



ADDIS ABABA UNIVERSITY

**COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
SCHOOL OF EARTH SCIENCES**

**PETROLOGY, PETROGRAPHY AND STRATIGRAPHICAL STUDY
OF THE EVAPORITE-CARBONATE ROCKS IN THE KORRAHIE
FORMATION (KORRAHIE LOCALITY), OGADEN BASIN,
SOUTHEASTERN ETHIOPIA**



MOWLID MOHAMED IDIRIS

A thesis submitted to the School of Graduate Studies in partial
fulfillment of the requirements for the Degree of Master of Science in
Petrology

June. 2020. G.C

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Declaration

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university, and all sources and materials used for the thesis have been dully acknowledged.

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Abstract

This thesis utilizes petrology, petrography and stratigraphical techniques to study the evaporite-carbonate rocks in Korrahie Formation, Ogaden Basin, southeastern Ethiopia, at Korrahie locality. Apart from detailed field observations and lithofacies descriptions as well as graphic logging made on the various outcrops in the studied section at Korrahie locality. A total of 29 representative samples composed of evaporite and carbonate rocks were described and analyzed in detail under petrographic microscope. The results obtained from these outcrop lithofacies and petrographic investigations permitted the interpretation of depositional paleoenvironment. Accordingly, the deposition of this sequence took place under three types of setting namely: shallow subtidal, intertidal and supratidal sabkha. The evaporite (gypsum) rocks were deposited on the intertidal and supratidal zones, mainly under subaerial conditions, and locally under subaqueous conditions along the tidal flats. Microfacies analysis of the carbonate rocks allowed the detection of six microfacies types that are associated with a shallowing upward pattern, and characterizes shallow subtidal through beach barrier/tidal bar to intertidal-supratidal setting. The presence of the bioturbated peloidal-bioclastic wackstone/packstone indicates a shallow subtidal setting and the overlying ooid-bioclastic grainstone represents a relatively high energy environment on the island beach barrier. Passing up on the section we have an interlaminated micrite-packstone which represents back barrier/wash-over setting, and in turn the overlaid by dark grey dolomudstone of upper restricted lagoon to lower intertidal. Laterally changing into microbial laminated boundstones indicates intertidal to supratidal environments along with non laminated and non fossiliferous micritic limestones on the sabkha. The lithological logs of this sequence indicate shoaling up stacked meter scale cycles where the lower part of each cycle is carbonate and the upper part is evaporite with thin layers of marl, shale and dolomite. Microscopic investigation shows that the gypsum in the outcropped part of Korrahie Formation is generally of secondary origin that formed from rehydration of precursor anhydrite during the evaporite return to the cooler and low salinity phreatic zone due to exhumation and uplift. Accordingly much of the gypsum textures observed under the microscope are secondary with minor anhydrite relics, and based on their fabrics four microfacies types of secondary gypsum were recognized which are: porphyroblastic gypsum, granoblastic gypsum, alabastrine gypsum and fibrous satin spar and selenitic gypsum.

Keywords: *Korrahie Formation, Ogaden Basin, Evaporite-Carbonate, Depositional environment, Secondary gypsum.*

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List of Acronyms

AGIP- Azienda Generale Italiana Petroli (General Italian Oil Company)

BNB-Blue Nile Basin

GSE- Geological Survey of Ethiopia

GPS- Geographical Positioning System

MoWR- Ministry of Water Resources

NWRC- National Water Resources Commission

OB- Ogaden Basin

SPG- Somali Plate Geosciences

UTM- Universal Transverse Mercator

UNESCO- United Nations Educational Scientific and Cultural Organization.

WSRB- Wabi Shabele River Basin

SMFT-Standard Microfacies Types

CHAPTER ONE

1. Introduction

1.1. Background

To study sedimentary rocks the application of petrography and stratigraphical approaches are very important, since these methods play an important role in understanding the formation and evolution of sedimentary rocks. In addition to this, paleontological, sedimentological and geochemical parameters are also other helpful approaches as far as the study of sedimentary rocks is concerned. When it comes to the use of petrology in sedimentary rocks, various criteria have to be taken into account such as the nature, origin and characteristics of the sediment components, as well as the macro and micro textures and structures of sedimentary rocks.

Generally the integration and application of two or more different approaches in the study of sedimentary rocks often prove to be very helpful in determining the depositional conditions and environments of the sedimentary rocks, and the possibility to infer their provenance settings (especially for siliciclastic sedimentary rocks) and the subsequent burial history of the rocks are also another advantages gained from the combination of these parameters, which otherwise remains difficult to deal by using only a single approach.

The fact that evaporite sequences were mostly formed under transitional and highly restricted depositional environments, and since their primary depositional textures are tend to be highly affected by later diagenetic processes due to their high degree of solubility and mobility than carbonate and siliciclastic sediments (Warren, 2016; Babel and Schreiber, 2014), the correlation and construction of their depositional model is often challenging. To overcome this problem an extensive study of petrology and stratigraphy of such rocks will be useful even when such rocks experience complex geological history.

Furthermore the previous studies of Paleozoic-Tertiary Sedimentary successions in Ogaden basin are mostly focused on general explanation of geology and stratigraphical sequences of the basin, their age sequences, depositional conditions and environments, and the overall tectonic

relationships with the surrounding rocks. The oil companies so far worked in the basin also produce more information about the subsurface structural and stratigraphical setup of the basin. Generally these works have been concerning the evolutionary history of the basin, and established the currently used stratigraphy of the Ogaden sedimentary basin. The recent studies conducted by the Geological survey of Ethiopia (GSE) are concerning surface geology and mapping at the scale of 1:250,000. Thus the sediments in the Ogaden basin have not been systematically studied and characterized in detail and specific scale with respect to the above mentioned methods.

As a result the present study deals the petrological and stratigraphical characteristics of the evaporite and associated carbonate rocks of the Korrahie Formation (in Korrahie locality) with the aim of their origin and depositional environment interpretation. Such detailed study conducted on a part of Korrahie Formation, although it may not be representative of the whole of Korrahie Formation which is a widespread Formation and with outcrops in different parts of the basin. But there is no doubt to help the understanding of environmental conditions under which Korrahie Formation was deposited.

The Korrahie Formation in the Ogaden basin represents the first major marine regression event in the early Cretaceous sea, caused by the Arabo-Ethiopian uplifting (Purcell, 1979), and as a result the Formation formed by cyclic intercalations of sediments ranging from shale, marl, carbonates, gypsum and anhydrites which makes it very interesting and motivating in the geological record which is yet not fully addressed.

1.2. Geographical Setting of the Study Area

1.2.1. Location and Accessibility

This research thesis was conducted in Ogaden basin, Southeastern plateau of Ethiopia. The area is located about 950Km from the capital city (Addis Ababa) and about 350Km from Jijjiga (the capital city of Somali region) in the southeast direction. It can be accessed via the main road that joins Addis Ababa and Gode city, from Addis Ababa through Adama- Harar- Jijjiga- Degahbur-Kebridaher to Gode. The specific interest area for the current study is found at about 30Km from

Kebri Daher towards Gode, and thus the area is along the main asphalt road. In UTM (Universal Transverse Mercator) the area is found in zone 38N and bounded by a grid of easting from 348986m to 425649m and Northing from 714915m to 737519m or in Geographic coordinate system (GCS) between longitudes of 43°30'E to 44°20'E and latitudes of 6°20'N to 6°30'N (Fig:1.1). The selected section for this study is named Korrahie locality and found in the central part of the Ogaden basin where the Korrahie Formation is exposed. Within the study area five outcropped sections (Fig.3.1) were selected and targeted, for detailed lithofacies description and sample collection.

