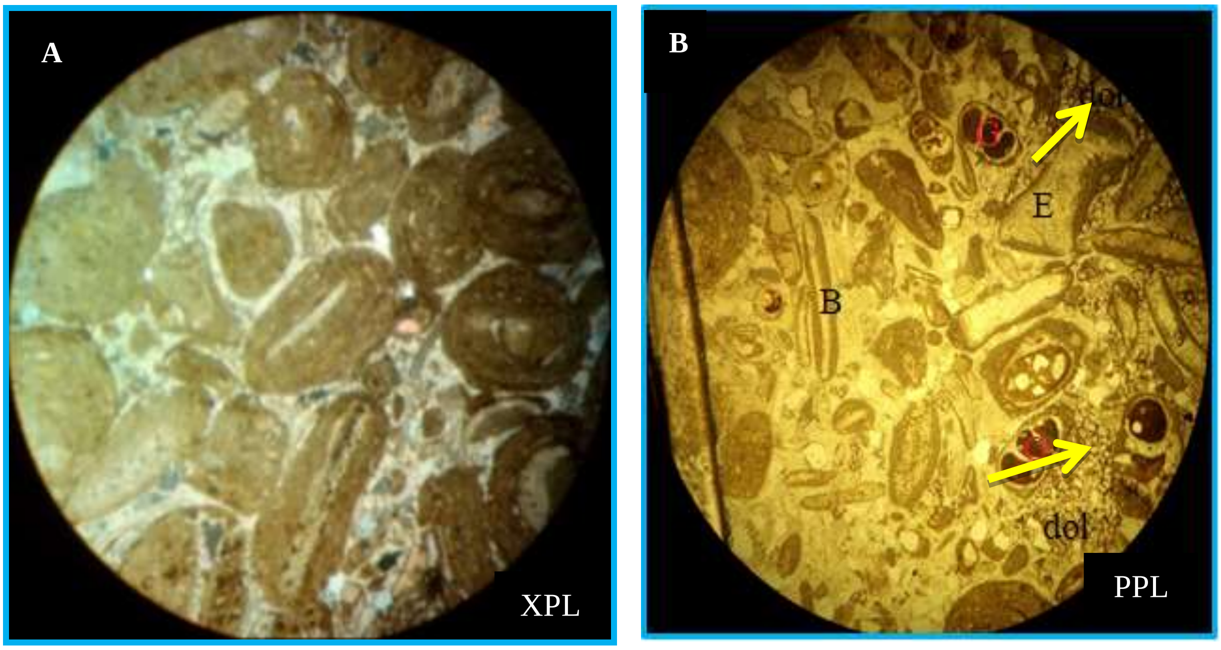


Figure 5.4: *Photo micrograph of dolomitized skeletal mudstone middle part of Wukro section and lower and middle part of Hagere-Selam section.* (**A**) *Euhedral rhombohedra planar dolomite crystal rich mudstone with scattered skeletal fragment and parallel simple stylolite arrow indicate sample HS12, PPL field of view, 4X.* (**B**) *Mudstone with extensive fenestrae fabric (F),parallel stylolite arrow indicate associated with some subhedral to euhedral dolomite crystal in the stylolite.*(**C-D**) *Fossil rich mudstone with scattered dolomite crystal consist of some Lenticular foraminifera(L),brachiopods (Br),peloids(P) and fenestrae fabric sample HS12,PPL field of view,10X.* (**E-F**) *Dolomite crystal rich mudstone with extensive bioturbation black arrow (E) indicates and skeletal rich of dolomudstone (F) sample WS27, PPL field of view, 4X.*

5.4.2. Oncolitic-packstone-grainstone microfacies (MFL2)

Description: This microfacies is recorded from the lower and upper part of Hagere-Selam section from sample HS13 and HS20, which is underlain and overlain by bioclastic dolomudstone, bioclastic mudstone and overlain by skeletal sandy limestone and unfossiliferous lime mudstone microfacies respectively. The main non skeletal grain or allochem in the oncolitic microfacies are characterized by presence of small to large oncoids with slightly deformed structure, small to large peloids, aggregate grains and abundant euhedral crystalline dolomite. It consists of a scattered detrital quartz grain, skeletal shell fragment and calcite crystal as their nuclei with some peloidal grains (Figure 5.5A-D). Additionally, this microfacies contains a diverse assemblage of skeletal allochems including abundant gastropods, bivalve shells, brachiopods, calcareous algae with scattered small detrital quartz grain and medium crystalline euhedral dolomite mineral (Figure 5.5A-D).

Interpretation: Presence of abundant small to large spherical to well rounded, normal and deformed oncoids with abundant euhedral dolomite crystal, aggregate grain, small to large peloids, different fenestrae fabric, gastropods shell, bivalve and scattered small detrital quartz represents deposition of this facies under low energy setting. This microfacies is compared with SMF type 13 of Wilson (1975) corresponds to facies belt 7 (FZ7), which deposited in laggonal environment. This interpretation is supported by predominant of aggregate, peloids, dolomite, micrite and lobate growth of the oncoids (Flugel, 2010) in moderately low energy area with very shallow water.



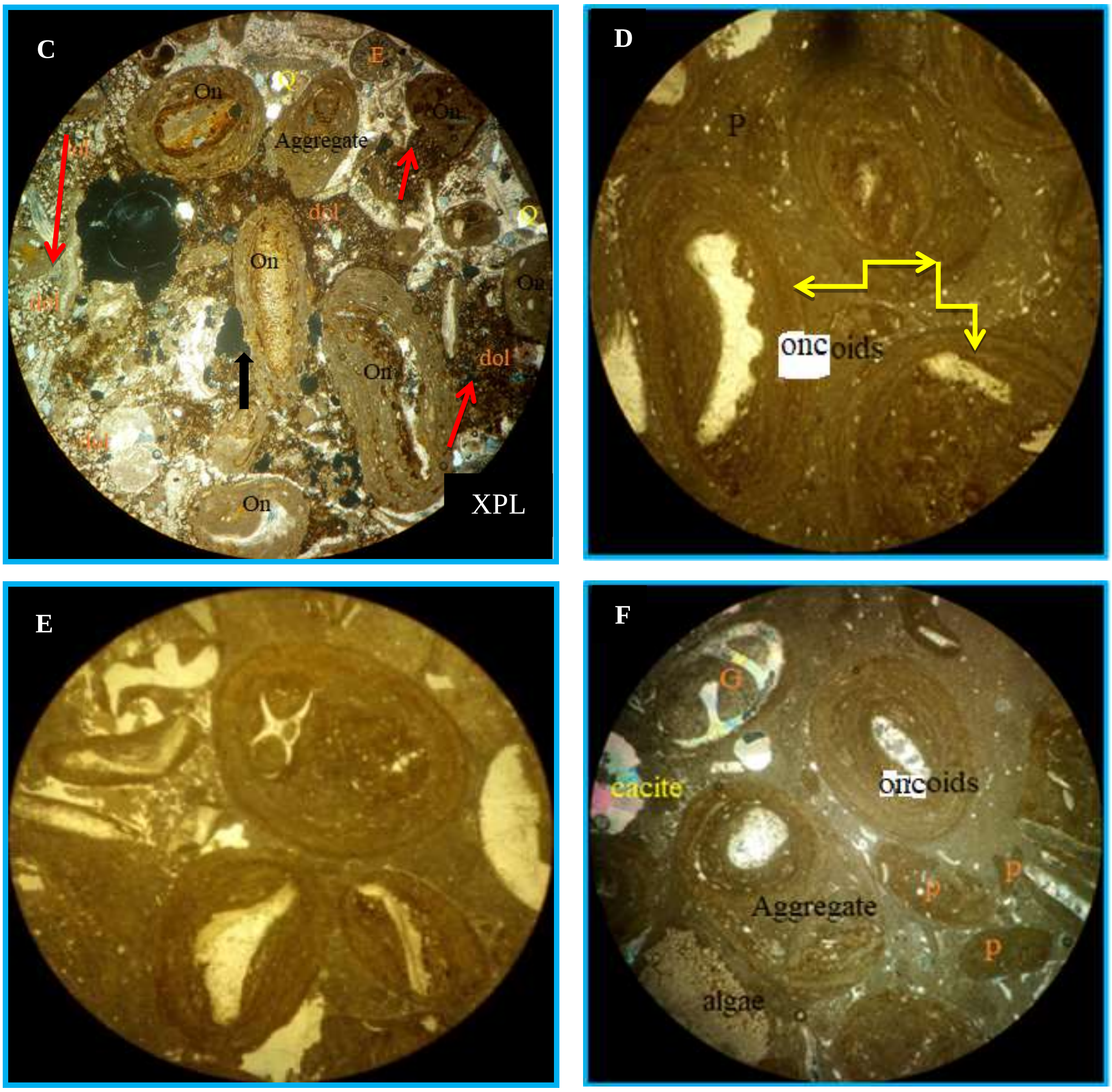


Figure 5.5: *Photomicrograph of oncoids microfacies lower part of Hagere-Selam section, sample HS13 and HS20, PPL and XPL field of view, 4X*. (**A-B**) *Spherical to well-rounded oolitic grain with rare detrital quartz grain.*(**C**) *Bivalve shell fragment*(B), gastro*pods(G) and echinoid spine(E) with sparse ooid ,oncoids allochem, and euhedral dolomite(dol)yellow arrow indicate PPL field of view* (**D**) O*oid, echinoid spine(black arrow) and scattered fine grain detrital quartz grain with moderately to high bioturbated euhderal dolomite(red arrow).*

5.5. Facies Association C (Carbonate sand bodies and/or barrier system)

Carbonate platform are a shallow marine depositional environment of carbonates sediment under high energy. The shoal facies is deposited in a platform margin sub-environment that separates open marine from restricted environment. Abundance of ooid and the mud-free sorted and cross bedded nature of this facies indicate high-energy condition, in which waves and currents reworked and transported carbonate grains. This facies association contains six facies types as follows:

5.5.1. Silicified coral framestone microfacies (MFS1)

***Description*:** This coral framestone microfacies is obtained from the lower part of Hagere-Selam section, which is underlain by skeletal wackstone and overlain by fenestreal spiculite mudstone-wackstone. It is characterized by abundant coral, which are partially to completely replace by blocky calcite and silicified silica as pore filling between each septum of the sclerectinian coral.

Interpretation: Presence of coralline microfacies in framestone suggesting a moderate to high energy shallow reefal environment close to a platform-patch reefal environment with periods of quite open platform conditions. This shallow reefal environment becomes more restricted upward, whereas the fenestrae spiculite mudstone was formed in the low energy proximal open marine environment. Therefore, this microfacies type is similar with SMF type 7 of Wilson (1975) represent reef, often found on platform margin.

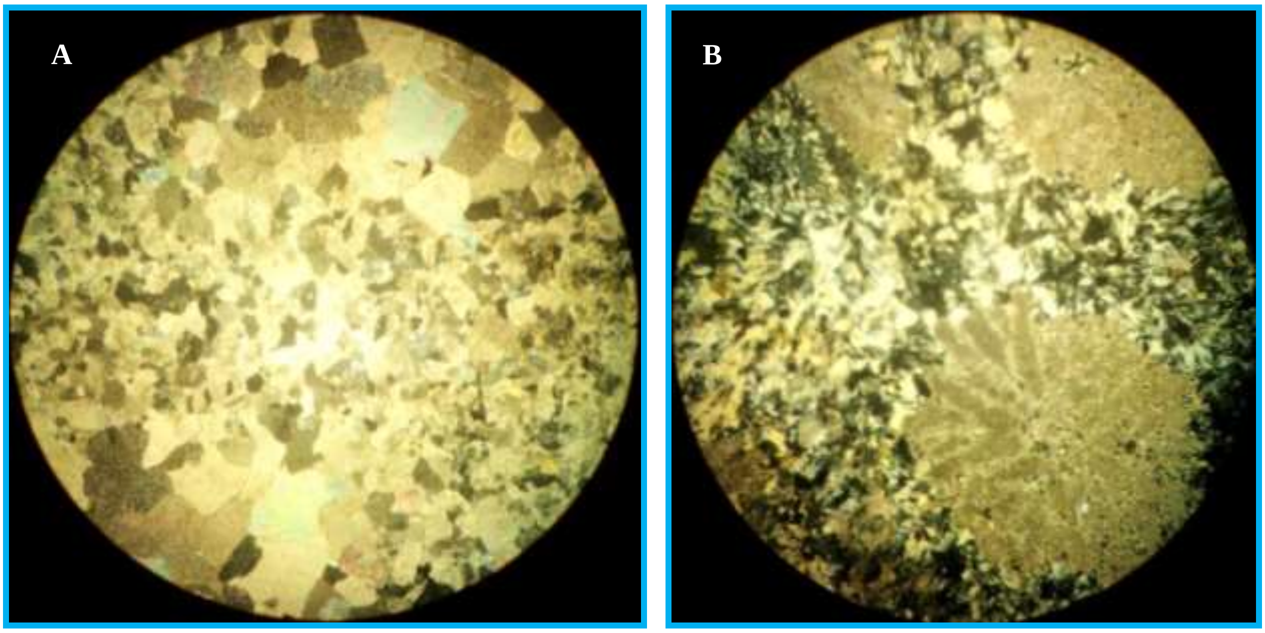
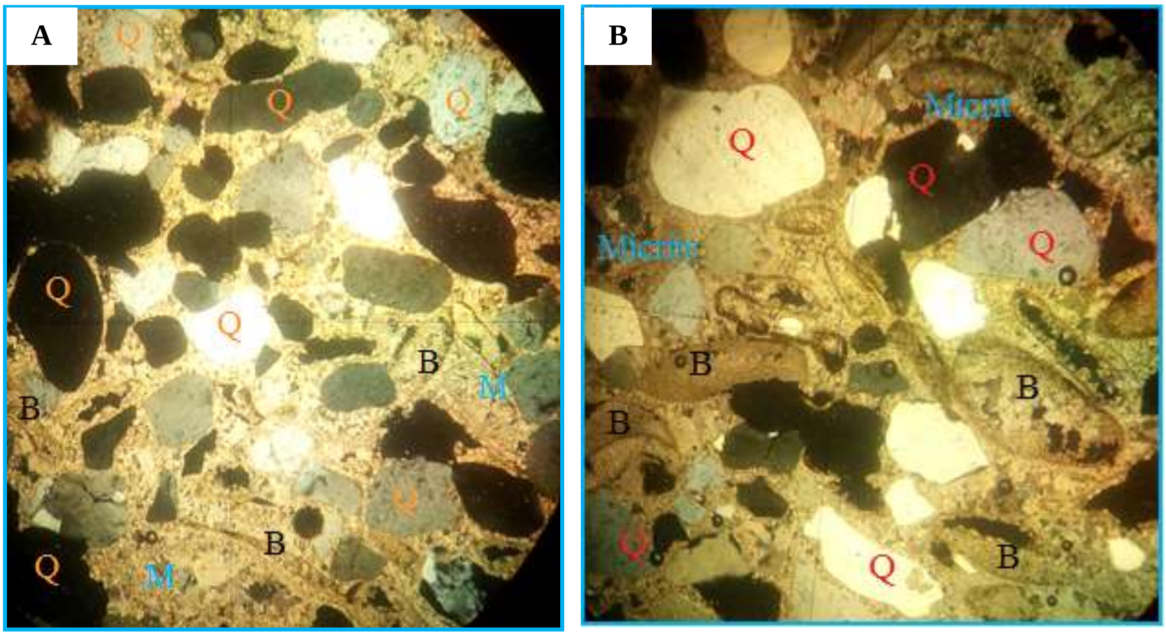


Figure 5.6: *Photomicrograph of coral framestone microfacies lower part of Hagere-Selam section, sample HS2, XPL field of view, 4X.* (**A**) *Coral framestone which represent total recrystallization the coral by calcite crystal*. (**B**) *Colonial coral framestone with partial silicification by microgranular quartz.*

5.5.2. Skeletal-sandy carbonates-packstone-grainstone microfacies (MFS2)

***Descriptions*:** This microfacies is recorded from the lower and middle part of Hagere-Selam (from sample HS4, HS9, HS11, HS14 and HS15) and lower part of Wukro stratigraphic section (from sample WS10, WS12, WS14 and WS33) of carbonate units of the study area. It consists of the various detrital quartz grains ranging from angular to well rounded, fine to coarse grain, unsorted to well sorting detrital quartz grains ranging from 60-92%, which are cemented by calcite (Figure 5.7A-G). The skeletal sandy limestone contains of abundant skeletal allochems including bivalve shell fragment with micritized envelope, gastropod, brachiopods, echinoderm spine and rare benthic foraminifera *mililoids* (Figure 5.7B&C). Additionally, this skeletal-sandy limestone affected by medium to high diagenetic process of silicification, which contains of fibrous chalcedony quartz mineral from sample HS14, WS12 and WS33 (Figure 5.7G & H).

***Interpretations*:** Sediments composed of detrital materials and mixtures of carbonate cement are deposited in agitated near-coast, inner shelf settings (Flugel, 2004 and Walker, 1992). Sand and silt size detrital grains with fragmented and reworked allochems and a micrite to sparitic matrix indicate that the sedimentary basin frequently received the supply of detrital quartz grains from nearby exposed continental part into the marine carbonate basin during its depositions by wave current. 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 detrital system. Skeletal sandy carbonate deposition is usually described within the context of a simplistic framework, in which detrital sediments occur in shoreward areas and carbonate sediments occur outward on a shelf or platform surface (Reading, 1996; Walker, 1992; Tucker and Wright, 1990). This microfacies interpret as marginal facies and compared with facies belt 6 of Wilson (1975), which is deposited in restricted platform conditions.



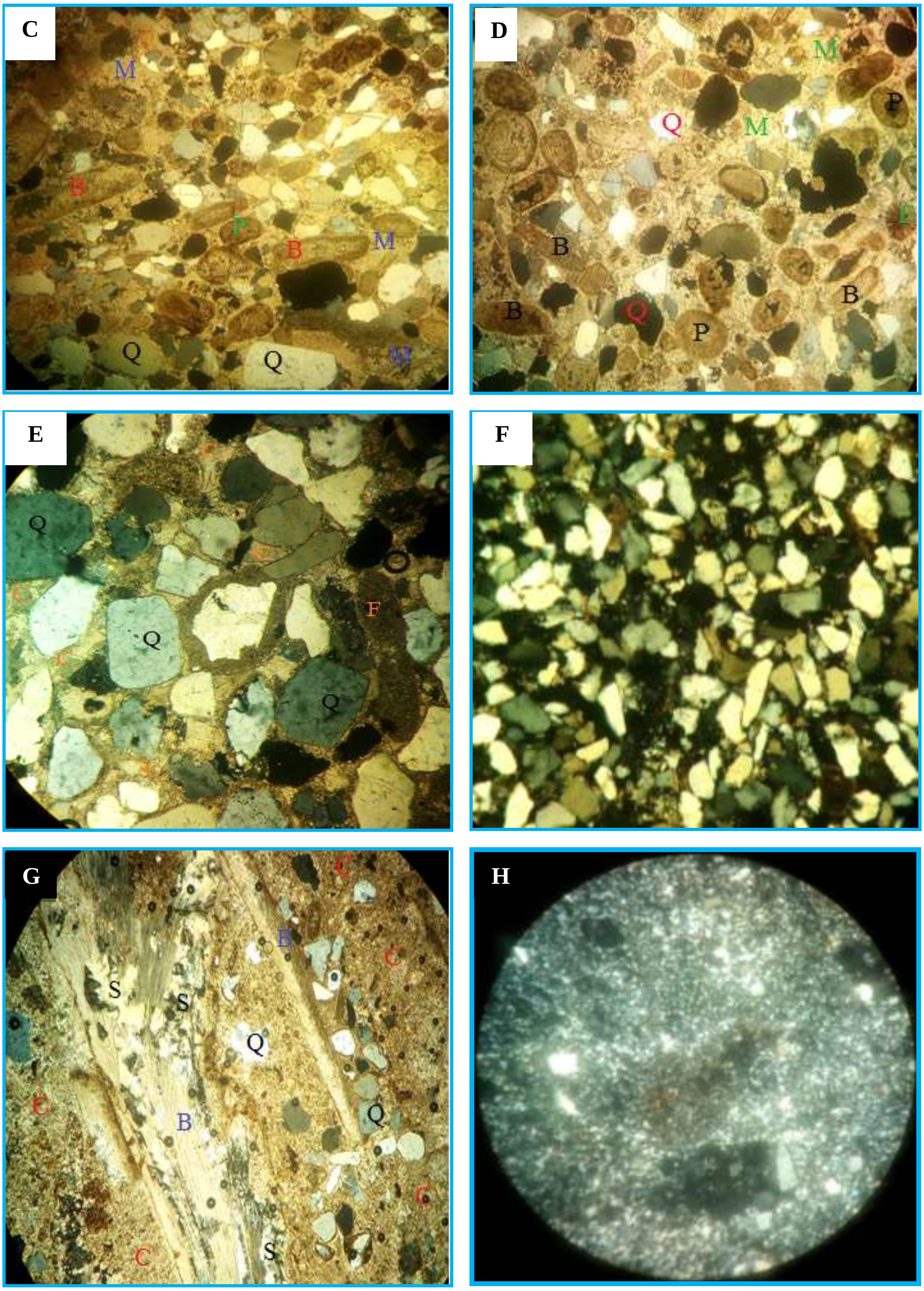


Figure 5.7: *Photomicrograph of skeletal sandy limestone microfacies lower and middle part of Hagere -Selam section and lower part of Wukro section*. (**A-C**) *Sub rounded to rounded quartz grain (Q) associated with abundant mollusk shell fragment (B) cemented together by micrite cement sample HS9 and HS11, XPL field of view, 4X.* (**D**) *Abundant peloids (P), some skeletal fossils (B) and detrital quartz grain impeded by calcite cement (M) sample HS11, XPL field of view, 4X.* (**E**)*Large grain detrital quartz with rare fossil fragment (F) sample HS4, XPL view, 4X.*(**F**) *Fine to medium well sorted detrital quartz arenite impeded by calcite cement lower part of Wukro section sample WS10, XPL field*

of view, 10X. (**G**) *Sandy limestone which show silicification of the mollusk shell (B) and contain sparse quartz grain (Q) and scattered bivalve shell (B) sample HS14, XPL field of view, 10X and* (H) *fine grain to medium, sub angular to rounded sandy limestone sample WS33, XPL field of view, 10X.*

5.5.3. Oolitic grainstone microfacies (MFS3)

***Descriptions*: ** This microfacies is the most dominant facies recorded from the lower and middle part of the carbonate rock unit of Hagere-Selam section and lower and upper part of Wukro stratigraphic sections, which is obtained from sample HS6, HS7, HS17, WS5 and WS36. These grainstones facies range between 0.3-75 m thick and consist of well-developed sedimentary structures apart form indistinct parallel, low angle stratification and ripple mark (Figure 4.8B-E). The main non-skeletal allochems in the oolitic grainstone are spherical, grain supported, tangentially and radially structured ooid grain, which are embedded in the sparry calcite cements with scattered peloids and sub rounded to rounded fine detrital quartz grains (Figure 5.8A-D), which comprise up to 85% of this microfacies. Most of the ooid grains contains skeletal fragment with some of quartz detrital grains and micritized peloidal grain as their nucleus. There are some skeletal allochems including gastropods, bivalve, echinoderms spine, brachiopods, dasycladacean algae and *Mililoids* foraminifera.

