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Addis Ababa University

College of Natural Sciences

School of Earth Sciences

Paleontology and Biostratigraphy of the Jurassic Carbonate Unit,
Lemi -Alem Ketema Section, Central Ethiopia



A Thesis submitted to the School of Earth Science of Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
(Paleontology and Paleoenvironment)

by

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May 2023

Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL SCIENCES
SCHOOL OF EARTH SCIENCES



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Ketema Section, Central Ethiopia

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By signing this declaration, I confirm that the thesis that I created is entirely original, hasn't been used to earn a degree at another college or university, and has been properly referenced.

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Acknowledgment

Before anything else, I would like to express my profound appreciation to Debre Birhan University and the School of Earth Sciences at Addis Ababa University for giving me the chance to get my master's degree and for sponsoring the research project. My second-deepest thanks are extended to my adviser Dr. Balemwal Atnafu, for his encouragement, support, and follow-up as well as for his insightful comments and suggestions. I want to express my gratitude and respect to Dr. Balemwal Atnafu for his assistance and helpful technical conversation; it meant a lot to me. Next, I want to thank my colleague Dr. Damenu Adefris from the bottom of my heart for his invaluable advice. Additionally, I want to thank the Ethiopian Geological Survey laboratory staff for making it possible to complete the thin section study on time. My friend Gemechu Getaneh gave me a lot of encouragement when I was conducting research in the field. I am unable to adequately convey how grateful I am for your vital assistance from the start to finish of this thesis work. My family deserves praise for giving me strength and continuous encouragement while I'm working on the project. Last but not least, I want to thank Jemma's government, citizens, and staff for allowing me to work there and for their support.

Contents

Declaration..... iii

Acknowledgment iv

ABSTRACT..... ix

CHAPTER ONE 1

1. Introduction 1

 1.1 General Background..... 1

2. Description of the study area..... 2

 2.2. Physiography..... 3

 2.3. Population and Settlement 4

3. Statement of the problem 4

4. Objectives..... 5

 4.1 General Objective 5

 4.2 Specific Objectives 5

5. Research questions 5

6. Significance of the study 5

7. Organization of this thesis 5

CHAPTER TWO 7

2. Regional geological setting of the Mesozoic sedimentary basins and their stratigraphy 7

 2.1 Introduction 7

2.2 General stratigraphy of Abay Basin..... 7

 2.2.1 Basement Rocks 8

 2.2.2 Pre-Adigrat Sandstone 8

 2.2.3 Adigrat Sandstone..... 9

 2.2.4 Gohatsion Formation 9

 2.2.5 Antalo Limestone 10

 2.2.6 Mughher Mudstone 11

 2.2.7 Debre Libanose Sandstone 12

 2.2.8 Volcanic Rocks..... 12

2.3 Age of Ethiopian Carbonate Units..... 13

CHAPTER THREE 14

3. Materials and methods 14

3.1 Methods 14

 3.1.1 Petrographic analysis 14

 3.1.2 Microfossil Preparation..... 14

3.2 Tools, Materials and Chemicals 15

3.3 Data collection	15
3.3.1 Sample Collection.....	16
CHAPTER FOUR	17
4. Lithofacies and Microfacies Analysis of Lemi- Alemketma sections.....	17
4.1 Lithofacies of Lemi- Alemketma sections	17
4.2 Antalo Limestone	18
4.2.1 Fossiliferous marl	18
4.2.2 Coquina	18
4.2.3 Bioclastic limestone	19
4.2.4 Micritic limestone	20
4.2.5 Alternated marl-limestone.....	21
4.2.6 Bioclastic limestone– clayey marl alternations.....	22
4.3 Mughar Mudstone	23
4.4 Debre Libanos Sandstone	24
4.5 volcanic Rocks	24
4.6. Petrographic Descriptions.....	25
4 .7. Microfacies Analysis.....	26
4.7.1 Introduction	26
4.7.2 Microfacies Type 1	26
4.7.3 Microfacies Type 2	27
4.7.4 Microfacies Type 3	27
4.7.5 Microfacies Type 4	28
4.7.6. Microfacies Type 5	28
4.7.7 Microfacies Type 6	29
4.7.8 Microfacies Type 7	30
4.7.9 Microfacies Type 8	30
4.7.10 Microfacies Type 9	31
4.8 Diagenesis	31
4.8.1 Micritisation	32
4.8.2 Compaction	32
4.8.3 Dissolution	33
4.8.4 Neomorphism	33
CHAPTER FIVE	34
5. Paleontology and Biostratigraphy of Lemi-Alemketma section	34
5.1 Introduction	34
5.2 Ostracoda.....	34

5.3 Chlorophyta (green algae)	35
5.4 Foraminifera.....	36
5.5 Echinoderms	50
5.6 Bivalves	50
5.7 Brachiopods	51
5.8 Gastropods.....	51
CHAPTER SIX.....	52
6. Discussion.....	52
6.1 Introduction	52
6.2 Biostratigraphy of Lemi- Alemketma Section	52
6.3 Facies association of study area.....	57
6.3.1 Lagoonal environment (FA1).....	57
6.3.2 Shoal environment (FA2)	58
6.3.3 Tidal Flat Environment (FA3)	58
6.3.4 Open marine environment(FA4).....	58
6.4 Paleoenvironmental model.....	59
6.5 Correlation	60
CHAPTER SEVEN	62
7. Conclusion and Recommendation	62
7.1 Conclusion.....	62
7.2 Recommendations	62
References	64

List of figure

Figure 1.1 Location map of the study area	2
Figure 1.2. Physiographic map	3
Figure 1.3. Dem	4
Figure 2.1 Abay basin chrono-litho stratigraphy (after Dawit, 2014 and Wolela, 2008).	8
Figure 3.1 photographs show the laboratory instruments.....	15

Figure 4.1. Field photographs of fossiliferous marly limestone.....	18
Figure 4.2. Field photographs of coquina.....	19
Figure 4.3. Field photographs of Bioclastic limestone.....	20
Figure 4.4. Field photographs of micritic limestone.....	20
Figure 4.5. Field photographs of marl- limestone alteration.....	22
Figure 4.6. Field photographs of bioclastic limestone and clayey marl.....	23
Figure 5.1. Bivalve mold and cast fossils in the study area.....	50
Figure 5.2. Gastropod cast fossils in the study area.....	51
Figure 6.1. Faunal distribution of foraminifera taxa in the Lemi section.....	55
Figure 6.2. Faunal distribution of foraminifera taxa in the Alem-ketma section.....	57
Figure 6.3. Schematic diagram showing paleodepositional environments for carbonate units in Jemma sections.....	59
Figure 6.4. Vertical distribution of microfacies types in Jemma sections.....	60

ABSTRACT

A study was conducted on the Jurassic carbonate unit in two sections along the Lemi–Alem ketema road across the Jemma River in the Blue Nile Basin. The unit hasn't been researched in terms of age, facies, depositional environment, and calcareous microfossil studies. Therefore, this study aimed to assess the biostratigraphy, facies, paleontology, and depositional environment of the carbonate unit in the Jemma sections. Detailed morphological descriptions, laboratory preparations, microscopic examinations and comparisons of the reported specimens with varieties of photos, field observations and measurements were used to achieve the objectives. Based on lithofacies analysis the carbonates in the study area were categorized into six types. They are fossiliferous marly limestone, coquina, bioclastic limestone, micritic limestone, marly limestone, and clayey marl. Based on petrographic examination nine microfacies were identified. These are bioclastic mudstone, bioclastic wackstone, non-laminated homogenous mudstone, bioclastic rudstone, pelbiopackstone, coated and rounded bioclastic packstone, bioclastic packstone, sandy limestone and marl-limestone alteration. The paleontological investigation of the studied sections indicated that the carbonates are abundant in macro and micro-fossils which provide information for biostratigraphic and paleoenvironmental interpretations. For biostratigraphic interpretations, index fossils of foraminifera assemblages; *Kurnubia palastiniensis* (Kp), *Anchispirocyclina lusitanica* (Al), *Kurnubia wellingsi* (Kw), *Nautiloculina oolithica* (No), *Alveosepta jaccardi* (Aj), *Pfenderella arebica*(Pa), *Siphovalvulina variabilis*(Sv), *Valvulina lugeoni* (VI), *Redmondoides lugeoni* (RI), *Conicokurnubia orbitoliniformis* (Co) and, *Everticyclammina virguliana*(Ev)were used. One index fossil from dasyclad green algae, *Clypeina jurassica* (Cj) was used. According to the index fossils, the Jemma sections of Antalo limestone are dated from Callovian to late Tithonian. Microfacies association indicates a depositional environment of the carbonate unit was deposited in a range of environments, that are open marine, shoal, lagoon, and tidal flat.

Keywords: Biostratigraphy, Blue Nile Basin, Depositional environment, Index fossil Lithofacies, Microfacies.

CHAPTER ONE

1. Introduction

1.1 General Background

Consequences of complex extensional stress following the initiation of the Gondwana Rifts and formation of the Neotethyan passive margin along the current day margin of eastern Africa resulted in the 2600 m thick Paleozoic-Mesozoic sedimentary succession in the Blue Nile basin (Lebenie and Bussert, 2009). These sedimentary rocks are classified into eight stratigraphic units (Assefa, 1981). According to Dawit and Bussert (2009), the early intracratonic basin creation during the late Permian is represented by the Pre-Adigrat I, Pre-Adigrat II, and Pre-Adigrat III formations which indicated sedimentation under a variety of depositional settings, including floodplain, crevasse-splay, aeolian, and alluvial flood plains. Adigrat Sandstone formation unconformably overlies the Pre-Adigrat units formed in an alluvial and fluvial environment (Dawit and Bussert, 2009). Gohatsion formation and Antalo limestone which are laid above the Adigrat sandstone respectively are believed to represent the transgressive stage and the East African craton's earliest flooding, which was related to the rifting and subsidence of the African continental margin (Russo *et al.*, 1994).

Three subcategories were applied to the Antalo Limestone unit (Russo *et al.*, 1994). A 180 m thick succession of burrowed mudstone is present at the base and grading into oolitic, quinoidal limestone, intercalated marl, massive limestone, and sporadic corals. A 200 m sequence of marly limestone and marls with fossiliferous interlayering occurs in the middle. The upper portion is characterized by a planar bedded oolitic and reefal limestone that is 50 meters thick. Each sub-unit reflects a different stage of sea transgression. The unit was categorized into three environments based on lithofacies and biofacies associations the bottom group depicts a shallow shelf to an open marine environment, the middle group represents a shelf to an open marine environment, and the top group represents a return to a shallow marine environment. The Neo-Tethyan Sea retreat is represented by the Debre Libanos Sandstone and Mughher Mudstone formations, which changed the sedimentation type from marine to continental (Assefa, 1991). The flood basalts cover the top of the basin where volcanic activity is considered to be a result of Arabia apart from eastern Africa and the Red Sea formation (Abbate *et al.*, 2015).

The Jemma River valley contains a section of the Mesozoic sedimentary sequence exposed in the Abay River Basin. Mesozoic rocks in Jemma sections comprise 600m thick terrigenous, orthochemical and calcareous sedimentary rocks unconformably overlain by Tertiary volcanic rocks. The sedimentary stratigraphic units are conformably overlying each other. The thin-section investigation of the carbonate samples was characterized, analyzed and interpreted using standard micropaleontological research and petrographic analysis. This work contributes by defining a precise age, depositional environment, paleontology, and facies properties of the carbonate rock in the specified stratigraphic place as well as the lateral and vertical linkages between the examined region and adjacent basin sections.

2. Description of the study area

The area lies within latitude 9°48'-10°00'N and longitude 38°50'-39°00' E and it is accessible by an asphalt road running 78 km over the Addis-Debre Markos highway and by another 72 km all-weather gravel road that drives from Muketuri to Alem Ketema. To the east and west of the main north-south road, the mapped area is not accessible by any motor vehicle.

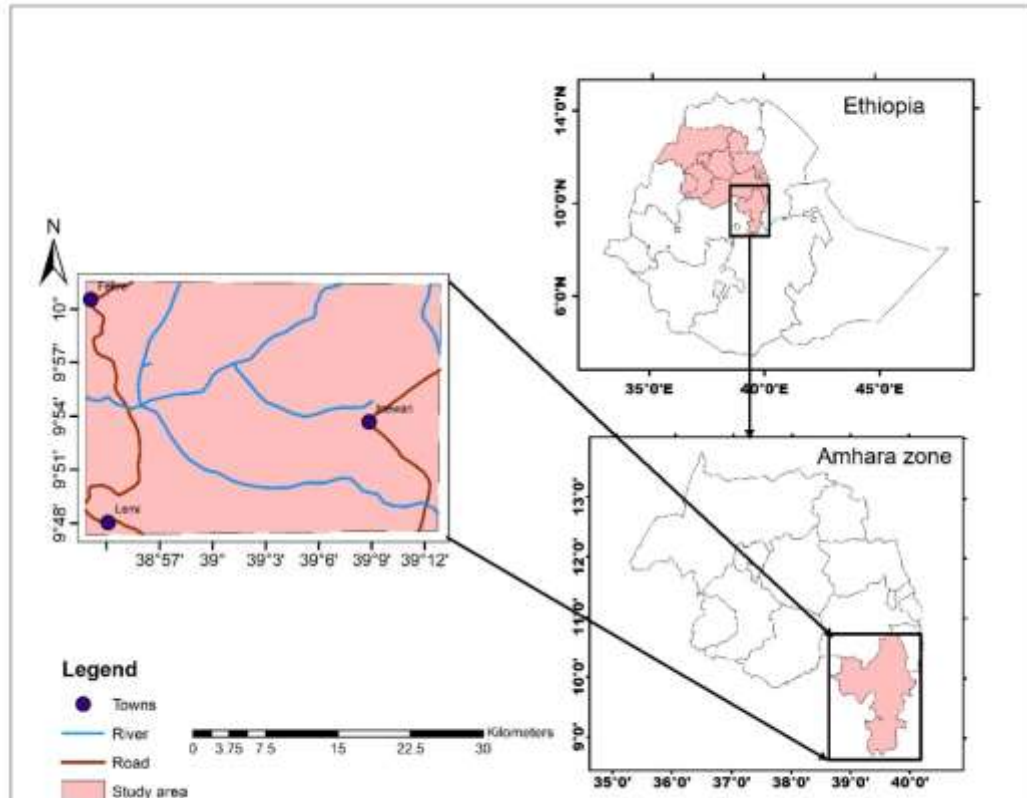


Figure 1.1 Location map of the study area

2.2. Physiography

Jemma River Valley is located in Central Ethiopia. The area is characterized by steep escarpments, deep and shallow valleys and stream channels. On the north and south, it is surrounded by cliffs that are at least 100 m high. There are elevations of 2650 m in the town of Lemi, 2150 m in Fetra, and 1300 m at the Jemma river bed next to the bridge, among other places. The River drains the region westward into Abay and its tributaries drain north-eastward and south-westward to join Jemma. During the rainy seasons, they are submerged, while during the dry season, they are hardly visible. Most streams follow potential fractures and weak zones with parallel to sub-parallel drainage patterns. According to the National Atlas of Ethiopia, the major rainy season runs from June to September with an average annual rainfall of 700 mm. The highest temperature is recorded in May, while the average yearly temperature is 20°C. The rocks are visible, and there is little vegetation cover.

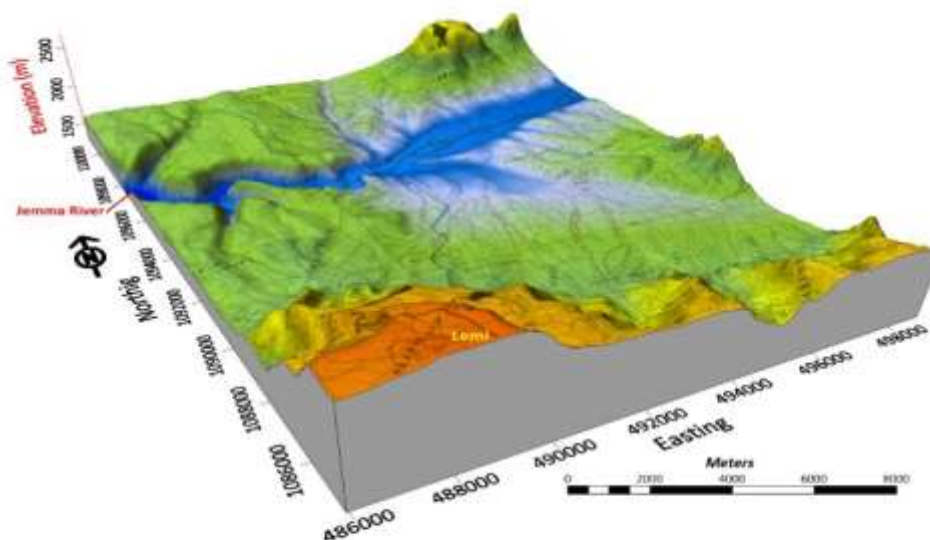


Figure 1.2. Physiographic map

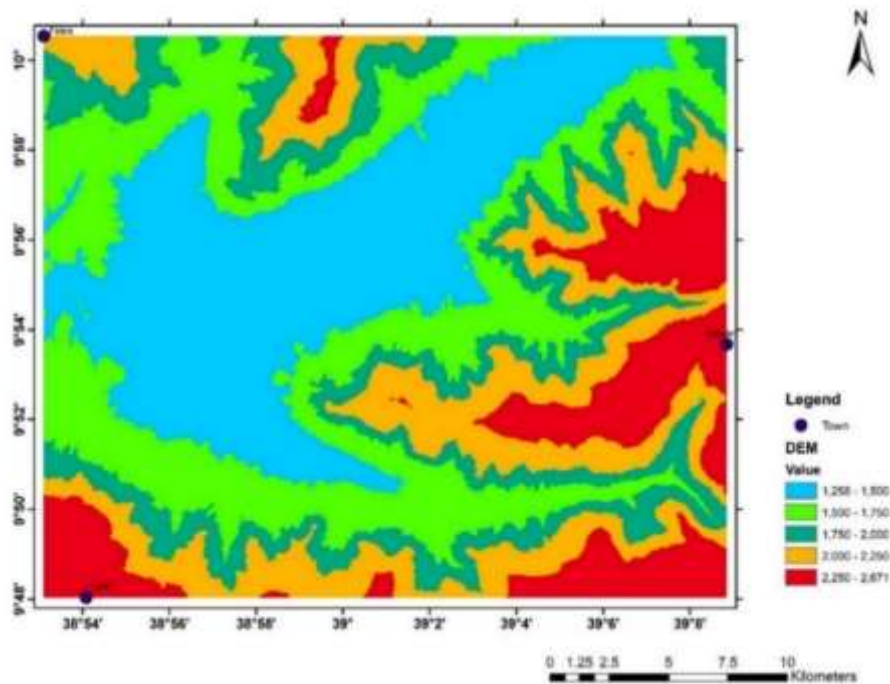


Figure 1.3. DEM Map

2.3. Population and Settlement

The three cities that are closest to the research sections are Alem Ketema, Fetera, and Lemi. Small villages can be found sporadically throughout the study area, which is sparsely populated.

3. Statement of the problem

On the road from the town of Lemi to Alemketema via Jemma River, the limestone is well exposed. However, it has not been thoroughly examined in terms of age, facies, depositional environment, and calcareous microfossil analyses. There is a paucity of information on the biostratigraphy and depositional environment of Jurassic carbonate units in Jemma sections. Previous studies depicted that, the age of Antalo limestone in the three sedimentary basins has been determined to range from the early Callovian to the early Valanginian using various index fossils. The index fossils used for dating are Nannofossils, foraminifers, ammonites, brachiopods, calpionellids and calcareous green algae. Therefore, the present study is conducted to assess the biostratigraphy and depositional environment of carbonate units in the Jemma sections using index fossils and facies associations.

4. Objectives

4.1 General Objective

The main objective of the research is to study biostratigraphy and reconstruct the depositional environment of the carbonate unit in the Lemi-Alemketma section.

4.2 Specific Objectives

- To establish the stratigraphy in the study area (from the basal Jemma exposures to Lemi-Alemketema towns).
- To identify and describe the micro and macro fossils in the Jurassic carbonate unit.
- To establish the age of carbonate sedimentary units found in the area.
- To reconstruct the depositional environment.

5. Research questions

The research questions examined and answered in the thesis are

1. What is the age of the carbonate unit in the Lemi-Alemketma sections?
2. What was the depositional environment of carbonate units in the Lemi-Alemketma sections?