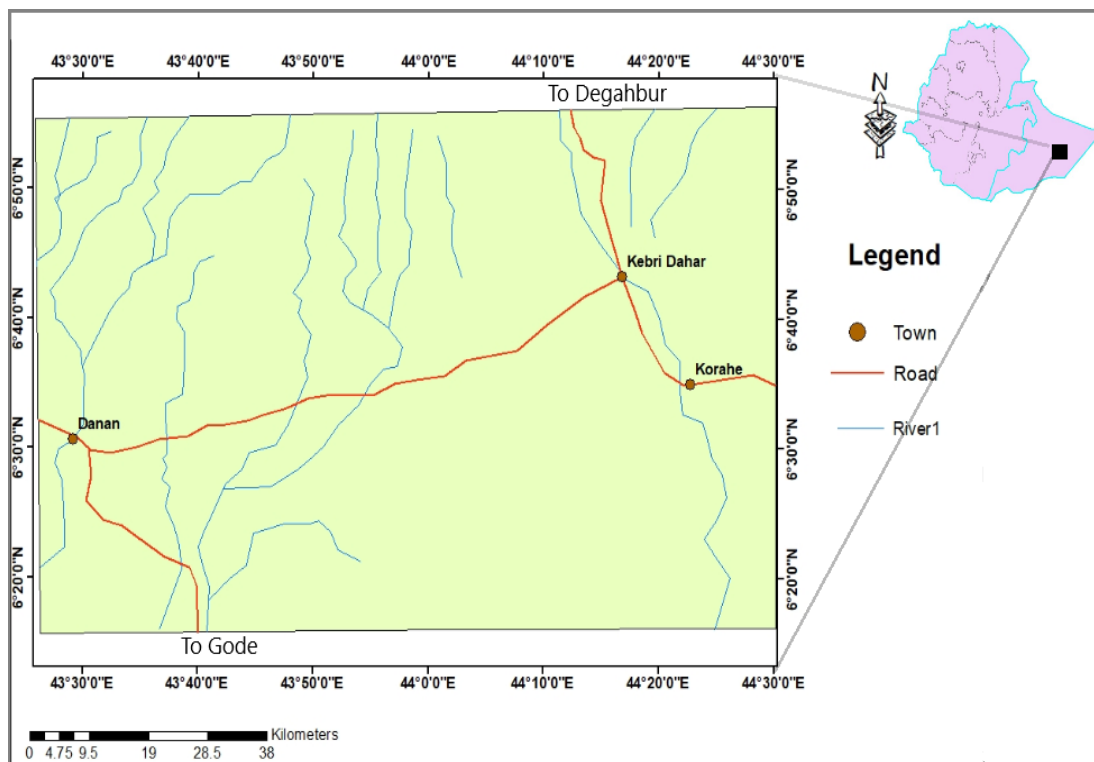


Fig.1.1. Location and accessibility map of the study area

1.2.2. Physiographic and Drainage

The Ogaden Basin is situated the southeastern Ethiopian lowlands with slightly variable topography. Physiographically most of the basin characterizes flat plain with an elevation ranging from 300m to 600m. The elevation progressively rises over 1km m.s.l to the west, southwest and northern edges of the basin (Assefa, 1998, as cited in Beressa Edessa, 2008). The major rivers

that dissected the basin's topography in the western and northwestern parts are Wabe shabelle and Gennale, which are the major drainage basins with spectacular upstream canyons; in contrast the eastern part of the basin characterizes a flat plain with gentle slope, which slightly dipping to the southeast with no rivers or pronounced topographic features and covered by red sandy soil (Mege et al., 2015).

The climatic condition in the Ogaden basin is mostly hot arid to semi-arid in the lowland areas and cooler in the high elevated areas (Beressa Edessa, 2008) and corresponds to the Ethiopian Bereha and Kolla climatic zones (Mege et al., 2015). The temperature range from 19C° to 40C° and the annual precipitation ranges between 150 to 1,000mm per year with a bimodal rainfall distribution across most of the basin which occur in March-June and September-November (Beressa Edessa, 2008).

The specific study area as a part of the Ogaden basin Characterizes by a flat planed and gently dipping surface to the east and southeast, slightly rugged topography with mountain ranges in the north and patches of small rounded hills in the central part. Fafam River is the main drainage system in the study area (fig: 1.2). In the central and southeastern parts of the study area alluvial plain with thick quaternary sediments covered the surface and along the flow direction of the Fafam River which form slightly undulating lowland or flat plain. The fluvisols (Mege et al., 2015) occur along the lower reaches of the streams like Fafam and supports agricultural activities around this area. However, gypsites (gypsiferous soil) cover most of the area and generally not suitable for agriculture. The dominant vegetation in the area is commonly short acacia trees, scattered minor short grass and Palm trees occur along some stream courses.

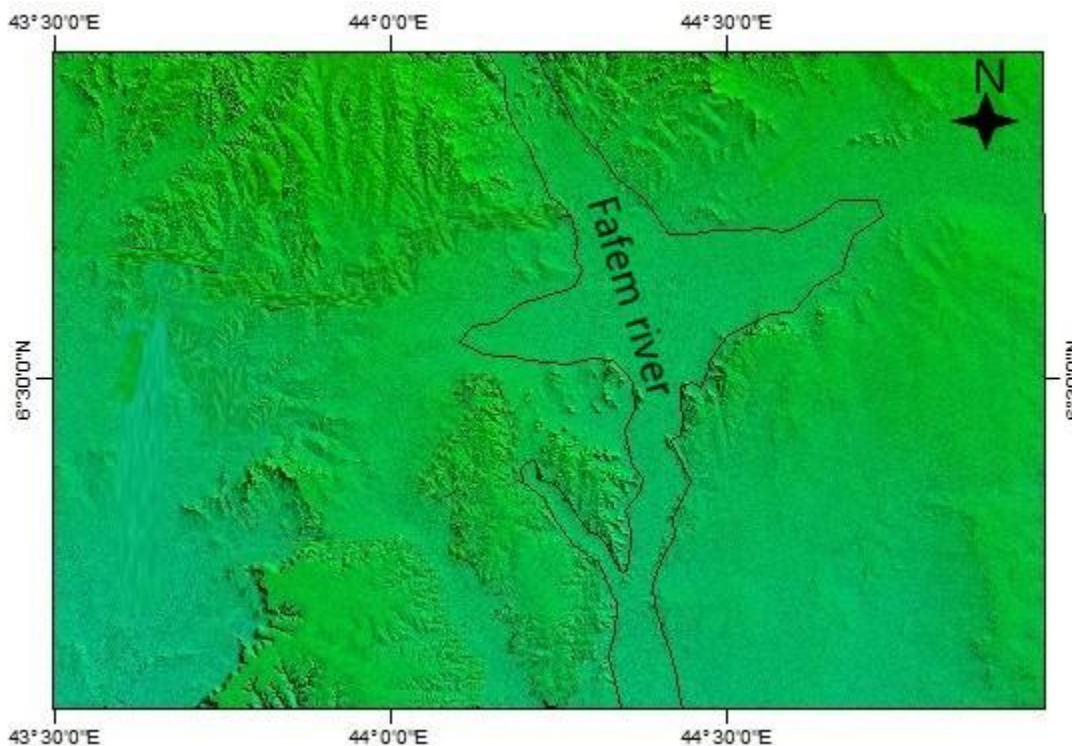


Fig: 1.2. Physiographic map of the study area.