The grains in this microfacies are moderate to well-sorted and ranging from medium grain to coarse pebble carbonate in size. Some of the ooid grains are calcified and dissolved at places and larger crystal cements are observed between the grains. There are also abundant micritic envelops on some skeletal grains and on the ooids grains mainly preserving their outer concentrating layer with deformed cortex grain.

***Interpretations*: ** This microfacies is interpreted to be deposited under high energy area of carbonate shoals and barrier islands or beaches. According to Burchette and Wright (1992) and Reading (1996) warm water grainstones formed of bioclast, ooids and peloids are usually occurring around high energy areas of shoals and beaches in inner ramp and/or an upper shoreface environment. This is inferred from the well-sorted fabric, which indicates continuous reworking by high-energy waves (Nichols, 2009). These carbonate sand bodies and material in the form of ooids, bioclastic debris and detrital quartz grain is reworked by wave action into ridges that form strandplains 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 strandplain beaches are typically well-sorted and with a low mud matrix content (packstone and grainstone). In addition, presence of cross-bedding and ripple mark are the key features for the upper shoreface environment deposition (Clifton, 2006). This microfacies is compared with SMF type 15 of Wilson (1975), correspond to facies belt 6, which is deposited in winnowed platform edges.

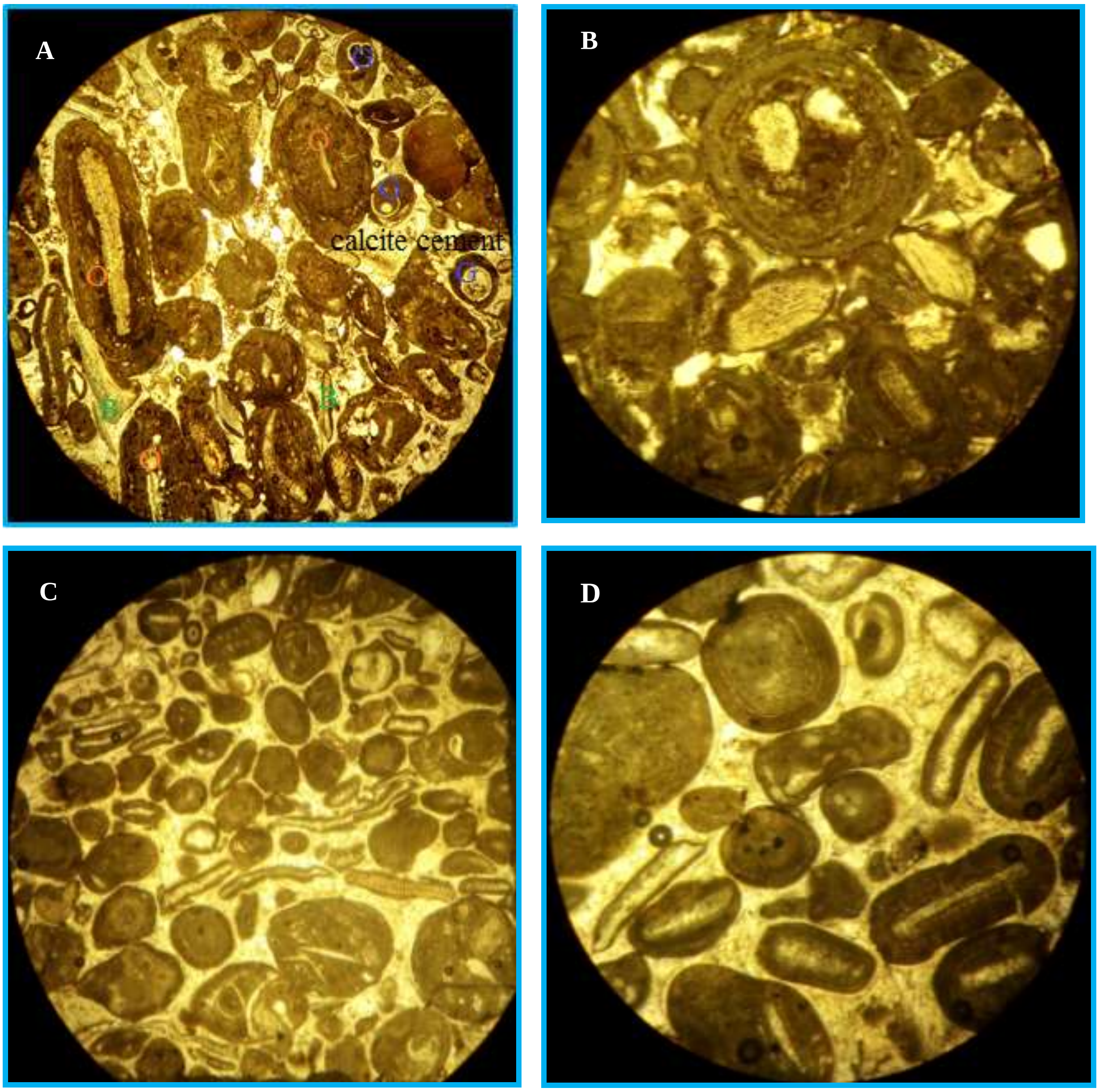
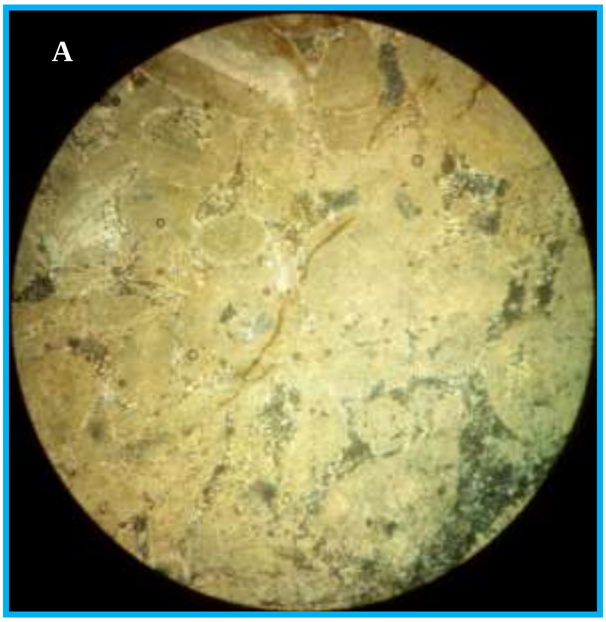


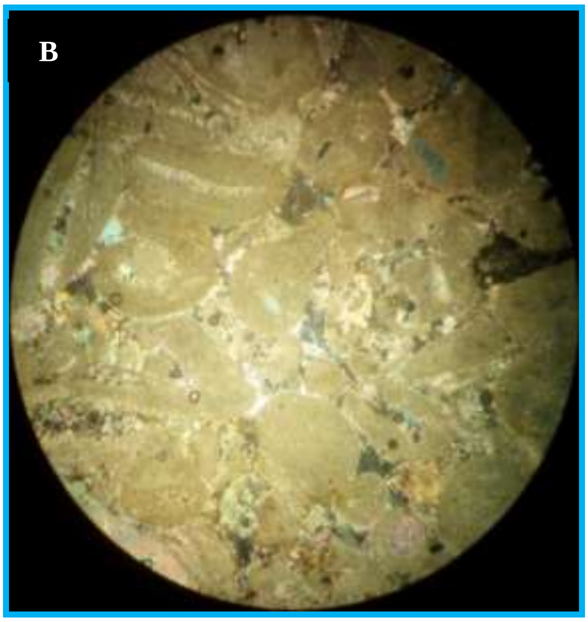
Figure 5.8: *Photomicrograph of oolitic grain stone micro facies. Lower part of Hagere-Selam section and lower and upper part of Wukro section*. (**A**) *Spherical ooids*(O) *with low preserved concentric layer associated with some skeletal shell of Gastropod(G) and some micritized bivalve shell (***B***) Impeded by calcite cement sample HS6,PPL field of view,4X. (*B*) spherical to rounded, small to large ooid, sample WS5.(***C-D***) Moderate to well sorted ,radial and superficial ooid with some bivalve shell sample WS36,PPL field of view,4X and 10X respectively.*

5.5.4. Peloidal-oolitic-skeletal-grainstone microfacies (MFS4)

Description: This peloidal-oolitic-skeletal grainstone microfacies is recognized from the lower part of Hagere-Selam section, which is overlain by skeletal sandy limestone and underlain by oolitic grainstone microfacies respectively, with maximum thickness about 25 m. This microfacies type is composed of well-developed planar cross bedding and symmetrical ripple mark (Figure 4.9E). The upper and lower contact of the peloidal-oolitic-skeletal grainstone microfacies with oolitic grainstone and skeletal sandy limestone is gradual, reflecting progressive shallowing and restriction. The main non-skeletal allochems in the peloidal-oolitic-skeletal grainstone are peloids (35-45%), ooid (20-25%) with accessory aggregate (1%) (Figure5.9A-D). These allochem are cemented by crystalline sparry calcite up to 12%. This facies contain a diverse assemblage of skeletal allochems including scattered crinoid, gastropods, echinoids and bivalve shell fragment. Several diagenetic overprints including cementation, stylolite and physical compaction may ultimately result significant deformation of the non-skeletal allochems.

Interpretation: The high degree of sorting and rounding as well as the well-developed cross stratification, presence of symmetrical ripple mark suggests constant, high energy conditions above fair-weather wave base, for the upper shoreface environment (Clifton, 2006). Furthermore, presence of marine fauna including crinoids, echinoids, bivalve shell and overlain and underlain by skeletal sandy grainstone and oolitic grainstone facies suggests well oxygenated condition of shallow marine setting. This microfacies is compared with SMF Type 15 of Wilson (1975), correspond to facies belt 6, which is deposited in moderate circulation conditions and efficiency of winnowing by wave current.





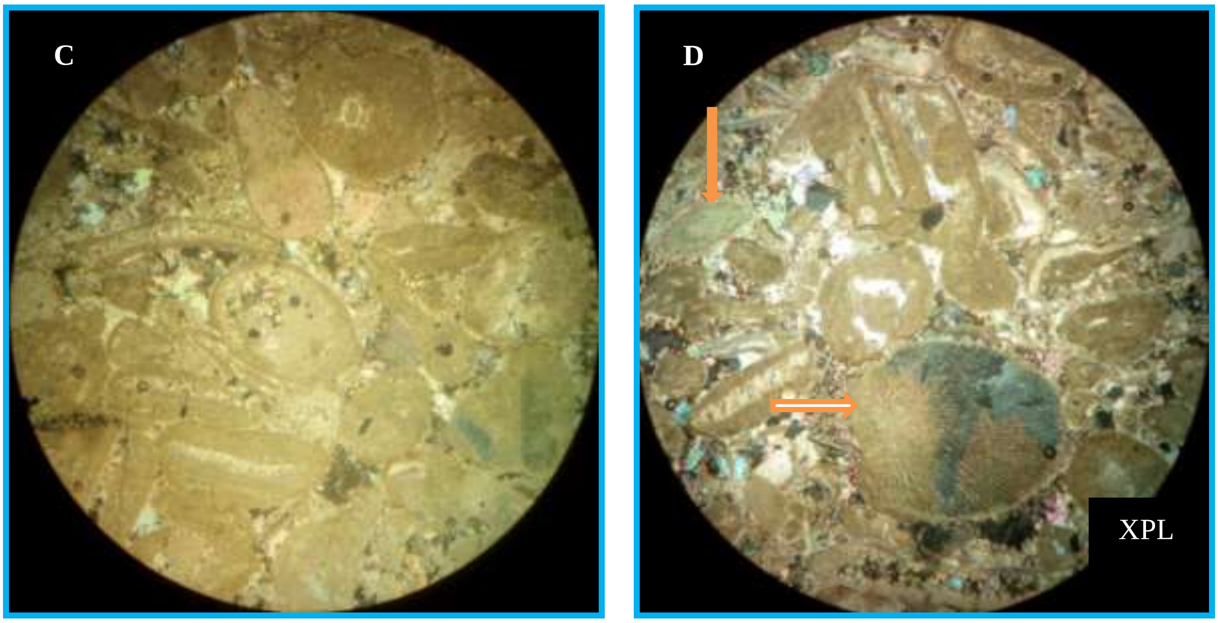


Figure 5.9: *Photomicrograph of peloidal-ooilitic-skeletal grainstone lower part of Hagere-Selam section, sample HS7, PPL and XPL field of view, 4X.* (**A-B**) *Deformed peloids and ooid impeded together by calcite cement*. (**C-D**) *Peloids, normal and superficial ooid(C) and crinoid fossil arrow (D) indicate.*

5.5.5. Ferruginous spherical oolitic grainstone (MFS5)

***Descriptions*:** This microfacies is recorded from the middle part of Hagere-Selam section overlain by skeletal rudstone and underlain by skeletal sandy grainstone microfacies. It is characterized by spherical, tangentially and superficial structure, partially to completely replace by iron rich ooid associated with scattered in skeletal grains, which is obtained from sample HS17. The tangentially and superficial structured with devoid of skeletal grain microfacies consist about 87%, which is embedded in the sparry calcite cements (Figure 5.10A-B). Most of the ooid grains have detrital 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 envelops on the skeletal grains and on some ooids grains mainly preserving their shape. All these components form the characteristic of carbonate sand bodies.

***Interpretations*:** This microfacies is interpreted to be deposited around high energy area such as carbonate shoals and barrier islands or beaches. Warm water grainstones formed of bioclast, ooids and peloids are usually formed around high energy areas of shoals and/or beaches in inner ramp and/or 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 strandplains 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 strandplain beaches is typically well-sorted and with a low mud matrix content (grainstone and packstone), which is the main features of this microfacies. This microfacies is compared with SMF Type 15 of Wilson, belongs to facies belt 6, which is deposited in winnowed platform edges.

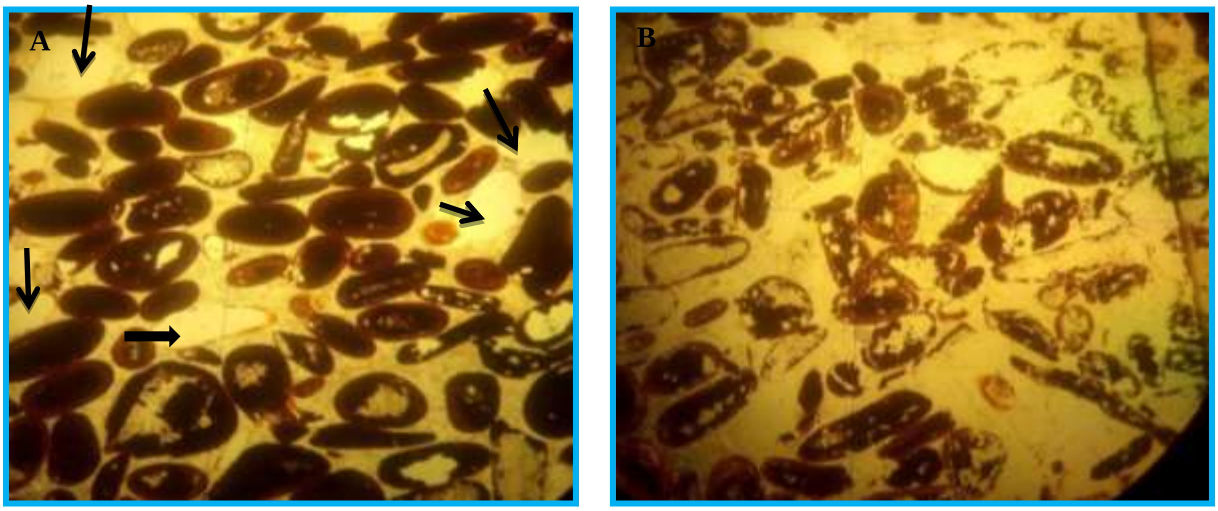


Figure 5.10: *Photomicrograph of Ferruginous spherical oolitic grain stone*. (**A**) *Iron rich well sorted, spherical to rounded oolitic grain stone with some completely dissolved ooids cemented by micrite arrow indicate* (**B**) *Partially to completely dissolve spherical to rounded ooids grains, sample HS17, PPL field of view, 4X.*

5.5.6. Fine-medium crystalline sandy dolomite microfacies (MFS6)

Description**:** This fine-medium crystalline sandy dolomite microfacis type is recorded from the lower and upper part of Wukro stratigraphic section of the carbonate units. This type of microfacies forms a dense, dark mosaic of interlocking subhedral to euhedral crystal with well-defined crystal boundaries that are brown, dark brown or grey in color. In this facies there are no skeletal grains, while some dissolved vugs, parallel stylolite and fractures are locally present in texture with scattered fine detrital quartz grains. This microfacies is present with fine crystalline in the lower part and medium crystalline dolomite crystal in the upper part of the Wukro section (Figure 5.11A-B&C-D respectively). Fine to medium crystalline microfacies consists of mainly interlocked calcified dolomite rhombs crystal, which is the rhombs crystals contain clear or cloudy textures without any replacement.

Interpretation: The fine crystalline dolomite crystal sizes are restricted to peritidal environments (Amthor and Friedmon, 1991). The fine crystal size is probably as result of an early replacement of precursor peritidal lime mudstone or a replacement of early diagenetic dolomite crystal (Zemger, 1983; Amthor&Friedmon, 1991), whereas the medium crystalize represent as an intermediate diagenetic replacement of dolomite because of nucleation and rate of growth (Amthor&Friedmon, 1991). This diagenetic microfacies is corresponding to SMF-23 of Wilson (1975) and Flugel (2010) of facies belt 8. The fine grain size, the presence of quartz grains, the lack of fauna, the fenestral fabric &vertical changes suggest that deposition occurred in a low-energy, restricted intertidal & supratidal environment (Wilson &Evans, 2002). However, this dolomitic unit is not indicating depositional environment, because it is formed as a result of dolomitization or replacement. Therefore, presence of fine to medium grain detrital quartz grain, some calcite and field relationship with overlain and underlain rock unit indicates deposited under agitated, high energy shoal environment. Thus, this microfacies is similar to facies belt of FZ6 of Wilson (1975), which is deposited in shoal environment above fair weather wave base (WWFB).

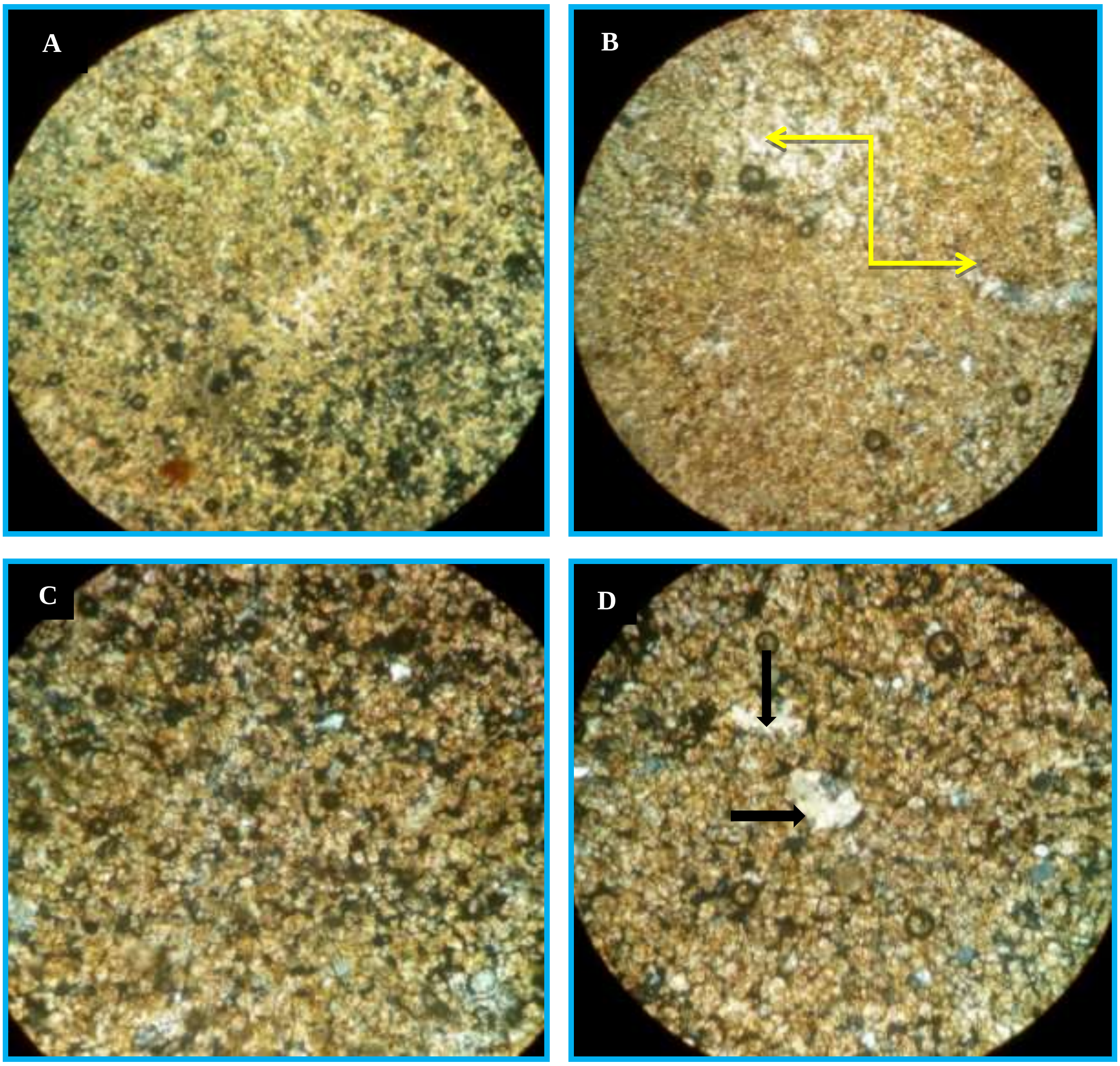


Figure 5.11: *Photomicrograph of fine-medium crystalline dolomite microfacies middle and upper part of Wukro section, sample WS17 and WS35,PPL and XPL field of view,10X.*(**A-B**) *Fine crystalline dolomite crystal ,sample WS17with rare sparry calcite(arrow indicate(B).* (**C-D**) *Medium crystalline*

dolomite with some sparry calcite in center of E (black arrow), associated with scattered detrital quartz grains, sample WS35, PPL and XPL field of view, 10X.