6. Significance of the study

The Lemi-Alem ketema limestone deposit has not been studied from various palaeontological and sedimentological perspectives. This study provides first-hand information about the age, paleontology, depositional environment and facies characteristics of carbonate rock in the chosen stratigraphic sections. It also enables observation of vertical and horizontal relationships between studied sections and the whole of basin stratigraphy. The collected sedimentological data can be helpful for future resource studies and intra-basinal correlation.

7. Organization of this thesis

There are seven chapters in the thesis. Introductions to the topic under study, description of the study area, statement of the problem, objectives, and significance, are provided in Chapter one. The regional geological context and general sedimentary basin evolution are reviewed in chapter two of this paper. In chapter three, a methodology that is used in the thesis is noted. In chapter four the lithology, sedimentary structure, and fossils of the study area that were discovered during the fieldwork are described in detail and petrographic description and microfacies analysis are discussed. In chapter five, the paleontology and biostratigraphy of

Jemma are described. Chapter six discusses biostratigraphy, depositional environments of carbonate units of the section, and the correlation made. Chapter Seven included a conclusion and a suggestion for additional research.

CHAPTER TWO

2. Regional geological setting of the Mesozoic sedimentary basins and their stratigraphy

2.1 Introduction

After the breaking up of the Gondwana supercontinent and the subsequent formation of the Permian Triassic Rift System, Ethiopian sedimentary history began with sedimentation in a fault-controlled sedimentary environment (Gani *et al.*, 2009). In the Ogaden, Abay, Mekele, Gambella, and Southern Rift basins, sedimentary rocks predominately cover much of the Ethiopian basins (Russo *et al.*, 1994; Bosellini *et al.*, 2001; Gani *et al.*, 2009). According to Bosellini (1992), three significant transgression-regression cycles were placed in East Africa throughout the Mesozoic. The first significant transgressive regression episode coincided with the Gondwanaland middle to late Jurassic split. The first transgression and retreat cycle is responsible for the majority of the Mesozoic deposits in the Abay basin (Russo *et al.*, 1994). The Ferfer and Mustahil formations in the Ogaden basin were formed by the second transgression event that occurred during the Aptian. During the late Cretaceous to mid-Eocene, the Ogaden Basin also experienced the third transgression cycle, Taleh, and Kerker formations which are formed as a result of it (Geleta, 1997).

2.2 General stratigraphy of Abay Basin

The Abay Basin's current sediment exposure spans about 120,000 km² along the Abay River and its tributaries (Russo *et al.*, 1994; Wolela, 1997). According to Gani *et al.* (2009), Neoproterozoic basement rocks and volcanic rocks are unconformably in contact with Mesozoic sedimentary rocks (Fig.2.1). The Paleozoic sandstones are unconformably overlain by the lower sandstone also known as Adigrat sandstone and conglomerate, sandstone, siltstone, and mudstone make up the majority of sandstone (Russo *et al.*, 1994). It is in contact with underlying gypsum and shale units known as the Gohatsion formation (Assefa, 1991), which gradually grades to carbonates that are rich in marine fossils and marl, shale, and mudstone. According to Assefa (1991), the evaporative unit and oceanic carbonate unit are assumed to reflect early Jurassic transgressions. Succeeding the marine carbonate are mudstone and sandstone units referred to as Mugher mudstones (Assefa, 1991), which consist of dolomite, gypsum, and shale as their substrata and contain a few layers of siltstone and shale and a higher level of alternating fine-grained sandstone and mudstone. The Debre Libanose sandstone overlain on the Mugher mudstones and is composed of sandstone with thin beds of mudstone, shale, and conglomerate (Assefa, 1991).

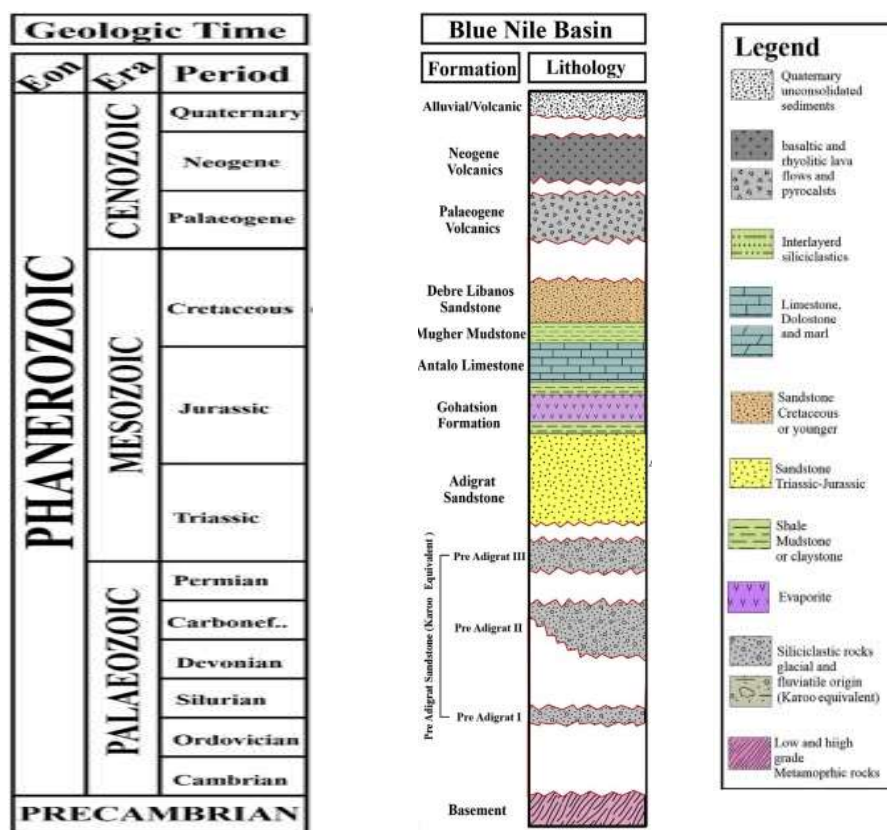


Figure 2.1 Abay basin chrono-litho stratigraphy (after Wolela, 2008 and Dawit, 2014).

2.2.1 Basement Rocks

Ethiopian bedrock constitutes a combination of metamorphose quartz, feldspar, schist, gneiss, migmatite, and intrusive rocks dating back to the Precambrian era and the beginning of the Paleozoic (Assefa, 1991). According to Ayalew *et al.* (1990), the basement age is Neoproterozoic, with an age range of 850 to 550 Ma.

2.2.2 Pre-Adigrat Sandstone

According to Lebenie (2010), the earliest sedimentary succession above the crystalline basement rock in the Abay Basin is indicated as Pre-Adigrat I. The group of rocks consists of cross-bedded, poorly sorted, medium to coarse grain, white sandstones and conglomerates. Informally, Pre-Adigrat I, Pre-Adigrat II, and Pre-Adigrat III stratigraphic units were defined by Lebenie (2010). Pre-Adigrat I is the bottom portion which is composed of poorly sorted, massive to cross-bedded, medium- to coarse-grained white sandstones and conglomerates. Whereas Pre-Adigrat II unconformably overlies either the Precambrian basement or pre-Adigrat I. Furthermore, its lower part is made up of lateral accretion deposits, floodplain and playa-lake mudstones which point to a meandering river-floodplain environment where the deposition may have taken place. Finally, Pre-Adigrat III is the upper portion and is

composed of three successive cycles of sandstone bodies that are crevasse splay deposits (Lebenie, 2010).

2.2.3 Adigrat Sandstone

Adigrat Sandstone is also familiar as lower Sandstone. The unit has been dated based on several bio-stratigraphic data and comparisons with overlying deposits that provide fossil dates (Russo *et al.*, 1994). The strata rest unconformably on Precambrian rock, except in some places (Mohr, 1962; Kazmin, 1975; Assefa, 1991; Wolela, 1997). This sandstone unit is widely distributed in three basins. It covers vast areas of the Abay Basin, forming vertical cliffs at Fincha, Dejen, Gendbret-Jeldu, Gohatsion, Amuru-Jarty, and Ejere (near the Jimma River Bridge). This formation is composed mostly of continental clastic conglomerate, sandstone, siltstone, mudstone, and carbonaceous material. In this basin, this layer is predominantly represented by sandstones that are texturally and compositionally immature to mature except for leaf imprints and fragments of wood, these formation fossils are rarely preserved (Wolela, 2008). According to paleontological evidence from carbonaceous strata, this Sandstone formation is Triassic to Early Jurassic in age (Wolela, 1997).

2.2.4 Gohatsion Formation

Abbei Beds was the formation's earlier name (Mohr, 1962). Assefa (1981) later changed its name to correspond with the name of the type section near the town of Gohatsion in central Ethiopia. Liassic to late Bathonian age assigned to Gohatsion formation based on indicative foraminifera (Assefa, 1981). The Gohatsion formation has been described as exhibiting annular intercalation between evaporite units and fine-grained siliciclastic, leading to various classifications for this formation (Russo *et al.*, 1994; Gani *et al.*, 2008). The Gohatsion formation of the Abay Basin characterizes a composite transitional sedimentary scheme in a semi-dry Peritidal sedimentary environment overlain with Antalo limestone (Russo *et al.*, 1994). The unit comprises a stratified thin average of 20 cm limestone and an upper interval of alternating layers of limestone and gypsum beds. The gray-bedded limestone is sparsely fossil-rich with burrows such as *Talassinoids*, *Planolite*, and *Ophiomorpha* features of gypsum bed mottled texture, interbedded with layers of glauconitic mudstone and rare thin layers of sandstone. The alternating gypsum and limestone on top of the unit indicate repeated drying and flooding of the evaporitic basin (Gani *et al.*, 2009).

2.2.5 Antalo Limestone

The term Antalo limestone was originally assigned by Blanford (1870), to the limestone unit in northern Ethiopia. Subsequently, it was extended to the limestone unit of the Blue Nile basin. Ethiopian Jurassic limestone has different names depending on the type of vicinity across the country. Antalo limestone formation in Abay (Assefa, 1991; Russo *et al.*, 1994), Mekele (Blanford, 1869; Beyth, 1972), and south-eastern plateau, Hammanlei formation, Urandab formation, Gabredare formation and Garbaharre formation in Ogaden Basin (Migliorini, 1956) was coined by the above-mentioned authors.

A 420 m thick carbonate sequence was described by Russo *et al.* (1994), which conformably lies above the Gohatsion formation and was divided into three parts. The lower part (180 m thick) is composed of burrowed mudstone that grades upwards into coquinoidal limestones and oolitic limestones beside or deprived of an intercalated layer of marl beds, then into massive limestone with scattered patches of corals, nerineids and stromatoporoid of a shallow water environment were inferred. According to Russo *et al.* (1994), the lower faunal content and sedimentological characteristics of the limestone suggested a complex palaeoenvironment with associated oolitic bars and small patches of coral. In contrast, the silty-limestone fauna is characterized by the presence of *eulamellibranchiate* in faunal siphon feeders and epifaunal suspension feeders, typical of continental shelf areas where silty or fine-grained sediments prevail. Marl layers are abundant in *Gryphea*, which is a reclining inhabits of a muddy substrate where euryhaline water conditions prevail.

The central part (200 m thick) consists of highly fossiliferous interbedding of marly limestone, limestone and marls. The presence of ammonite fauna (*Lithacoceras sp* and *Subplanites spathi*) in association with brachiopods (*Terebratula pelagica* and *Nanogyra*) and other underwater siphon feeders (*Anisocardia*, *Venilicardia*, *Somalirhynchia somalica*, *Zeillleria latifrons*) suggests that a shelf to open marine environment and an upper part (50 m thick) consists of planar-bedded oolitic and reefal limestones that have been interpreted to indicate a return from shallow-water conditions (Russo *et al.*, 1994). The age of the Antalo limestone in three basins is dated between the early Callovian to early Valanginian. The Age has been given by different authors using various index fossils, such as Nannofossils, Foraminifera, and Ammonites. The Antalo limestone in the Mekelle Basin which was aged between the Callovian and Tithonian provides the first systematic descriptions of multiple

species of calpionellids, benthic foraminifera, and calcareous green algae (Adefris *et al.*, 2021).

On the other hand, Brassier and Geleta (1993) documented the presence of the universally occurring planktonic foraminifera *Globigerina oxfordiana* from the eastern part of the Ogaden Basin beside the underline of the Uarandab formation (i.e., above the Hamanlei limestone). Approaching the Callovian/Oxfordian boundary between *Squadron* and *G. oxfordiana* has a long stratigraphic development, punctuated by several acmes at different time intervals. Brassier and Geleta (1993) found that *G. oxfordiana* is related to two dinoflagellate taxa *Systematophora areolate* and *Belodinium asaphum* were widespread and ranged from late Titonian to early Valanginian.

At Dejen, the mid-Callovian to early Kimmeridian age was recognized due to the presence of ammonites (Jain and Schmerold, 2021). Antalo limestone formation is re-dated using ammonite records from two Jurassic basins. Ogaden Basin was dated in the late Callovian to early Titonian and the Mekelle Basin was dated in the late mid-Oxfordian to early Kimmeridgian. The irregular echinoid *Pygurus meslei* was first described in late Jurassic limestone in the Mugher and represented a long-ranging species (from upper Callovian to upper Tithonian) (Radwańska and Jain, 2020).

Conversely, Santos *et al.* (2021) elaborated that, the primary palynological assembly from the top part of the limestone formation in Abay Basin and the age ranges of several important taxa together with other biostratigraphic data, suggest that the top part of the limestone formation is from the Late Kimmeridian to the Late Titonian.

2.2.6 Mugher Mudstone

The top sandstone has been divided into the Mugher Mudstone and the Debre Libanos by Assefa (1991). Then, he described the lithostratigraphy and the official naming of the two units in each type location (Debre Libanos and Mugher River). Based on polymorphs Goodwin *et al.* (1999), determined the Tithonian age of the Mugher mudstone. Transitional environments to low-energy meandering river depositional systems are assumed to be the range of Mugher Mudstone depositional environments. According to Assefa (1991), a depositional environment of Mugher mudstone is characterized by brackish to fluvial siliceous environments. Such environments contain a succession of subordinate subtidal and

lagoonal deposits and fluvial sandstones by the lens system of both fine-grained deposits and coarse clasts. In addition, Schmidt and Werner (1998), advocated the influence of marine water-influenced brackish lakes and pools and considered the Mughher mudstone itself to be a coastal plain deposit.

2.2.7 Debre Libanose Sandstone

Debre Libanos Sandstone is also recognized as Upper Sandstone. The unit was aged from the late Jurassic to the early Cretaceous based on its stratigraphic relationship to the overlying and underlying units due to the absence of accessible biostratigraphic or radiochronological data (Assefa, 1991; Russo *et al.*, 1994). According to Wolela (2004), the sandstone pinches out toward the Abay River Gorge and reaches a thickness of 280 meters close to Lemi, 200 m along the Jemma River, 230 m in Debre Libanose, and 312 m in the Mughher River portion. Dune-scale cross-bedding and horizontal stratification can be seen in the upper sandstone. Locally, there are noticeable pebble layers. However, it is uncommon to see narrow channels with lateral accretion surfaces. It is believed that this unit's overall depositional environment is continental alluvial to fluvial. A horizon of whitish-pink sandstone, made primarily of sandstone with sedimentary structures and representative considerable hiatus, marks the boundary between the upper sandstone and volcanic rocks of the early to late Oligocene (Gani *et al.*, 2009).

2.2.8 Volcanic Rocks

The flood basalts cover the top of the basin where volcanic activity is considered to be a result of Arabia apart from eastern Africa and the Red Sea formation (Abbate *et al.*, 2015). The volcanic rocks that cover much of Ethiopia are divided into five major provinces based on lithological development, activity type and frequency, volcanic center, and eruption ages (Abbate and Sagri, 1980). These include northern plateau volcanoes; southern plateau volcanoes; Somali Plateau volcanites; Afar volcanites and Main Ethiopian Rift Valley (MER) volcanites (Abbate *et al.*, 2015). Assefa (1991) indicated there are thick massive flood lavas chiefly of basalt, unconformably overlying the Paleozoic and Mesozoic sediment. The quaternary volcanic activity caused the eruption of ~ 300 m thick basalt. Sheet joints and vesicles with a diameter of 2 mm to 1.5 cm are present in the volcanic rocks, which are very young and barren of columnar joints. Red to brown palaeosol layers of ~ 30 cm thickness indicate several eruption pulses (Gani *et al.*, 2009).

2.3 Age of Ethiopian Carbonate Units

The first genera recorded from the Dejen area of the Blue Nile Basin were investigated using yielded ammonites (Jain and Schweiger, 2022). *Oxylenticeras sp.* and the dimorphic pair of *Djurjuriceras cf. sinuosum tavera* were reported. Recently, Jain *et al.* (2021), recorded two calpionellid zones, *Bonetinae* and *Chitinoideids* which are primitive Calpionellids subzone allocated to the upper Tithonian recorded from the Kurar section of Dejen in the Blue Nile Basin. The existence and domination of *Nannoconus* and *Polycostella beckmannii* also established the extensive Tithonian age for the top part of the Antalo Limestone formation (Jain and Singh, 2019). Adefris *et al.* (2021), provided the first systematic descriptions of several species of benthic foraminifera, calcareous green algae and calpionellid from the Antalo limestone of the Mekelle Basin. The authors used index fossils for age dating, such as various *Kurnubia*, *Pseudocyclamina lituus*, *Alveosepta jaccardi* and dasyclad green algae by assigning a Callovian - Tithonian age. The study of Santos *et al.* (2021), identified palynomorphs that provided the initial palynological record of the upper Jurassic of Ethiopia, and one of the few paleobotanical data from the northeast of Gondwana. Age ranges of about significant taxa together with other biostratigraphic data suggested a Late Kimmeridgian-Late Tithonian age for the upper part of the limestone.

CHAPTER THREE

3. Materials and methods

To achieve the research objectives, standard methods, and different field and laboratory equipment outlined in various literatures were adopted. The following methods and resources described hereafter were used for this thesis work.

3.1 Methods

3.1.1 Petrographic analysis

For microfacies investigations, thin sections were carried out on 21 carbonate rock samples obtained from the two sections. By utilizing a petrographic plane polarizing microscope in a petrology lab, petrographic research on these 21 thin sections was conducted. The identification between the skeleton and non-skeletal grains, cementing material, minerals and mineral constituents in hand specimens of carbonate rocks was difficult. To describe all the characteristics of carbonate rocks, petrographic thin-section studies were used. Later, based on Dunham's (1962), and Folks' (1962), classification of carbonate rocks were done, then standard microfacies categories of (Flügel, 1982, 2004, 2010) and (Wilson, 1975) were employed for describing and interpreting observed carbonate microfacies types.

3.1.2 Microfossil Preparation

Unconsolidated 50-75 g of sediment samples were collected and soaked with 50 ml of concentrated 30% H₂O₂ (Fig. 3.1C) and 100 ml of water and the mixture was left for three days in a beaker (Fig. 3.1A). Then, after three days, the mixture was sieved using various US standard sieves and the sediment was washed with water. The washed sediments were left till they dried and the dried samples were gently spread on a black picking tray and scanned with a binocular reflecting microscope (Fig. 3.1D). Finally, a cavity slide microfossil card was filled with identifiable microfossils of ostracods and foraminifers which were picked using a tiny paintbrush (Fig. 3.1B).



Figure 3.1 photographs show the laboratory instruments A) beaker B) sieves and brush C) H₂O₂ D) Binocular microscope

3.2 Tools, Materials and Chemicals

Various chemicals such as hydrogen peroxide (H₂O₂) and dilute HCl (10%); tools including sieves, a binocular microscope, fine brush, Geological hammer, lens, GPS, petrographic microscope, a topo-sheet of Lemi area (1:25,000 scale), images from Alaska satellite for DEM of Jemma were used for the research. Moreover, other materials for instance notebook with labeling markers, a beaker, a digital camera, and software like Arc GIS and Adobe Illustrator were used for analysis and interpretation.

3.3 Data collection

Both field and laboratory data which are essential to the present study were collected. For instance, the collection of limestone and marl samples, macrofossil collection, describing and making a stratigraphic log for each stratum and capturing photographs of outcrops were

conducted in the field while microfossil extraction and thin section examination were done in the laboratory.

3.3.1 Sample Collection

In December 2022 G.C., a collection of rock samples in the chosen stratigraphical sections was completed. Representative samples of the carbonate units were collected at the research location by following road and river cut exposures. Rock samples had been gathered for petrographic examinations, whereas marl samples were gathered for the extraction of microfossils. Nearly 25 samples of carbonate rock, 8 samples of marl, and macro-invertebrate fossils of bivalves and gastropods were collected.