1.3. Previous Works

General works of the geology of Ethiopia with descriptions of the Phanerozoic sediments of the Ogaden basin include: (Kazmin, 1972 and its explanatory notes, 1973, 1975; Merla et al., 1973 and Mengesha et al., 1996), which outlined the geological map of Ethiopia at the scale of 1:2,000,000.

Moreover different studies mainly concerning about petroleum exploration have been conducted in the Ogaden sedimentary basin. These works dated back to early 1930th (Ministry of Water Resources (MoWR), 2004). During the Italian occupation of Ethiopia (1936-1941), AGIP (Azienda Generale Italiana Petroli) conducted a reconnaissance geological survey in the Ogaden area between the years of 1936-1939 (Clift, 1956; Migliorini, 1948, as cited in Purcell, 1976, 1981). The results of these surveys were compiled as a series of unpublished reconnaissance maps and manuscripts dealing with description of sections, paleontology and stratigraphy of the sedimentary sequence.

After the end of Italian Occupation, five oil companies carried out petroleum exploration in the Ogaden Sedimentary basin until 1975. Studies conducted include surface geological surveys, varying amounts of subsurface geophysical surveys (magnetic, gravity and seismic), drilling to various depths, stratigraphic studies, hydrocarbon source rocks and reservoir studies within their respective concession areas (Migliorini, 1948; Clift, 1956; Elwerath, 1967; Taylor, 1947, as cited in Purcell, 1979).

Clift (1956, as cited in Purcell, 1981) has summarized the exploration works of AGIP (1936-1939) and Sinclair (1945-1957) and used the data to reconstruct the sedimentary history of the Ogaden Sedimentary basin; he has also indicated that it was the AGIP geologist who proposed the currently used sedimentary rock Formation names.

The seismic, gravity and magnetic surveys and drillings have all added significantly to the understanding of the structure and stratigraphy of the sedimentary sequences of the Ogaden Sedimentary Basin as a whole.

In addition to the search for petroleum, a number of works have contributed to the understanding of the geology in Ogaden sedimentary basin in the eastern Ethiopia. These include Clift (1956), Hutchinsons (1970), Canuti et al., (1972), Purcell (1976a, 1979, 1981), Tamrat Warku and Astin (1992), John (2016), Kazmin (1972, 1973, 1975), Mengesha et al. (1996) and Merla et al. (1973). Furthermore Gebreyohanese (1989, as cited in John, 2016) on his PhD dissertation conducted a study of the facies, depositional environments, diagenesis and hydrocarbon potential of the Jurassic Hamanlei Formation (Carbonate-Evaporite sequence) in the Ogaden Sedimentary Basin. Shegut (1998) also made a study on the bio-stratigraphy, depositional environment, basin evolution and hydrocarbon potential of the Late Triassic to Late Jurassic succession of the Ogaden sedimentary basin.

BEICIP (1985, as cited in John, 2016), French Company, produced a 1:1,000,000 scale geological map of the Ogaden and surrounding area (Kenya and Somalia) based on Landsat image interpretation and previous available geological maps without field checking. The map covers the Ogaden sedimentary basin between 8°N latitude and the Kenya-Somalia borders in the south and up to the Arsi and Bale highlands to the west. The map provides a good version of the

regional geology of the Ogaden sedimentary basin and was prepared as part of the exploration efforts for petroleum in the Ogaden sedimentary Basin by the Ethiopian Government, thus the map is one of the recent geological maps in the area.

BCEOM-ORSTOM – French Company undertook a geological survey of the Wabi Shebele River Basin (WSRB) between 1969 and 1974 within the context of the Ethio-French Cooperation Program, the Wabi Shebele survey (BCEOM-ORSTOM, 1972). The survey resulted in the production of a generalized 1:1,000,000 scale geological maps of the basin and an accompanying brief explanatory note, as well as seven separate sheets of 1:250,000 scale geological maps of the Lower Wabi Shebele River Basin, covering approximately 83,000 km² area of the basin and brief explanatory note from mainly aerial photographs interpretation with some ground checking.

Generally the geological and stratigraphical framework of the Ogaden Basin was discussed by many works (Kazmin, 1972, 1973, 1975; BEICIP, 1985; Tamrat and Astin, 1992; Mengesha et al., 1996; Shigut, 1998, John, 2016, Purcell, 1976a, 1979, 1981) and other oil companies. The integration of these works has been established the present known stratigraphic formations in the basin.

Korrahei Formation (Neocomian) or main gypsum as formerly defined by Kazmin (1972) represents a period of sedimentation under varied marginal marine sub-environments ranging from lagoonal, intertidal and sabkha settings that marks a phase of sea regression and coastal progradation towards sea (Merla et al., 1979; Mengesha et al., 1996). It is overlain by an Aptian - Albian Calcareous limestone unit (Mustahil Formation) (Russo et al., 1991), and underlain by Portlandian Gabredarre Formation conformably. According to Purcell (1979) the type section of the Formation which is near Gebrideharre town and the present study area, a 200m thick succession comprising gypsum intercalated with marl, shale and limestone were recorded. Migliorini (1948, as cited in Purcell, 1979) assigned the age of this section as Portlandian-Barremian and reported an increasing thickness to the east and southeast. However, Kazmin (1973, 1975) dated the Korrahe Formation as Neocomian on the basis of Foraminifers, and in Somalia it was suggested as of lower Cretaceous age (Barnes, 1976, as cited in Purcell, 1979).

Generally the lithofacies of this Formation involves cyclic inter-bedding of marl, shale, massive gypsum and anhydrites in thick beds, dolomitic limestone and sandstone predominates in the west (Kazmin, 1975). This Formation appears in the Southern and central parts of the Ogaden basin and restricted in the lower part of Gennale and Wabe Shebelle valleys; its thickness increases southwards and exceeds 300m (NWRC, 1972).

1.4. Problem Statement

As far as the paleoenvironmental reconstruction of an evaporitic basin is concerned, a detailed study of the evaporites and associated sediments is crucial, since evaporite rocks can provide important information about the paleoenvironment of deposition, paleoclimate as well as the paleochemistry of the brine. In addition to this, evaporite rocks can also record and indicate the tectonic setting of the basin. According to Warren (2006) and Schreiber et al. (2007) evaporites display different textural and facies assemblages with respect to the tectonic nature (active or passive) of their formative basins. Similarly varied textures and structures were recorded in evaporite rocks formed in different depositional environments and conditions. Therefore, evaporite rocks record information in different ways and it is important to study evaporites in different aspects to reveal their geological records.