5.6. Facies Association D (Open marine system)

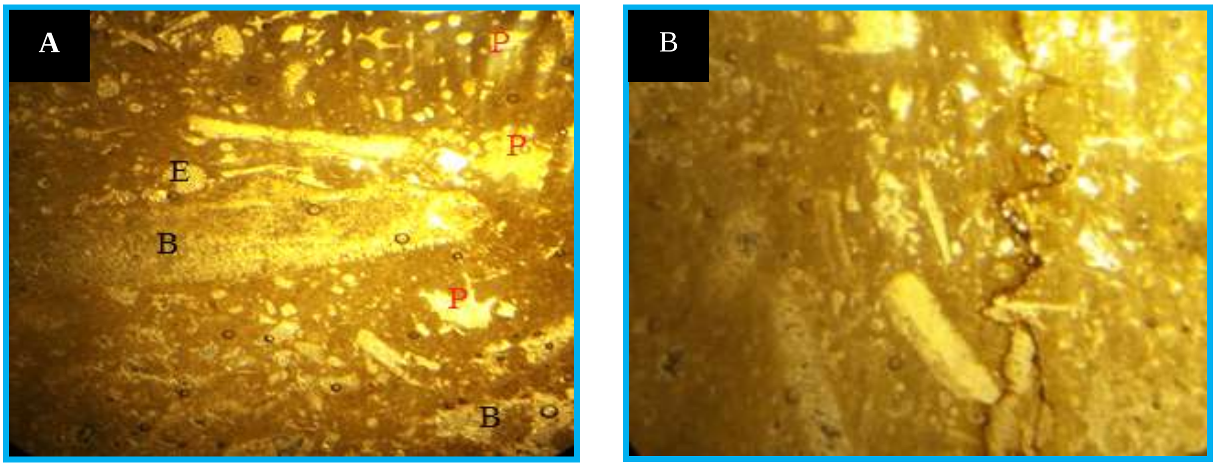
This facies association contains seven facies as follows:

5.6.1. Bioclastic wackstone (MFO1)

Description: This microfacies is recorded from the lower part of Hagere-Selam, middle part of Messobo and lower part of Wukro section from sample HS1, MS6, MS7, WS1, WS2, WS3 and WS8. It is underlain by marl rock unit and overlain by coral framestone in the Hagere-Selam section and by oolitic grainstone in the Wukro section. This skeletal wackstone microfacies is characterized by abundant dens micrite and drusy sparry calcite with some macrofossils including bivalve shell, echinoids, gastropods, crinoids and scattered *Mililoids*, *Nautiloculina oolithica*, *Valvilina* sp. and *Kurnubia palestiniensis* associated with some undifferentiated calcareous algae. Additionally, it is dominated by dolomite crystal, fenestrae fabric, moderately to intensive bioturbation, simple-extensive parallel stylolite and neomorphic diagenetic features (Figure 5.12B).

Petrographic analysis of this microfacies includes examination and point counting of six thin sections. The percent of mollusks range from 5%-12%, echinoids range from 2%-10%, calcareous green algae ranges from 2%-4%, benthic foraminifera range from 3%-13% and matrix material range from 27%-80%.

Interpretation: Wackstone containing dense micrite, benthic foraminifera and some macrofossil reflect a low energy depositional environment below fair weather wave base and above storm wave base. The excellent preservation of these skeletal shells indicates that they are replacing rather than reworked on the sea floor. The fragmented bivalve and echinoderms, bioturbated with micritized bioclast indicate SMF type 9 of shallow water with open circulation close to wave base. Therefore, this facies is comparable with the FZ-3 facies of Wilson (1975), which is deposited in open platform or open sea shelf.



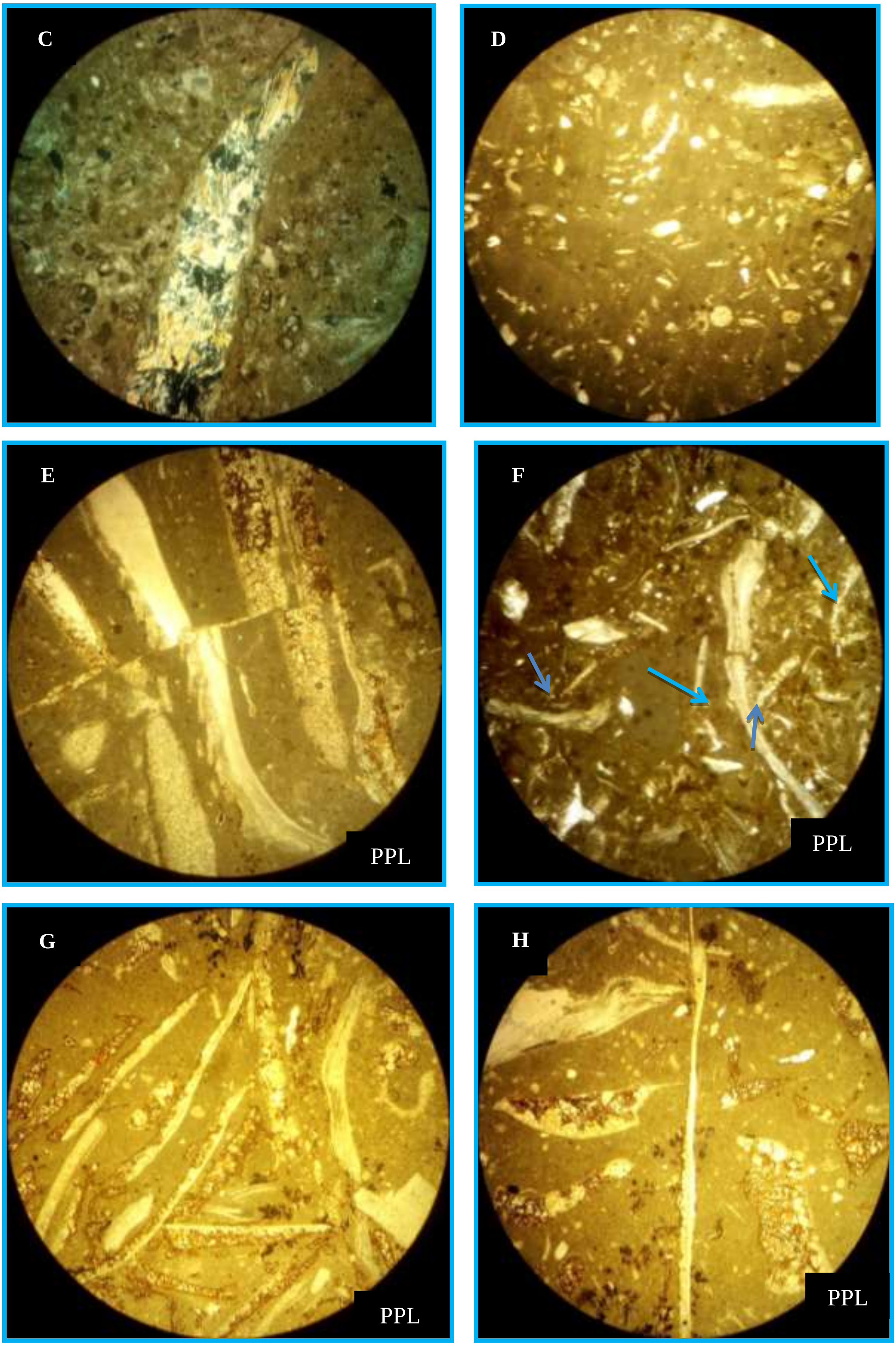


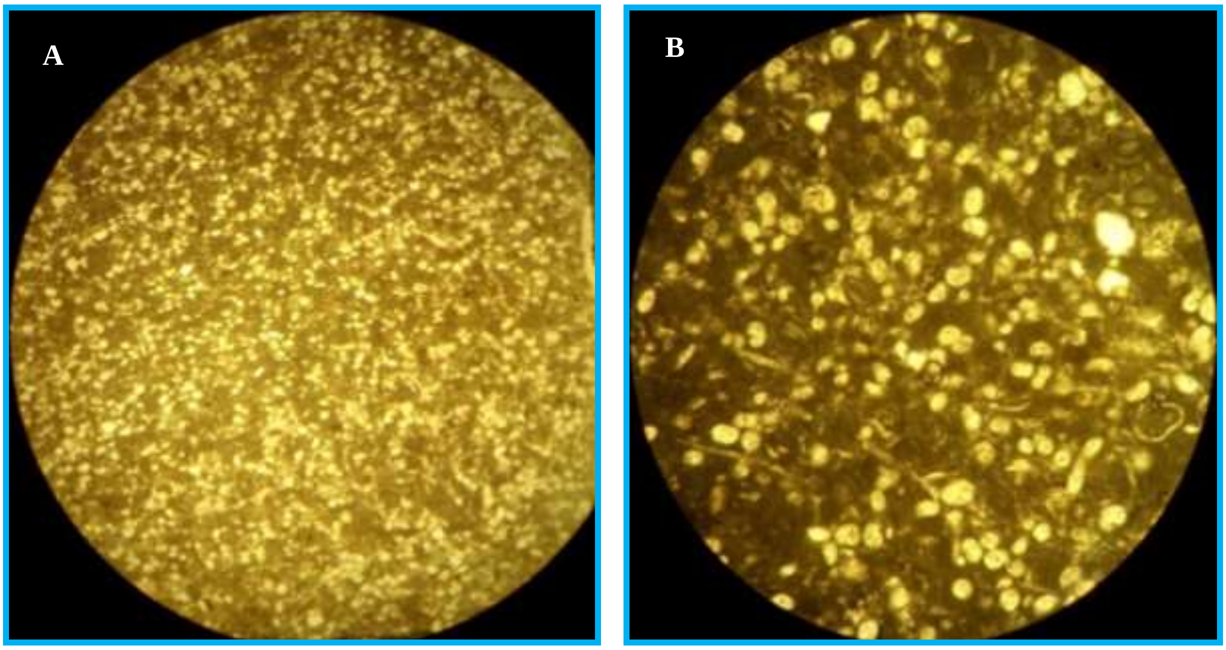
Figure 5.12: *Photomicrograph of bioclastic wackstone lower part of Hagere-Selam and Wukro section.*(**A**) *Bivalve(B),echinoids, fenestrae fabric(P).*(**B**) *Stylolite with some bivalve shell and fenestrae fabric imbedded with dense micrite, sample HS1,PPL field of view,4X.*(**C**)*bioclastic*

*wackstone with extensive silicification ,sample WS2,XPL field of view,4X and (**D**) Skeletal wackstone with scattered Alveosepta jaccardi, sample WS1,PPL field of view,4X. (**E-F**) Bioclastic wackstone contain calcified shell fragment (B) and (**G-H**) Bioclastic wackstone with abundant mollusk shell partially to completely dolomitized sample WS20 and WS27, 4X.*

5.6.2. Bioclastic-spiculite-wackstone (MFO2)

Description: Bioclastic-speculite-wackstone microfacies are recorded from the lower part of Hagere-Selam and Wukro section, which is obtained from sample HS3 and WS18 respectively. In outcrop they form 3-10 m thick, which is sandwiched between coral framestone and skeletal sandy limestone in the Hgere selam and sandwiched between sandy dolomite rich microfacies in the Wukro section. It is characterized by abundant sponge spicule (monoaxon and diaxon), abundant *Mililoids* foraminifera, which embedded in dense homogenous micrite (Figure 5.13 B, C and D).

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



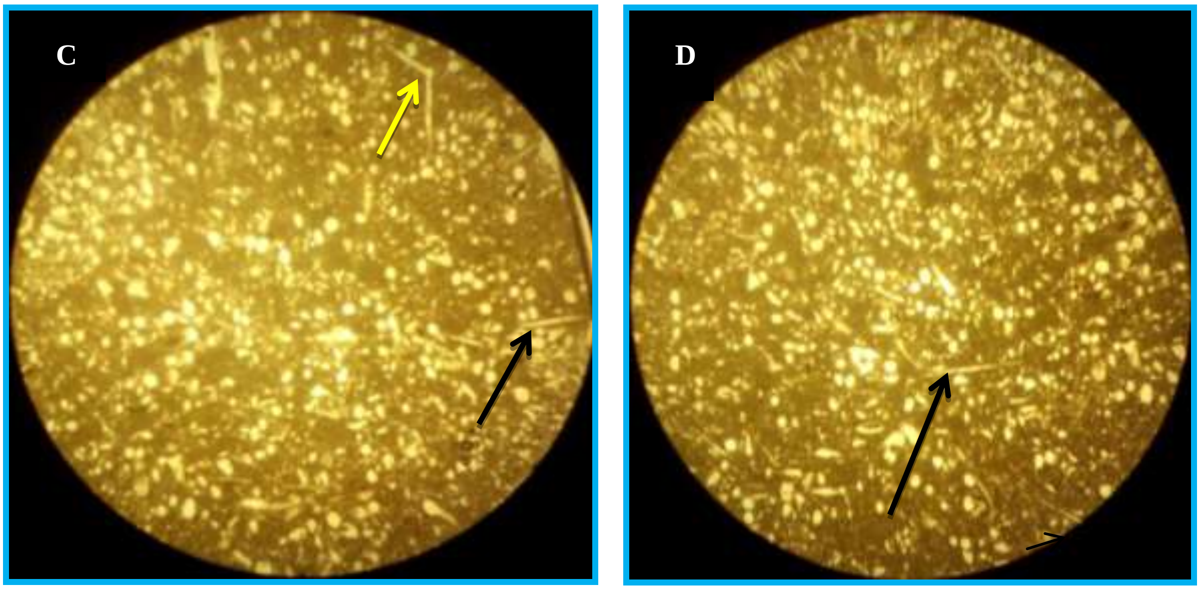


Figure 5.13: *Photomicrograph of bioclastic-spiculite wackstone lower part of Hager selam section and middle part of Wukro section*. (**A-B**) *Mililoids foraminifera rich mudstone sample HS3, PPL field of view, 10X*. (**C-D**) Mono a*xon (black arrow) and diaxon (yellow arrow) rich mudstone empeded by dense micrite mud, sample WS18, PPL field view, and 4X.*

5.6.3. Stromatoporoidal mudstone- wackstone microfacies (MFO3)

Description: This microfacies is obtained from the lower part of Hagere-Selam section from sample HS5 and HS10, which is overlain by oolitic grainstone and bioclastic sandy limestone and underlying by skeletal sandy limestone microfacies respectively. It is characterized by presence of branched stromatoporoid assigned to *cladocoropsis mirabils* Felix together with abundant sponge spicule (monoaxon and triaxon) and different fenestrae fabric (Figure 5.14A-B). Additionally, this microfacies consist of dense micrite; scattered gastropods, *Nautiloculina oolithica* benthic foraminifera and medium bioturbated euhedral crystalline dolomite crystal (Figure 5.14D).

Interpretation: Presence of branched stromatoporoids, abundant homogenous fine carbonate mud and sponge spicule in this facies indicates a low to moderate energy depositional setting of the protected proximal mid ramp, probably within fair-weather wave base. Based on presence of dense micrite, benthic *Nautiloculina oolithica* and bioturbated medium crystalline dolomite crystal are considered to have best developed in the distal part of the lagoon, in the lee of a bank, where the direct higher energy would be damped. Therefore, this microfacies is corresponding with facies zone 3 deposited in proximal middle ramp of open marine environment near the shoal environment.

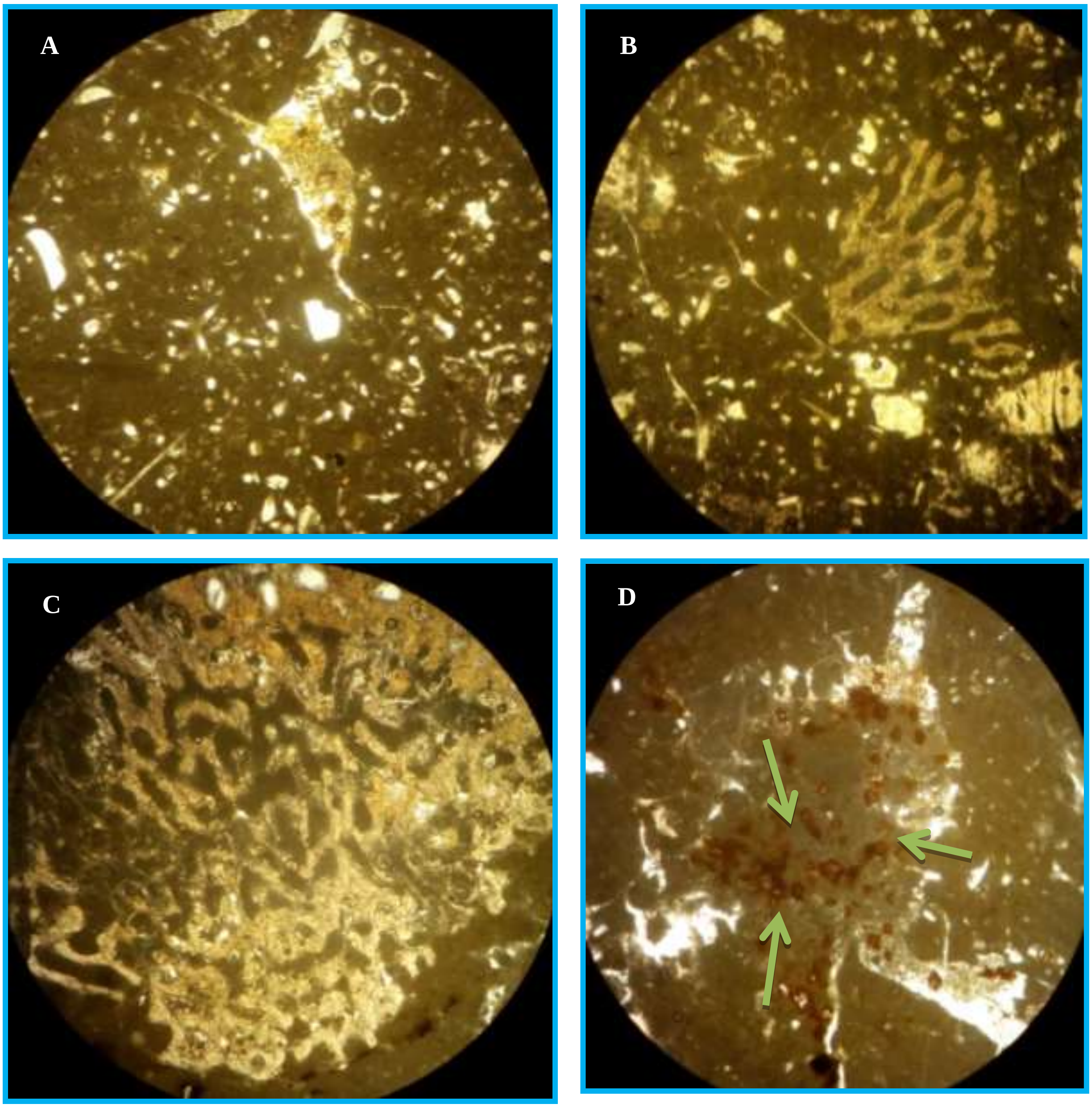
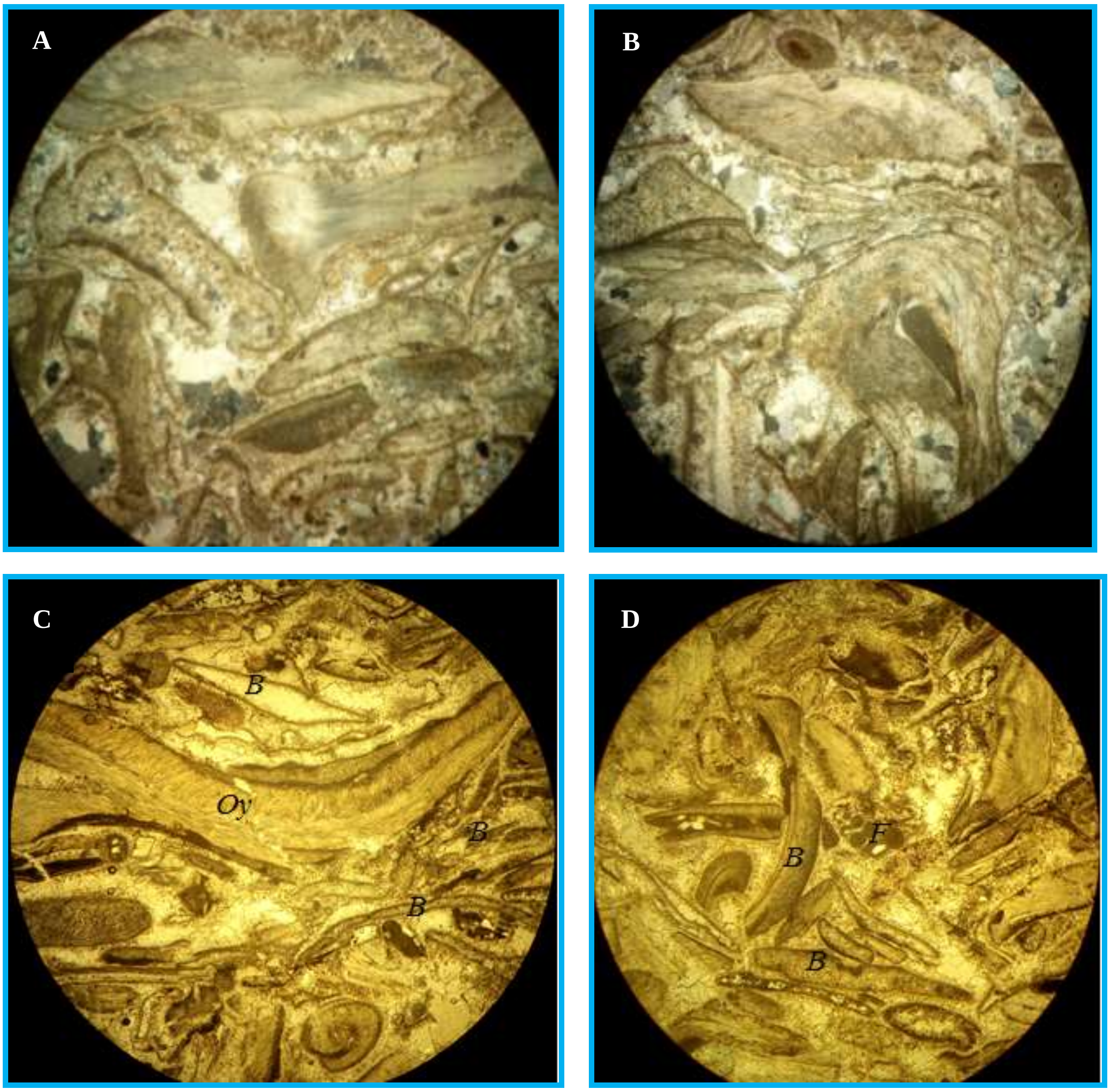


Figure 5.14: *Photo micrograph of stromatoproidal mudstone lower part of Hagere-Selam section.* (**A**) *Monoaxon and triaxon sponge spicule rich mudstone with extensive fenestrae fabric sample HS5, PPL field of view, 4X*. (**B-C**) *Branched stromatoporoids with same fenestrae fabric sample HS10,PPL field of view,4X.*(**D**) *Bioturbated medium euhedral crystalline dolomite(arrow)indicate with extensive fenestrae fabric and dense micrite sample HS10,PPL field of view,4X.*

5.6.4. Bioclastic rudstone microfacies (MFO4)

Description: This microfacies is a type of facies exposed in the middle part of Hagere-Selam section and lower part of Messobo stratigraphic section, which obtained from sample HS18, MS2 MS3 and MS5 respectively. It is characterized by medium to coarse grain bivalve shell and large oyster, which is cemented together by sparry calcite cement. Additionally, this microfacies consist of scattered foraminifera and detrital quartz grain (Figure 5.15D & F). Most of the mollusk shell fragment is slightly micritized, which show micrite envelope at the realm of their shell and calcified or show aggrading neomorphism, that completely replaced by calcite mineral (Figure 5.15E-F).