CHAPTER FOUR

4. Lithofacies and Microfacies Analysis of Lemi- Alemketma sections

4.1 Lithofacies of Lemi- Alemketma sections

Carbonate rocks make up 20–25% of the total sedimentary rock types in the geological record (Flügel, 2011). Over 50% of the minerals in limestone are CaCO_3 . Dolomite is broken down into calcite dolomite (50-90% dolomite), which contains more than 50% $\text{CaMg}(\text{CO}_3)_2$, and dolomite itself (Flügel, 2011). Although comprehensive separation of carbonate rocks is best carried out in a laboratory, it may also be done in the field with 10% diluted HCl (limestone react well while dolomite exhibit little to no reactivity).

The Jemma River valley contains a section of the Mesozoic sedimentary sequence exposed in the Abay River Basin. Mesozoic rocks in Jemma sections comprise 600m thick terrigenous, orthochemical and calcareous sedimentary rocks unconformably overlain by Tertiary volcanic rocks. The sedimentary stratigraphic units are conformably overlying each other. According to several studies, the Antalo Limestone is 420 m thick. The bottom unit of the Abay sequences is not shown in the research region. Hence, it is impossible to calculate the real thickness of the limestone unit in the Lemi-Alem ketema section. About 150 m of Jemma limestone have been measured in the Lemi section and 250 m in the Alem ketema section; the limestone unit thickness in the two measured areas is not equal. Where the lower part of Antalo limestone is buried and not revealed. The stratigraphy from the basal Jemma exposures to Lemi-Alemketema town was established. At the bottom of the section along the Jemma River fossil-bearing marly limestone is exposed with strata ranging from (26 - 130 cm) thick alternating with coquina unit with strata ranging from (6 - 15 cm) thick, and bioclastic limestone with strata ranging from (15- 26cm) thick, micrite limestone also exposed around the Jemma river, with a total thickness of about 27 m. Alternated marl-limestone lies above micritic limestone embedded between 20-30 cm thin layers of marl and limestone, with a total thickness of 16 m. The upper part of the section bioclastic limestone-clayey marl alternations is present in four layers. The top layer is 60 cm thick bioclastic limestone, the second layer is 120 cm thick clay-rich calcareous marls, the third layer is 60 cm thick bioclastic limestone, and the fourth bed is 1 m thick marly limestone.

4.2 Antalo Limestone

In the present study, carbonates are mainly composed of slightly fractured and fractured limestone intercalated with thin layers of marl. carbonates mainly appear light grey-grey and yellow. In some places, weathering changed its color to darker. Limestone forms mostly cliffs, although some outcroppings show gentle slopes. The contact with the underlying mudstone formation is gradual.

4.2.1 Fossiliferous marl

The fossiliferous marl along the Jemma River was recorded with strata ranging from 26 -130 cm thick, alternating with coquina and bioclastic limestone. It is exposed by the Jemma River and hill cuts. The fossils found within this unit are dominated by shell fragments of bivalves. The rock samples were taken from this layer of the limestone unit which was coded AK-14, AK-16, AK-18, AK-23, and, AK-26 the layer from which the samples were obtained from the Alemketma section is indicated in Fig 4.1.



Figure 4. 1 Field photographs of fossiliferous marly limestone A) Alternated with bioclastic limestone B)Fossiliferous marly limestone along the Jema river

4.2.2 Coquina

This coquina unit is exposed in the lower Jemma River, with strata ranging from 6 - 15 cm thick, alternating fossil-bearing marly limestone and bioclastic limestone. It is exposed by the Jemma River and hill cuts. This rock unit is characterized by light gray, dark color, and coarse skeletal grains composed of entirely fossil shells of bivalves and marine invertebrates. The rock samples were taken from this layer of the limestone unit which were coded AK-20, AK-21A, and AK-21B, The layer from which the samples are taken from the Alemketma side is shown in Fig 4.2.



Figure 4.2. Field photographs of coquina A) Alternated coquina and biomicritic limestone B) Coquina consists entirely of fossil shells of bivalves and marine invertebrates

4.2.3 Bioclastic limestone

This rock unit is exposed by river and hill cuts in the lower part of the Jemma River with a thickness of about 15 – 26 cm. The bioclastic carbonate unit is found over the fossiliferous marly limestone and coquina. It is characterized by a brownish-weathered color and light grey to dark fresh color. In some exposures, gastropods were observed (Fig 4.3 B). The rock samples were taken from this layer of the limestone unit which were coded AK-15 and AK-9, AK-3 and shown in Fig 4.3.

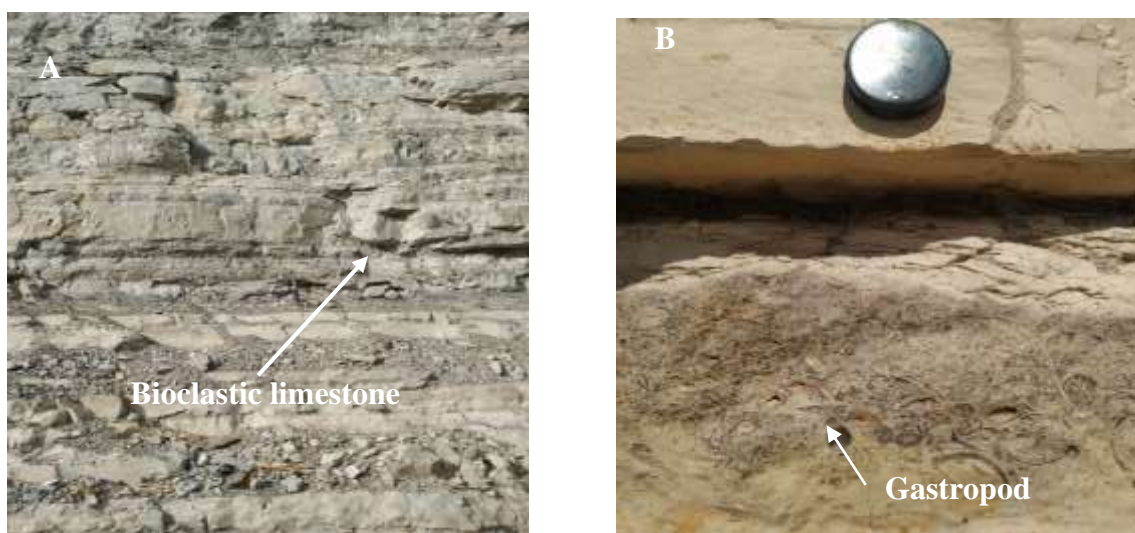


Figure 4.3. Field photographs of Bioclastic limestone A) Alternated bioclastic limestone with fossiliferous marly limestone and coquina B) Bioclastic limestone containing gastropods

4.2.4 Micritic limestone

The micrite limestone exposed around the Jemma River, with a total thickness of about 27 m, has a fine-grained texture consisting of thin to thick layers (44 cm - 6 m) and is light gray to gray fresh color and black weathered color. Several foraminiferal faunas have been identified from thin-section analyses of rock samples taken from this layer of the limestone unit. Bioturbation, diagenesis (recrystallization) and dissolution occurred in different sedimentary processes as shown in (Fig 4.4; D; Fig 4.4; B, Fig 4.4; C), respectively. The upper part of this succession contains layers that are bioclastic limestones where the rock samples were taken from the micritic beds of the limestone unit obtained from Lemi (Fig 4.4 A) and samples were coded as LM-1, LM-2, LM-3, LM-5A, and, LM-5B.

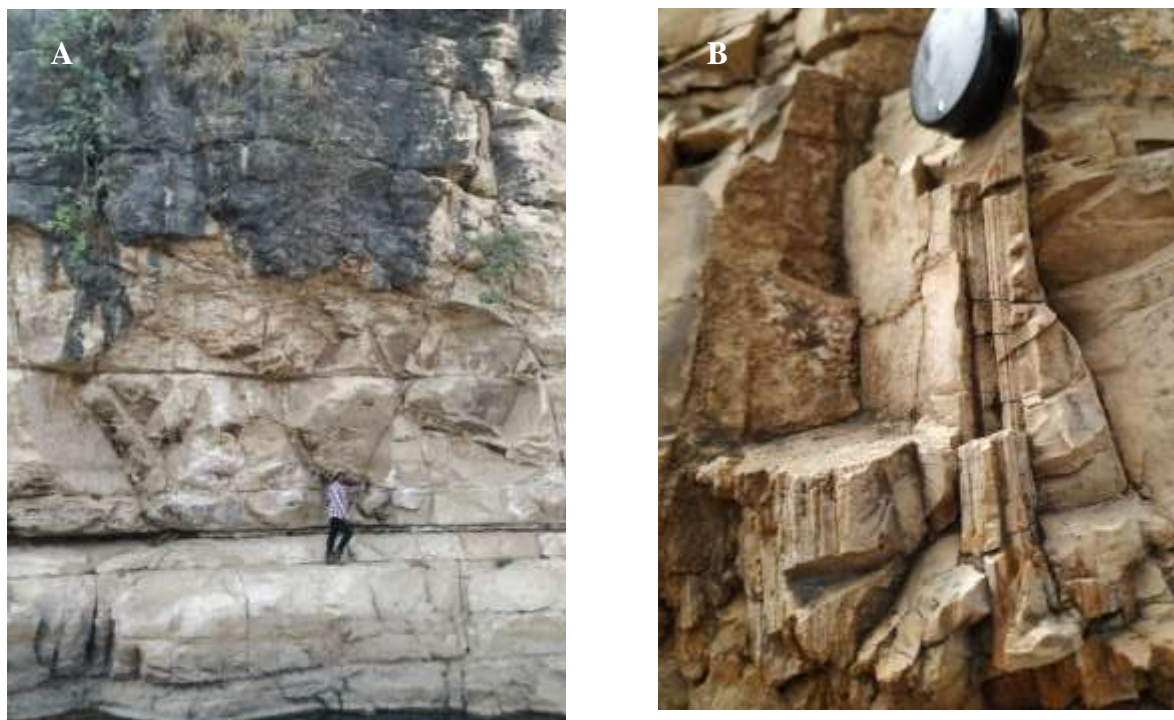
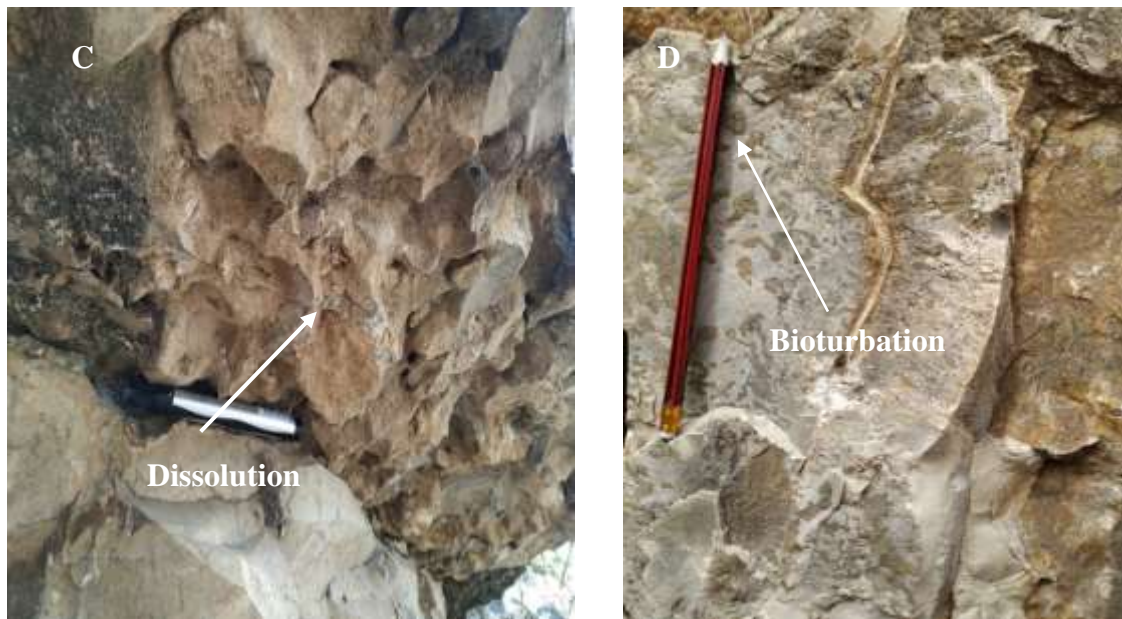
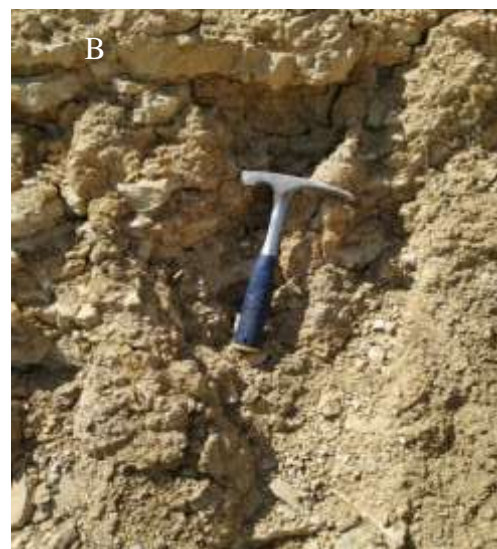


Figure 4. 4 Field photographs of micritic limestone A) Micritic limestone around Jemma River B) Recrystallization C) Dissolution D) Bioturbation



4.2.5 Alternated marl-limestone

This layer is embedded between 20-30 cm thick layers of marl and limestone, with a total thickness of 16 m, cut by the road. It is light grey, white, brownish, and dark in color, characterized by. In the current study area, the marl-limestone sequence coupled with the lithology of the Alem ketema section was found similar as presented in Fig 4.5 A & B and Fig 4.5 C&D. These rock units vary in fossil content depending on their location. In some places, they consist of sparse macrofossils such as gastropods and bivalves, there are no fossil macroinvertebrates. The rock sample taken from this layer of the limestone unit was coded LM-6A and LM-6B while the layer from which the samples were obtained from Lemi and Alemketma side samples were coded as AK- 6A and AK-6.



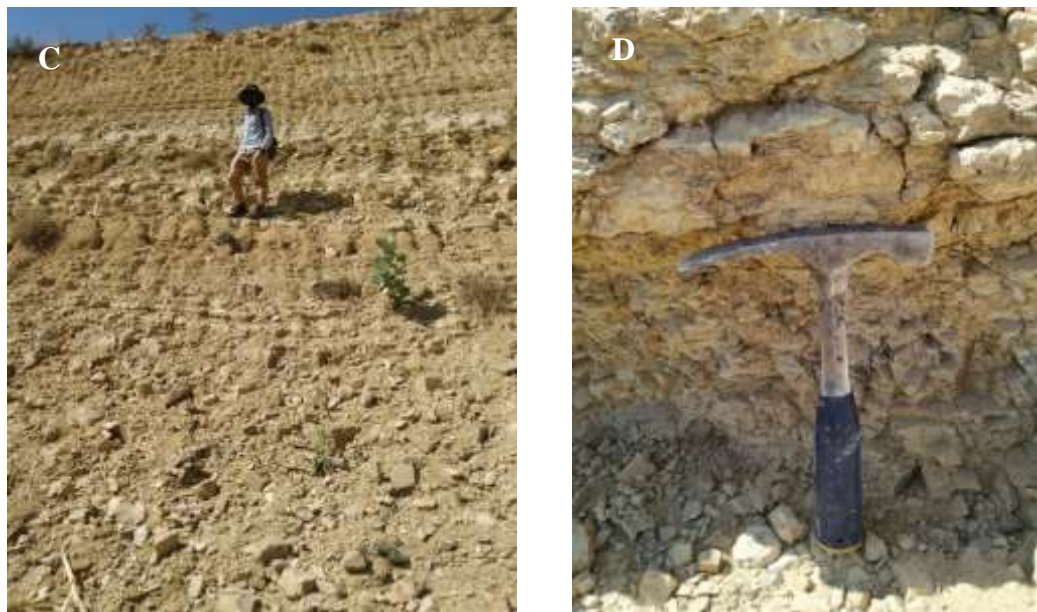


Figure 4.5 Field photographs of marl- limestone alteration A)alternation of marl and limestone in Lemi section B)marl in Lemi section C) alternation of marl and limestone in Alem ketema section D)marl in Alemketma section

4.2.6 Bioclastic limestone– clayey marl alternations

These units are exposed in the upper part of Alemketma and four facies are distinguishable in situ because the limestone layers are more weather-resistant than the interbedded clayey marl layers. The top layer consists of 60 cm thick brown bioclastic limestone, the second layer is dark brown and consists of 120 cm thick clay-rich calcareous marls and the third layer is 60 cm thick and light grey. There were little clasts compared to the 1st bed. The 4th bed was marly limestone which was 1 m thick and earthy and light grey. The rock samples were taken from this layer of the limestone unit which were coded as AK-1, AK-2, AK-3, and AK-4, and the layer from which the samples were obtained from Alemketma is shown in Fig 4.6.

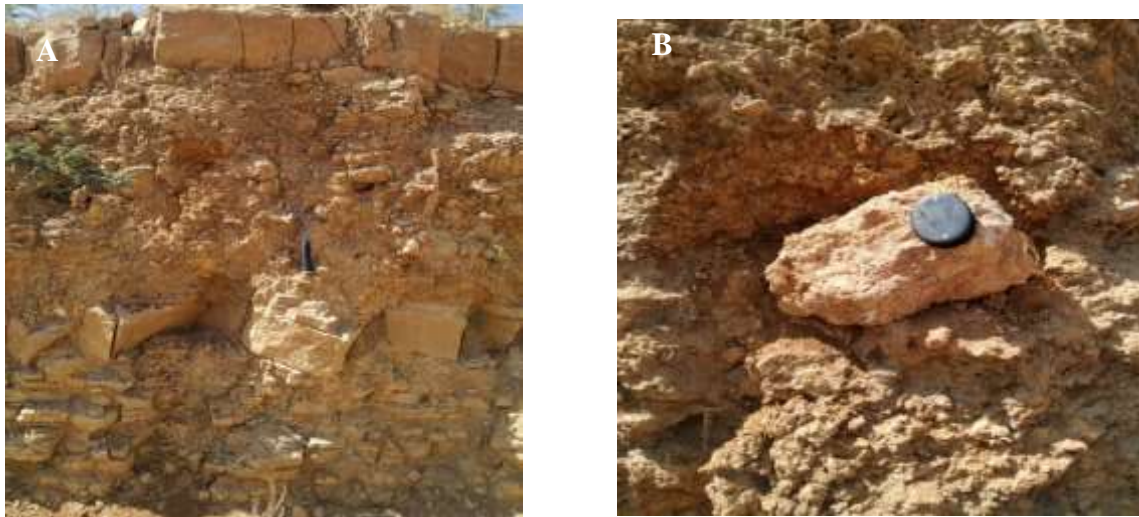


Figure 4.6. Field photographs of bioclastic limestone and clayey marl A)alternated bioclastic limestone with clayey marl B) clayey marl layer

4.3 Mughher Mudstone

Mughher mudstone has multi-colored red mudstone, light green to grey shale, yellow to white siltstone, and brown dolomite. It is highly weathered, forming gentle slopes, usually in lowlands. It is overlain conformably by a sandstone unit and underlain by Antalo limestone having gradational contact with both. The formation's name comes from the Mughher River, a tributary of the Abay River. According to Assefa (1991), the average composition of the sequences is 58% mudstone, 34% sandstone, 3% gypsum and 5% dolomite which is a total of 320 m thick. The thickness of mughher mudstone in the Jemma sections was recorded as 245 m. Mudstone is the dominant lithofacies, hence the name proposed here as Mughher Mudstone.

4.4 Debre Libanos Sandstone

The sandstone is white and pink, fine to medium-grained texture, and has a cross-bedded sedimentary structure. The sandstones presented in Fig 4.7A are white to pink in color and are medium to coarse-grained. The upper sandstone as shown in Fig 4.7B is cross-bedded and has horizontal stratifications. Confirming the report of Assefa (1991), Debre Libanos Sandstone is interpreted as a deposit of sandy braided rives on the broad alluvial plain. The thickness of Debre Libanose sandstone in the Jemma section is 260m. Lignite and Carbonaceous siltstones were also found in the preset in Jemma during the study and deposited in local reducing environments such as oxbow lakes, swamps, or abandoned chutes on tops of point bars (Assefa, 1991).