Moreover Korrahie Formation is one of the stratigraphy rock formations known in Ogaden basin and it is a thick lithostratigraphic unit dominantly composed of evaporite lithology as reported by several works conducted in the basin. Although the previous works generally studied, classified and described the different lithology of this unit, no detailed study has been conducted and has not been given the proper attention considering the amount of information it can offer about the paleoenvironmental history of the sedimentary basin. Consequently the present study undertakes detailed petrologic and petrographic investigation of this unit. By applying these approaches along with stratigraphic section logging, this thesis research will try to answer the following questions.

- What is the depositional environment of the evaporite-carbonate rocks in the Korrahie Formation?
- What is their diagenetic evolution?

- What is the depositional relationship between evaporites (gypsum) and the carbonate sequences in the Korrahe Formation?

1.5. Objectives

1.5.1 General Objective

The major objective of this study is to characterize the paleoenvironment and depositional conditions favored for the formation of evaporite-carbonate rocks in the Korrahe Formation (Korrahe locality) in the Ogaden basin.

1.5.2. Specific Objectives

The specific objectives of the thesis are:

- ❖ To determine the petrological and petrographical signatures that traces the depositional environments of the sequence.
- ❖ To construct lithostratigraphic section of the succession in the investigated site.
- ❖ To describe macro and micro textures and structures both in the field and laboratory, to determine and distinguish the depositional and diagenetic signatures.
- ❖ To discuss the depositional relationship between the gypsum and carbonate rocks in the Korrahe Formation.

1.6. Methodology

In order to reach the research objectives outlined above and to successfully complete this thesis research, appropriate methods and materials were used at the different stages of the work. The overall activities related to this study were divided into three sequential stages as pre-field work, field work and post field work. The activities and methods applied are discussed in the following sub-sections.

1.6.1. Pre-field work

At the beginning of this study a simple preliminary survey has been conducted to get general overview and the existing situation of the investigated area by means of informal interviews and personal discussions. Moreover, available literature materials, documents,

geological/topographical maps and published or unpublished previous researches carried out within or adjacent areas of the basin and any other geological researches related to this topic has been collected and reviewed. Planning of field work execution and selection of traverse routes and exposure sites were also other activities done during the course of this stage.

1.6.2. Field work and Data collection

The field work comprises several activities and systematic approaches. Apart from field observations, lithological logging and structural descriptions as well as the collection of samples for the detailed and laboratory investigations, it involves a systematic categorization of lithology facies based on their distribution in the investigated site. During the field investigation of the present work the following activities have been carried out: collection of 35 representative samples and sedimentological data such as the description of the lithology, texture, structures and lithological logging by taking pre-defined traverse routes across the outcropped geological features. During this stage different materials were also used including; two topographic maps each with a scale of 1:50,000, Global Positioning System (GPS), geologist hammer, compass, a bottle of diluted hydrochloric acid (HCL) for carbonate test, hand lenses and geological map of 1:250,000 scale, amongst other stationary materials.

1.6.3. Laboratory data analysis and research compilation (Post field work)

1.6.3.1. Laboratory and Petrographic analysis

The representative samples collected during the field for the purpose of detailed study in the laboratory to decipher their microscopic texture and structures were submitted to prepare thin sections. A total of 35 samples were collected from both carbonate and evaporite (gypsum) rocks and 29 of which, were prepared for thin sections, and the petrographical investigations were conducted by using Lecia Petrographic microscope at Addis Ababa University thin section laboratory. The following table (Table.1.1) shows the number of samples submitted for each rock type.

1.6.3.2. Data presentation and research compilation

The various data collected throughout the course of this study at different stages such as reviewing the literature and previous works, interpretation of available geological maps, field observations and laboratory results were integrated, analyzed and synthesized for the completion of the research thesis report.

Table.1.1.The analyzed rock types via petrographical method, and the purpose of the analysis.

Method of analysis	Rock type	No. of samples analyzed	The aim of the analysis
Petrographic analysis	Carbonate rocks	9	Analysis were made to determine modal composition by the relative abundance among the carbonate grains, matrix and sparite, and observations on micro textures to classify Rocks in terms of microfacies, analyze their depositional setting and to decipher effect of post depositional processes.
	Evaporite rocks	20	Mainly to observe micro texture and determine the effect of the diagenetic alteration.

1.7. Significance of the Research

It is believed that a detailed study concerning about petrological and stratigraphical aspects of sedimentary rocks, particularly evaporite and associated carbonate sequences often reflects the nature and genesis of such rocks. Hence, by applying modern petrographic techniques and integrating it with the sedimentological and lithostratigraphical data we can get and develop a good picture about the paleoenvironments and conditions that enabled the formation of this evaporite-carbonate sequence.

Moreover, the results gained from this research will add our understanding about the evolution of the Ogaden sedimentary basin. As a result it will be more useful to the scientific community, since it will have the potential to generate other researches in the near future. Hopefully, it will start an era of detailed and extensive petrological, petrographical as well as geochemical studies of the evaporites and the other deposits found in the Ogaden sedimentary basin, which is one of the least studied sedimentary basins in the country with respect to these methods.

1.8. Limitation of the study

As mentioned in the previous sub-topics, the previous published works conducted in the Ogaden sedimentary basin were mainly focused on general geology and stratigraphical construction of the basin. These were mainly carried out on the aspect of petroleum exploration. Consequently the available resource is limited as far as this research topic is concerned. Another limitation of this research is in the aspect of exposure. The only available exposures are mainly along the main asphalt road (as road cut exposure) and few seasonal streams in the study area, thus away from the road in both sides the unit is highly weathered to a thick alluvial deposit and forms a flat plain. Due to this constraint the end result of this research may not be well representative to the whole unit (Korrahie Formation), which is a widespread formation and outcropped in different parts of the basin.

1.9. Outline of the Research

This thesis research was organized into six main chapters. These chapters were subdivided into sections and sub-sections. The first chapter gives a brief introduction about the purpose and approaches adopted in this study, the research significance and limitations; it also introduces the location and physiographic setup of the study area and summarizes the previous works conducted on the Ogaden sedimentary basin. Chapter two discusses and outlines the regional geological setting along with summarized description of the stratigraphical units in the basin, and chapter three presents the geology of the study area and describes the different lithofacies found in this area while chapter four describes the petrographical features of the analyzed samples collected from the study area along with the categorization of carbonate microfacies types.

Chapter five is all about the discussion and interpretation of depositional environments and stratigraphy section logs as well as diagenetic processes and their attributes, and finally the conclusion drawn from this study and the forwarded recommendations for the future works are presented in chapter six.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Regional Geological Setting

Wide variety of rocks, differ in terms of age and origin are underlain the geology of Ethiopia. These variable rock formations, range in age from Precambrian to recent can be classified based on their origin and evolution. As a result, the geology of the country is generally divided into three geological Formations namely: Precambrian basement rocks, Paleozoic-Tertiary sediments and Cenozoic volcanic rocks.