Interpretation: The well sorted skeletal grain, compositionally and texturally mature, presences of coquinoid bivalve, oyster and brachiopods without micrite indicate deposition in upper shore face (storm) environment under high agitated energy. This skeletal rudstone microfacies is crossponding to SMF 12 (Wlson,1975) of facies zone FZ3.



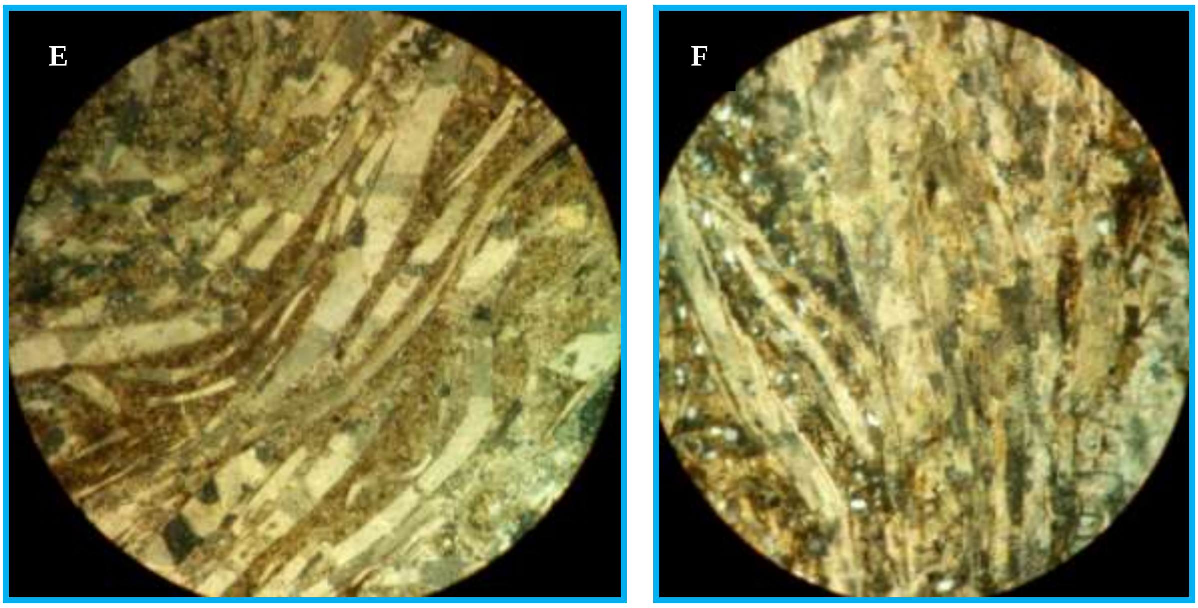


Figure 5.15: *Photomicrograph of bioclastic rudstone microfacies middle part of Hagere-Selam section and lower part of Wukro and Messobo stratigraphic section.*(**A-B**) *Medium to large bivalve shell fragment and oyster with scattered detrital quartz grain imbedded by calcite mineral XPL, field of view,4X.*(**C-D**) *Bivalve shell(B) ,oyster(Oy) and some benthic foraminifera(F) (D) PPL field of view,4X. Sample HS18.* (**E-F**) *Calcified (neomorphism) bivalve shell with scattered fine detrital quartz grain left side of (E) and micrite forming parallel bedding showing some intercalation center of (*F*), sample MS2and MS3, XPL field of view, and 4X.*

5.6.5. Bioclastic mudstone microfacies (MFO5)

Description: This is the most common type of microfacies in the measured sections especially in the middle and upper part of Hagere-Selam and Wukro section. This microfacies is micritic limestone layers dominantly. The skeletal mudstone consist of a diverse fossils including mollusks, *Alveosepta jaccardi, Pseudocyclammina lituus* large benthic foraminifera, sponge spicule (triaxon and monoaxon) and scattered other shells fragments with scattered fine detrital quartz grain. Micritic with some triaxon spicules and bioturbated and dolomudstone are also added to this microfacies. This microfacies are obtained from sample number HS19, MS11, WS21, WS25 and WS37 these are collected from lower, middle and upper part of the three stratigraphic sections, which indicate fluctuation in sea level or change in depositional environment. Most of these micritic microfacies are highly, bioturbated, fractured and dissolved, which are in turn filled by sparry calcite cements at places as fenestrael fabric (Figure 5.16A-D). In the Messobo stratigraphic section the micritic layer are black, dark and gray in color, bedded and scares in skeletal grains (Figure 4.16A-C). This microfacies is also associated with karastified, some silicified and chert layers at Wukro and Hagere-Selam stratigraphic section.

Interpretations: Calcareous mud in warm water setting comes from the breakdown of calcareous algae, in organic precipitations from sea water and from disintegration of large skeletal particles into their smallest crystallographic unit. These mudstones accumulated in quite water areas that are not affected by tidal or strong oceanic currents (Tucker & Wright, 1990). According to Brain and Andre (1992), those habitats are found in deep water shelf and/or outer ramp areas below wave base or in the protected islands and shoals environment. These skeletal mudstone microfacies are characterized by fine grained, massive to bedded and light gray to dark in color during the field observations. Therefore, this facies is compared with SMF type 8 of facies belt 3 of Wilson (1975), which is deposited in open marine shelf, with open circulation and low energy water below normal wave base.

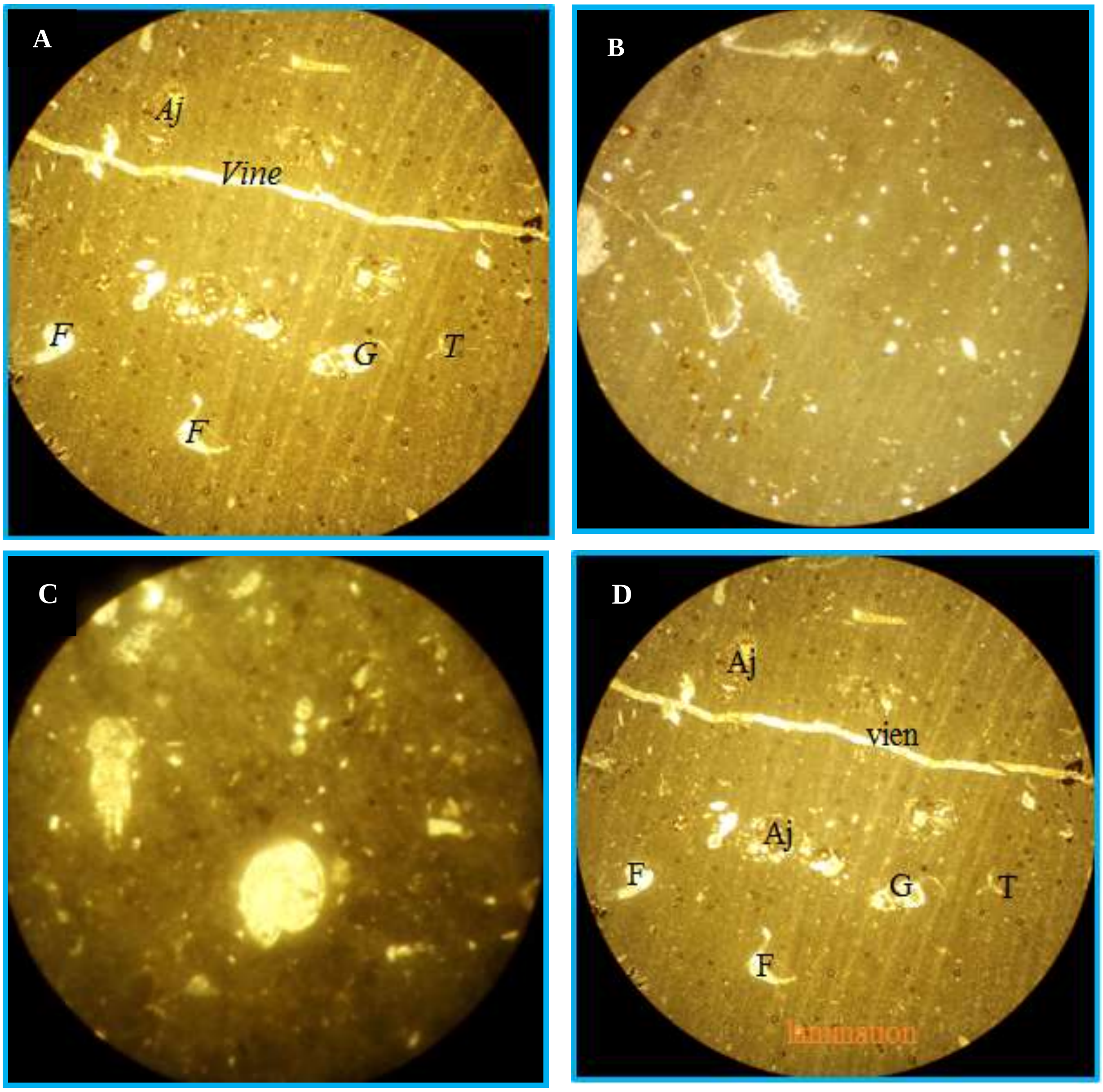


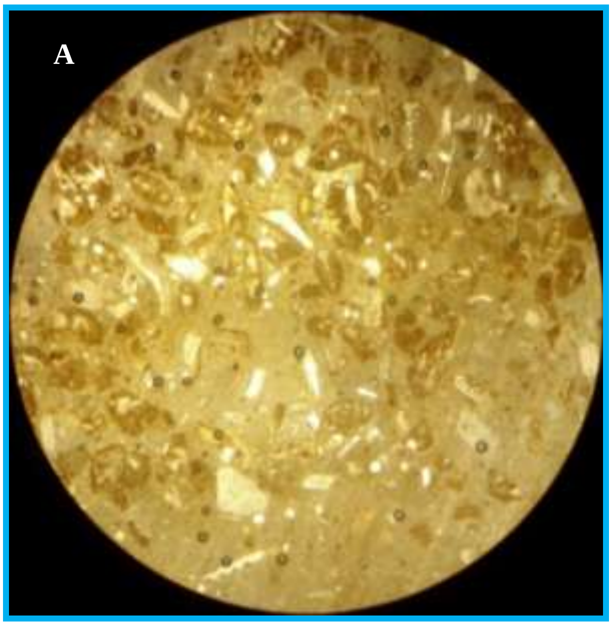
Figure 5.16: *Photomicrograph of bioclastic mudstone upper part of Hagere-Selam, Messobo and middle part of Wukro section*. (**A**) *Bioclastic mudstone consist of Alveosepta jaccardi (Aj),sponge spicule(T),gastropods and abundant fenestrae fabric(F) sample HS19,PPL field of view,4X*. (**B-C**) *Consist of gastropod(left central) with some fenestrae fabric* (C), *Lenticulina* sp *lower part*(C) *sample*

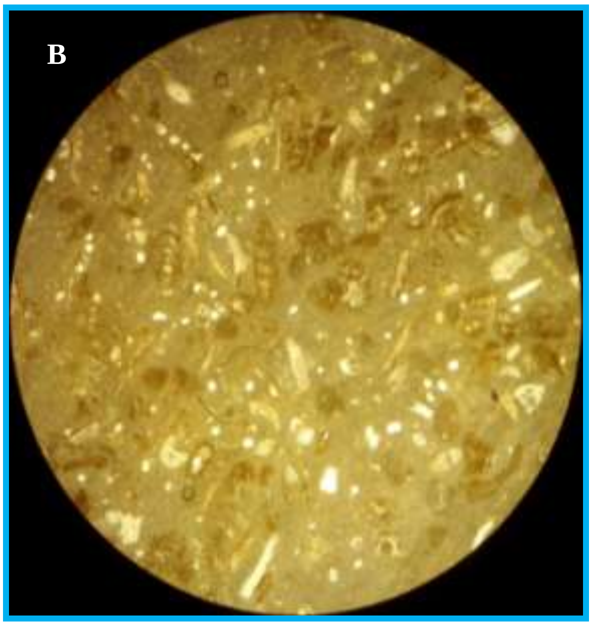
WS21 and WS15, PPL and XPL field of view.(**D**) *Bioclastic mudstone with some large agglutinated foraminifera of Alveosepta jaccardi(Aj) and gastropods(G) with abundant fenestrae fabric and scattered sponge spicule(T) sample WS29 and MS11, PPL field of view,4X.*

5.6.6. Skeletal grain-dominated grainstone microfacies (MFO6)

Description: This microfacies consists of abundant benthic agglutinated foraminifera, different mollusks and calcareous algae comprise the middle and upper part of Wukro section and upper part of Hagere-Selam section in the study area. The skeletal grain dominated grainstone microfacies is composed of abundant, open marine skeletal allochems about 85% including abundant large agglutinated foraminifera of *Alveosepta jaccardi*, *Pseudocyclammina lituus*, *Nautiloculina oolithica* and *Valvilina* sp. associated with other accessory skeletal allochems including bivalve shell fragment and unidentified calcareous algae, which is embedded in very dense micrite (Figure 5.17A-F). While, this microfacies constitutes of lime mud, peloids and abundant fenestrae fabric represent the dominant non-skeletal allochems (Figure 5.17A-F)

Interpretation: Presence of dominant benthic foraminifera associations with abundant *Alveosepta jaccardi*, *Pseudocyclammina lituus, Nautiloculina oolithica* embedded with diverse micrite and some dissolved fenestral fabric indicate a shallow depositional setting with well oxygenated condition below fair weather wave base. This is comparable with facies belt of FZ3 (Wilson, 1975).





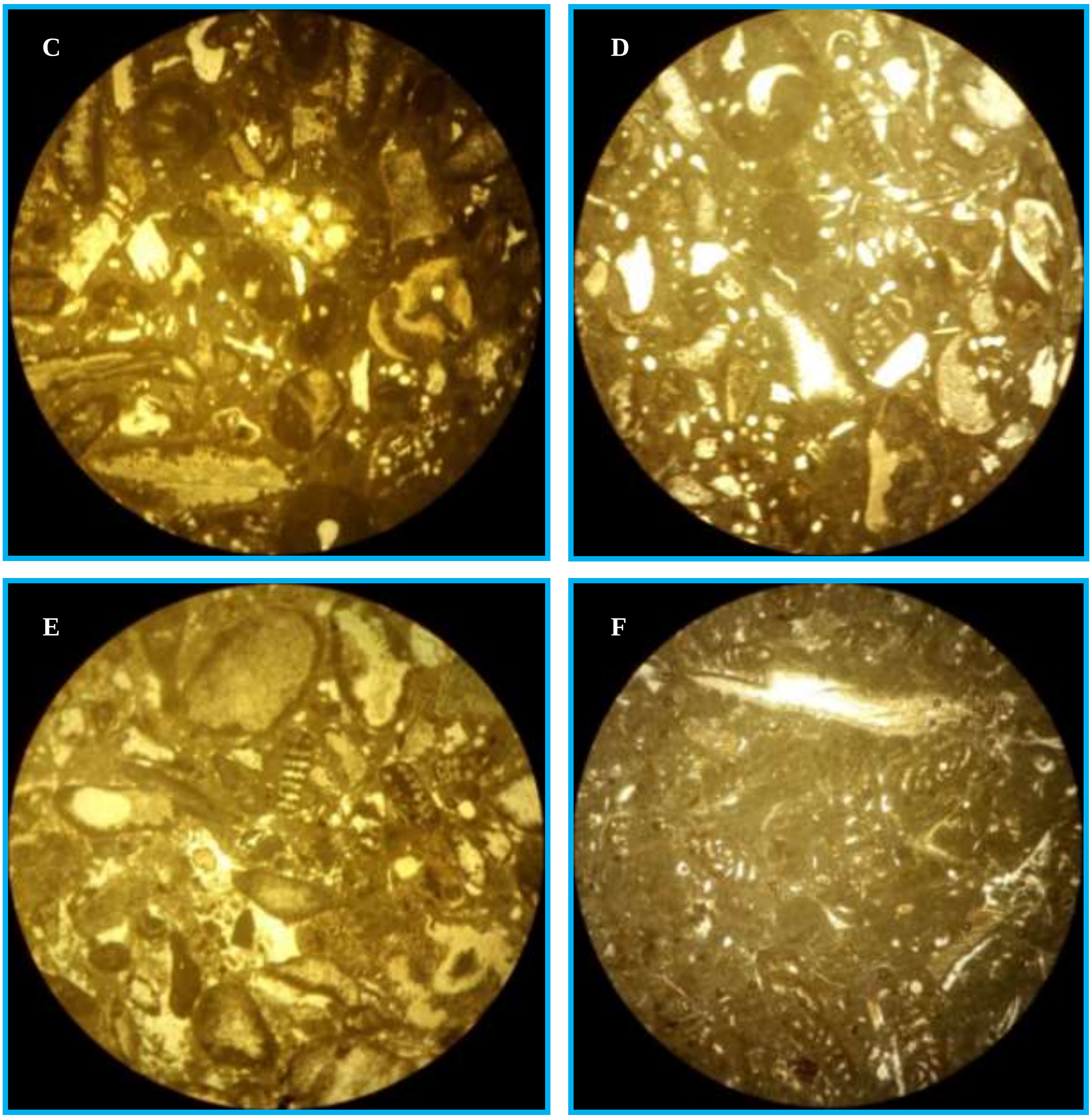


Figure 5.17: *Photomicrograph of skeletal grain-dominated grainstone upper part of Hagere-Selam section, lower and upper part of Wukro section*. (**A-B**) *Abundant agglutinated benthic foraminifera of Alveosepta jaccardi (Aj), Pseudocyclammina lituus (P), Nautiloculina oolithica, Valvilina* sp, *Choffatela* sp, *and scattered peloids, sample WS23, PPL field of view, 4X*. (**C-E**) *Bioclastic grainstone consist of abundant mollusk shell fragment, coral, peloids and fenestrae fabric sample HS22, PPL field of view, 4X*. (**F**) *Alveosepta jaccardi and Pseudocyclammina lituus rich grain stone with rare mollusk shell sample WS38, PPL field of view, 4X.*

5.6.7. Skeletal-grain dominated packstone microfacies(MFO7)

Description: The skeletal grain dominated packstone consists of thick rock unit that are moderatly bioturbated. This is obtained from the upper part of Wukro section from sample WS30, which is underlain by unfossiliferous lime mudstone and overlain by sandy dolostone respectively. It is charactereised by abundant, open marine skeletal allochems up to 70%

including abundant mollusks, *Pseudocyclammina lituus*, *Mililoids*, *Nautiloculina oolithica*, echinoderms and scattered peloids, which are embedded with dense micrite (Figure 5.18A-D).

***Interprtion*: ** Increased sorting relative to underlying unfossiliferous mudstone and rounding of open marine grains as well as the presence of bioturbated stratification and some lime mud suggest that this microfacies type was deposited in the middle shoreface environment. This microfacies is comparable with SMF type of 10 in the high energy environment, slope to low energy settings (Wilson,1975).

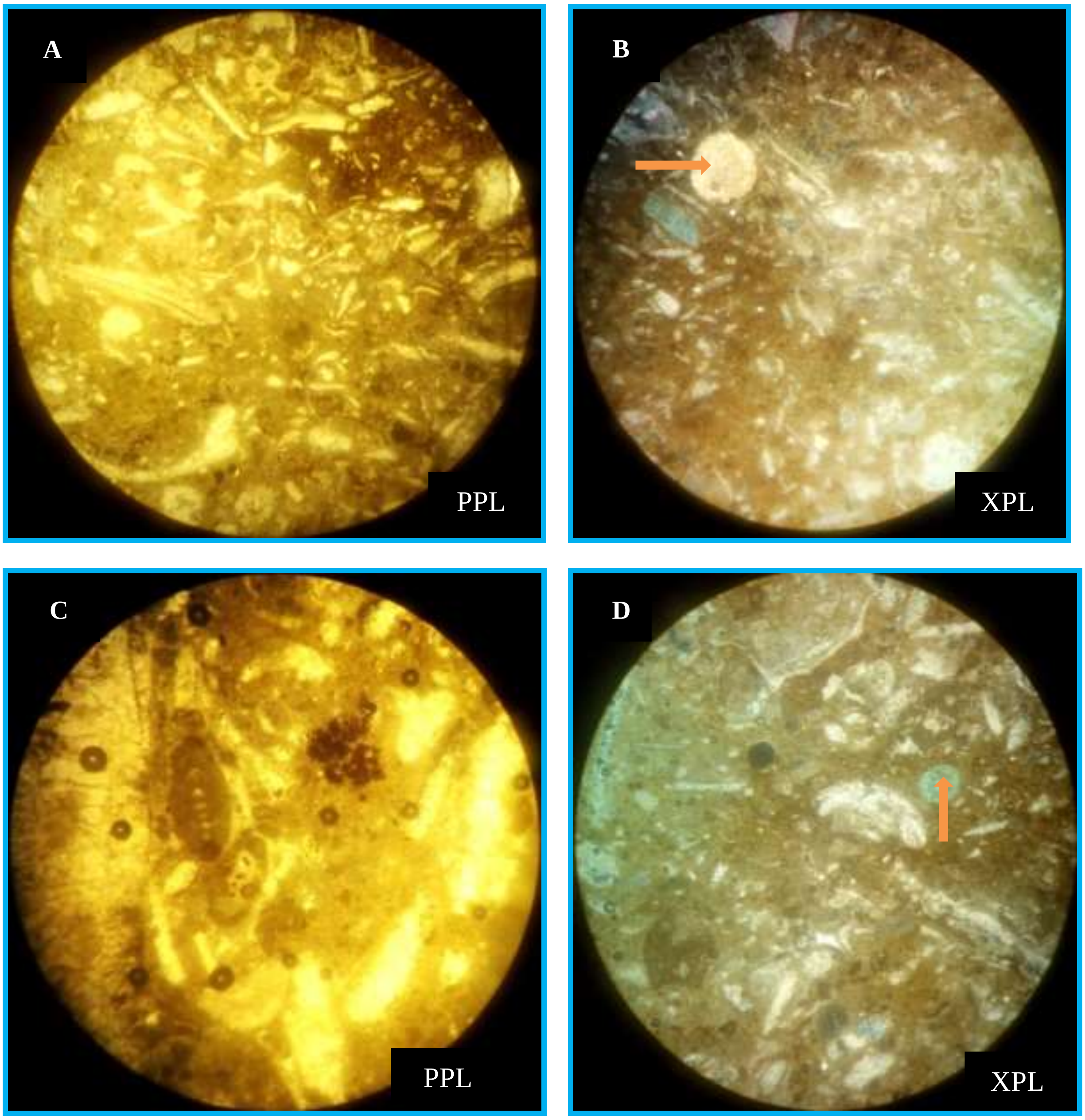


Figure 5.18: *Photomicrograph of bioclastic packstone upper part of Wukro stratigraphic section composed of different calcified mollusk shell* (**A-D**) *which is empeded by dense micrite moderatly dioturbated.* (**B&D**) *Different shell fragment with echinoderm macrofossil arrow indicateand (C) Bioclatic packston with Nautiloculina oolithica center left side,sample WS30, 4X.*

5.6.8. Skeletal-intraclast-peloidal wackstone microfacies (MFO8)

Descriptions*:* This skeletal-peloidal wackstone microfacies type obtained from the lower part of Wukro stratigraphic section, which is sandwiched between the two overlain and underlain bioclastic wackstone microfacies type obtained from sample WS7and WS6. It is characterized by abundant small to medium peloids without any concentric layer. Additionally this facies consists of abundant shelf fragment and intraclast grain, which embedded in the dense micrite (Figure 5.19A-B).