Figure 4.7. Field photographs of Debre Libanos sandstone in Lemi(A) Grain size variation (B) Cross-bedding

4.5 volcanic Rocks

On the upper sections of the sandstone, a substantial amount of early-late Oligocene and Quaternary volcanic rocks are resting unconformably. These early-late Oligocene flood basalts (26.9-29.4 Ma) based on $^{40}\text{Ar}/^{39}\text{Ar}$ age dating and magneto stratigraphy of Hofmann *et al.* (1997), were composed with minor trachytes and rhyolites. Additionally, Hofmann *et al.* (1997) reported the presence of these volcanic rocks in the north-western Ethiopian Plateau, and their variety in thickness ranged from 500 - 2000 m. However, in the present study of the Jemma area, the thickness was approximately 735 m volcanic rocks.

4.6. Petrographic Descriptions

Examination of thin sections under the microscope is a key part of any study of carbonate sediments. The most commonly used classification systems are Folk (1959) and Dunham (1962), which are also used in this study. Folk’s classification was based on the relative abundance of three constituents: carbonate grains, lime mud (micrite) and sparry calcite cement whereas the classification of Dunham (1962), was based on grain packing and the abundance of carbonate grains relative to micrite; and depositional binding of grains.

	Major rock components							Rock name	
	Carbonate grains % (Allochems)				Interstitial material %		Others	Folk	Dunham
Sample code	Fossil	Peloid	Ooid	Intraclast	Micrite	Sparite			
LM 1A	6.5	-	-	2	89	2	0.5	Biomicroite	Mudstone
LM1B	5	-	-	2	90	2	1	Biomicroite	Mudstone
LM2	0.5	-	-	-	91.5	2	6	Biomicroite	Mudstone
LM3	4	-	-	1	92	1	2	Biomicroite	Mudstone
LM5A	20	-	-	2	75.5	1.5	1	Biomicroite	Wackstone
LM5B	5.5	-	-	0.5	84	1	9	Micrite	Mudstone
LM6A	7	8	-	10	27	46	2	interapelsparite	Wackstone
LM 7					15		85	Sandy limestone	
AK 1	16	20	-	2.5	32	28	1.5	pelbiomicroite	Packstone
AK3	30	-	-	5	48	28	1	Biomicroite	Packstone
AK4	1.5	-	-	2	88	4	4.5	Micrite	Mudstone
AK6	4.5	-	-	1	81	7.5	6	Micrite	Mudstone
AK9	4.5	-	-	-	92.5	2	1	Micrite	Mudstone
AK10	6	0.5	-	3	87.5	1	2	Micrite	Mudstone
AK11	4	-	-	3	92	-	1	Micrite	Mudstone
AK13	20	-	-	2	77	-	1	Biomicroite	Wackstone
AK15	3	-	-	-	95	-	2	Micrite	Mudstone
AK17	4	-	-	2	92.5	0.5	1	Micrite	Mudstone
AK19	2	-	-	-	97	-	1	Micrite	Mudstone
AK22	-	-	-	1	98	-	1	Micrite	Mudstone
AK24	45	-	-	-	55	-	-	Biomicroite	Packstone

Table 4.1. Petrographic descriptions of carbonate rock samples collected from the Lemi-Alemketma section.

4.7. Microfacies Analysis

4.7.1 Introduction

Understanding current carbonates and the earth's historical, biological and geological changes is necessary for the microfacies study of carbonate rocks. The origin of at least 90% of the carbonates present in contemporary marine ecosystems is biological (Flügel, 2010). Microfacies standards and paleontological data reflect paleoenvironmental conditions. According to Flügel (2010), microfacies is the collective term for all the paleontological and sedimentological criteria that have been described and examined from thin sections. To get a complete picture of the measured section, it offers basic microfacies data analysis of the carbonate rocks in the field along with a thorough microfacies research of the thin sections in the laboratory.

Through 21 thin-section investigations, the microfacies of the carbonate unit in the Lemi-Alemketma section were examined. Each sample was examined with a petrographic microscope, and each thin section's description and composition were recorded. The standard microfacies classification schemes of Wilson (1975) and Flügel (1982, 2004, 2010,) as well as the ramp microfacies type of Flügel (2010) have been used for the microfacies study of the carbonate unit of the examined sections. Based on compositional, textural, fabric, and sedimentary data as well as by comparison with the contemporary carbonate environment, paleoenvironmental reconstructions of carbonate units were interpreted. From the examined section, the following microfacies types have been recognized and defined.

4.7.2 Microfacies Type 1

This microfacies is representative of the major bioclastic mudstone in the Lemi-Alem ketema region. Rarely, less than 10% of skeletal and non-skeletal grains were discovered. Foraminifers, gastropods and bivalves fossils were discovered in these facies (Fig 4.8). Rock samples from the two sections labelled as Lm1a, Lm1b, Lm2, Lm3, Lm5b, Ak4, Ak6, Ak9, Ak10, Ak11, Ak15, Ak19, were used to determine this facies.

The thickness of these facies is 27 m exposed by Jemma River and has a fine-grained texture made up of beds that range in thickness from 44 cm - 6 m. These facies in the field exhibit bioturbation, dissolution and diagenetic characteristics. This bioclastic wackestone

facies resembles Flugel (2010) SMF-9 and it originates in shallow, open-circulation neritic water at or just below the wave base (Flugel, 1972).



Figure 4.8. Photomicrograph of bioclastic mudstone microfacies

4.7.3 Microfacies Type 2

These bioclastic wackestone facies (Fig 4.9) revealed similar observable bioclasts to bioclastic mudstone. 20% of skeletal (Foraminifers, gastropods and bivalves) and 2% of non-skeletal grains were discovered in these facies. A Rock sample from the two sections labeled as, Lm 5a and Ak 13 were used to determine this facies. The thickness of these microfacies is 90 cm exposed by the Jemma River. These bioclastic wackestone facies originate in shallow, open-circulation neritic water at or just below the wave base (Flugel, 1972).

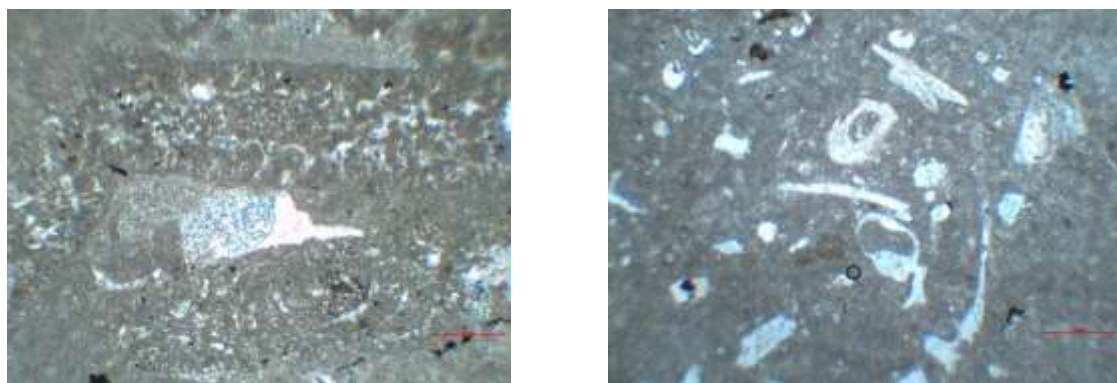


Figure 4. 9. Photomicrographs of bioclastic wackestone microfacies

4.7.4 Microfacies Type 3

Non-laminated homogenous mudstone facies were with coquina and marl in the studied section. The lack of fossils and the presence of a vein in the mudstone are characteristics of a carbonate mudstone (Fig 4.10). The non-fossiliferous mudstone facies were deposited as a result of the low-energy circumstances. Shallow, limited intertidal zones have clam

conditions (Flügel, 1982). This microfacies, which is similar to Wilson (1975) and Flügel (2010) SMF-23, is primarily deposited in weakly salinated or evaporative tidal ponds. A Rock sample from the Alemketma way section Ak 22; and was used to determine these facies.

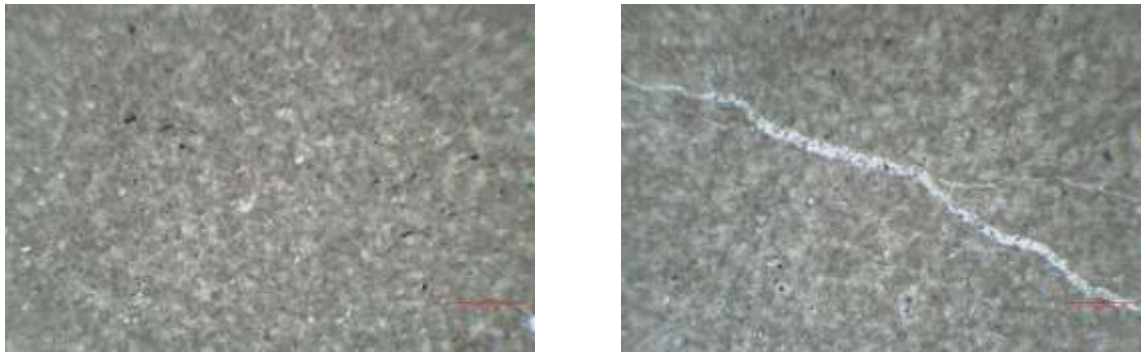


Figure 4.10. Photomicrograph of unfossiliferous mudstone

4.7.5 Microfacies Type 4

Micro-rounded aggregates and locally eroded lithoclasts (intraclasts of Folk) are components of bioclastic rudstone microfacies. Some are peripherally micritized intraclasts and peloids. The cement is mostly sparry calcite with little micrite as presented in (Fig 4.11). Bioclasts in these facies include echinoderm and algae. This alternates with a marly limestone unit in the Lemi region. These facies were identified using the rock sample Lm- 6A. Standard microfacies 24 Flügel (2010), coarse litho-clastic-bioclastic rudstone or floatstone facies. It is common to refer to the debris as an intraformational limestone pebble conglomerate. Wilson (1975), suggests that this facies develops as a lag deposit in tidal channels.

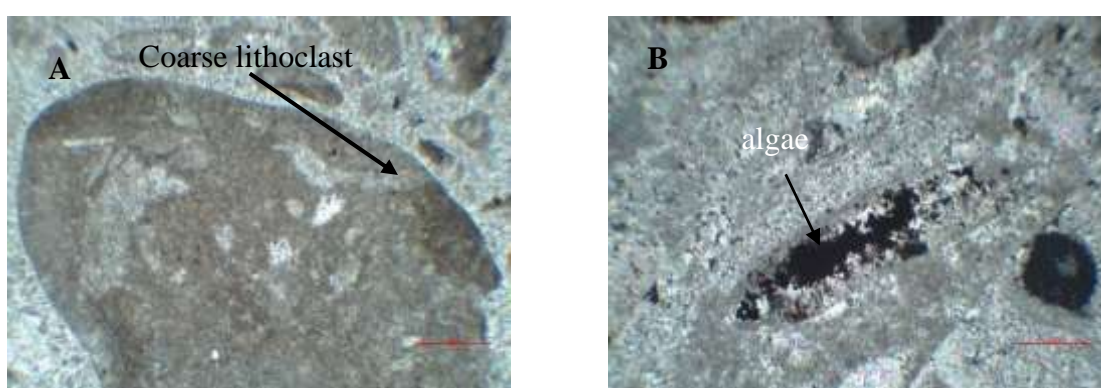


Figure 4.11. Photomicrographs of bioclastic rudstone A) coarse lithoclast B) Algae

4.7.6. Microfacies Type 5

Pelbiopackstone microfacies are made up primarily of what are probably hardened fecal pellets with occasional additions of concentrated ostracod tests as shown in (Fig 4.12).

Similar microfacies include SMF 16 (Flugel, 1972). Peloids may only be a very slender indicator of water movement and are assumed to be created by the biological pelleting of mud (Flugel, 1972). These qualities characterize tide flats. These facies were discovered using an Ak-1 rock sample of the Alemketma section.

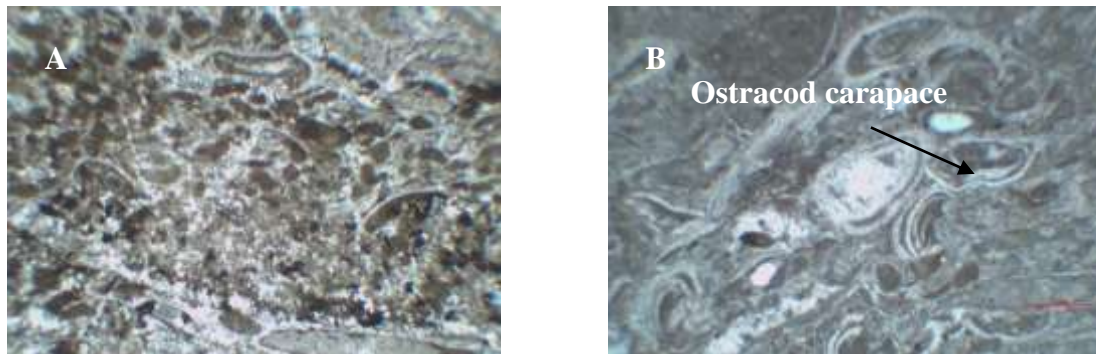


Figure 4.12 Photomicrographs of biopelmicrite A) Fine peloidal sediment and B) Bioclasts are disarticulated and have some fragmented ostracods.

4.7.7 Microfacies Type 6

Coated and rounded bioclastic packstone facies demonstrate bivalve, ostracod, and gastropod bioclasts. There are micritic envelopes in these microfacies as presented in (Fig 4.13). These rocks have coated bioclasts in sparite, which is quite similar to Flugel's (1972) SMF-11. The sorting and granular texture of the microfacies point to a high-energy setting. According to Flugel (2004), the shoal environment is where the sediments would have developed. At or above the wave base, where there was continuous wave action, this sediment was formed (Wilson, 1975). To identify these facies, a rock sample from the Ak 3 portion of the Alemketma section was used.

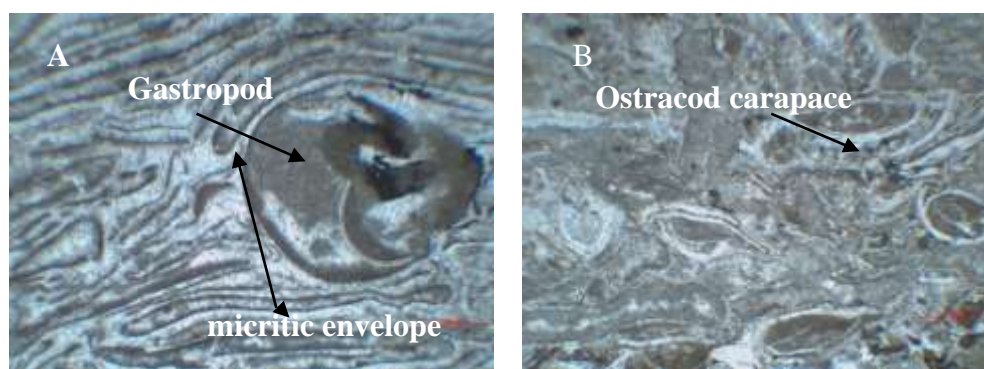


Figure 4.13. Photomicrograph of well-sorted bioclastic packstone A) Gastropod and micritic envelope are casts of molluscan fragments B) compacted ostracod carapace

4.7.8 Microfacies Type 7

Bioclastic packstone facies containing a few prominent bivalve, gastropod, and brachiopod skeletal grains as presented in (Fig 4.14). The predominant particles have moved from high-energy to low-energy environments, such as adjacent shoals and swales. The occurrence of the facies is a shoal environment and is common on the inner and middle ramps (Flügel, 2010). These facies were identified using a rock sample from section Ak 24 of the route to Alemketma.

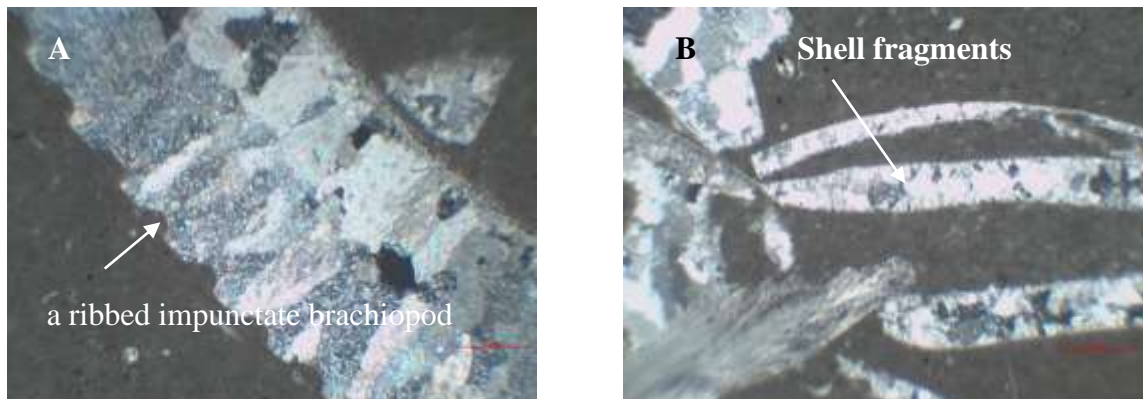
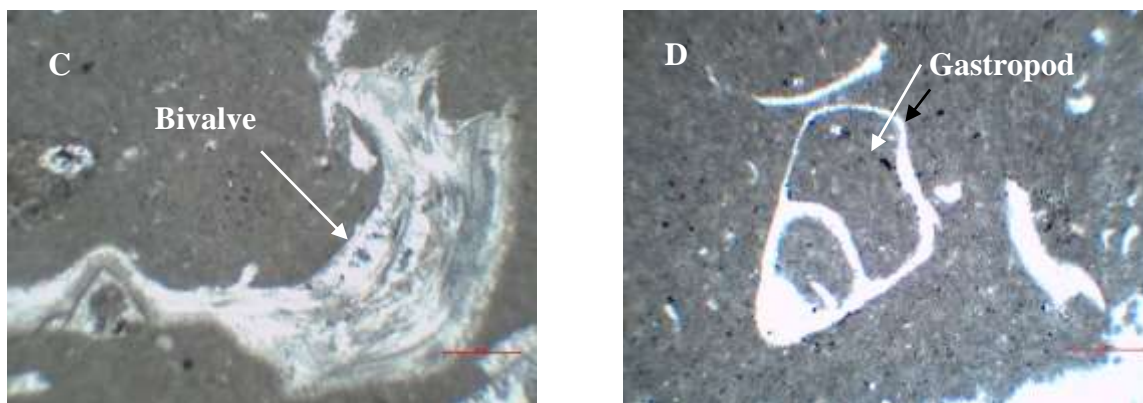


Figure 4.14. Photomicrograph of Bioclastic packstone A) A ribbed impunctate brachiopod B) Shell fragments C) Bivalve D) Gastropod



4.7.9 Microfacies Type 8

These sandy limestone facies is exposed in the upper part of the Jemma section. It is characterized by fine to medium-grained, angular to subangular quartz as revealed in (Fig 4.15). This facies is overlain by Muger mudstone and underlain by marl sediment and the presence of sand-sized quartz suggested depositions in supratidal to the intertidal environment (Jamalian *et al.*, 2011).

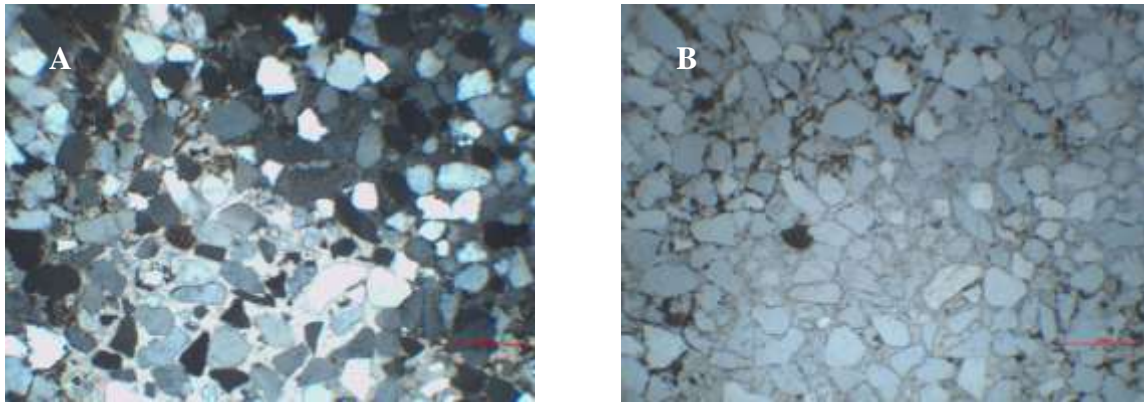


Figure 4.15 Photomicrograph of sandy micrite in A)Xpl and B)ppl

4.7.10 Microfacies Type 9

Marl-limestone alternations dominate in both sections characterized by a weathered texture that is dominated by microfossils of ostracods, foraminifera, and macrofossils of Bivalves and Gastropods. The area around Alemketma shows well-exposed and laterally continuous outcrops of marl-limestone alteration. Both sections are approximately 90 meters thick and consist of a regular alternation of limestones and marls. Einsele and Ricken (1991) noted that marl-limestone alternations occur in the majority of pelagic to hemipelagic marine settings. Marl-limestone alternations might be a result of both environmental cyclicity and diagenetic overprint. According to Einsele and Ricken (1991), they may be a direct response to cyclical changes in the environment, which cause periodic changes in the carbonate productivity during the steady deposition of clay, the supply of terrigenous material during steady carbonate productivity, the input of carbonate mud from nearby shallow-water carbonate factories, the dissolution of carbonate, and the redox conditions at the sea floor.