Apart from Tertiary volcanic rocks and Precambrian basement, the country holds a vast sedimentary succession which accumulated in the five major sedimentary basins. These are the Ogaden basin (350,000 sq.km), Blue Nile basin (63,000 sq.km), Mekele basin (8,000 sq.km), Gambela basin (17,000 sq.km) and Southern Rift basins (15,000 sq.km), (Hunegnaw, 2007, as cited in Beressa Edessa, 2008). Among these sedimentary basins the first three are relatively older than the last two basins. It is believed that they were formed as a result of polyphase break up and extensional stress of the Gondwanaland accompanied by reactivation of pre-existing structures and the formation of Neotethyan passive margin along the present day margin of the eastern Africa (GSE, 2016).

Structurally the East African region has been affected by two major phases of crustal extension. The first phase was the widespread intracontinental rifting commonly known as the Karoo rift, which occurred at Late Paleozoic, probably the Permian period. This rift stretches from the present day southern to eastern parts of African margin and corresponds to the commencement of the Gondwanaland fragmentation (Norton and Sclater, 1979, as cited in Tamrat Warku and Astin, 1992). During this crumbling further subsidence and rifting continued throughout the Mesozoic era and with the associated sea-level fluctuations, resulted the formation of cyclic patterns of shallow- marine carbonates, shales, evaporites and minor clastic deposits.

The second phase of rifting occurred primarily in the Tertiary period and related to the separation of Arabia and Africa along the Gulf of Aden, the Red Sea and the recent proto-fragmenting of the African plate along the East African rift system (Purcell, 1981).

Tectonic evolutions throughout east African margin and the general effect of sea level fluctuations throughout geologic time have great roles for the formation and development of the Ethiopian sedimentary basins and their thick accumulated sediments. The development of most of these basins is related to the extensional tectonic episodes that have operated on the region since the late Paleozoic and continued up to Tertiary (Merla et al., 1979; Blanford, 1970 as cited in Beksa amente, 2018). The beginning of the breakup of Gondwanaland gave rise to the Jurassic flooding of the entire Horn of Africa with a marine transgression from the Paleotethys and the Indian/Madagascar nascent ocean (Abbate et al., 2015), and thus most of the Mesozoic sedimentary successions in the country is part of the vast sedimentary successions of East Africa which was deposited during the Mesozoic transgression.

Furthermore an alternate sinking and uplifting of the landmass under the Horn of Africa triggering transgression of the Indian Ocean from the southeast to the northwest, marked the early Mesozoic continental inundation (Getaneh Assefa, 1991; Bosellini, 1989 as cited in Beksa amente, 2018), and reaching its maximum limit in western Ethiopia and Eritrea.

According to Kazmin (1972), Beyth (1972b), Purcell (1981) and Mengesha Tefera et al. (1996) three major transgression and regression cycles occurred during the Mesozoic era, (the Triassic-Jurassic, the Aptian-Albian and the Cenomanian-Maestrichtian). The first cycle initiates and responsible for the formation of the widespread Mesozoic sediments accumulated in the major sedimentary basins of Ethiopia. However, the second and the third cycles are recorded only in the Ogaden Basin and responsible for the deposition of Mustahil and Ferfer Formations and the Belet Uen and Jessoma Formations respectively (Abbate et al., 2015). The Mustahil Formation marks the beginning of the Aptian transgression whereas the Belet Uen Formation marks the beginning of the Cenomanian transgression. As a result the Mesozoic sedimentary succession of Ethiopia is present in three sedimentary basins namely: the Mekele outlier, the Blue Nile basin

and the Ogaden basin (Kazmin, 1972; Merla et al., 1979; Beyth, 1972b; Getaneh Assefa, 1991; Purcell, 1981).

The Ogaden basin is one of the Ethiopian sedimentary basins, evolved similarly through that long-term tectonic situations discussed above. It is located in southeastern part of Ethiopia and covers an area of over 350,000 square kilometers (Hunegnaw, 2007, as cited in Beressa Edessa, 2008; Purcell, 1979, 1981). The basin extends into Somalia and Kenya and contains over 7000 meters of Permian to Tertiary sediments (Purcell, 1981).

According to Getaneh Assefa (1988), the Ogaden basin was initiated in Paleozoic time as part of the regional trough induced by the break-up of Gondwanaland, and is dominated by non-compressional tectonic processes. Also BEICIP (1985, as cited in John, 2016) concluded that the Ogaden sedimentary basin developed in a triple junction rift system during Upper Paleozoic-Mesozoic, the Bodle deep north-south (N-S), the Calub Saddle east-northeast to west-southwest (ENE-WSW) and the Blue Nile northwest-southeast (NW-SE). These three directions of rifting are the result of a northwest to southeast system of extensional stresses and related to the opening process of the North Atlantic and proto-Indian oceans. This extensional tectonics is considered to be the most dominant features for the development of the Ogaden sedimentary basin.

According to Purcell (1979), the isopach maps of the Jurassic and lower Cretaceous formations show that sedimentation in the Ogaden basin was controlled by two major troughs, one trending north/northeast from Kenya through Somalia to western Ogaden basin and the other trough trending northwest from coastal Somalia through Ogaden into Blue Nile basin, the eastern part of this trough is referred to as the eastern Ogaden sub-basin. In contrast the isopachs of the upper Cretaceous and Tertiary formations in the eastern Ogaden basin show that a NNE-trending coastal Somalia basin which penetrated into the eastern Ogaden basin and presents only as an embayment. The presence of unconformable contact relationship between the Upper Cretaceous and Tertiary formations in the eastern Ogaden sequences and the underlying Jurassic-Lower Cretaceous sequences in the Ogaden basin is also evidence that Purcell (1979) used to make this distinction, and as a result he defines the Ogaden basin as an Upper Paleozoic to Lower Cretaceous feature.

Furthermore, Mesozoic and Tertiary sediments outcrop in the basin with a linear contact along the northwest-trending Marda Fault lineament (Fig.2.1), which divides the Ogaden basin into western and eastern sub-basins (Purcell, 1976, 1981). The Ogaden basin represents a sedimentary succession of full transgression and regression accommodated by rifting and subsidence of the present day passive margin of eastern Africa. It is one of the five major sedimentary basins found in Ethiopia, composed of Precambrian crystalline basement rocks, Paleozoic-Cenozoic Sediments and patches of Tertiary volcanic rocks.

According to Mengesha et al., (1996), Abbate et al., (2015), John (2016) and Purcell (1979, 1981), the geodynamic history of Ogaden basin can be summarized as follows:

- Period of collision and terrain accretion of African cratons and formation of East African Orogeny followed by tectonic quiescence and intense weathering and erosion of basement rocks. As Purcell (1976) suggested, the Marda Fault and the Galadi Fault appear to have been a controlled element in the structure and stratigraphy of the Paleozoic rift system in the Ethiopian Ogaden basin.
- The intracontinental rifting due to the breakup of Gondwanaland which began probably in the Late Carboniferous and subsequently filled by different sediments as rifting and subsidence progressed, which led to the sea transgression from southeast and advanced to northwest through the Ogaden in early to late Jurassic. This inturn related to the tectonics of the separation of Madagascar from Africa coast and the development of the nascent Indian Ocean.
- General uplift of the Ethio-Yemen or Arabo-Ethiopian dome continued in the Paleocene, elevating the flanks of the western Ogaden sub-basin, and at the same time subsidence of the coastal zone caused the Paleocene seas to advance westward, up to the eastern Ogaden basin(Purcell,1979).