Interpretations: The skeletal peloids are characterized by the similar composition of the micrite forming the peloids and the micritic matrix and irregular contact between areas with and without peloids (interpreted as bottom reworking). They area formed by syn-sedimentary and post sedimentary reworking of carbonate mud and micrites (Flugel, 2004). Many wackestone and packstone are formed as 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. They tend to form away from edges of platforms (Burchette and Wright, 1992; Walker, 1992). This skeletal-peloidal wackstone is overlain and underlain by open marine bioclastic wackstone. Therefore, this facies is compared to facies belt 3 of Wilson (1975), which is deposited in open marine environment within the fair weather wave base.

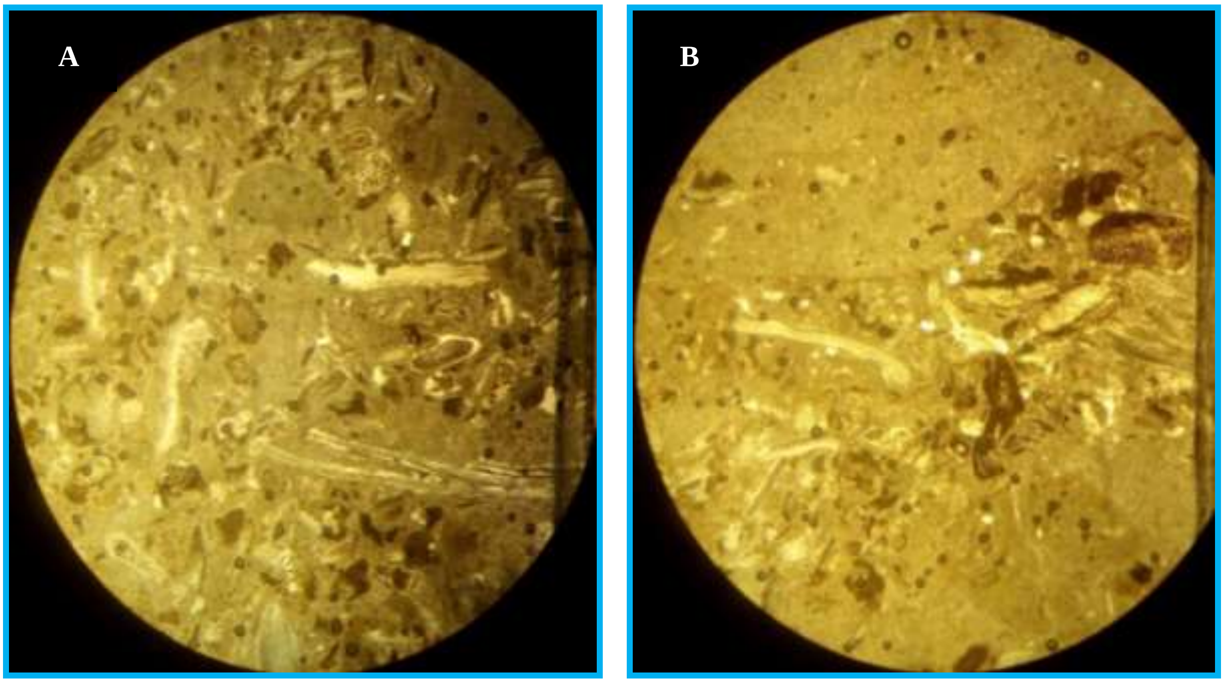


Figure 5.19: *Photomicrograph of skeletal-peloidal wackstone microfacies from lower part of Wukro section, sample, WS7, 4X.* (**A-B***) Indicate different peloids with abundant shell fragment, intraclast with dense micrite which is affected by bioturbation*.

5.7. Diagenetic feature of the carbonate succession

5.7.1. Introduction

The diagenesis is defined as al1 the processes that affecting sediments immediately after deposition and continuing until metamorphism at elevated temperatures and/or pressures (Tucker 1981; Tucker and Wright 1990). After deposition, carbonate rocks are subjected to a variety of diagenetic processes that range from early to late stage that bring about changes in porosity, mineralogy, texture and chemistry (Al-Dabbagh, 2006). These changes and/or alterations involves compaction, dissolution, recrystallization and replacement (e.g. aragonite to calcite, calcite to dolomite, etc). The exact nature of the changes that take place during diagenesis depends upon the specific conditions (temperature, pore-fluid composition and pH) of the diagenetic realm or environment. Carbonate rocks are particularly susceptible to early and late diagenetic modifications, because most of the marine carbonate sediments consist of metastable carbonate mineral, such as aragonite and high magnesium calcite, which are easily soluble in fresh meteoric waters and marine water than other naturally occurring minerals which are subject to dissolution and re-precipitation (Peter and Dana, 2003; Ahr, 2008). Carbonate rock unit of Mekelle Outlier especially in the study area (Hagere-Selam, Messobo and Wukro sections) underwent different types of diagenetic alterations that range from early to late diagenetic processes. The major diagenetic processes affecting the carbonate rock units of the study area are micritization, dissolution, cementation, physical compaction, pressure solution (stylolitization), recrystallization and/or neomorphism, dolomitization and the replacement of carbonate grains and matrix by non-carbonate minerals (e.g. silicification). Therefore, this section deals on the different type of diagenetic process that occurs in the study carbonate unit.

5.7.2. Compaction

During progressive burial of the carbonate mineral, and increase in overburden pressure resulted in a reduction in sediment thickness and the development of compaction textures. Compaction processes are classified as either mechanical (physical) or chemical (pressure solution) (Choquette&James, 1981; 1990).

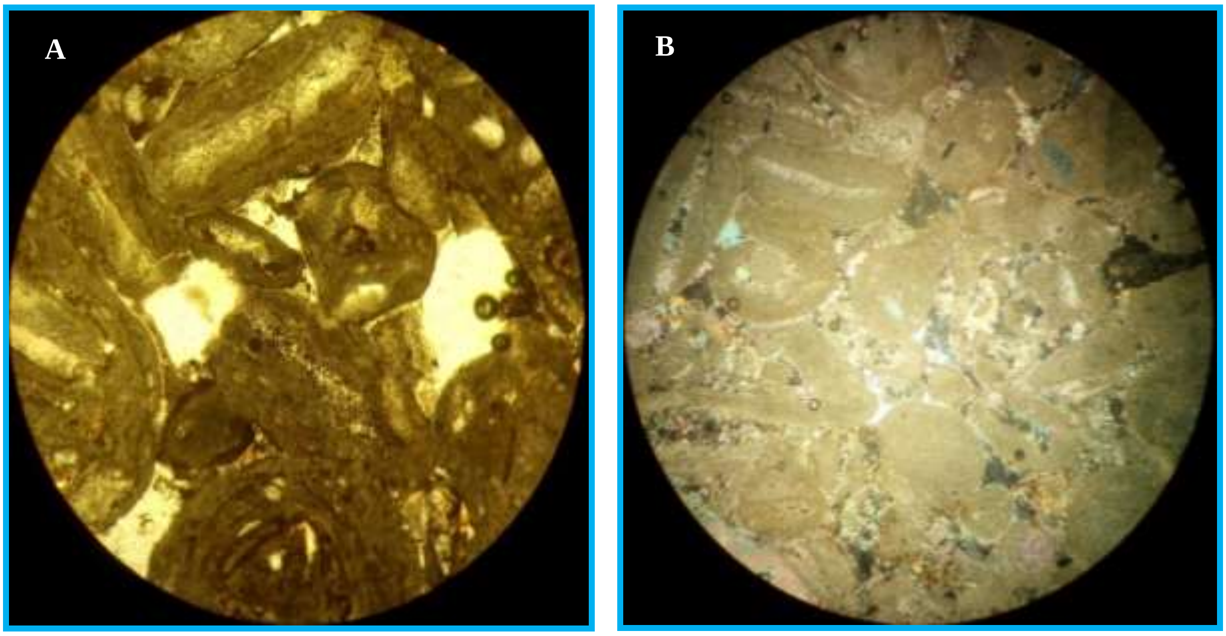
5.7.2.1. Physical compaction

Physical compaction involves tighter packing and deformation of grains due to overburden pressures as burial into the subsurface proceeds. Grains are deformed by brittle fracturing and breaking and by plastic or ductile squeezing which reduce in porosity, permeability and sediment thickness dewatering and fracturing, re-orientation, breakage of allochems, and closer packing of grains (shinn and Robbin, 1983; Choquette, and James, 1981). This type of diagenetic alteration is obtained from sample collected from the lower, middle and upper part of Hagere-Selam and Wukro section (Figure 5.20 A-B).

5.7.2.2. Chemical compaction (stylolitization)

Chemical compaction involves pressure solution at grain to grain contacts resulting in interpenetrating and/or sutured contacts between grains. On a larger scale, pressure-solution seams called stylolites develop. The stylolite seams are marked by the presence of clay minerals and other fine-size noncarbonate minerals (commonly referred to as insoluble residue).

In addition to grain to grain suturing, pressure-solution seams commonly develop approximately parallel to bedding. Presumably, the reason stylolite are usually parallel overall to bedding is that bedding surfaces are usually the paths of easiest flow of pore solutions (Adams and Mackenzie, 1998). The common type of microstylolite observed under thin sections that occur in the lower part of carbonate rock unit of Hagere-Selam section is presence of a parallel sedimentary stylolite (Figure 5.20C-F). The abundance of the horizontal stylolite seams in this carbonate rock unit strongly suggests dissolution and chemical compaction that probably took place during the diagenetic processes of the preexisting carbonates.



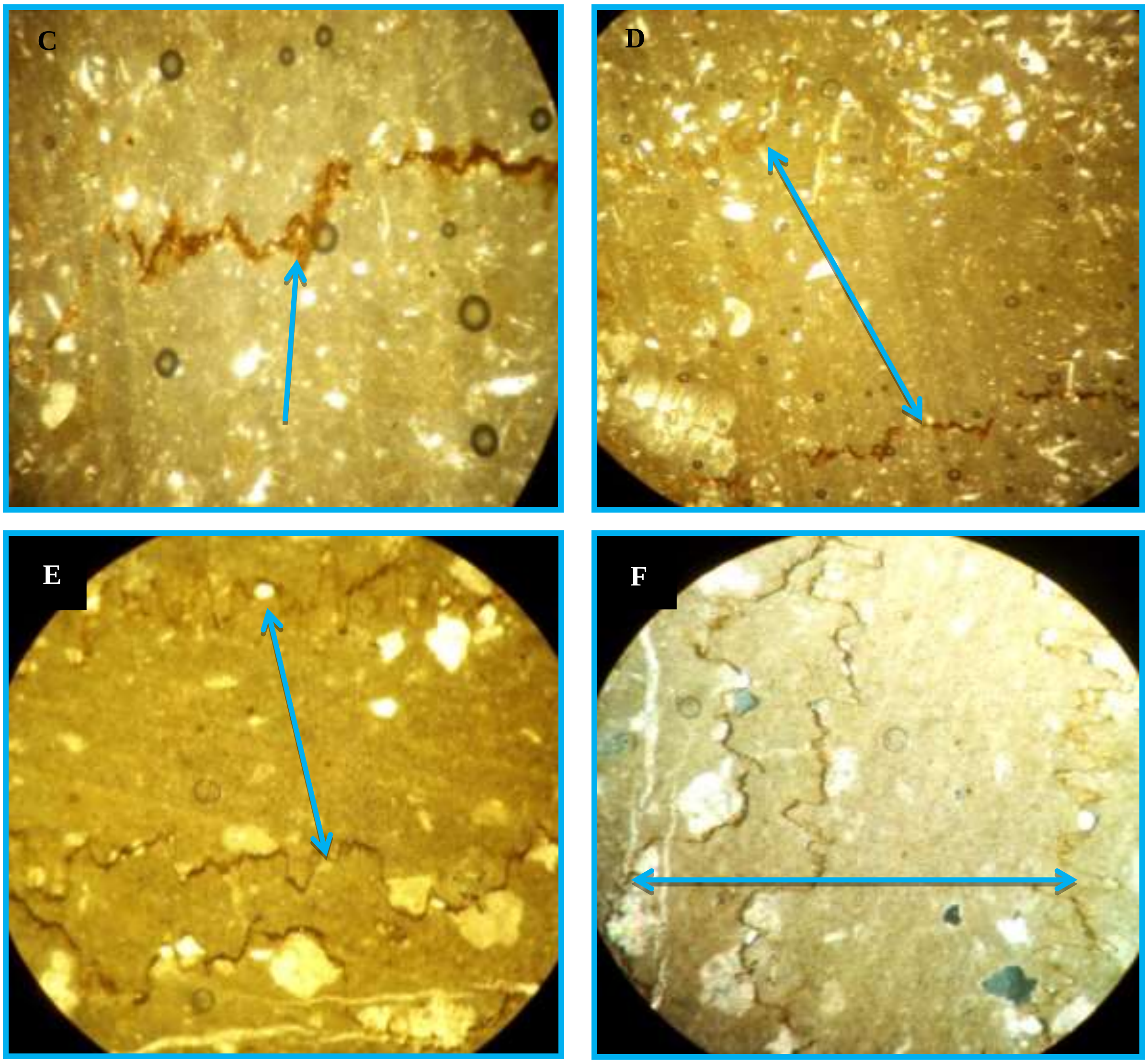


Figure 5.20: *Photomicrograph of mechanical compaction and parallel sedimentary stylolite lower part of Hagere-Selam and Wukro section*. (**A-B**) *Mechanical compaction of the oolitic and peloids sample WS5, PPL view and HS, XPL field of view, 4X*. (**C-D**) *Parallel stylolite sample HS1 PPL field of view, 4X*. (E-F) *parallel stylolite **C**.PPL and **D**. XPL view, 4X arrow indicate*.

5.7.3. Fractures

Fractures are the results of compaction processes and commonly found at various levels in the measured sections. It is particularly effective and common in carbonate rocks because, of their brittle nature of carbonates relative to the more ductile fine-grained siliciclastic, which they are often interbedded (Longman, 1980). Fracturing can take place at practically any time during the burial history of a carbonate sequence starting with shallow burial because of common early lithification. In the study area the mudstones and wackstone facies are particularly bearing more fractures, which are at places highly fractured with several phases of fracturing up to faulting (Figure 5.21A-C). However, some of the bioclastic, oolitic and peloidal microfacies are affected by different degree of fracturing with rare ductile structure (Figure 5.21D).

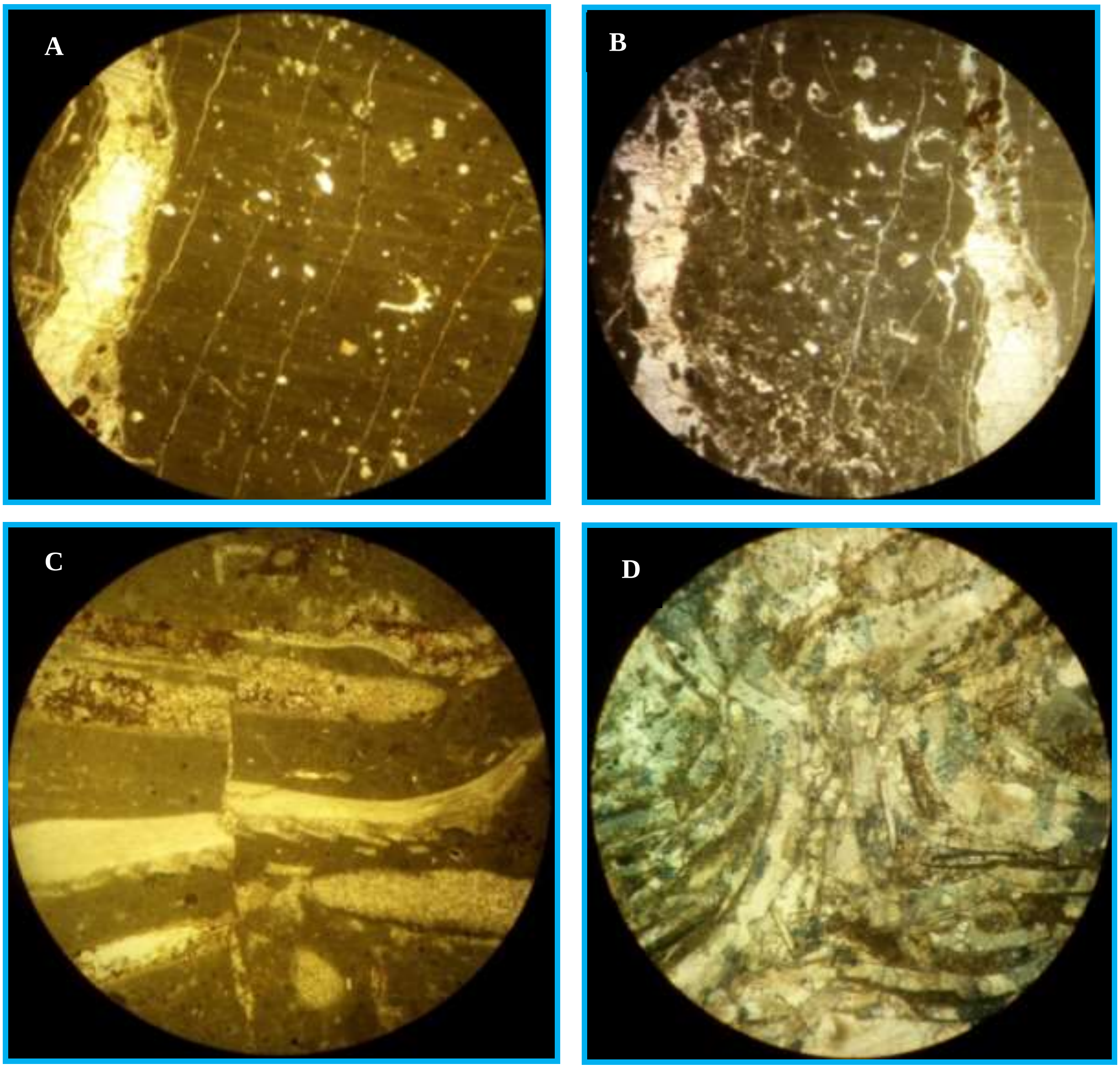


Figure 5.21: *Photomicrograph of fracture diagenetic features recorded from lower part of Hagere - Selam, Messobo and upper part of Wukro section*. (**A-B**) *Show extensive parallel fracturing sample HS10, PPL field of view, 4X.* (C) *Normal fault fracture, sample WS2 WS27, PPL field of view, 4X, and* (**D**) *Deformed bivalve shell, sample MS2, XPL field of view, 4X.*

5.7.4. Micritization

Reworking of carbonate sediments by boring, burrowing and sediment-ingesting activities of organisms, just as they do in siliciclastic environments are common in the study area. These activities may destroy primary sedimentary structures in carbonate sediment and leave behind mottled bedding and various kinds of organic traces (Tucker 1981; Tucker and Wright, 1990). Addtionally, many kinds of small organisms, such as fungi, bacteria and algae create microborings in skeletal fragments and other carbonate grains. Fine-grained (micritic) aragonite or high-magnesian calcite may then precipitate into these holes (pore space). These boring and micrite-precipitation process may be so intensive in some warm-water environments that carbonate grains are reduced almost completely to micrite, with a process called micritization. If boring is less intensive, only a thin micrite rim or micrite envelope, may be produced around the grain. In the bioclastic rudstone sample HS18, most of the skeletal fragments show a micritic envelope around the skeletal fragments and sandy limestone sample HS11 (Figure 5.22A-B).

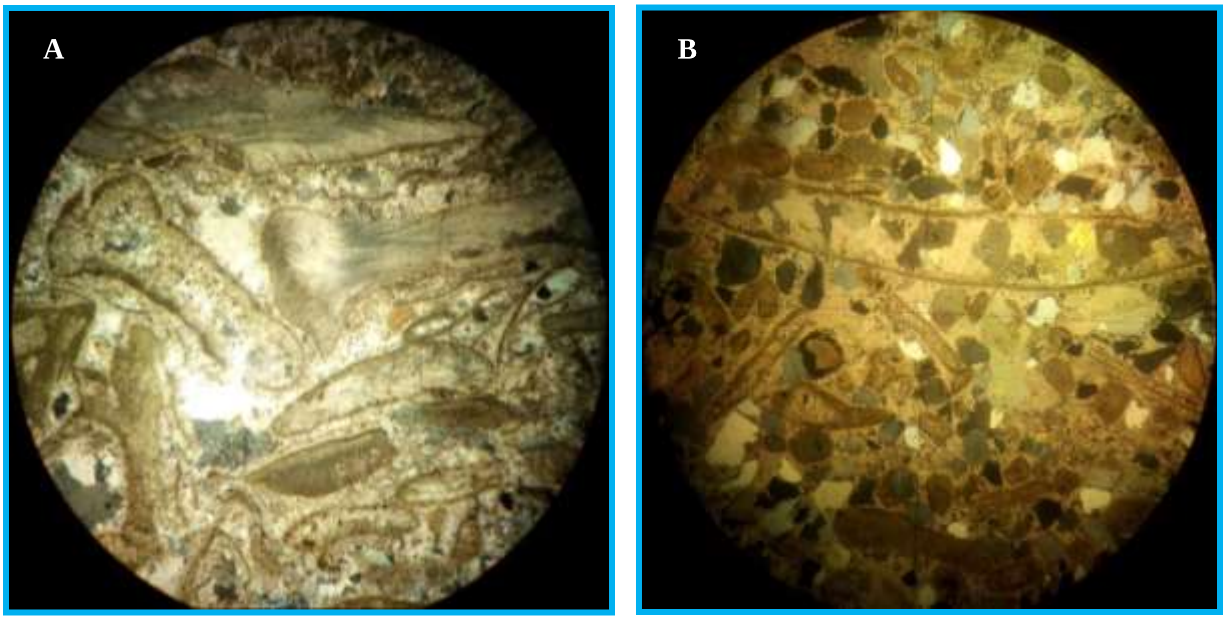


Figure 5.22: *Diagenetic alteration of the skeletal and non-skeletal grain Hagere-Selam section.* (**A**) *Large skeletal grain with thin dark micrite envelope at ream of the shell, sample HS18, XPL view, 4X.* (**B**) *Thin micrite envelope with the skeletal grains sample HS11, XPL view, 4X.*

5.7.5. Cementation

Cementation is the precipitations process of minerals within the pore spaces of grain-rich sediments or in cavities. Areas of the seafloor along the platform margin, where sediments become well cemented are referred to as hardgrounds (see Figure 4.23A-B). Cemented carbonate beach sand is called beachrock. Cementation is the most dominant diagenetic processes throughout the study sections of Mekelle Outlier carbonate units from sample HS7 and WS5. It is the process, in which chemical precipitates (in the form of new crystals) form in the pores of a sediment or rock, and binding the grains together (McIlreath and Morrow, 1990). 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).