4.8 Diagenesis

The term "diagenesis" refers to the physical and chemical changes that sedimentary materials undergo after deposition, before metamorphism and in the time between deposition and weathering (Milliken, 2003). Carbonate minerals are often more susceptible to diagenetic processes such as dissolution, recrystallization, and replacement than most silicate minerals. Additionally, they are far more likely to be attacked by creatures that might crack or shatter shells or puncture carbonate grains. They also tend to be destroyed by physical processes more quickly (Boggs, 2009). Shallow-marine subsurface, seafloor and, a meteoric regime with deep subsurface are the three main diagenesis regimes. The primary diagenetic processes that change carbonate sediments and rocks include compaction, dissolution,

cementation, neomorphism, dolomitization and the replacement of carbonate grains and matrix with non-carbonate mineralogies (such as silicification and chertification).

4.8.1 Micritisation

When micrite substitutes the edges of carbonate grains, the process is known as micritisation. Because of the presence of micrite envelopes enclosing the original grains, certain rock displays only reflect the depositional texture and the rock is largely made up of bivalve molluscan castings, except for a transverse portion of gastropods at the center of the image (Fig 4.16). All the original aragonite was destroyed during diagenesis, leaving just the micrite envelopes to determine the shell forms.



Figure 4.16. Photomicrograph shows micrite envelopes around the grains

4.8.2 Compaction

The compaction that occurs after burial causes many carbonates to lose part of their initial porosity. The consequences of compaction are most noticeable in rocks that lack or have poorly formed early kinds of cement, such as marine and near-surface meteoric cement. Ostracod bioclasts may be found in some facies. Due to a lack of cement or sediment inside, the two-valved shell collapsed (Fig 4.17A). The compaction that occurs after burial causes many carbonates to lose part of their initial porosity.

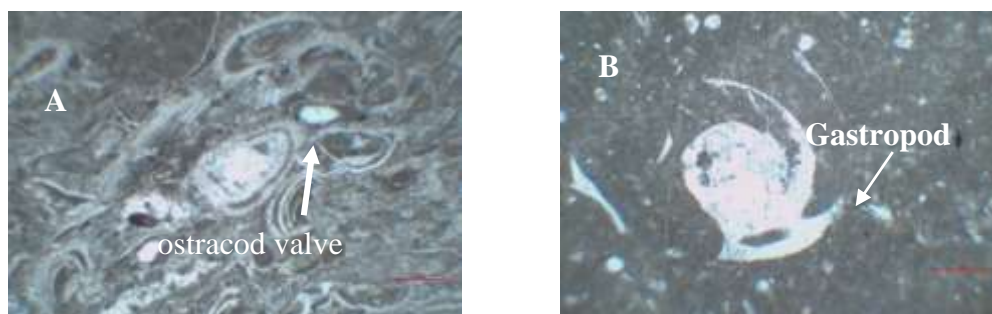


Figure 4.17 Photomicrographs show compaction A) ostracod B)Gastropod

4.8.3 Dissolution

The disintegration of metastable carbonate grains and cement as indicated in (Fig.4.18) is caused by the undersaturation of pore fluids to carbonate. In shallow near-surface meteoric conditions, deep burial, and cold waters, as well as the deep sea (Berelson *et al.*, 1994), water becomes undersaturated to aragonite and Mg-calcite (Morse, 2002).

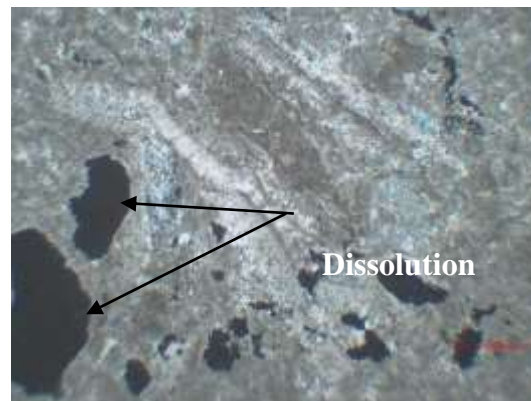


Figure 4.18 Photomicrograph shows the dissolution

4.8.4 Neomorphism

The simultaneous replacement and recrystallization processes are referred to as neomorphism. In opposition to a replacement, which describes the transition of one mineral to another, recrystallization denotes a change in crystal size or form with little to no change in chemical composition or mineralogy (Moore and Wade, 2013). As indicated in Fig. (4.19), equant blocky is formed as a result of aragonite's inversion, which also produces the skeletal elements and cement in the molluscan shells found in limestone.

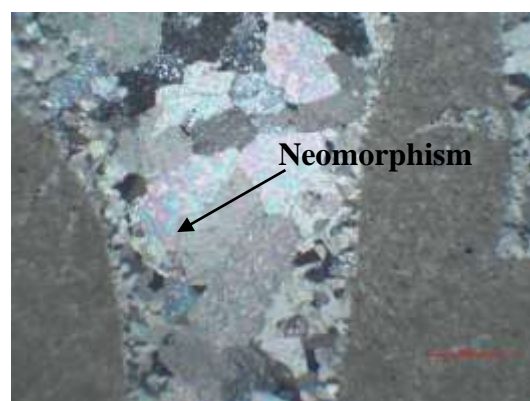


Figure 4.19. Photomicrograph showing neomorphism

CHAPTER FIVE

5. Paleontology and Biostratigraphy of Lemi-Alemketma section

5.1 Introduction

Biostratigraphic units, or zones (biozones), are groups of strata having specific fossil material. Zones' lateral extent and thickness vary significantly (Lucas, 2020). The Ethiopian dating instead of widely recognized invertebrate species like ammonites and calcareous nannofossils is based on numerous foraminiferal taxa. This is mostly caused by a scarcity of age-diagnostic taxa, particularly ammonites, which leads to sloppy and frequently incorrect biostratigraphy correlations (Singh and Jain, 2019). Foraminifera is an excellent zonal indicator for marine rocks since they are small, numerous, widely dispersed, and frequently extremely diversified. In addition, many have complicated morphologies that make it simple to monitor evolutionary changes. An important scheme of transcontinental linkages of Mesozoic (especially upper Cretaceous) and Cenozoic rocks is based on planktonic foraminifera. Although their distribution is typically more constrained, benthic foraminifera offers a helpful framework for local correlation (Armstrong and Martin, 2005). Recognizing various species systematic categorization is used to distinguish between several species of ostracods, foraminifera, gastropods, and green algae. The in-depth summary is shown below.

5.2 Ostracoda

Ostracods are tiny crustaceans that belong to the phylum Crustacean, Class Ostracoda. Bivalve carapaces on ostracods can be slight to extremely calcified. The carapaces are typically between 0.5 and 2.0 mm in size, however, some varieties can grow up to 30 mm long. They are nekto-benthic, pelagic and benthic. They are one of the best groups in colonizing a variety of habitats, including humid, terrestrial areas, lakes, deep and shallow marine environments, and freshwater habitats. Ostracoda is one of the most significant groups in paleoenvironmental reconstruction since salinity and temperature are the main environmental factors affecting their distribution (Armstrong and Martin, 2005). Particularly for lake sediments devoid of other calcareous shells, the chemistry of the Ostracoda carapace offers useful information regarding hydrology and precipitation. Since its evolution in the Ordovician, it has a long geological history of more than 400 million years.



- 1). *Cytherella praecadomensis* (Knitter and Riegraf, 1984, Right lateral sample Ak-21
- 2). *Ektyphocythere ambo* sp. nov. sample Lm-6b
- 3). *Ektyphocythere ambo* sp. nov. sample Ak-7
- 4). *Cytheropteron byfieldensis* sample Ak-14
- 5). *Rutlandella?* sp. sample Ak-7
- 6). *Cytherella praecadomensis* (Knitter and Riegraf, 1984) sample Ak-14

5.3 Chlorophyta (green algae)

Green algae are the most diverse group of algae.

Phylum Chlorophyta Pascher, 1914

Class Ulvophyceae Mattox and Stewart, 1978

Order Dasycladales Pascher Family Polyphysaceae Kützing, 1843

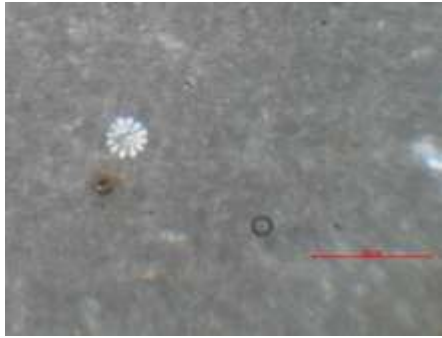
Genus *Clypeina* Michelin, 1845

1991. *Clypeina jurassica* Favre – Darga and Schlagintweit, p. 211, Fig. 1, Fig. 6.

1994. *Clypeina jurassica* Favre – Senowbari-Daryan et al. p. 232, pl. 5, figs. 4 – 6.

1999. *Clypeina jurassica* Favre – Yilmaz, p. 85, pl. 1, Fig. 6.

2004. *Clypeina jurassica* Favre – Clark and Boudagher-Fadel, p. 490, pl. 2, Fig. 4.



Description: It was made up of spicules that were oriented radially and had a starlike appearance when cut transverse. The thallus of some specimens of this species, which is evident in the oblique section, is segmented or chain-like in appearance. Partitions and calcite plates that are readily apparent set it apart from the other species.

Occurrence: Lemi section, sample Lm-2

Stratigraphic range: Upper Kimmeridgian – Lower Berriasian (Yilmaz, 1999), Middle Kimmeridgian – Tithonian (Velic, 2007).

5.4 Foraminifera

The most important group of microfossils is the foraminifera because of its stratigraphic importance and value as paleoenvironment indicators. They have been discovered in rocks exposed to conditions similar to those of the Cambrian and earlier eras. They are now found in a range of marine environments, from shallow to deep oceans. Some of the species are so common that as they accumulate on the deep sea floor, foraminiferal ooze, a significant lithological unit, is produced. Planktic foraminifera makes up the majority of the oozes created outside of the continental slope. Similar to this, benthic foraminifera are abundant in shallow-water carbonates. Foraminifera are unicellular organisms that are related to amoebae and as such are within the Protista kingdom. However, they differ from other protists in that they have a shell or test and have thread-like, anastomosing pseudopodia (granuloreticulopodia). However, the molecular evidence suggests that some freshwater foraminifera may lack tests. The ways of life that foraminifera have adopted are both benthic and planktic. They typically range in size from 0.1 to 1.0 mm, however, some individuals grow to enormous proportions of more than 10 cm. By examining their wall composition, microstructure, chamber layout, suture depression or elevation, apertural characteristics, chamber morphology wall, and ornamentation, foraminifera can be distinguished from one another. On a general level, the most significant characteristics employed in the classification

and taxonomy distinction of foraminifers are wall composition and microstructures (Cushman, 1928). The primary components of foraminifera are organic (proteinaceous), agglutinated, and secreted calcium carbonate or, less frequently, silica. The detailed systematic description is summarized below.

Family Hauraniidae (Septfontaine, 1988)

Subfamily Amijellinae (Septfontaine, 1988)

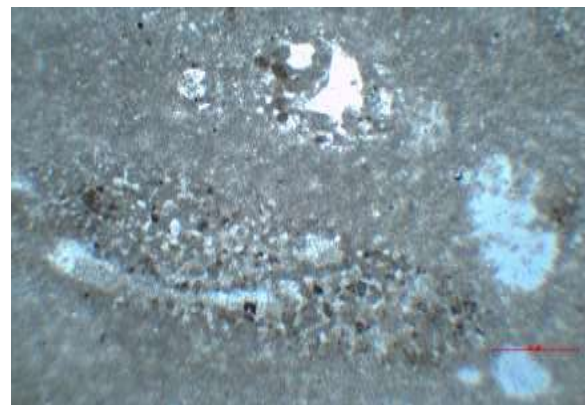
Genus *Anchispirocyclus* (Jordan and Applin, 1952)

Cf. Anchispirocyclus lusitanica (Egger, 1902)

1967 - *Anchispirocyclus lusitanica* (Egger, 1902) - Hottinger, p. 74, Pl. 13, figs. 6-8.

1987 - *Anchispirocyclus lusitanica* (Egger, 1902) - Granier, Pl. 48, fig. k.

2005 - *Anchispirocyclus lusitanica* (Egger, 1902) - Schlagintweit et al., p. 25, Fig. 5.a-c



Description: In the juvenile stage, the test is big, compressed, and planispiral to asymmetrically coiled; in the adult stage, the spread is peneropliform or circular. The wall is finely glued and not perforated. The hypodermis is composed of layers of beams and rafters that resemble webs. Numerous radial interseptal columns serve as a representation of the test's center portion. Particularly in the adult stage, the chambers are enlarged and divided by highly curved septa. The opening area is covered by ribs that cross over it.

Occurrence: Lemi section, sample Lm5A

Stratigraphic range: Stratigraphic range: Tithonian-lower Berriasian.

Family Pfenderinidae (Smout and Sugden, 1962)

Genus *Kurnubia* (Henson, 1948)

Kurnubia palastiniensis (Henson, 1948)

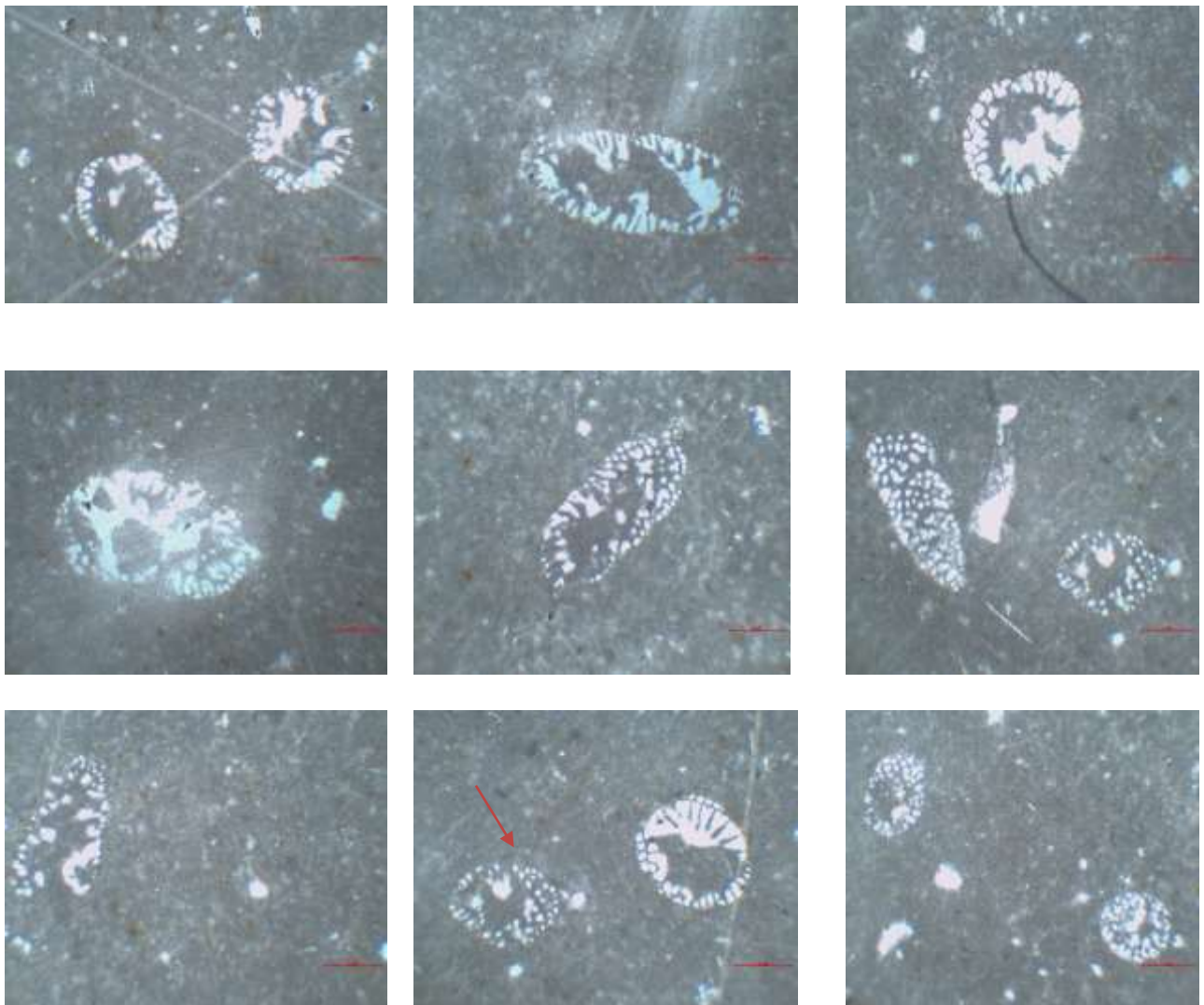
1948. *Kurnubia palastiniensis* Henson, p. 609, Pl. 16, Figs. 8, 11, Pl. 18, Figs. 10, 11.

1967. *Kurnubia palastiniensis* Henson – Maync, p. 12, Pl. 5, Figs. 1–7.

1967. *Kurnubia palastiniensis* Henson – Hottinger, p. 167, Figs. 30–34, Fig. 45, 46.

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

2004. *Kurnubia palastiniensis* Henson – Ivanova and Koleva-Rekalova, p. 226, Pl. 3, Figs. 3,4.



Description; *Kurnubia palastiniensis* (Henson, 1948). The test is semi-circular to ellipsoidal, spirally coiled, perforated, and has just a few elongated variations. It is made up of tiny granular calcite crystals, sometimes without a well-developed central column and sometimes with one. It included thin, arched septal lines as well, which are hidden at the test's edge and gradually thicken and converge towards the central column. The majority of studies also revealed first- and second-order vertical and horizontal divisions of the septal lines/chamber lumen, primarily at the periphery zones, leading to intricate calcite network formation on the chambers/septa.

Occurrence: Alemketma section, samples Ak-9, and Ak-21.

Stratigraphic range: Callovian – Kimmeridgian (Mansour, 1975), Oxfordian – Portlandian (Septfontaine, 1988), Lower Oxfordian – Tithonian (Hughes, 2000; Velic, 2007), Oxfordian – Kimmeridgian (Tasli, 2001; Hughes, 2004), Kimmeridgian (Omaña and Arreola, 2008).

Kurnubia wellingsi (Henson, 1948)

Family Pfenderinidae Smout and Sugden, 1962

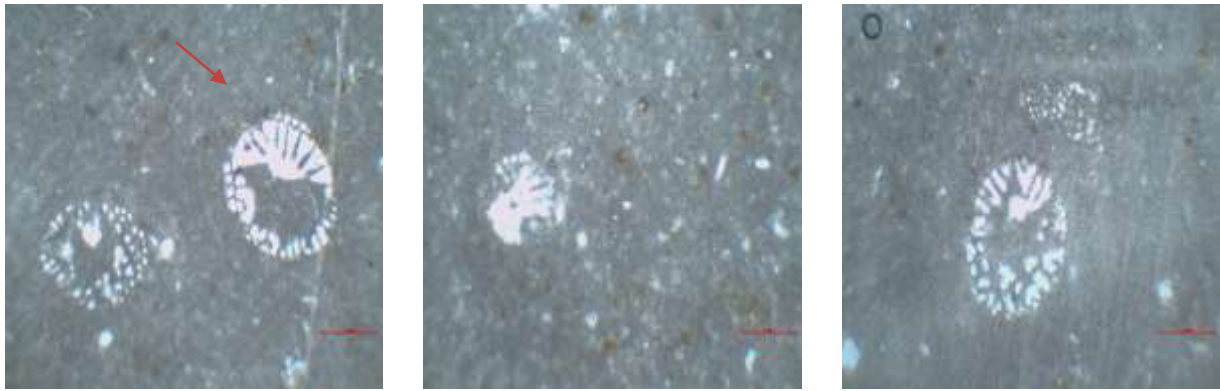
Genus *Kurnubia* Henson, 1948

1962.*Kurnubia wellingsi* (Henson) – Smout and Sugden, p. 590, pl. 76, figs. 1 – 8.