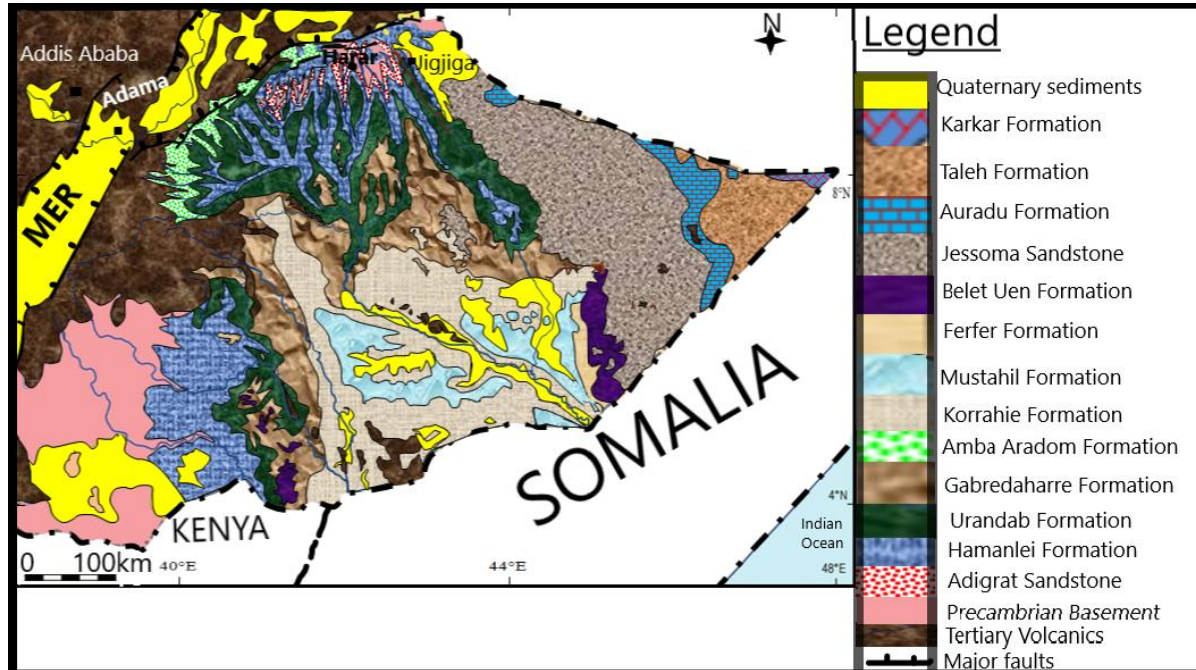


Fig.2.1. Regional Geological map of the southeast Ethiopia and the Ogaden basin (modified after Mengesha et al., 1996 and Mege et al., 2015).

2.2. General Stratigraphy of the Ogaden basin

The Ogaden Basin is one of the three major sedimentary basins found in Ethiopia; it has high potential for hydrocarbons and stratigraphically composed of crystalline basement rocks, Paleozoic-Cenozoic sediments and patches of volcanic rocks.

The currently used general stratigraphy of the Ogaden sedimentary basin has been established from studies by several oil companies and by the Ethiopian Institute of Geological Surveys as well as unpublished works (Mohr, 1963; Kazmin, 1972, as cited in Tamrat Warku and Astin, 1992).

The geological map of the Ogaden basin is shown on (Fig.2.1), and as far as the sedimentary surface geology of the Ogaden basin is concerned, the basin is subdivided into the Mesozoic and Tertiary sedimentary provinces by the Marda fault zone (Mege et al., 2015; Purcell, 1976a). As a result the western part of the Ogaden basin is covered by Jurassic sediments and overlain by Cretaceous sediments around the basin margin and in the basin center, whereas the Tertiary

sediments cover the entire eastern part of the basin and display an outcrop pattern that reflects the NNE-trending trough of the Somalia coastal basin (Purcell, 1979).

The Paleozoic history of the basin is represented by the subsurface continental Karroo sediments as evidenced by the drilled wells in the basin. Within this Paleozoic sediments, three Formations have been recognized (Calub Sandstone, Bokh Shale and Gumburo Sandstone) (Purcell, 1979, 1981; Kazmin, 1972; Tamrat Worku and Astin, 1992), which are considered to be either Permian (Purcell, 1979) or lower Paleozoic age (Elwerath, 1967, as cited in Purcell, 1981).

The four major geological units commonly found in all East African basins including the Ogaden Basin, from the oldest to the youngest are:

- 1) The Precambrian basement complex
- 2) The Karroo Rift Sediments (Late Paleozoic sediments)
- 3) The Mesozoic-Cenozoic sedimentary succession, and
- 4) The Tertiary and Quaternary volcanic rocks which cap the older deposits.

The following is the description and summary of the stratigraphic units found in the basin.

2.2.1. Precambrian basement complex

The Precambrian geology in the Ogaden Basin is little understood due mainly to limited exposure of the Precambrian rocks. Except for few exposures bounded the basin's periphery; like the Chercher block in the north, Negele block in the southwest and Bur massif in the south (Purcell, 1979). Most information about the Precambrian rocks is obtained from deep well drilling. The Precambrian basement rocks beneath the Ogaden basin are considered to be Mozambique Belt of southeastern Africa (Unesco, 1969, as cited in Purcell, 1979). However, Kazmin (1972) related this as part of Upper Proterozoic Red Sea Geosynclines.

2.2.2. Late Paleozoic sedimentary succession

The Paleozoic history in the Horn of Africa has been traditionally described as a period of denudation, where erosion slowly leveled the Precambrian terrain (Purcell, 1981), which made

uncertain the different scale significance indications of the upper Paleozoic sediments in the region. The presence of extensive Permian sediments in the Ogaden basin is now well established (Purcell, 1979), and estimated by analogy to the Mandera-lugh basin, about 4000m in the western Ogaden sub-basin. Thus the oldest sedimentary rocks in the basin are the continental Karroo Rift sedimentary rocks. The name “Karoo” is given in south and east Africa to mostly continental clastic sediments that range in age from Carboniferous to Liassic. It is named after the type area of Karroo Basin in South Africa (Tamrat Warku and Astin, 1992). Similar sedimentary rocks also occur in the same set of rifts both at outcrop and in subsurface, in Zimbabwe, Mozambique, Tanzania, Madagascar, Kenya, Somalia and Ethiopia (Mayne, 1971; Flores, 1973; Kent, 1974; Kamen Kaye, 1978; Cannon et al., 1981, as cited in Tamrat Warku and Astin, 1992). Although thick Upper Paleozoic sediments were reported in the subsurface by drilled wells, there are two known localities in the Ogaden basin where the Paleozoic sediments are outcropped; such outcrops are located near Negele and Ramis river valley (Purcell, 1979).