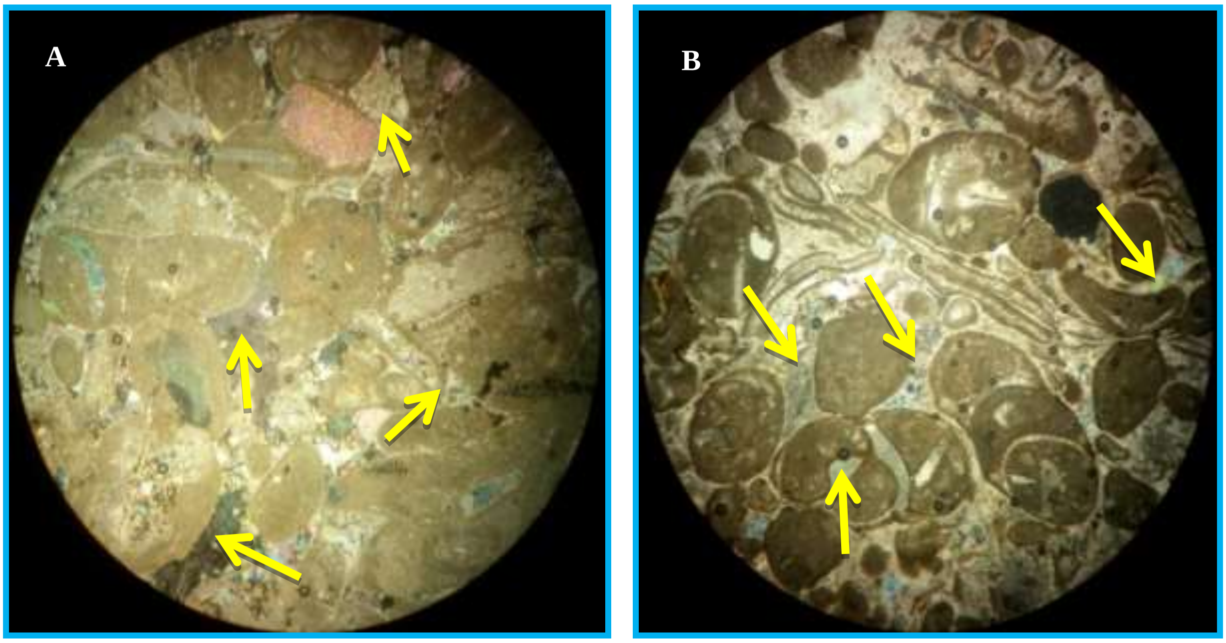


Figure 5.23: *Photomicrograph of cementation diagenetic features of carbonate unit from lower part of Hagere-Selam and upper part of Wukro section sample HS7 &WS36, XPL field of view, 4X* (**A-B**) Calcite cement.

5.7.6. Dissolution

Dissolution is a process of chemical destruction of carbonate minerals by chemically aggressive pore waters highly charged with CO_2 and/or organic acids. It requires conditions essentially opposite to those that lead to cementation (precipitation). Dissolution is favored by unstable mineralogy (presence of aragonite or high-miagnesiam calcite), cool temperatures and low pH (acidic) pore waters that are undersaturated with calcium carbonate (McIlreath and Morrow, 1990). In such a case, the water is under-saturated with respect to CaCO3. 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). 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 vugy porosity, and enlarging preexisting fractures in lithified rock. This is of course, epidiagenesis. If this process continues uninterrupted then cavernous porosity may develop, leading ultimately to karstic topography (Figure 5.24 C-E).

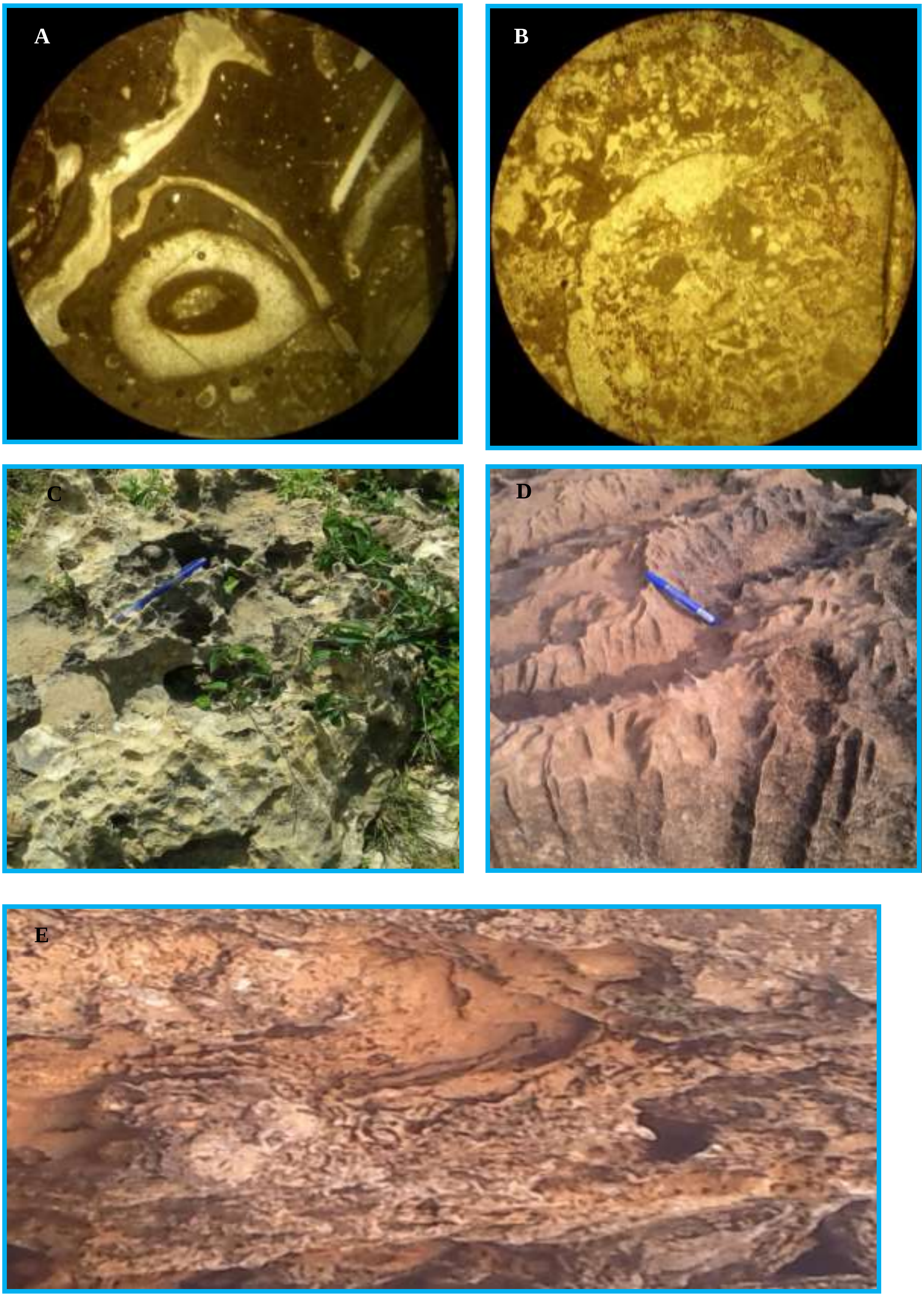


Figure 5.24 : *Photomicrograph and outcrop field photo of dissolution diagenetic features (***A-B***) Upper part of Hagere -Selam section (***A***) sample HS20,PPL field of view,4X and lower part Wukro section (***B***) Sample WS3,PPL fields of view,4X. (***C-E***) Karastified limestone from lower part of Hagere-Selam section (D&F) and upper part of Wukro section (C).*

5.7.7. Neomorphism

Neomorphism is the combined processes of inversion (e.g., transformation of aragonite to calcite) and recrystallization (transformation of micrite to microsparite). Inversion refers to the change of one mineral to its polymorph, such as aragonite to calcite (calcitization) where as, recrystallization indicates a change in size or shape of a crystal, with little or no change in chemical composition or mineralogy.

Most of the scleractinian corals and mollusk shell in the study area show inversion means changing aragonite, which forms the skeletal materials and cement into equant blocky calcite crystal. The term neomorphism has been introduced by Folk (1965), which includes aggrading and degrading recrystallization. Aragonite and high magnesium calcite are the most soluble carbonate polymorphs. The aragonite forming skeletons of the present samples have been highly recrystallized during the meteoric diagenetic stages to crystalline, more stable low Mg-calcite, with the presence of micritic relics in between (Figure 5.25A-D). The original aragonitic microstructures are completely obliterated. They have been dissolved and subsequently infilled by equant blocky calcite cement.

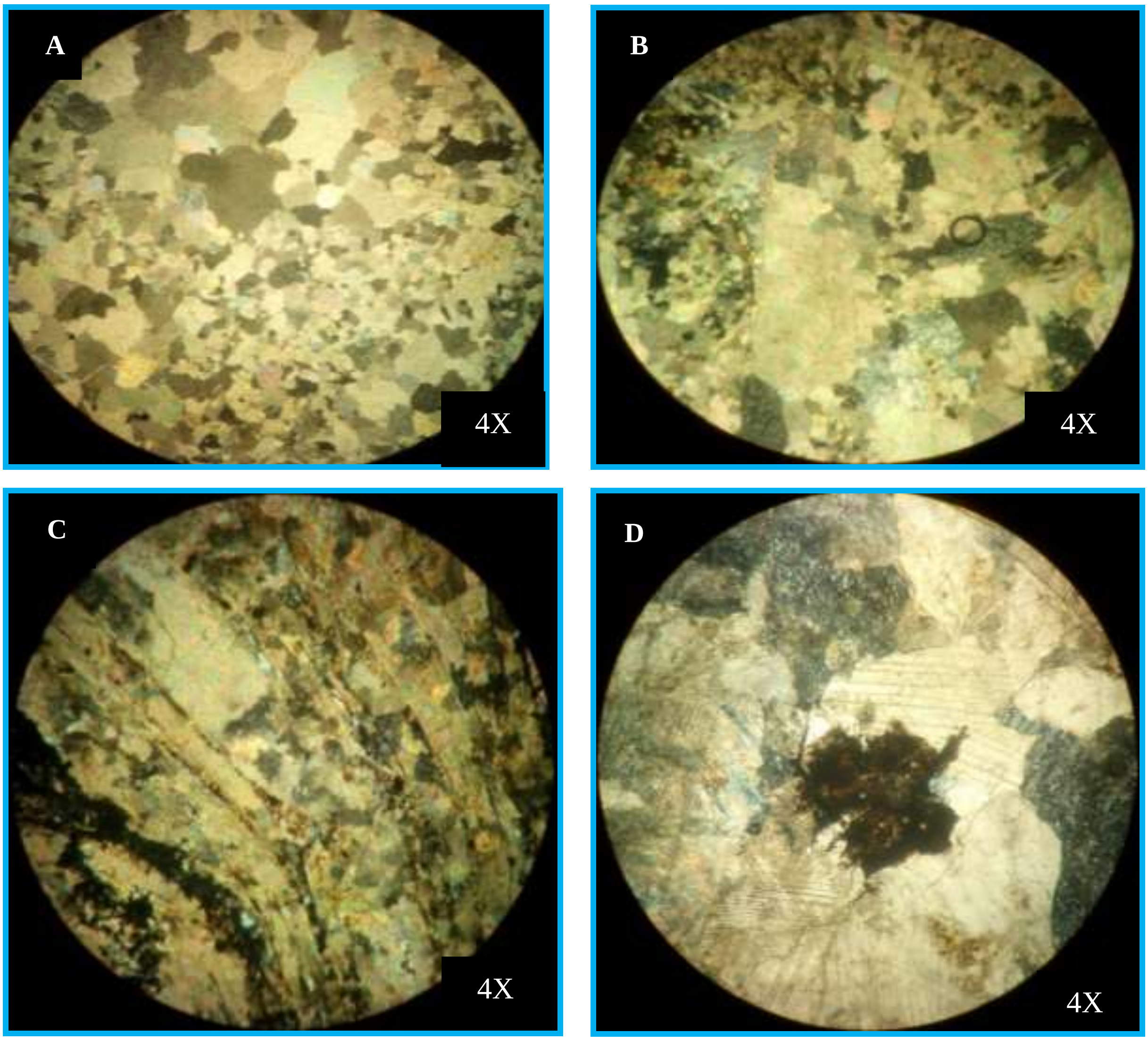
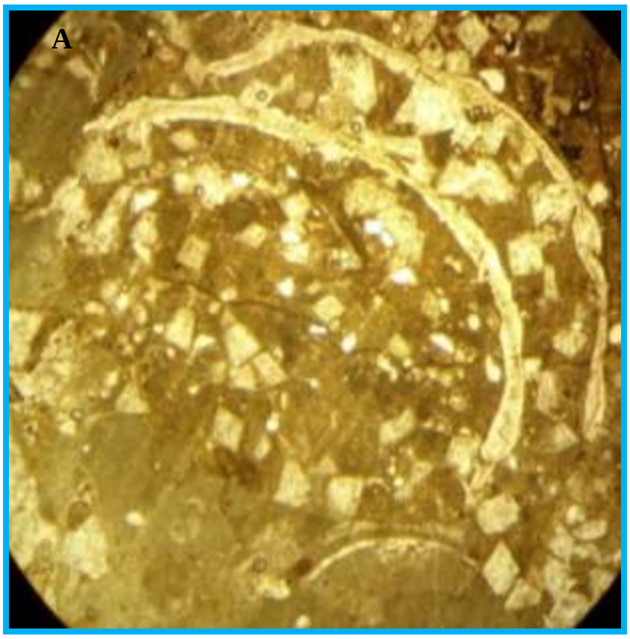
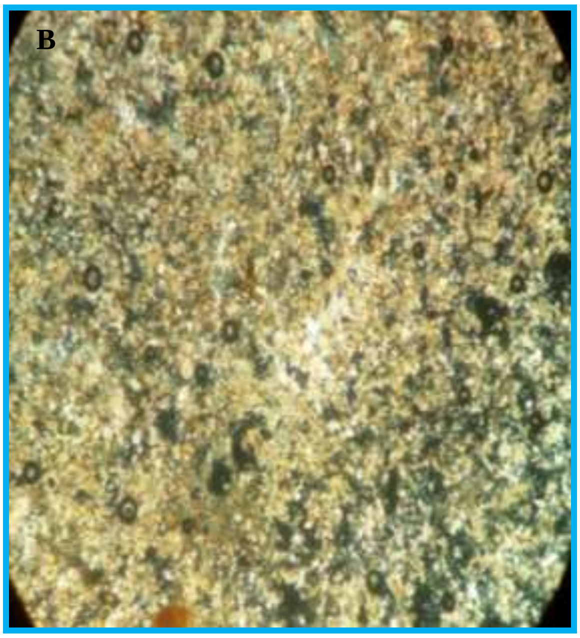


Figure 5.25: *Photomicrograph of recrystallization of digenetic process lower part of Hagere-Selam and Messobo section sample HS2* (**A-B**) *and MS3* (**C**) *&MS5* (**D**), XPL field of view, 4X. (**A-B**) *Show complete recrystallization of aragonite rich coral by blocky* calcite *crystal*. (**C-D**) *Recrystallization of bivalve shell by blocky calcite mineral with scattered mud between the shell fragments.*

5.7.8. Dolomitization

Dolomite, $CaMg\ (CO_3)_2$ is one of the major component of carbonate rock unit in the studies sections next to limestone and mixed siliciclastic-carbonate rock unit. It is usually secondary, form by replacing of pre-existing carbonate minerals. Dolomite is identified by its euhedral rhombic shape, often zoned and untwined habit than limestone under thin section. Dolomitization is the diagenetic processes, in which the calcite to dolomite conversion and results in volume reduction and an increase in porosity (McIlreath and Morrow, 1990). According to McIlreath and Morrow (1990) to this conversions takes place in two main environments: **A.** Coastal areas where mixing of meteoric waters and seawater takes place, this process form coarse-grained dolomite, and **B.** Sabkha (supratidal) areas where Mg-rich, Ca -poor brines seep into limestone and form fine-grained dolomite. In the study sections, dolomitization processes are obtained mainly in the lower, middle and upper subunits of the carbonate units of the area, at Wukro and lower part of Hagere - Selam sections and middle of Messobo section. The dolomitization stage ranges from partially to complete dolomitization of calcite grains (Figure5.26 A-D). Aragonite and high-Mg calcite is far more susceptible to dolomitization than low-Mg calcite.





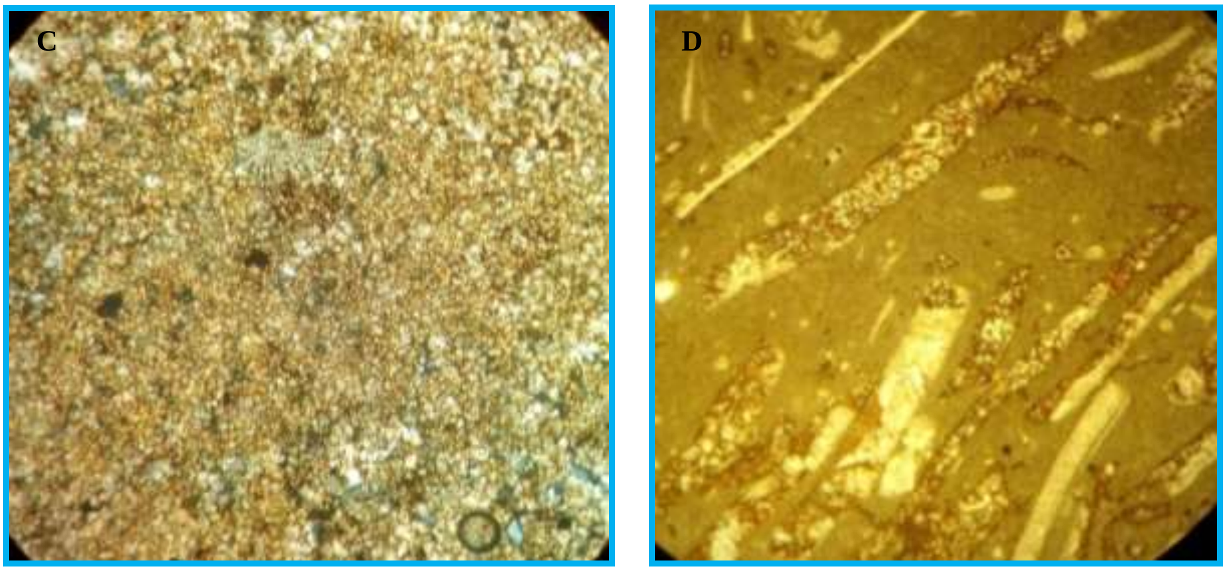


Figure 5.26: *Photomicrograph of dolomitization lower part of Hagere-Selam section and lower, middle and upper part of Wukro section sample WS17, WS20, WS35 and HS12.* (**A**) *Medium euhedral crystals associated with micrite and scattered shell fragment sample HS12, PPL field of view, 4X. (***B-C***) Fine to medium crystalline complete dolomitization with rare detrital clastic input, sample WS17 andWS35, XPL field of view, 10X. (***D***) Partial to complete dolomitization of the mollusk shell, sample WS20, PPL field of view, 4X.*

5.7.9. Silicification

Silicification is the common type of diagenetic process, which is recorded from the study carbonate rock unit of Hagere-Selam and Wukro sections especially in the corals rich limestone, sandy limestone, stromatoporoid mudstone and some packstone to grainstone rock unit either as pore-filling among allochems spaces (Figure 5.27B) or as partial to complete replacement of mainly bivalve skeletons and corals (Figure 5.27C-F).This is obtained from sample HS1, HS2, WWS11, HS9, HS14, HS15, HS16, WS3, WS14, and WS12.

Replacement by silica is highly allochem selective while generally leaving the host rock material unaffected. They precipitated in the form of equigranular microquartz and fibrous quartz as spherculitic chalcedony. Some of the crystals possess wavy extension and others are cracked. The contact of quartz crystals with the skeleton boundary is sharp and the boundaries are not dissolved or replaced by silica. This indicates that the quartz crystals were precipitated as cavity-filling cement after stabilization of the wall boundaries. Most researches dealing with silicification suggest replacement that took place during early diagenesis before significant burial and compaction of sediments (Mansour, 2004; Schubert et al., 1997) or as proceeding lithification (Brunton, 1984). Carson (1991) indicated that silicification may occur at burial depths up to 10 m.