2004.*Kurnubia wellingsi* (Henson) – Clark and Boudagher-Fadel, p. 487, pl. 1, figs. 3–4; pl. 3, Fig. 1, C; pl. 4, Fig. 6, A.

2004.*Kurnubia wellingsi* (Henson) – Hughes, p. 94, fig. 15, 1.

2018.*Kurnubia wellingsi* (Henson) – Boudagher-Fadel, p. 270, pl. 4.8, figs. 16–21; pl. 4.9, fig. 14, C.



Description: It is distinguished by the presence of radial septal barriers surrounding the central column without pillars. The center column is divided into two or three portions by the comparatively unpartitioned septa that surround the columella and form a reticular fabric.

Occurrence: Alemketma section, samples Ak-9 and Ak-11.

Stratigraphic range: Callovian – Kimmeridgian (Clark and Boudagher-Fadel, 2004), Upper Oxfordian – Upper Kimmeridgian (Velic, 2007), Upper Oxfordian – Lower Kimmeridgian (BouDagher-Fadel, 2018).

Nautiloculina circularis (Said and Barakat, 1959)

Suborder Nezzazatina (Kaminski, 2004)

Family Nautiloculinidae (Loeblich and Tappan, 1985)

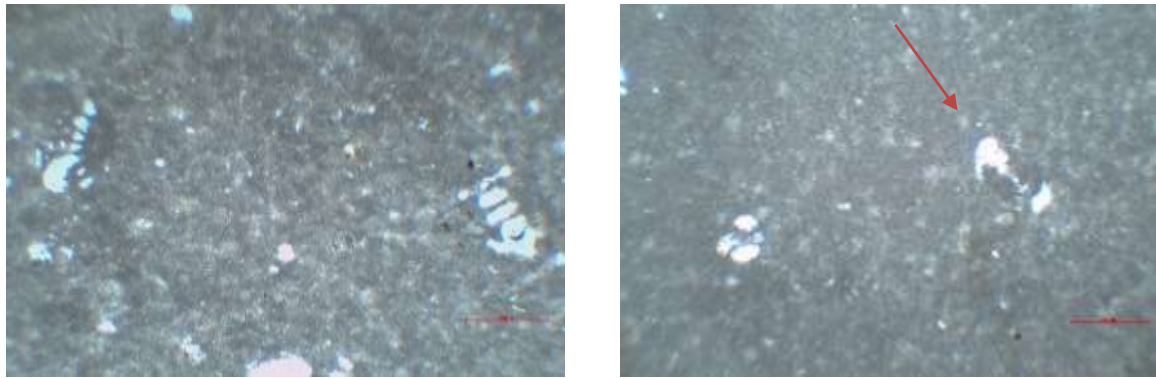
Genus *Nautiloculina* (Mohler, 1938)

species: *Nautiloculina oolithica* (Mohler, 1938)

1966. *Nautiloculina circularis* (Said and Barakat).- Derin and Reiss, Photo Numbers. 70, 71, 83, 254, 263, 264, 271, 280, 283, 286-289, 309.

1968. *Nautiloculina circularis* (Said and Barakat).- Bronnimann, p. 64, fig. 3, pl. 1, figs. 1-8, pl. 2, figs. 1-6.

1985. *Nautiloculina circularis* (Said and Barakat).- Fourcade, Arafa and Sigal, pl. 3, fig. 4.



Description: The test is lenticular to elliptical in the equatorial and axial regions, with a sharp margin along the axial part. It is planispirally coiled.

Occurrence: Lemi section, sample Lm-1.

Stratigraphic range: Kimmeridgian (Mansour, 1975), Lower Kimmeridgian (Clark and Boudagher-Fadel, 2004), Lower Oxfordian (Velic, 2007), Callovian (Boudagher-Fadel, 2018)

Nautiloculina oolithica Mohler, 1938

Suborder Nezzazatina Kaminski, 2004

Family Nautiloculinidae Loeblich and Tappan, 1985

Genus *Nautiloculina* Mohler, 1938

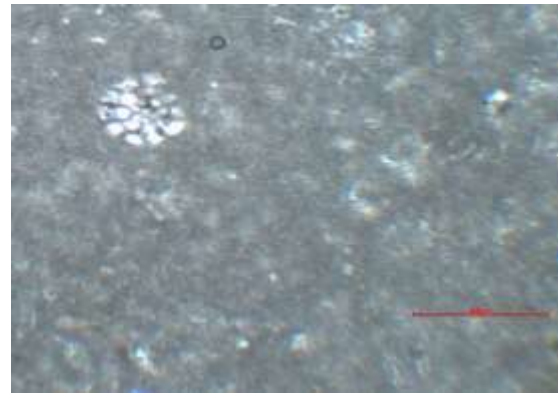
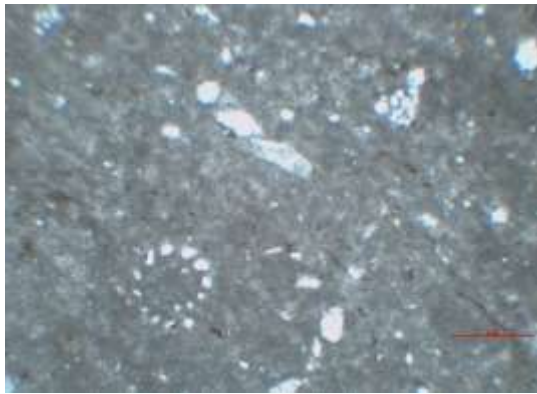
Nautiloculina oolithica Mohler, 1938 Fig. 9(d)

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

1977. *Nautiloculina oolithica* Mohler.- Velic, pl. VIII, fig. 7, 8.

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

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



Description: The shell has well-developed radial septa, lenticular and planispiral evolute tests in the equatorial region, a visible umbilical side, a proloculus, and chambers that gradually get bigger. Several chambers follow the spherical proloculus and eventually get bigger. The agglutinated wall structure has suture lines that range from radial to somewhat arched. Due to secondary deposits of calcites that have formed atop the original chambers, the proloculus, and older chambers are sometimes invisible in testing. According to the testing, the axial part has a rounded perimeter.

Occurrence: Lemi section, sample Lm-1b, and Alemketma section, sample Ak-11.

Stratigraphic range: Oxfordian – Tithonian (Hughes, 2000), Oxfordian – Kimmeridgian (Tasli, 2001; Hughes, 2004), Oxfordian (Velic, 2007), Kimmeridgian (Omaña and Arreola, 2008), Bajocian – Lower Kimmeridgian (BouDagher-Fadel, 2018)

Alveosepta jaccardi (Schrodt, 1894)

Suborder Orbitolinina Kaminski, 2004

Family Hauraniidae (Septfontaine, 1988)

Genus *Alveosepta* (Hottinger, 1967)

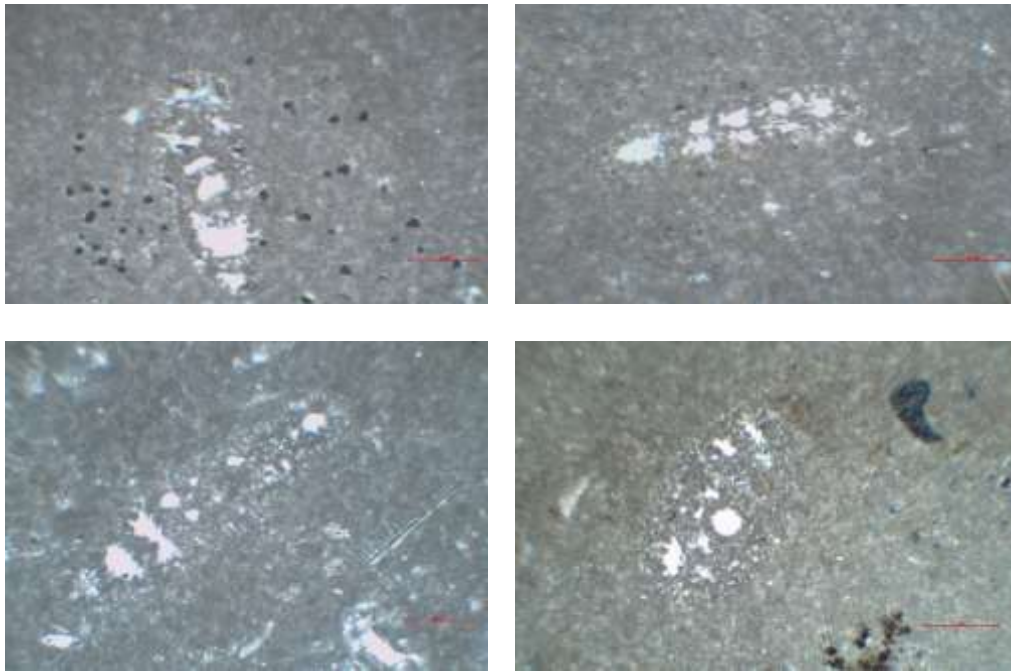
1967. *Alveosepta jaccardi* (Schrodt) – Hottinger, p. 79, Pl. 15, Figs. 15–18.

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

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

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

2001. *Alveosepta jaccardi* (Schrodt) – Clark and BoudagherFadel, p. 681, Pl. 1, Figs. 3–6



Description: Test that is elongated and ellipsoidal, bulged in the middle, and narrow at the ends of its long axis. It features a rounded periphery with a trochospirally coiled, agglutinated wall that is lined by subepidermal networks, alveolar structures, and septa. The existence of lateral and periphery chamber walls is another characteristic. The chambers come in a variety of sizes, and you can tell which ones are bigger by looking at their axial planes, and which ones are smaller by looking at the edges of the test walls. Some tests included very thin exoskeletal projections that partially or completely divided the lateral chambers by forming a median lamella.

Occurrence: Lemi section, sample Lm-1b, and Lm-5b, and Alemketma section, sample Ak-10.

Stratigraphic range: Kimmeridgian (Velic, 2007; Omaña and Arreola, 2008), Upper Oxfordian – Kimmeridgian (Boudagher-Fadel, 2018).

Siphovalvulina variabilis Septfontaine, 1988

Family Pfenderinidae Smout and Sugden, 1962

Genus Siphovalvulina Septfontaine, 1988

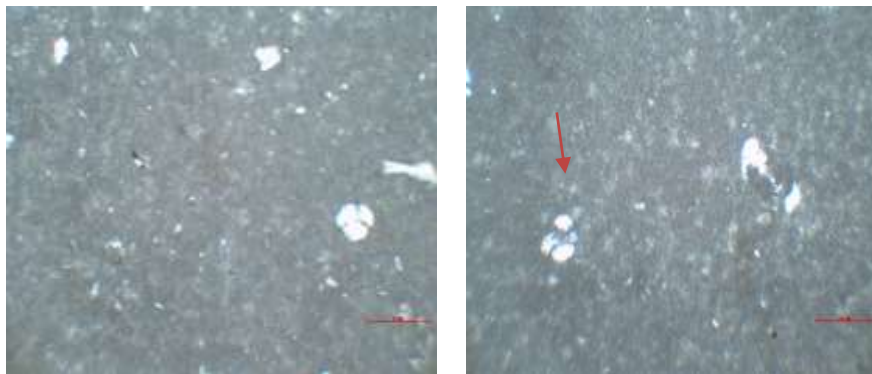
Siphovalvulina variabilis Septfontaine, 1988

1991. *Siphovalvulina variabilis* Septfontaine – Darga and Schlagintweit, p. 214, fig. 14.

2004. *Siphovalvulina sp.* – Hughes, p. 94, fig. 15, 4; p. 104, fig. 26, 6 – 7.

2016. *Siphovalvulina sp.* – Sarfi and Yazdi-Moghadam, p. 193, pl. 2, D.

2018. *Siphovalvulina sp.* – Boudagher-Fadel, p. 267, pl. 4.6, Fig. 2, B.



Description: It is trochospirally coiled and distinguished by the presence of a columellar siphon that passes across the test's long axis, showing up in the axial section as an elongated opening at the central column and in the transverse section as a circular opening. There are chambers in the test wall that surround the medial aperture (siphon).

Occurrence: Lemi section, sample Lm-1a and Lm-5b, and Alemketma section, sample Ak-10.

Stratigraphic range: Lower Jurassic (Hettangian) to Lower Cretaceous (Septfontaine, 1988; Boudagher-Fadel et al., 2001), Lower Sinemurian – Lower Tithonian (Velic, 2007)

Valvulina lugeoni (Septfontaine, 1977)

Suborder Textulariina (Delage and Hérouard, 1896)

Family Valvulinidae (Berthelin, 1880)

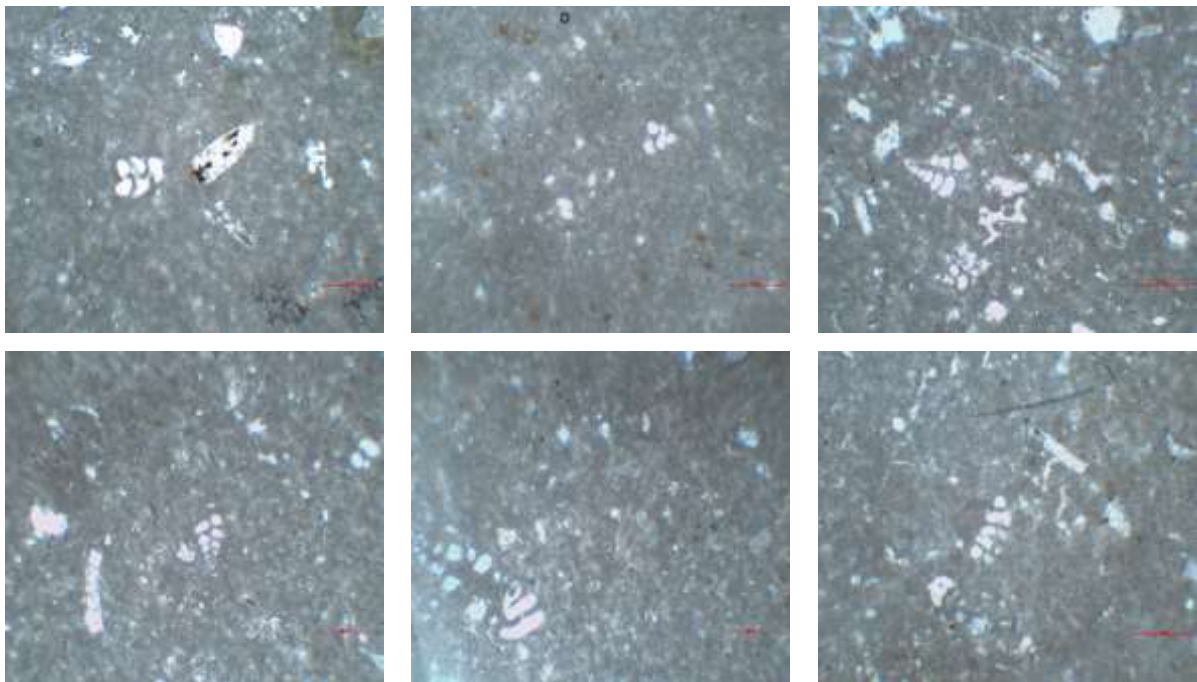
Genus *Valvulina* d' (Orbigny, 1826)

1977. *Valvulina lugeoni* Septfontaine, (pl. 1, fig. 17; pl. 2, figs. 22, 24, 25; pl. 4, figs. 8, 14)

1977. *Valvulina lugeoni* Septfontaine – Septfontaine, p. 624, pl. 2, figs. 2 – 5.

1991. *Valvulina lugeoni* Septfontaine – Darga and Schlagintweit, p. 214, Fig. 4 , fig. 7–8.

2004. *Valvulina* sp. – Hughes, p. 88, fig. 6, p. 94, fig. . 104, fig. 26, 4–5



Description: The initial spire of the test has been reduced to one whorl and is trochospirally coiled. It had an open middle zone, arched chambers, and a wall of hummocks that were thickened in the central area.

Occurrence: Lemi section, sample Lm-1b, and Alemketma section, samples Ak-10, Ak-11, and, Ak-9.

Stratigraphic range: Bajocian – Recent (Septfontaine, 1988)

Redmondoides lugeoni (Septfontaine, 1977)

Order Textulariida

Suborder Textulariina (Delage and Hérouard, 1896)

Family Paravalvulinidae Banner, (Simmons and Whittaker, 1991)

Genus *Redmondoides* Banner, (Simmons, and Whittaker, 1991)

Redmondoides lugeoni (Septfontaine, 1977) (pl. 1, Fig. 6; pl. 2, fig. 24; pl. 3, Fig. 4)

2004. *Redmondoides lugeoni* (Septfontaine) – Hughes, p. 88, fig. 6, 9– 12; p. 94, fig. 15, 7; p. 99, fig. 19, 5; p. 105, fig. 27, 2.

2018.*Redmondoides lugeoni*(Septfontaine) – Boudagher-Fadel, p. 273, pl. 4.11, Figs. 7



Description: Trochospirally coiled multi-chambers consist in the test, and they are divided by somewhat curved suture lines. The chambers gradually get smaller and converge into a single, tiny chamber to produce the apex. The chambers are larger on the apertural side.

Occurrence: Lemi section, sample Lm-1a, and Alemketma section, sample Ak-17.

Stratigraphic range: Lower Aalenian – Tithonian (Velic, 2007)

Conicokurnubia orbitoliniformis Septfontaine, 1988

Family Pfenderinidae Smout and Sugden, 1962

Genus *Conicokurnubia* Septfontaine, 1988

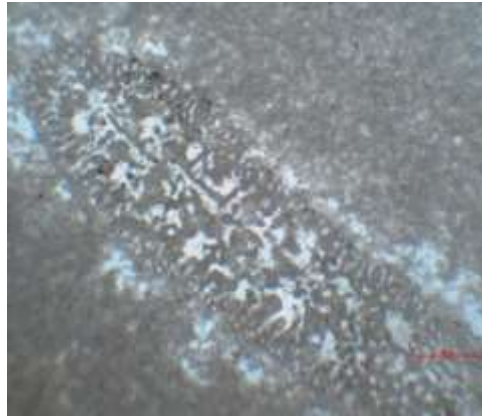
Conicokurnubia orbitoliniformis Septfontaine, 1988

Conicokurnubia orbitoliniformis Septfontaine, 1988 (pl. 1, Fig. 12; pl. 2, figs. 20, 21; pl. 3, Fig. 6; pl. 4, Fig. 1

1988.*Conicokurnubia orbitoliniformis* Septfontaine – Septfontaine, p. 247, pl. 2, fig. 13.

2001.*Conicokurnubia orbitoliniformis* Septfontaine – Tasli, p. 6, pl. 2, figs. 13, 15, 16.

2018.*Conicokurnubia orbitoliniformis* Septfontaine – BouDagher-Fadel, p. 270, pl. 4.8, Fig. 1.



Description: A convex base and a gently pointed, rounded apex characterize this conical to subcylindrical test. Additionally, the central zone, intricate epidermal networks, highly partitioned chambers, and septa are all visible in the test. It lacks a central column, unlike other *Kurnubia* species like *Kurnubia palastiniensis* and *Kurnubia morrisi*.

Occurrence: Lemi section, sample Lm-2, and Alemketma section, sample Ak-9.

Stratigraphic range: Oxfordian – Kimmeridgian (Septfontaine, 1988; Tasli, 2001), Kimmeridgian (Velic, 2007)

Everticyclammina virguliana (Koechlin, 1942)

Family Everticyclammina (Septfontaine, 1988)

Genus Everticyclammina (Redmond, 1964)

1967. *Everticyclammina virguliana* (Koechlin) – Hottinger, p. 84, Pl. 9, Figs. 10–16.

1984. *Everticyclammina virguliana* (Koechlin) – Péliissié et al., p. 487, Pl. 2, Fig. 3.

1995. *Everticyclammina virguliana* (Koechlin) – Bucur et al., p. 359, Pl. 1, Fig. 8.