According to Tamrat Warku and Astin (1992) the Karroo sedimentary succession in the Ogaden basin is subdivided into four Formations (Calub Sandstone, Bokh Shale, Gumburo Sandstone and Adigrat Sandstone), which are encountered in deep wells drilled for petroleum exploration in southeastern and central parts of the Ogaden sedimentary basin. This subdivision considers the complete gradation between Gumburo Sandstone and Adigrat Sandstone, and presumes continuous deposition for the continental clastic sediments until terminated by lower to middle Jurassic carbonate deposition. It also follows the usage elsewhere in east Africa region, where all continental sediments below the widespread Mesozoic marine transgression are included in the Karroo, and were named ‘Karoo sequences’ (Kamen Kaye, 1978; Cannon et al., 1981, as cited in Tamrat Warku and Astin, 1992). However, the term ‘Pre-Adigrat’ is more commonly used in Ethiopia all the Paleozoic sediments below the Adigrat Sandstone (Purcell, 1979). These sedimentary sequences from the oldest to the youngest are included:

Calub Sandstone, Bokh Shale and Gumburo Sandstone, these are correlable to other upper Paleozoic sedimentary rocks which have been reported in many parts of Ethiopia; such as, northern Ethiopia (Enticho Sandstone), central Ethiopia (Pre-Adigrat Sandstone) and southwestern Ethiopia.

Table: 2.1. Key features of the Karroo stratigraphy in the Ogaden Basin (modified after Tamrat Warku and Astin, 1992).

Formation	Approx.Age	Basal contact	Description	Average thickness(m)
Gumburo Sandstone	Late Triassic?	Transitional	It is light green to grey medium sized subarkosic sandstone and becoming more quartzitic upwards. It Consists of amalgamated, parallel bedded, and cross-bedded with minor beds of well sorted fine pebble conglomerate consisting of quartz, feldspar, wood and reworked green mudstone and siltstone.	290
Bokh Shale	Early Triassic	Transitional	Dominantly it contains dark grey and minor dark green to reddish brown finely laminated shales with interbeds of siltstone and fine sandstone which become abundant to the top of the formation	300
Calub Sandstone	Permian?	Unconformity	It is an arkosic sandstone with coarse grains and moderately sorted, it consists of some granular conglomerate and minor beds of reddish brown siltstone, beds of lithic sandstone rich in basic volcanic clasts in association with beds of intermediate to basic volcanic tuffs are also present,	120

2.2.3. Mesozoic-Cenozoic sedimentary succession

The Mesozoic sedimentary succession is widespread throughout the country and commonly found in the major sedimentary basins. It is believed that as they were formed from the known SE-NW trending marine transgression (Kazmin, 1973). In the Ogaden basin the Mesozoic sediments comprise from the oldest to the youngest as follows:

Adigrat Sandstone: this unit occurs in all sedimentary basins in country and even it is correlable to other east African and Arabian sediments (Kazmin, 1973). In Ethiopia it is unconformable or conformably rests on either Precambrian basements or Paleozoic sediments (Karoo sediments). It was first defined in northern Ethiopia as its type locality near the village of Adigrat and named by Blanford, (1870, as cited in Purcell, 1979). It has a thickness ranging from 200-300m in the Blue Nile basin (John, 2016), in the Ogaden basin it is underlain by Paleozoic sediments (Karoo sediments) and passes upward into a transition zone to Hammenlie formation (Purcell, 1981), and in the northern part of the basin it is outcropped and rests on basement rocks and it consists of an intercalation of sandstones, calcareous sandstone, dolomite, shale and marl (Kazmin, 1972; Purcell, 1979; John, 2016). According to John (2016) the Adigrat sandstone is a typical fluvial succession with braided-stream deposits at the base, point-bar sequences in the middle, and coastal plain to lagoonal sediments at the top. Thus Adigrat Sandstone can be considered a time-transgressive unit, which marks the beginning of Jurassic sea transgression that invades across the horn of Africa.

Hammanlei Formation: this unit was originally recorded at the type locality near the village of Hamanlei in the northern part of the basin (Purcell, 1979). It overlays on and partly intercalated the Adigrat Sandstone, although a transitional zone between these two Formations were reported (John, 2016; Purcell, 1979; Kazmin, 1972) and in some areas it directly overlays on basement rocks such as in the western part of the basin and Harrer area. Generally the Hamanlei Formation contains a transgressive carbonate-evaporite succession which changes upward into basinal shale and marl of the Urandab Formation. In the northern and central part of the country Hamanlie Formation is equivalent to Jurassic limestone of Antalo Formation (Kazmin, 1973, Purcell, 1979).

According to John (2016) in the Ogaden basin Hamanlei Formation is subdivided into three lithological units as;

Lower Hamanlei clastic-carbonate mixed facies; which is only found in the Ogaden basin and reported its equivalent in the Blue Nile basin as a transitional sand facies (Gebreyohannes, 1989, as cited in John, 2016). It represents the first marine deposits formed from the sea transgression (Kazmin, 1973; Greitzer, 1970). This part of the Hamanlei Formation reflects open lagoon-marine conditions and beginning of a carbonate platform in the Ogaden Basin as its thickness indicates. It thins to the northeast and thickens to the south (Shigut, 1997, as cited in John, 2016). Thus its thickness decreases from 338.7 at El-kuran-well 1 in the south, to 256m at Gumburo-well 1 and 165m at XEF-2.

Middle Hamanlei: is an evaporite-carbonate sequence and it presents both in the Ogaden and Blue Nile basins. It contains an alternating lithology of limestone, dolostone, and evaporites with abundant oolites, algal stromatolites, green algae, foraminifera, echinoids, gastropods etc. (John, 2016). The depositional setting of this part of Hamanlei Formation was suggested under hot climatic conditions adjacent to a gently shelving seafloor (Migliorini, 1956, as cited in John, 2016).

Upper Hamanlei: is composed of mainly skeletal, peloidal grainstones and mudstones and at places near the base it contains high energy oolitic grainstones. This part of the Hamanlei Formation is overlying by Urandab Formation in the Ogaden basin, but in the Harare area it is overlain by the regressive Amba aradam sandstone. The thickness of the upper Hamanlei is range from 396-488m with maximum thickness of 544m at Hilala-1 (BEICIP, 1985 as cited in John, 2016). The age of this unit was assigned from Liassic-Bathonian in the basin axis (Purcell, 1979).

Urandab Formation: it conformably overlays the Hammanlie Formation and characterizes a dark greenish gray carbonaceous fissile shale and argillaceous limestone with marl and gypsiferous limestone with a thickness of about 400m (Mengesha et al., 1996; Purcell, 1979). It is assigned Oxfordian-Kimerdgian age on the basis of microfossils (Kazmin, 1975, 1972; Purcell, 1979). At its type section near Urandab village in the Ogaden basin it is measured a

thickness of 55m. The overall thickness of the unit decreases towards northeastern part of the basin where it reaches a thickness of about 115m at Gumboro-1 well (John, 2016).