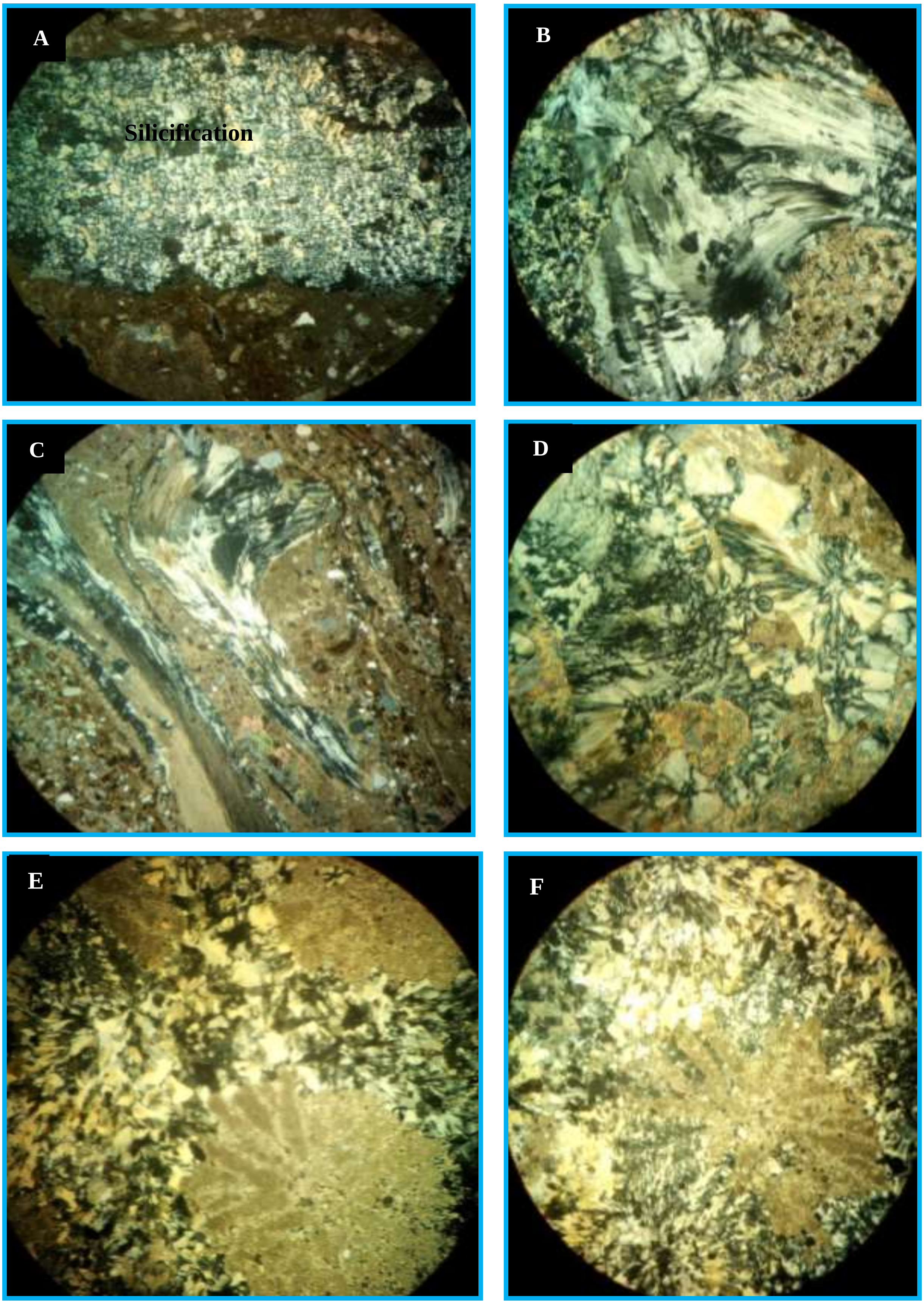


Figure 5.27: *Photo micrograph of silicification diagenetic features Hagere - Selam section* (**A** and **C-H**) *Partial to complete replacement of the bivalve skeletons* (**A**, **C&E**) *and individual corals septa* (**F&G**) *sample WWS11,HS14,WS14and HS2,XPL field of view, 4X.*

CHAPTER SIX

7. DISCUSSION

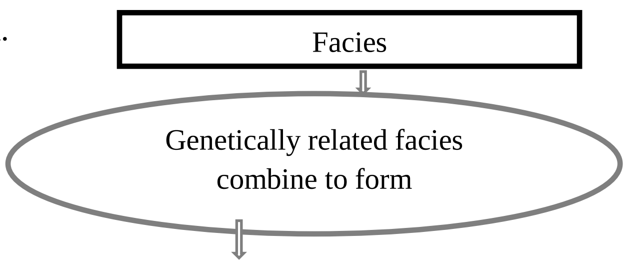
6.1. Introduction

According to a detailed field investigations and laboratory analysis of 65 thin sections and 26 productive dry marl sediment, the Hagere-Selam, Messobo and Wukro sections, the Upper Jurassic (Oxfordian-Kimmeridgian) carbonate deposits are characterized by thick layers of carbonate rocks, mainly limestone rock unit with some dolomite and mixed silicicalstic-carbonate rock unit. These carbonate successions have various distribution of skeletal and non-skeletal allochems which are embedded by microcrystalline (micrite) and/or sparry calcite cement, which ranges from mudstone to grainstone microfacies of the carbonate succession. Additionally, these rock units consist of various sedimentary structures, textures, depositional environment with different paleontological distribution. Based on these varying sedimentological and paleontological information collected from the measured three sections and laboratory data description and analyses, depositional environment interpretation, age determination, facies pattern and their facies model, intrabasinal and regional correlation are discussed as follows:

6.2. Facies associations and depositional environments

A depositional system refers to a three-dimensional assemblage of process related to sedimentary facies that record a particular palaeogeomorphic element, i.e., a particular depositional environment (Galloway, 1989). The nature of depositional systems and facies associations that fill a sedimentary basin is a reflection of the structural mechanisms controlling the formation of the basin. It is therefore, imperative to constrain and acquire a good understanding of the geometry and internal architecture of the depositional systems involved before proceeding with construction of facies model and stratigraphic correlations.

The carbonate rock unit of the study sections refers to a complex arrangement of microfacies units deposited in variety of depositional environments ranging from restricted near coast tidal environment up to open marine carbonate environment above and within fair weather wave base. Therefore, this section presents a brief account of the microfacies associations, depositional system and facies models bearing on the study carbonate succession of the study area.



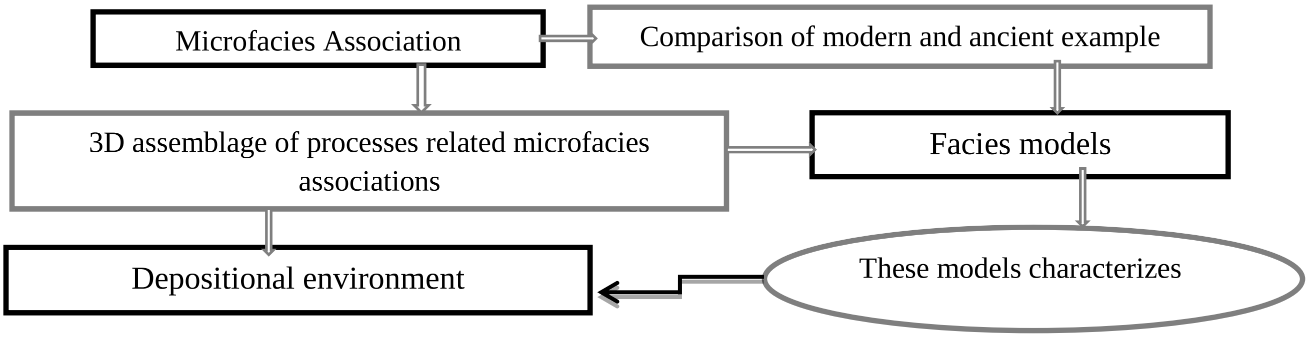


Figure6.2: *Relationships between facies, microfacies associations and depositional systems (modified after walker, 1992).*

6.2.1. Facies associations

Facies association is a groups of facies genetically related to one another, which have the same depostional environment. On the basis of lithology, sedimentary structures, trace fossil association, textures, presence and proportion of non skeletal (ooid, poloids, oncoids, aggregate, and intraclast) and skeletal (bivalve, brachiopods, gastropods, corals, echinoids, crinoids and other benthic forminiferal) grains, and field relationship with overlain and underlain rock unit, 19 different microfacies type have been recognized and grouped into shallow marine carbonate deposits of (**A**) tidal flat, (**B**) lagoon, (**C**) barrier/shoals and (**D**) open marine environment). They include sediment deposited in near costal tidal flat (MFT1-3) environment of shallow marine, sediment deposited in low energy of lagoon (MFL1-2), sediment deposited in shoal environment (MFS1-6), above fair weather wave base and sediment deposited in open marine (MFO1-8) settings of relatively deep-water environments of the middle and outer ramp marine environment between fair weather wave base and storm wave base and below storm wave base with rapid cyclicity mainly by auto cyclic (see Appendix one, Plate I, Figure B-D). These are described and interpreted basin ward as below:

6.2.1A. Tidal flat system

Carbonate tidal flat occur in settings, which are protected from open ocean waves by wide shelf lagoons, which dampening the incoming waves by its position behind barrier land that separate back shoal lagoons from open ocean (Walker, 1992 and Reading, 1996). These tidal flat are partly sea and partly land, which are flooded during high tides and are exposed during low tides that is why they contains clastic and carbonate layers alternatively as observed in the carbonate rock unit (Figure 5.1-5.3). The upper part of the carbonate units of the Hagere-Selam section and almost all part of the Messobo sections except some cyclic laggonal sediment with restricted tidal sediment are deposited under low energy conditions of tidal flat system. These carbonate rock unit comprises the successive intercalation of calcareous mudstone and some clastic mudstone deposits. The very fine dolomudstone (MFT1), unfossiliferous lime mudstone (MFT2) and siliciclastic mudstone (MFT3) of the area are the characteristic deposits of tidal flat system. Therefore, the Messobo section is characterized almost by this tidal depositional environment with some laggonal deposit in the lower and middle part, which indicate deposition of these carbonate unit near continent as the water level of the sea decrease southeastern direction of the Mekelle Outlier relative the two measured section with lack of the shallow shoal sediment (see Appendix one, plate I, Figure D).

6.2.1B. Lagoon carbonates system

Lagoons form along carbonate coastlines, where a beach barrier is wholly or partly encloses an area of shallow water, which have very limited connection to the open ocean. Seawater reaches a lagoon directly through a channel to the sea or via seepage through a barrier (Nichols, 2009). Sediment of the laggonal facies were deposited in an extensive, semi-restricted to restricted shelf lagoon landward of the shelf margin shoal or barrier facies. The restricted condition is suggested by the lack of normal-marine biota and abundant skeletal components of restricted fauna. Lagoons generally develop along coasts, where there is a wave-formed barrier and are largely protected from the influence of open ocean waves (Reading and Collinson, 1996). Carbonate lagoons are sites of fine-grained sediment forming layers of carbonate mudstone and wackestone with scattered carbonate packstone and grainstone deposited as washover near the beach barrier. They are accumulated on platforms, where current activity has been insufficient to remove out the mud size grain (Flugel, 2004). As a transitional they are located away from the edges of platforms and/or on deeper parts of ramps, where there is some protection (Brain and Andre, 1992; Walker, 1992; Burchette and Wright, 1992). In lagoon sediments pellets formed by fecal pellets are abundant associated with some wackstone and packstone. Presence of predominant peloids, oncoids, bioclastic wackestone and packstone associated with calcareous algae and benthic foraminifera also indicating lagoonal environment, which deposited under low energy. The source of the fine-grained carbonate sediment, oncoids and pellet in lagoons are largely calcareous algae and mollusks living in the lagoon with coarser bioclastic accumulation from them (Flugel, 2004, and Reading, 1996). Presence of the predominance large oncoids and aggregate grain indicate deposition of the rock unit under restricted subtidal lagoon environment. Therefore, the dolomitized bioclastic wackestone (MFL1) and oncoidal grainstone (MFT2), in the lower and upper part of Hagere-Selam sections are the common typical carbonate sediment deposited in this low energy restricted lagoonal shelf environment.

6.2.1C. Carbonate sand bodies

Carbonate platform are shallow marine depositional environment of carbonates sediment under high, agitated energy. The shoal facies was deposited in a platform margin sub-environment that separates open marine from restricted environment. This is the typical facies of platform margin carbonate sands or ooilitic sand barrier deposits. The non-skeletal grains in these facies are well sorted, well-rounded, tangential, radial ooids, lithified forming horizontal beds of grainstone and some grains surrounded with micrite envelops, which is the result of reworking by wave and tidal currents at these margins. Additionally, this carbonate bodies is characterised by presence of planar cross bedding, symmetrical ripple mark structure and by presence of abundant skeletal and non-skeletal grains. Ooids reflects physical and chemical conditions of the depositional environments in marine settings and they are proximal for high water energy. Stronger or more frequent currents are mostly common in shallower depth. The loose sediments are removed by the wave current and allochems become well sorted and with continued abrasion better rounded (Prothero and Schwab, 2014). Thus bioclast, ooids and peloidal grainstones are usually occurring around high energy areas such as shoals and beaches in inner part of ramp or shelf environment (Burchette and Wright, 1992; Reading, 1996). Their formation shows that presence of barrier or islands at these margins because, barrier is a wave-dominated environment, where wave action reworks marine sediment such as bioclastic material and other sediment due to long shore drift to form a barrier (Nichols, 2009). Therefore, the silicified coral framestone (MFS1), skeletal-sandy packstone-grainstone limestone (MFS2), oolitic grainstone (MFTS3), peloidal-oolitic-skeletal grainstone (MFS4), ferruginous oolitic grainstone (MFS5) and fine-medium crystalline sandy dolomite (MFS6), which are obtained from the lower, middle and upper carbonate unit of the Hagere-Selam and Wukro section, which comprises sand size ooids, abundant detrital quartz grain and some amounts of skeletal grain embedded within sparry calcite and microcrystalline calcite cement.

6.2.1D. Open plat form system

This open marine depositional system occurres in the middle and outer part of proximal to distal part of mid ramp environment. This is characterized by moderate and low energy, which is affected by storm current that located proximal to organic build up environments.

These open marine sediment are deposited in the proximal mid ramp environment between fair weather wave base and storm wave base, which are characterized by open marine skeletal grain such as stromatoporoids, sponge spicule, *Nautiloculina oolithica*, *Alveosepta jaccardi*, *Pseudocyclammina lituus*, echinoderms, storm related coquina, bivalve shell, *Lenticulina* sp and abundant sedimentary structures including hummocky cross stratification and presence of abundant trace fossil association such as *Thalassinoides* isp and *Diplocraterion*. Therefore, the bioclastic wackstone (MFO1), bioclastic speculite wackstone (MFO2), stromatoporoidal wackstone (MFO3), bioclastic rudstone (MFO4), bioclastic mudstone (MFO5), skeletal-grain dominated grainstone (MFO6), skeletal-grain dominated packstone (MFO7) and skeletal -

intraclast-peloidal wackstone (MFO8) are the main characteristics of the open marine environment, which range from proximal mid ramp up to deep outer ramp environment.

6.3. Facies model for the carbonate succession of study sections

Ramp environment was recognized by Ahr (1973) as a major type of depositional setting for carbonate rock unit and was used as an alternative to the carbonate shelf. A carbonate ramp is a gently sloping surface with a slope of less than 1^{o} from near costal land extends up to basin. Ramps slope gently range from intertidal to basinal depths, with no major change in gradient. On a ramp environment, the shallow water carbonate units pass gradually to offshore into deeper and deeper water then into basinal sediments. Therefore, on the basis of detailed sedimentological and paleontological informations, the vertical and lateral distribution of the facies types, and comparison with similar modern facies, the carbonate successions indicate deposition in a homoclinal carbonate ramp setting (Figure 7.4).

6.3.1. Inner ramp facies

The inner ramp is the shallow zone above fair weather wave base (FWWB), which is most affected by wave and/or tidal action above 60 m water depth, or it is distributed between upper shore face (beach or lagoon shoreline) and fair weather wave base. It ranges from the shallow subtidal to the intertidal zone. 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 deposits (Ahr, 1973; Burchette and Wright, 1992). Ramps with mesotidal regimes will show a mixture of beach barrier, tidal inlet, lagoon and tidal flat deposition. Hence, agitation of carbonate sediment in shallow nearshore water results in a shoreface facies of carbonate sand bodies with skeletal debris and ooids formed in the shallow water forms bioclast and oolitic carbonate sand shoals is characteristics of this inner ramp environment. From the present study area, the silicified coral framestone (MFS1), skeletal-sandy packstone-grainstone (MFS2), oolitic grainstone (MFS3), peloidal-oolitic-skeletal grainstone (MFS4), ferruginous oolitic grainstone (MF5) and fine-medium crystalline sandy dolomite (MFS6) are the main microfacies of the carbonate unit obtained from the lower and middle part of the Hagere-Selam, lower and upper part of Wukro stratigraphic section, which are deposited under high energy of inner part of the ramp environment. Additionally, the protected lagoonal settings of the inner ramp are characterized by dolomitized bioclastic wackstone (MFL1) and oncoidal grainstone (MFL2) and sediments deposited in restricted tidal flat environment of near continent including the very fine crystalline dolomite (MFT1), unfossiliferous lime mudstone (MFT2) and siliciclastic mudstone (MFT3) are the common type of inner ramp facies type, which are deposited in restricted shallow marine environment (Figure 6.4).

6.3.2. Middle ramp facies

A middle 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). Most of the carbonate units of the study area are deposited in this middle ramp environment. The bioclastic wackstone (MFO1), bioclastic-speculite wackstone (MFO2), stromatoporoidal wackstone (MFO4), skeletal grain dominated grainstone (MFO6), skeletal grain dominated packstone (MFO7) and skeletal-intraclast-peloidal wackstone are the main components of this proximal to distal mid ramp environment.

Additionally, presence of storm related coquina, open marine invertebrate and foraminifera fossil, hummocky cross stratification and trace fossil association such as *Thalassinoides* isp and *Diplocraterion parallelum* support the interpretation of these microfacies in mid ramp environment between FWWB and SWB (Figure 7.4).

6.3.3. 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). Deeper parts of the ramps characterized predominantly by low energy setting. The bioclastic mudstone (MFO5) and some marl unit are the main facies type of outer ramp environment. Generally the overall facies associations of carbonate deposits of the area are showing a low gradient of depositional dip from inner-ramp domains (tidal flat, lagoon and shoreline high-energy shoals deposits) to mid-outer ramp areas of foreshoal to offshore low energy deposits. From this the vertical nature of these microfacies suggests cyclic deposition. Therefore, the Hagere-Selam and Wukro section are similar in vertical and lateral facies type, which display a complete-deep to shallow environment between open marine and shoal environment with scattered lagoon deposit in the lower and tidal environment in the upper part of the Hagere-Selam section, whereas the Messobo section is characterized by shallow marine of low energy tidal flat with some loggonal environment in the lower and middle part of the Messobo section and the upper part is dominated totally by homogenous deposits of tidal flat environment without any shoal environment.

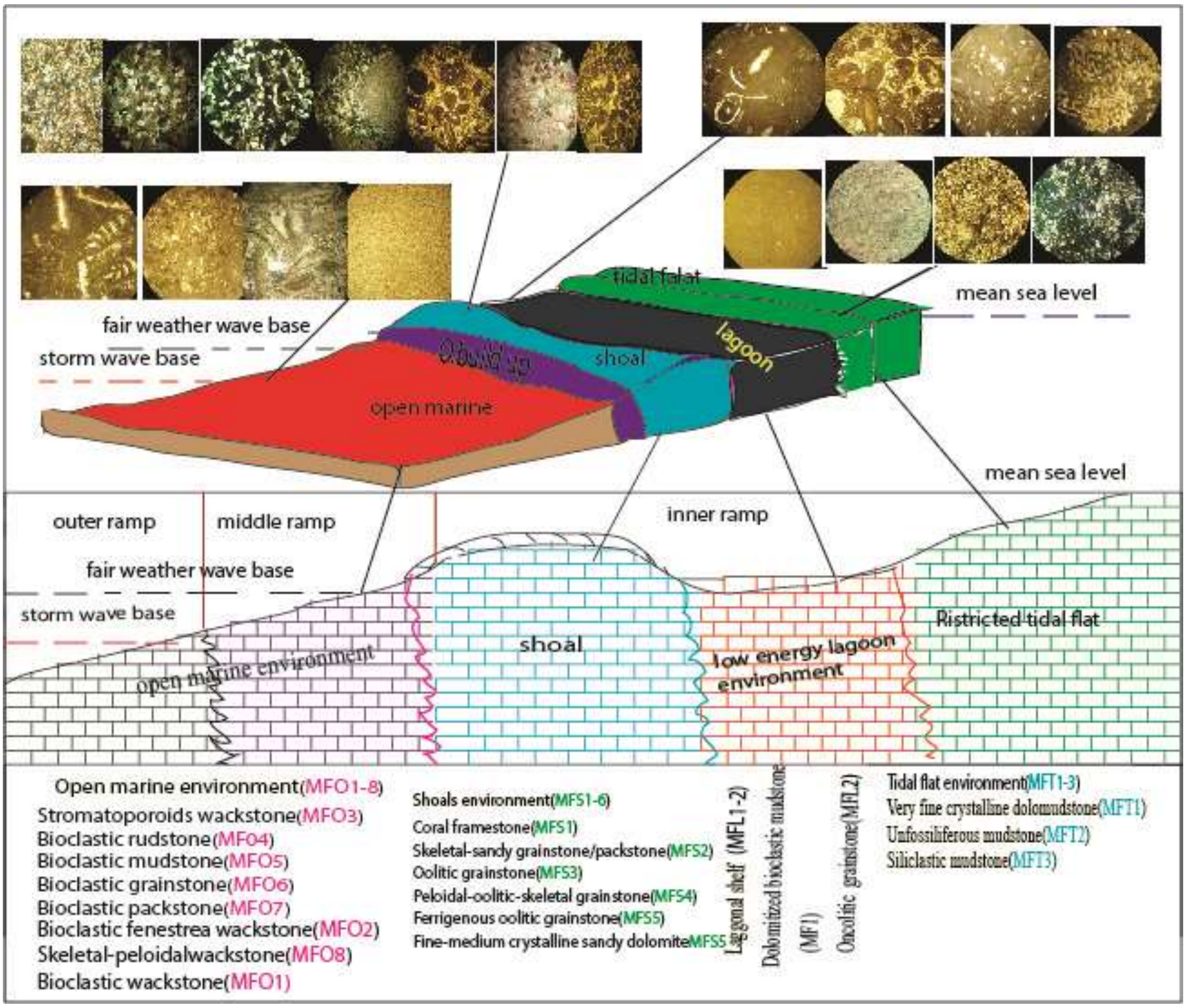


Figure 6.4: *Idealized depositional model for the carbonate rock unit of the study sections (not to scale), showing the depositional setting as a gently sloping ramp that is episodically affected by storm events.*

6.4. Correlation

6.4.1. Intrabasinal correlation

The large-scale spatial and temporal stratigraphic stacking patterns within a sedimentary basin fill are believed to be results of the interaction between regional to global causal factors and modifying by local environmental processes (allogenic and autogenic factors, *sensu* Beerbower (1964, cites as Dawit Lebenie, 2010). An important requirement for distinguishing the relative roles of these factors is to link the appropriate process with an observation and correlate with similar observations from different regions that occurred within equivalent time periods. Numerous inner to middle to outer ramp deposit of the carbonate stratigraphic unit have been identified in the measured three sections. The main purpose of this section is to correlate these carbonate stratigraphic units among the measured three sections and to demonstrate the overall similarities and differences in facies associations and depositional systems of age equivalent units. This correlation is based on detailed biostratigraphy and lithostratigraphy information obtained from the measured three sections in combination with previously published and unpublished information. Accordingly, this section deals with intrabasinal correlation of the three stratigraphic section and the enclosed depositional systems that build the various portions of the basin fill as they were recognized from the three vertical profiles described and discussed in the previous section. The basin wide stratigraphic correlation is illustrated based on a detailed constructed stratigraphic log of the Hagere-Selam, Messobo and Wukro section from the present study and Tsebela, Beite Christian Michael and Agula section previously studied sections (Figure 7.5), in which it referred to as the western-southeastern and northeastern segment. The West-East-North segment connects the Tsebela, Beite Christian Michael and Hagere-Selam section from west by crossing the Mekelle to the Messobo in the north and Wukro and Agula section from northeast.