Description: The test is medium to large, planispirally coiled, coarsely agglutinated, and has thick septa, massive alveolar structures, and coarse subepidermal networks. The majority of the species known tests are enormous and elongated, with a maximum length of 2 mm, and are distinguished by intricately divided inner chambers and complex epidermal networks that resemble honeycombs.

Occurrence: Lemi section, sample Lm-1b.

Stratigraphic range: Kimmeridgian – Hauterivian (Mansour, 1975; Boudagher-Fadel, 2018), Lower Oxfordian – Tithonian (Velic, 2007), Kimmeridgian (Omaa and Arreola, 2008) Kimmeridgian – Tithonian (Mircescu *et al.*, 2016).

From the marl samples, the foraminifera microfossils listed below were found.

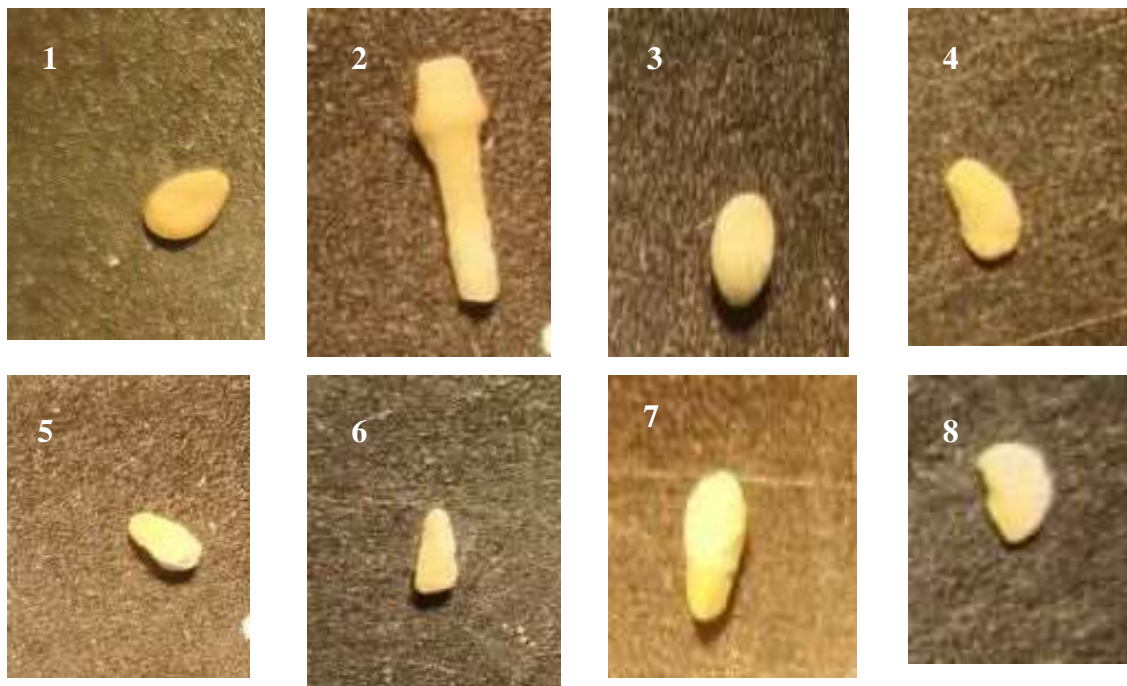


Plate 1 Foraminifera

- 1). *Pfenderina neocomiensis* sample Lm-6b
- 2). Miliolids sample Lm-6b
- 3). *Haurania deserta* Henson, paratype, figured by Henson (1948) sample Lm-6b
- 4). *Pfenderina neocomiensis* sample Ak-7
- 5). *Pseudonodosaria vulgata* (Bornemann, 1854) sample Lm-6b
- 6). *Verneuilinoides minuta* Said and Barakat, 1958 sample Ak-7

7). *Pfenderella arabica* Redmond sample Ak-7

8). *Lenticulina quenstedti* (Gumbel) sample Ak-7

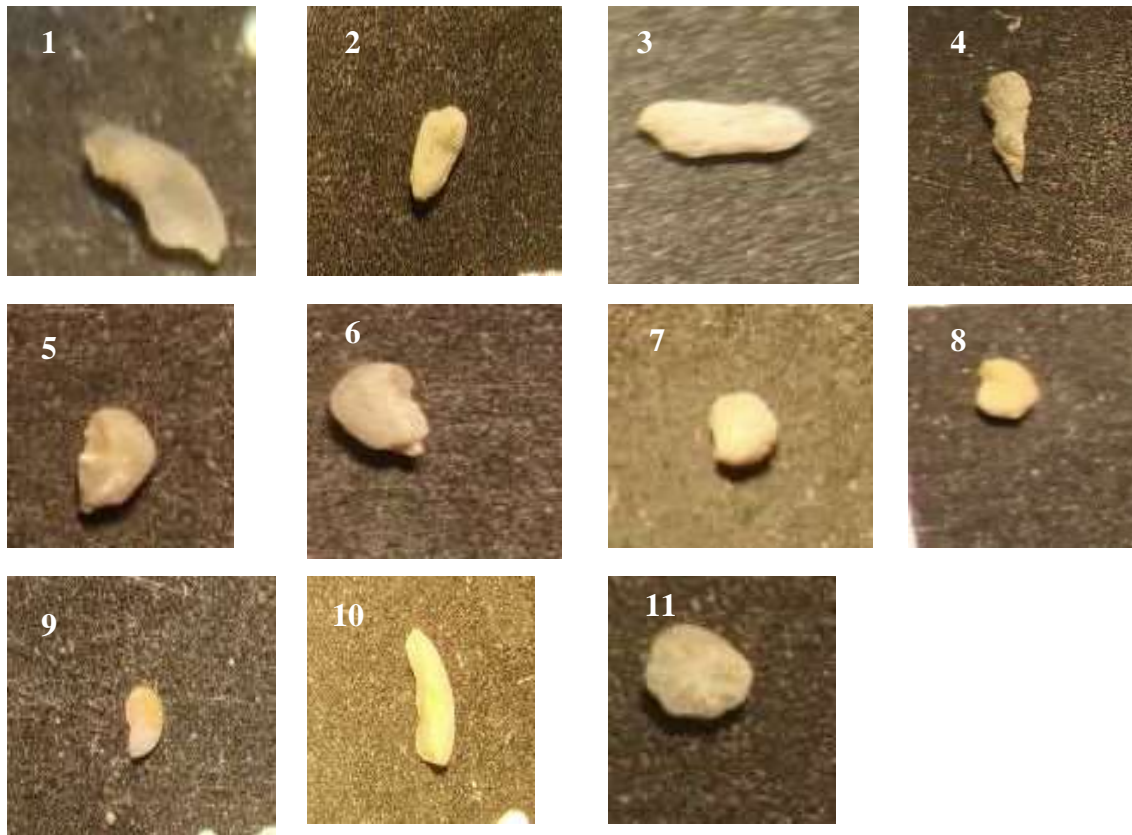


Plate 2 Foraminifera

1) *Peneroplis* sample Ak-14

2). *Pseudomarssonella reflexa* (Redmond, 1964) sample Ak-14

3). *Cuneolina cylindrica* sample Ak-14

4). *Pfenderella arabica* Redmond sample Ak-14

5). Holotype sample Ak-14

6). Holotype sample Ak-14

7). *Dictyopsella kilian* sample Ak-21

8). *Hemicyclammina chalmas* sample Ak-18

9). *Lenticular subalata* (Reuss) sample Ak-18

10). *Kurnubia palastiniensis* sample Ak-21

11). *Choffatella sp.* (Schlumberger, 1858) sample Ak-2

5.5 Echinoderms

Phylum Echinoderms are a benthic group of fossils. Their pentamerous symmetry serves as their main identifying trait. Only marine species, the bulk of which are benthic, are echinoderms. They can be found in nearly every marine environment with typical salinities, from the shallow intertidal to the abyssal zone. Others are herbivores, predators, or scavengers, while some echinoderms feed through suspension. A few of them eat deposits. There are recognized regular and irregular subgroups of echinoids. Echinoids that are common and have approximately perfect pentamerous symmetry. In irregular echinoids, a secondary bilateral symmetry is superimposed over the underlying pentaradiate pattern. Although no echinoid fossils were found in the samples that were gathered, they have been found in specimens.

5.6 Bivalves

A left and right valved shell distinguishes the phylum Mollusca class known as bivalves. At a hinge, the valves are attached. Most bivalves use sockets and teeth to articulate along a hinge line. The plane of symmetry runs parallel to the hinge line between the two valves. Bivalves have equal left and right valves, which sets them apart from brachiopods. The main factors used to categorize bivalves are their shape and microstructure, concentric and radiating growth lines, the position of the ligament, muscle scar, and teeth size, shape, and number. It is challenging to classify the bivalve fossils because they were preserved as mold and cast in the investigated study area.



Figure 5.1 Bivalve mold and cast fossils in the study area

5.7 Brachiopods

Brachiopods are a phylum that exclusively exists in aquatic habitats. The brachiopod's shell is composed of two asymmetrical but equal-sized valves. Depending on whether or not they have articulation, they have been divided into two major categories: the inarticulate and the articulate. Muscles bind inarticulate brachiopods together. Calcitic shells and articulating hinges are features of articulate brachiopods. The bulk of Early Jurassic faunas contain. Although brachiopod fossils have been found in specimens, the samples that were gathered do not contain any samples of brachiopods that have been preserved.

5.8 Gastropods

Gastropods belong to the phylum Mollusca they are distinguished by univalved and coiled morphology. They are a diverse group of fossils that live in terrestrial, sea, and freshwater. For identification presence or absence of the siphon, the coiling axis, size and form of the aperture, the number of coils, growth line pattern, coiling direction, shape of the aperture, and presence or absence of spines are used.

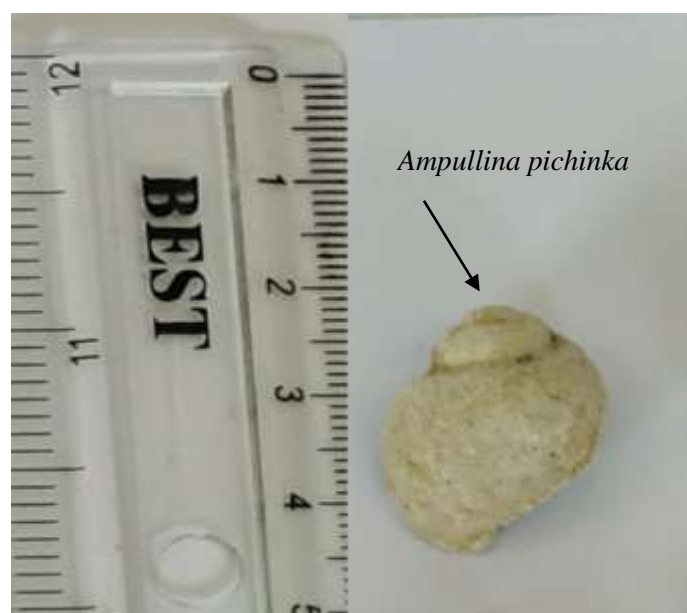


Figure 5.2 Gastropod cast fossils in the study area

CHAPTER SIX

6. Discussion

6.1 Introduction

The majority of the carbonates in the study are marl with limestone alteration and foraminiferal mudstones. Several index foraminifera taxa have been identified from this facies, The identified foraminifera fossils are *Kurnubia palastiniensis* (Kp), *Anchispirocyclus lusitanica* (Al), *Kurnubia wellingsi* (Kw), *Nautiloculina oolithica* (No), *Alveosepta jaccardi* (Aj), *pfenderella arebica*, *Siphovalvulina variabilis* (Sv), *Nautiliculina circularis* (Nc), *Valvulina lugeoni*(Vl), *Redmondoides lugeoni*(Rl), *Conicokurnubia orbitoliniformis* (Co) and, *Everticyclammina virguliana* (Ev) and one index fossil from dasyclad Green Algae, *Clypeina jurassica* (Cj) as well as nonfossiliferous mudstone, fossiliferous wackestone to packstone biopeloidal packstones, and intraclast wackestone with echinoderm and algae bioclasts that appear in the sequence's upper portion. The marly limestone unit, which is located in the uppermost portion of the succession and is intercalated with mudstone and bioclastic wackestone to packstone limestone, is the other facies found in the study area. The amount of fossils in this rock unit varies widely, with some places having gastropods, bivalves, ostracods, and foraminifers while others have fewer fossils and less exposure.

6.2 Biostratigraphy of Lemi- Alemketma Section

Benthic foraminifera recovered from the Lemi section from the 1293m to1335m are *Siphovalvulina Variabilis*, *Redmondellina Powersi*, *Nautiliculina circularis*, *Redmondoides lugeoni*, *Alveosepta jaccardi*, *Everticlamcmina virgulina*, *Conicocurnubia*, *Pseudocyclammina sphaeroida*, *Pseudospirocyclus maunci*, cf. *Anchispirocyclus Lusitanica* and one taxon from Calcareous dinocysts(*Crustocadosina semiradiata olzae*) and, dasyclad green algae(*Clypeina jurassica*). *Alveosepta jaccardi*, *Redmondoides lugeoni*, *Kurnubia palastiniesis*, *Valvula lugeoni*, *Pfenderina sp.*, *Kurnubia wellingsi*, and *Nautiliculina oolithica* are all recovered faunal assemblage on the route to the Alemketma area from 1283 to1420m.

The most significant genus is *Kurnubia* (Velic, 2007). The stratigraphic range of distinct species from the late Callovian to the middle Tithonian classifies this genus as typically indicating a Late Jurassic age, regardless of the presence of other index species or those

species that are extremely abundant in some levels. The Lemi-Alem ketema section provides accounts of species of the genus *Kurnubia*, including *K. palastiniensis* and *K. wellingsi*. Foraminiferal assemblage for Callovian age in the study area includes *S. variabilis*, *R. lugeoni*, *P. arabica*, *N. Oolithica*, and, probably *Everticyclammina sp* (Velic, 2007)

Foraminiferal assemblage for early Oxfordian (Velic, 2007) includes *Siphovalvulina variabilis*, *Redmondoides lugeoni*, *Pfenderella arabica*, *Kurnubia palastiniensis*, *Nautiloculina oolithica*, *N. circularis*, and *Everticyclammina virguliana*. And Foraminiferal assemblage for late Oxfordian (Velic, 2007) *Kurnubia wellingsi*, *K. palastiniensis*, *N. oolithica*, *N. circularis*, *S. variabilis*, *R. lugeoni*, *P. arabica* and *E. virguliana*. In the assemblage cited above which is discovered in the study area, the only form which represents an index fossil for the Oxfordian (occurring in quiet subtidal and/or lagoonal facies) (Velic, 2007).

Foraminiferal assemblage for early Kimmeridgian (Velic, 2007) includes *S. variabilis*, *E. virguliana*, *R. lugeoni*, *P. arabica*, *K. palastiniensis*, *K. wellingsi*, *Conicocurnubia orbitoliniformis*, and *Alveosepta jaccardi*. And for late Kimmeridgian: *S. variabilis*, *E. virguliana*, *R. lugeoni*, *K. palastiniensis*, *K. wellingsi* *C. orbitoliniformis* and *A. jaccardi*. Index fossils for the Kimmeridgian deposits of the Lemi-Alemketma section are *C. orbitoliniformis* and *A. jaccardi*, as well as the occurrence of the Late Jurassic species *Clypeina jurassica*. Dasyclad algae are found in the Lemi section from the Middle Kimmeridgian to the transitional level between the Tithonian and Berriasian. *Crustocadosina semiradiata olzae* is also an index fossil for Upper Berriasian which is discovered in the study area.

Foraminiferal assemblage for early Tithonian (Velic, 2007) includes *S. variabilis*, *E. virguliana*, *R. lugeoni*, and *K. palastiniensis*. Late Tithonian: *E. virguliana*, *R. lugeoni* *K. palastiniensis* and *Anchispirocyclus lusitanica*. Due to extensive micritization, Jurassic carbonates of the Lemi-Alemketma section contain *Anchispirocyclus* individuals that were practically difficult to identify and probably belong to index fossils for Tithonian. Based on the assemblages of index foraminifers the Antalo Limestone of the Lemi-Alemketma section is dated as Callovian to late Tithonian based on these index fossils.

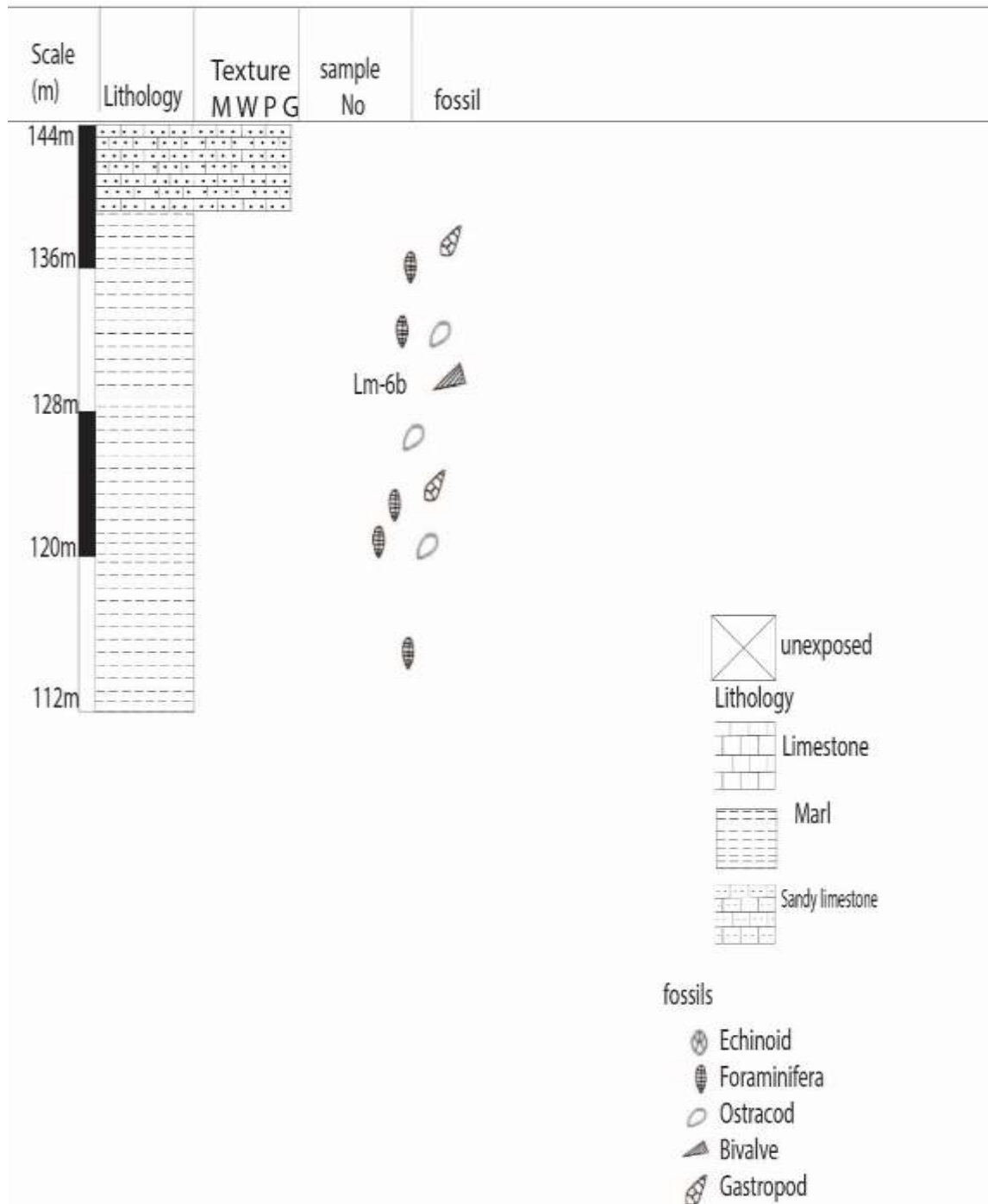
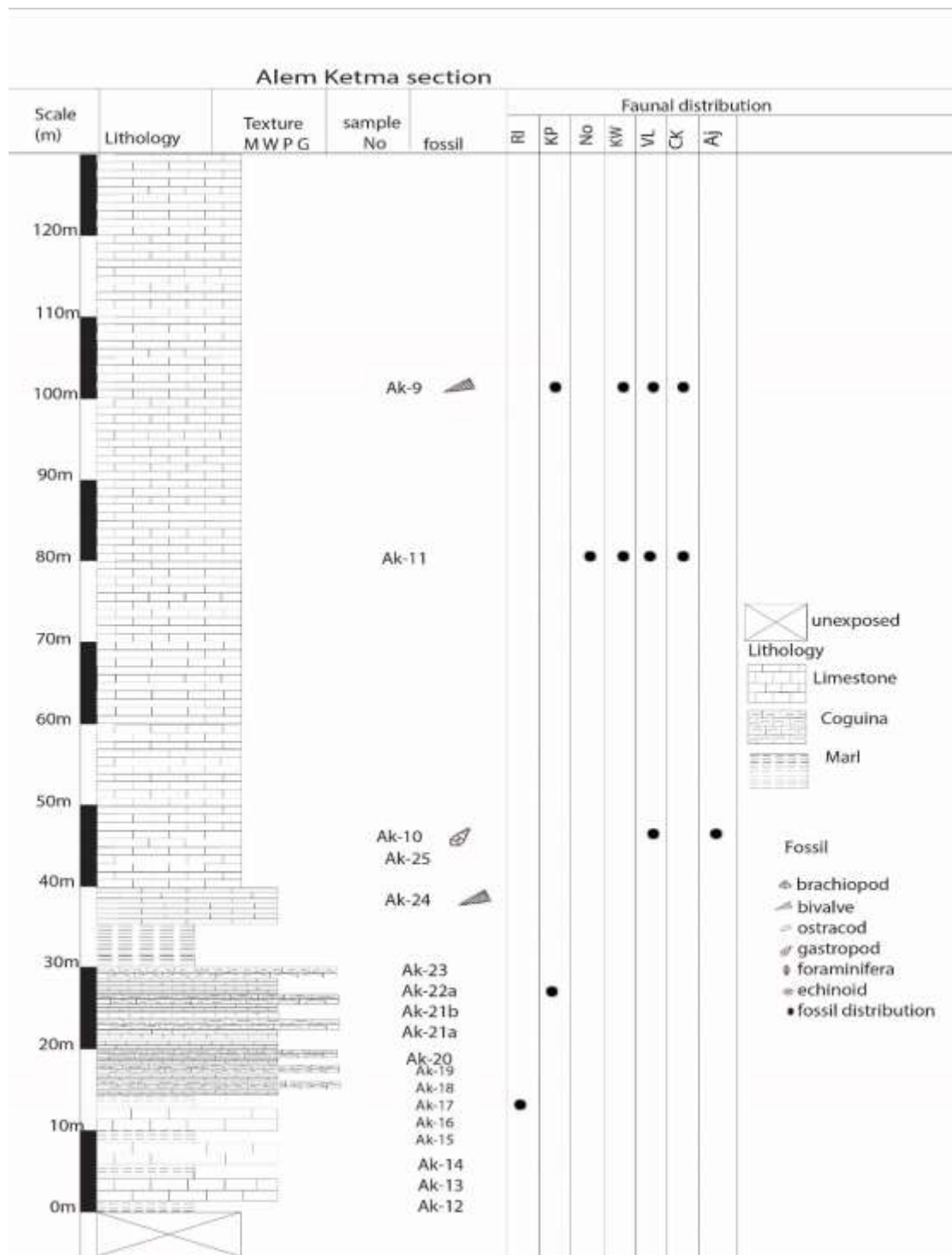


Figure 6. 1 Faunal distribution of foraminifera taxa in the Lemi section.



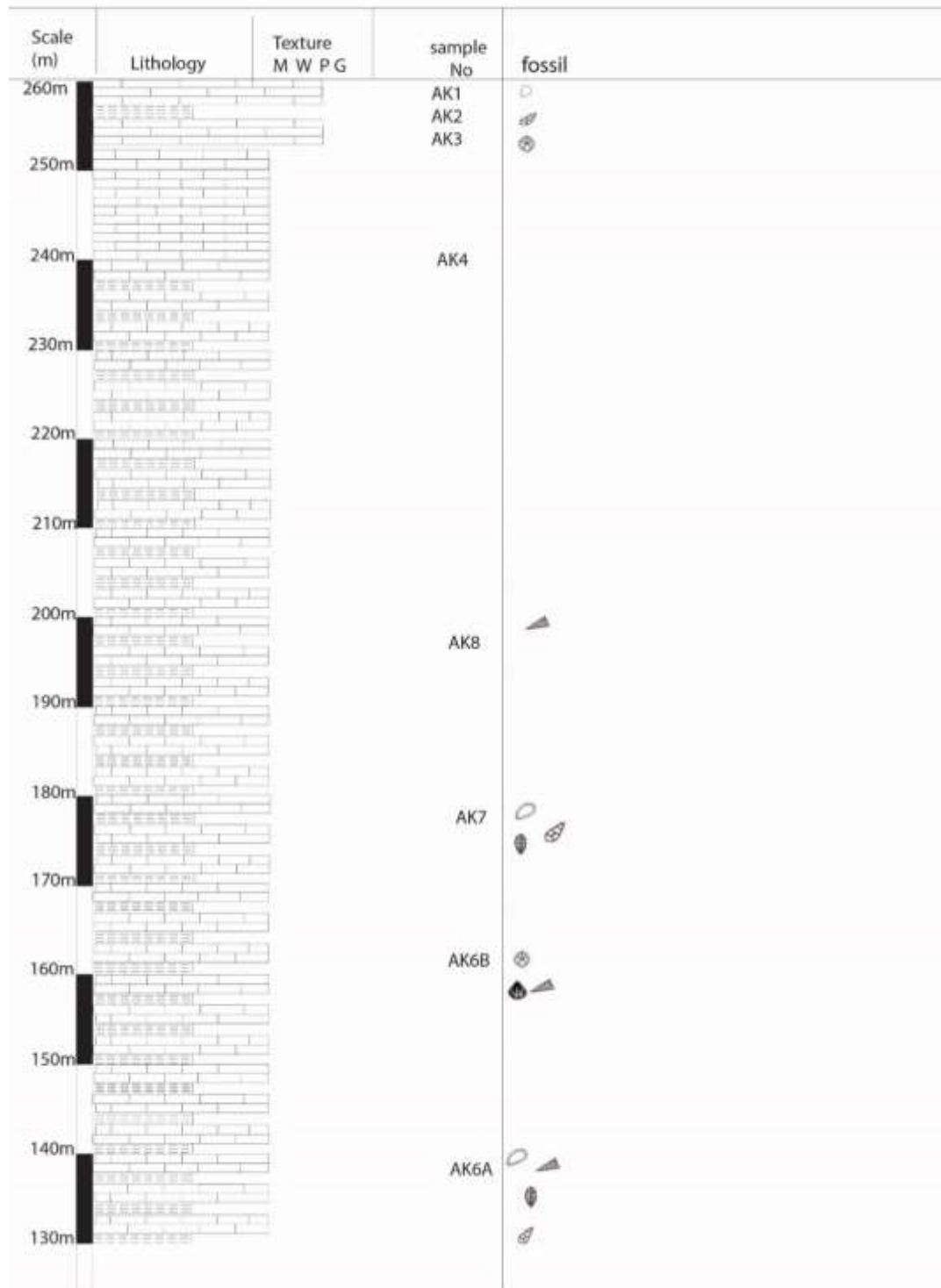


Figure 6. 2 Faunal distribution of foraminifera taxa in the Alem-ketma section.

6.3 Facies association of study area

6.3.1 Lagoonal environment (FA1)

Bioclastic mudstone and bioclastic wackestone are all part of the Facies Association FA1 group. A foraminiferal assemblage comprising *N. circularis*, *N. oolithica*, and *K. wellingsi* is

present in the bioclastic mudstone to wackestone facies, indicating a lagoonal/shelf environment (Hughes, 2004). Despite this, a substantial population of these benthic foraminifera suggests a well-oxygenated environment (Flügel, 2004). A variety of foraminifera, dasycladalean green algae, bivalves, and gastropods are among the diverse skeletal elements of the lagoonal facies, which are thought to be indications of a typical shallow water environment (Flügel, 1982).

6.3.2 Shoal environment (FA2)

Facies association (FA2) is characterized by thick beds of grain-supported facies that contain both well-sorted and coated bioclastic packstone, coquina, and, skeletal packstone with a few dominating skeletal grains of gastropods, bivalves, and brachiopods. These well-sorted grainy facies were deposited in an inner-ramp setting sand shoal depositional system (Flügel, 2004, Wilson, 1975). The sand shoal setting illustrates the euphotic zone, which is a region of high energy and persistent wave agitation with distinctive sediments primarily composed of ooids, skeletal grains, and coarse peloid sands, between the upper shoreface and fair weather wave base (Flügel, 2004).

6.3.3 Tidal Flat Environment (FA3)

Facies association (FA3) consists of sandy limestone, Intraclast wackestone, and, non-fossiliferous lime mudstone. Intraclast wackestone microfacies are comparable to Standard microfacies 24 Flügel (2009), coarse litho-clastic-bioclastic rudstone or floatstone facies. According to Flügel (2009), these microfacies are deposited in a restricted environment. The lack of bioclasts indicates a tidal flat environment (Jamalian *et al.*, 2011). Sandy mudstone characterized by the presence of sand-sized quartz suggests deposition in supratidal to the intertidal environment (Jamalian *et al.*, 2011). Non-fossiliferous lime mudstone was probably formed on low-energy, shallow, confined intertidal zones (Flügel, 1982). These facies, which are comparable to Wilson's (1975) and Flügel's (2010) SMF-23, are mostly deposited in barely salinated or evaporative tidal ponds.

6.3.4 Open marine environment (FA4)

Marl and limestone are all part of the Facies Association FA4 group. Most pelagic to hemipelagic marine environments are where marl-limestone alternations were formed (Einsele and Ricken, 1991). Marl-limestone alternations may be a reflection of diagenetic overprint, environmental cyclicity, or both.

6.4 Paleoenvironmental model

In this present study, the combined stratigraphy and general facies associations are represented by a depositional model, that is conceptual frameworks that illustrate paleogeography and depositional environments. The Jurassic carbonate at Jemma was deposited in a range of environments, that are open marine, shoal, lagoon, and tidal flat. Therefore, from the present study, the interpreted depositional environment of Antalo limestone of Jemma comprises an open marine environment, shoal environment, lagoonal environment and tidal flat environment (Fig.6.3). The tidal flat environment comprises sandy limestone, Intraclast wackestone, and, non-fossiliferous lime mudstone facies in the study sections. The lagoonal environment contains bioclastic mudstone and bioclastic wackestone facies. The shoal environment comprises thick beds of grain-supported facies that contain both well-sorted and coated bioclastic packstone, coquina, and, skeletal packstone facies. An open marine environment comprises marl-limestone alternations and fossiliferous marl limestone rich in bivalves.

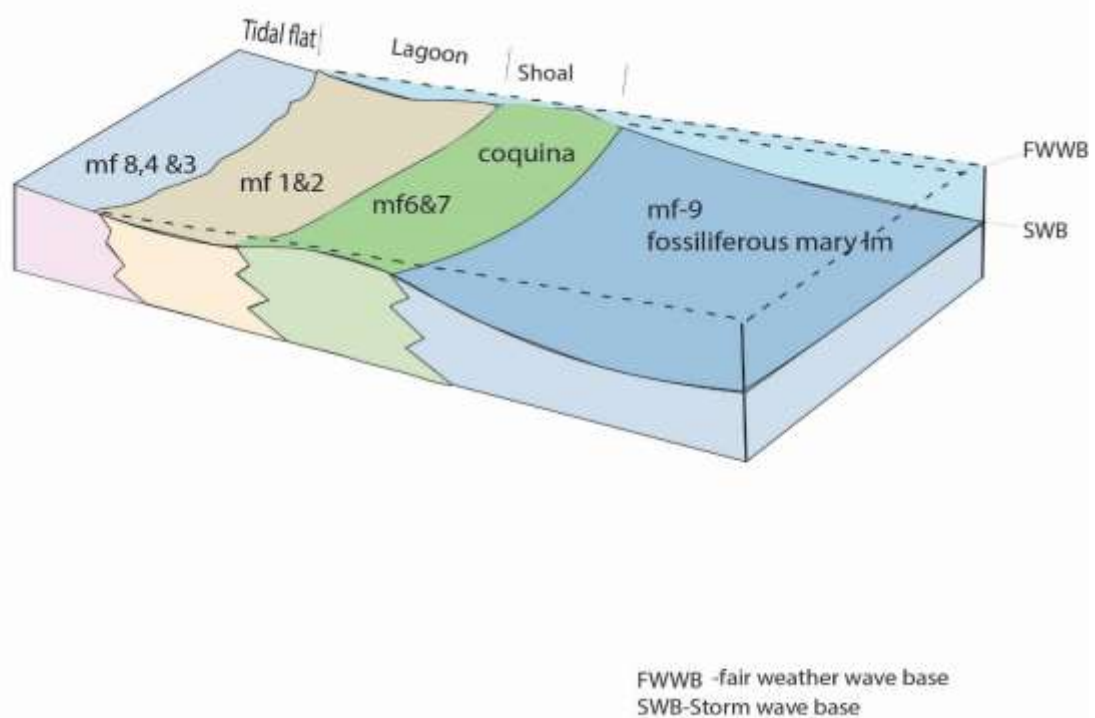


Figure 6. 3. Schematic diagram showing paleoenvironments for carbonate units in Jemma sections

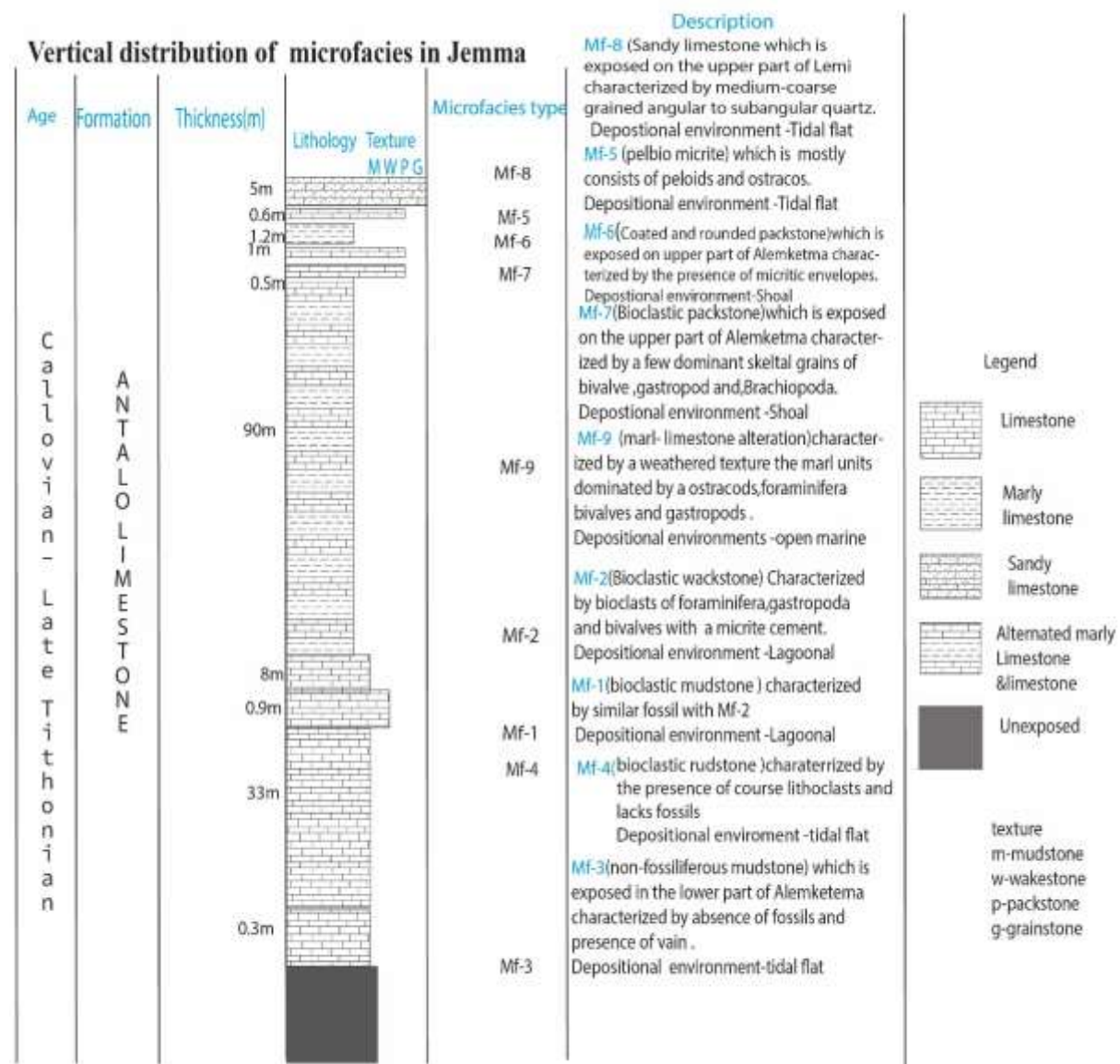


Figure 6. 4 Vertical distribution of microfacies types in Jemma sections

6.5 Correlation

According to numerous researchers, the Antalo Limestone is 420 meters thick. The bottom unit of the Abay sequences is not exposed in the research area, hence it is impossible to calculate the real thickness of the limestone unit in sections. The limestone unit's thickness in the two measured portions is not equal. The thickness of limestone in Lemi is 150 m while 250 m in the Alemketma section. Several index fossils have been discovered from the two sections. Foraminiferal assemblages that used for biostratigraphy of the study sections are *Kurnubia palastiniensis* (Kp), *Anchispirocyclina lusitanica* (Al), *Kurnubia wellingsi* (Kw), *Nautiloculina oolithica* (No), *Alveosepta jaccardi* (Aj), *Pfenderella arebica* (Pa),

Siphovalvulina variabilis(Sv), *Valvulina lugeoni* (VI), *Redmondoides lugeoni* (RI), *Conicokurnubia orbitoliniformis* (Co) and *Everticyclammina virguliana*(Ev). Based on the index fossils, the Jemma sections of Antalo limestone are dated from Callovian to late Tithonian. Paleontological data in Abay have been found in the Antalo Limestone with the identification of some benthic foraminifers and some macrofossils including a few ammonites. The existence of *Nautiloculina oolithica* and *Pfenderina sp* at the base of the limestone unit points to a Callovian age (Russo *et al.* 1994). *Parurgonina caelinensis*, *Kurnubia palestiniensis*, *Salpingoporella annulata* and *Conikurnubia sp* at the top of the unit indicates a Kimmeridgian age (Atnafu 1991). The presence of the above-listed index fossils in study sections indicated that Antalo Limestone in the Blue Nile basin is considered to be correlative with the Jemma sections.

CHAPTER SEVEN

7. Conclusion and Recommendation

7.1 Conclusion

- Large benthic Foraminifers are abundantly associated with the examined sequence, and this thesis cites and describes them for the first time.
- Systematic classification is used to distinguish between various species of ostracods, foraminifera, gastropods, and green algae.
- The Antalo Limestone of the Lemi-Alemketma section is dated as Callovian to late Tithonian based on faunal assemblages of index foraminifers.
- The Antalo Limestone exists concealed beneath the Jemma River.
- Species that are normally found in lagoon settings are frequently found with other species.
- The Jurassic sequences found at Jemma were deposited in a range of environments, that are open marine, shoal, lagoon, and tidal flat.
- The presence of benthic foraminifera, calcareous algae, and the predominance of mudstones in the Jurassic limestone section from the Jemma area are indicators that suggest a subtidal, protected lagoon environment.
- The index foraminifer's zone boundary is not effectively known.

7.2 Recommendations

- The Jurassic carbonate unit of Jemma presents bio-stratigraphic challenges in determining the zone boundary of index foraminifers in carbonate units due to a limited number of samples. In any case, more investigation should be done.
- Due to extensive micritization, the *Anchispirocyclina* individuals found in the Jurassic carbonates of the Lemi-Alemketma section are extremely challenging to identify and probably make up the index fossils for the Tithonian.
- The absence of a scanning electron microscope makes it difficult to identify microfossils and examine the ostracod's and foraminifer's delicate morphology.
- By using petrographic analysis and microfacies analysis, the paleoenvironment was established. However, if just a few samples and field measurements are employed, probably, this method probably does not provide an accurate estimate of the depositional environment. A complete investigation is required, especially a microfacies analysis of additional samples and sections. Additional sections requiring comprehensive facies and microfacies analysis are necessary to see the lateral changes

and continuity of the depositional environment and to reconstruct the facies model of the region.

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