6.4.1A. Lithostratigraphic correlation

The carbonate rock unit of the study sections are characterized by oolitic, sandy, fossiliferous, coqunoid, dolomitic, karastified, bedded mudstone and marly limestone associated with some stylolite, cross bedded, ripple mark, erosional, bioturbated and bedded sedimentary structures in the Hagere-Selam and Wukro section whereas, the Messobo section is characterized by mudstone, bedded micritic limestone, fossiliferous and bioclastic wackstone to packstone rock unit. Additionally, with the help of a detailed field investigation and microfacies analysis of the studied thin section in terms of depositional environment, the carbonate succession of the measured sections deposited in shoal and open marine environment with some tidal and lagoonal environment dominantly in the Hagere-Selam and Wukro section whereas, in the Messobo section it represent as low energy tidal and lagoon marine environment with lack of high energy shoal environment, which indicate shallowing of the sea toward southeast of the basin. Therefore, the measured three sections are considered to be correlative lithologically and biostratigraphcally especially in the Hagere-Selam and Wukro section (Figure 7.5).

6.4.1B. Biostratigraphic correlation

In addition to lithologically the carbonate units of the study sections are correlated on the base of different index fossils, which are obtained from the different part of measured sections. Based on predominant benthic foraminifera including *Alveosepta jaccardi*, *Pseudocyclammina lituus*, *Nautiloculina oolithica*, *Valvilina* sp, crinoids, echinoids, coral, stromatoporoids, *lenticulina* sp, bivalve, sponge spicule from the Hagere-Selam and Wukro section the carbonate unit of the two section are correlated; However, due to presence of some *Alveosepta jaccardi*, *Pseudocyclammina lituus*, bivalve, gastropods and abundant trace fossil association including *Diplocraterion* and *Thalassinoides* the carbonate unit of the Messobo section should be correlated with Hagere-Selam and Wukro section.

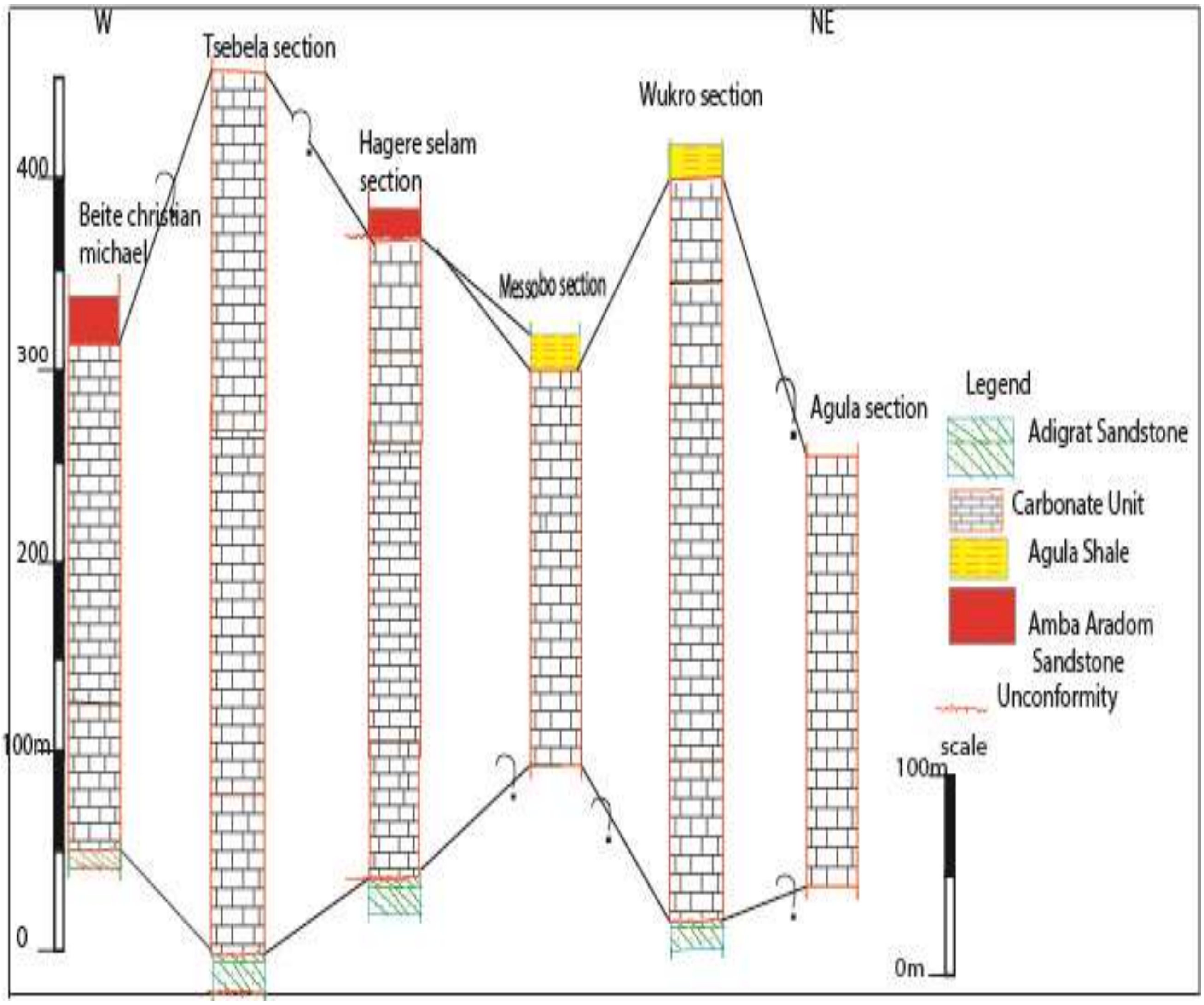


Figure6.5: *A cross-section illustrating intra basinal correlation of the study three sections (Hagere-Selam, Wukro and Messobo) with previous study section (Tsebela, Beite Christian Michael, and Agula) recorded on the base of a detailed field data and microfacies and paleontological data recorded with the carbonate unit.*

6.4.2. Regional correlation

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

Mekelle Outlier in the Northern Ethiopia (Tigrai province), the Blue Nile Basin in central Ethiopia and Ogaden basin in the Southeast and Arabian platforms are correlated.

Therefore, this section deals with regional correlation of the carbonate unit with other contemporaneous stratigraphic unit in the central, southeastern Ethiopia, Eretria, Yemen and Saudi Arabia using biostratigraphy and lithostratigraphy (Figure 7.6).

In the **Blue Nile basin** of central Ethiopia, up to 420 m thick carbonate successions of shallow marine origin, also named 'Antalo Limestone Formation' are described by Russo et al. (1994) and Atnafu (2003), which conformably overlying the Gohatsion Formation and can be divided into three parts (lower, middle and upper limestone).

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

The middle part (200 m thick) consists of highly fossiliferous interbedding of marly limestone and marls. Presence of ammonite fauna (e.g., *Lithacoceras* sp. and *Subplanites spathi*) in association with brachiopods (e.g., *Terebratula pelagica and Nanogyra*) and other infaunal siphone feeders (*Anisocardia*, *Venilicardia*, *Somalirhynchia somalica, and Zeillleria latifrons*) suggests a shelf to open marine environment (Russo et al., 1994, and Atnafu, 2003).

The upper part (50 m thick) comprises planar laminated oolitic and reefal limestone, which was interpreted to indicate the return of shallow water conditions. Based on presence of oolitic bars, coral patches, offshore and more protected facies inshore, this unit is interpreted to represent a shallow water environment similar to the lower unit. Presence of *Pfenderina* sp. and *Nautiloculina oolithica* at the base of the limestone unit used to assign a Callovian age (Russo et al., 1994) and presence of *Kurnubia palestiniensis*, *Parurgonina caelinensis*, *Conikurnubia* sp. and *Salpingoporella annulata* at the top of the unit indicates a Kimmeridgian age (Turi et al., 1990, Atnafu, 1991, 2003, Russo et al., 1994).

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

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

In the **Eretria** the Adailo (Antalo) Limestone is one of the major carbonate unit, which underlain by Merbet (Adigrat) Sandstone and overlain by Upper Sandstone forms pockets of sandstones that have been preserved from erosion. The Antalo Limestone is exposed over a large area in the Danakil and is characterized by compact, partly shelly, fossiliferous and layered limestone. In the **Sana'a basin of Yemen**, found at north direction from Ethiopia country, according to the works of Al-Thour (1997); Simmons and Al-Thour (1994) (as cited in Bosellini, 2001); Al-Wosabi and Al-Mashaikie (2006), and Hadden (2012) the Jurassic carbonate deposits known by 'Shugra Formation' are conformably overlaying the lower clastic deposits known by the name' Kohlan Formation', which is correlated with Adigrat Sandstone Dawit Lebenie (2010) and unconformably underlies the upper clastic deposits called Tawilah Group, which is correlated with Agula Shale of the Mekelle Outlier (Figure 7.6). These Jurassic carbonates, Shugra Formation, are varying between 410-520 m in thickness and subdivided into three formations. From base to tops as: **1**) Al- Khothally Formation (Late Callovian-Oxfordian age): it consists of sandy, ooilitic, oncolitic, peloidal, partly dolomitic, massive, thick limestone. **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 and **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 limestone. In detail correlations, from the Amran Group of Sana'a area, the Al- Khothally Formation (Late Callovian-Oxfordian age) is correlative with the carbonate unit of the study area using biostratigraphy and lithostratigraphy.

In the central Saudi Arabia the carbonate succession of **Hanifa Formation** with thickness up to 140 m, which underlain by Tuwaiq Mountain and overlain by Jubaila Formation were recorded (Hughes et al., 2008). A sequence stratigraphic framework of the Late Jurassic (Oxfordian**)** Hanifa Formation as its exposure in central Arabia consists tabular cross bedded quartz-peloidal-skeletal grainstone, cross-bedded skeletal-peloidal grainstone, bioturbated foraminifer's wackstone, and oncolitic rudstone and coral-stromatoporoid-bioherms.

This formation contains abundant skeletal grains including echinoderms, brachiopods, *Nautiloculina oolithica*, *Alveosepta jaccardi*, *Kurnubia palestiniensis*, *Thalassinoides*, coral and stromatoporoids. A ramp depositional model having normal open-marine conditions is proposed and characterized by a high-energy inner ramp shoreline, which is deposited in high energy and due to presence of the index fossil discussed above the Hanifa Formation assigned as Oxfordian age Fallatah (2017). Therefore, the carbonate succession of the Mekelle Outlier is correlated with the Hanifa Formation of the Saudi Arabia.

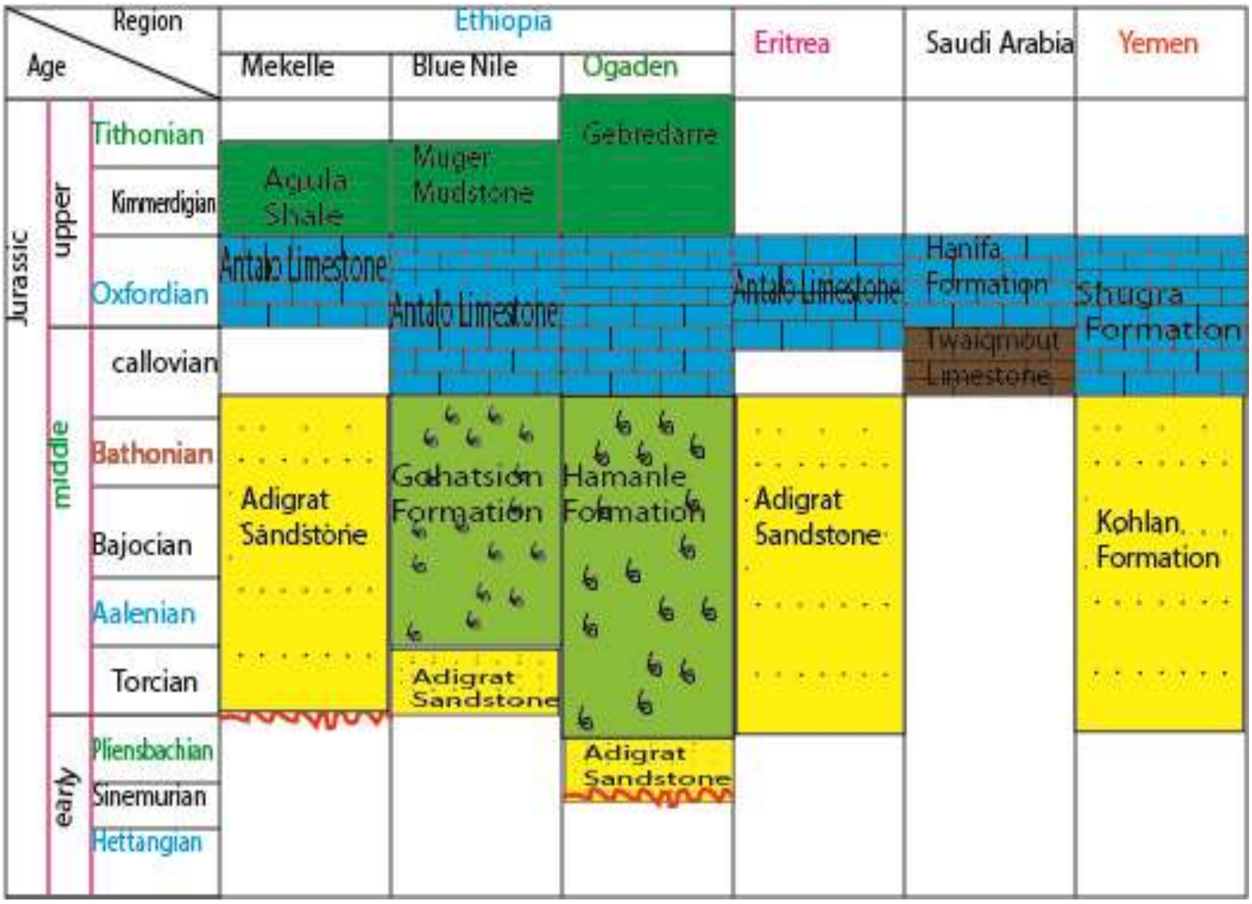


Figure 6.6: *Regional correlation of the carbonate rock unit throughout Ethiopian basin (Mekelle, Blue Nile, and Ogaden), Saudi Arabia, Yemen, and Eretria. Sources: Mekelle (from present work for carbonate unit and Levitte, 1970; Beyth, 1972a& b; Bosellini et al., 1997), Blue Nile (Russo et al., 1994), Ogaden (Abbate et al., 1974; Worku and Astin, 1992; Hunegnaw, 1998; Shigut , 1998) & Yemen (Al- Thour,1997; Simmons & Al-Thour 1994; Al-Wosabi & Al-Mashaikie,2006; Hadden, 2012), Saudi Arabia (cited in Fallatal,2017).*

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The study area is situated in Northwestern Plateau (NWP), Mekelle Outlier locally in the Hagere-Selam, Messobo and Wukro stratigraphic sections. The facies analysis and paleontology study on the study sections provides the first detailed understanding of the carbonate rock unit exposed along the western (Hagere-Selam), southeastern (Messobo) and northeastern (Wukro section) margin of the Mekelle Outlier. This study provides the depositional environment interpretations, age determination, a detailed microfacies analysis, intrabasinal and regional correlation with time equivalent carbonate rock unit. Pre-fieldwork, detailed fieldwork and laboratory description and analysis were the main methodology implemented to achieve the stated research problem and the objective of the present study.

Stratigraphy: The carbonate successions in the Hagere-Selam, Messobo and Wukro sections consist of different rock units including thin-thick bedded limestone, mudstone-grainstone, fossiliferous, coquinoidal and mixed siliciclastic-carbonate limestone with different skeletal grains (bivalves, echinoderms, gastropods, brachiopods, sceleractinian coral, stromatoporoids, sponge spicule and benthic foraminifera) and various sedimentary structures and different trace fossil associations that range in age from Oxfordian-Kimmeridgian.

Microfacies analysis: Based on a detailed field investigation and laboratory description and analysis of 65 thin-section and 26 productive dry marl sediment, 19 different facies type are recognized. These microfacies are grouped into four facies association including restricted tidal flat environment, laggonal shelf, high energy shoal and proximal-distal open marine environments. These facies type are identified with the help of different skeletal and non-skeletal grain, sedimentary structures, relative abundance of micrite and sparry calcite.

Diagenetic features: The major diagenetic processes affecting the carbonate sediments and rocks are micritization, dissolution, cementation, compaction, neomorphism, dolomitization and the replacement of carbonate grains and matrix by non-carbonate minerals (silicification).

Depositional environment: Based on a detailed field investigation, petrographic description and analysis and paleontological investigation the carbonate succession of the measured sections are deposited in homoclinal part of ramp environment, which includes the shallow inner ramp of near coast tidal environment, restricted laggonal and high energy shoal, and proximal mid to outer ramp open marine environment.

Correlation: Finally, the carbonate unit of the measure sections are correlative with previously studied carbonate unit in the Mekelle Outlier and regionally with some time equivalent carbonate rock unit including Antalo Limestone of Blue Nile basin, Urandab Formation of Ogaden basin, Antalo Limestone of Eretria, Hanifa Formation of central Saudi Arabia and Shuqra Formation of Yemen based on biostratigraphy and lithostratigraphy.

7.2. Recommendation

Based on the present study results the following recommendations are forwarded:

Since the carbonate unit of the Mekelle Outlier is the least investigated in terms of microfacies analysis, depositional environment interpretation, diagenetic features, paleontology especially in micropaleontology, the first recommendation goes in strengthen this study in other sections of the Mekelle Outlier with a detailed field investigation and more sampling in order to a obtained a complete picture of the Mekelle Outlier.

Additionally, the structural evaluation of the Mekelle Outlier is controversy in evolution. Therefore, in order to solve this confusion, a detailed geodynamic evolution, paleobiogeography, detailed geophysical and structural study is worthy recommended.

Finally, these carbonate units are significant economic importance because, they act as reservoir rocks for petroleum, as aquifer for ground water and can be useful for agricultural and industrial purposes. Hence, detailed sedimentological, paleontological, stratigraphical and diagenetic features studies of the carbonate rock units in the Mekelle Outlier are dully recommended.

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Appendix one

Plate I

Idealized sequence of Standard Facies Belts (from Wilson, 1975)

re-drawn by Nassir Alnaji (2002)

Belt	BASIN	OPEN SEA SHELF	DEEP SHELF MARGIN	FORESLOPE	ORGANIC BUILD UP	WINNOWED EDGE SANDS	SHELF LAGOON OPEN CIRCULATION	RESTRICTED CIRULATION SHELF & TIDAL FLATS	EVAPORITES ON SABKHAS - SALINAS
Diagrammatic cross section & Facies Number	1	2	3	4	5	6	7	8	9
Facies	a) Fine Clastics b) Carbonates c) Evaporites	a) Carbonates b) Shale	Toe of Slope carbonates	a) Bedded fine grain & slumps b) Foreset debris & lime sands c) Lime mud mases	a) Boundstone b) Crust on accumulations of debris lime mud, bindstone c) Bafflestone	a) Shoal lime sands b) Islands w. dune sands	a) Lime snad bodies b) Wackestone-mudstone areas, bioherms c) Areas of clastics	a) Bioclastic wackestone, lagoons and bays b) litho-bioclastic sands in tidal channels c) Lime mud-tide flats d) Fine clastic units	a) Nodular anhydirte & dolomite on salt flats. b) Laminated evaporites in ponds
Lithology	Dark shale or silt, thin limestones (starved basin); evaporite fill w. salt	Very fossiliferous lime-stone interbedded with marls; well segregated beds.	Fine grain limestone; cherty in some cases.	Variable, depending on water energy upslope; sedimentary breccia and lime sands	Massive limestone-dolomite	Calcarenitic-oolite lime sand or dolomite	Variable carbonate and clastics	Generally dolomite and dolomitic limestone	Irregularly laminated dolomite and anhydrite, may grade to red beds
Color	Dark brown, black, red	Gray, green, red, brown	Dark to light	Dark to light	Light	Light	Dark to light	Light	Red, yellow, brown
Grain type and depositoinal texture	Lime mudstone; fine calcisiltites	Bioclastic and whole fossil wackestone; some calcisiltites	Mostly lime mudstone with some calcisiltites	Lime silt and bioclastic wackestone-packstone; lithoclastics of varying sizes	Boundstones and pockets of grainstone; packstone	Grainstones well sorted; rounded	Great variety of textures; grainstone to mudstone	Clotted, pelleted mudstone & grainstone; laminated mudstone; coarse lithoclastic wackestone in channels	
Bedding and sedimentary structure	Very even mm lami-nations; rhythmic bedding; ripple cross lamination	Thoroughly burrowed; thin to medium; wavy to nodular beds; bedding surfaces show diastems	Lamination may be minor; often massive beds; lenses of graded sediment; lithoclasts & exotic blocks. Rhythmic beds	Slump in soft sedi-ments; soleset bedding; slope bioherms; exotic blocks	Massive org. structure or open framework with roofed cavities; Lamination contrary to gravity	Medium to large scale crossbedding; festoons common	Burrowing traces very prominent	Birdseye, stromatolites, mm lamination, graded bedding, dolomite crusts on flats. Cross-bedded sand in channels	Anhydrite after gypsum; nodular, rosettes, chickenwire, and blades; irregular lamination; carbonate caliche
Terrigenous clastics admixed or interbedded	Quartz silt & shale; fine grain siltstone; cherty	Quartz silt, siltstone, & shale; well segregated beds	Some shales, silt, & fine grained siltstone	Some shales, silt, & fine grained siltstone	None	Only some quartz sand admixed	Clastics and carbonates in well segregated beds	Clastics and carbonates in well segregated beds	Windblown, land derived admixtures; clastics may be very important units
Biota	Exclusively nektonic-pelagic fauna preserved in abundance on bedding planes	Very diverse shelly fauna preserving both infauna & epifauna	Bioclastic detritus derived principally from upslope	Colonies of whole fossil organisms & bioclastic debris	Major frame building colonies with ramose forms in pockets; in situ communities dwelling in certain niches	Worn and abraided coquinas of forms living at or on slope; few indigenous organisms	Open marine fauna lacking; mollusca, sponges, forams, algae abundant; patch reefs present	Very limited fauna, mainly gastropods, algae, certain foraminifera & ostracods	Almost no indigenous fauna, except for stromatolitic algae