Gabredarre Formation: this Formation represents the upper most Jurassic successions in the Ogaden basin and was formerly named by Kazmin (1975; 1972) as Gabredarre series. It contains light colored oolitic limestone, marl and shale becoming brecciated pisolitic limestone with marl and gypsiferous eastward, its thickness is 410m at the type section near Gebrideharre town (Kazmin, 1972; Purcell, 1979). It has a sharp to gradational contact to the underlying Urandab formation in the eastern and western parts of basin respectively, and gradational to the overlying Korrahe formation (Mengesha et al., 1996). In the western flanks of the basin this unit is laterally changes to sandstone which is termed Garbaharre Formation in the southwestern Ethiopia and Somalia, and in the northern flank of the basin it changes to Amba aradam sandstone (Purcell, 1979). The Formation was assigned Kimerdgian-Portlandian age (Kazmin, 1972). It was recorded a variable thickness across the unit from 1259m at Shillabo-1 well to 165m at Galadi and totally missing far to the northeastern part of the basin mainly due to uplift and erosion or non deposition (John, 2016).

Korrahei Formation: Korrahei Formation or main gypsum as formerly named by Kazmin (1972, 1975) is the lower most unit of the Cretaceous sediment in the basin, and marks the deposition under a period of sea regression and shoreline progradation towards sea. The unit outcrops over large areas of the western part of the Ogaden basin and extends into the Mandera-Lugh trough, where it consists of gypsum and limestone with interbedded shale. The type section of the Korrahei Formation is at Korrahe village near Gabredarre town in Ethiopia and comprises 200 meters of gypsum intercalated with limestone, marls and shale (Purcell, 1979).

According to (Mengesha et al., 1996; Kazmin, 1972, 1975; Purcell, 1979; John, 2016) the lower part of the Korrahei Formation consists of alternations of dolomitic limestone, marl, shale and anhydrite with sandstone in the west, whereas the upper part of the Formation consists of massive, white and grey anhydrite with beds of dolomite and shale. It has a gradational contact of both the underlying and the overlying Formations. In the western Ogaden sub basin, the Formation is thickest in the basin centre where Bodle-1 well encountered 1680m of interbedded

shale, sandstones, limestone and dolomites with anhydrite and salt and at El Kuran-1 well it was encountered a thick section of shale, limestone and sandstones, increasingly clastic in the upper part which is characterized by interbeds of red shale and gypsum.

The Korrahei Formation has been assigned Neocomian age on the basis of *Choffatella* and *Orbitolina* found in the unit (Merla, 1979, as cited in Mengesha et al., 1996). It is interpreted as inner shelf deposits formed as a result of large evaporitic areas left behind during the regression of the Jurassic sea (John, 2016).

Mustahil Formation: this Formation is exposed in the Fafam valley and in the lower reaches of Wabi Shabele valley of the Ogaden basin and it rests on Korrahie Formation. At its type section near Mustahil village, it consists of alternating light grey limestone interbedded with shale and marl in the lower part and fossiliferous limestone rich in *Orbitolina* dominate on the upper part (Mengesha et al., 1996; Purcell, 1979; Russo et al., 1991). On the basis of paleontology it is assigned an Aptian-Albian age and was deposited inner to outer shelf environment (Kazmin, 1975, 1972; Russo et al., 1991; John, 2016). This Formation marks a Cretaceous sea transgression across the East Africa and Middle East. The Aptian limestone found at western margins of the Ogaden basin particularly at Sheik huseein and Gramulata mountains near Harar which mostly overlain on sandstone unit indicate the aerial extent of the Cretaceous re-established sea transgression. The underlying sandstone (Amba aradam Sandstone) represents the shoreline facies of the Korrahie Formation (Purcell, 1979)

Ferfer Formation: this Formation belongs to the upper Cretaceous sediments which are considered by some authors (Purcell, 1979 and others) to be part of the Coastal Somalia basin rather than Ogaden basin. The upper Cretaceous sediments in the Ogaden basin outcrop only in the lower Wabi Shebelle valley, and are subdivided into two Formations, the Ferfer Gypsum and the Belet Uen Formation. The Ferfer Formation outcrops along a narrow strip in the southeastern part of the Ogaden basin and stretches along the lower reaches of the Wabi Shebelle River. It has lithological similarity to Korrahie Formation, as it contains alternating lithology of dolomite, limestone, marl and gypsum/anhydrite. It marks a re-established period of regressive deposition (Mengesha et al., 1996; Purcell, 1979). It was postulated an age of Albian-Cenomanian based on

its stratigraphic position (Mengesha et al., 1996). It is interpreted as restricted lagoonal deposits (John, 2016).

Belet Uen Formation: this Formation represents the uppermost unit of the Cretaceous sediments. It was first recorded as its type section near Belet Uen in southern Somalia and extends northward into Ogaden basin of Ethiopia following the Wabi Shabele valley (Mengesha et al., 1996; Kazmin, 1972). The unit consists of light grey partially reefal limestone with intercalations of greenish grey glauconitic shale and brownish to green sandstone with minor gypsum at the top part, its thickness varies from 87m to 232m and has a gradational contact to both the underlying and the overlying unit (Mengesha et al., 1996; Purcell, 1979; John, 2016).

Jessoma Formation: this unit marks the lowermost unit in the Tertiary sediments of the Ogaden basin (upper Cretaceous-Paleocene). It was first observed at its type locality near Jessoma village in Somalia. According to Mengesha et al. (1996) the Formation contains dominantly by unfossiliferous cross-bedded sandstone with some shale intercalations and laterites, its thickness varies from west to east across the basin (from 100m to over 300m). Similarly its depositional environment is variable from west to east (fluvial continents to near shore littoral). In the eastern part of the Ogaden basin the Formations below the Jessoma Sandstone get older progressively from south to north and conformably overly by the Auradu Formation. The Jessoma Sandstone is a transgressive unit (Kazmin, 1972; Purcell, 1979). However, some authors suggested that the Jessoma Sandstone represents the end-Cretaceous regression facies rather than the beginning of the Tertiary transgression (Purcell, 1979)

Auradu Formation: Is a limestone dominated unit that was first defined and named as Urade by Gregory (1921, as cited in Purcell, 1979) and assigned to Cretaceous in the northern Somalia, but by later works changed and renamed as Auradu and assigned to Eocene. This Formation presents in the easternmost part of the Ogaden basin and consists of: in the lower part pink to grey massive limestone with cherty concretions and in the upper part it is a chalky limestone with shale, this part is termed Allahkajid beds (Mengesha et al., 1996). This Formation typically occurs in the Coastal Somalia, and represents in Ethiopia an Eocene marine transgression that reached in the eastern extreme edges of the Ogaden basin.

Taleh Formation: this Formation is also outcropped in the extreme margin of the eastern Ogaden basin and represents shallowing water depth caused by either shoreline progradation and/or regional uplift (Purcell, 1979). This unit is conformably rests on the lower part of the underlying Auradu Limestone but interfingers the upper part of the Auradu Formation. It has a gradational contact to the overlying Karkar Formation. Based on this contact relationship to the other Formations, Taleh anhydrite was assigned an age of early to middle Eocene (Mengesha Teferra et al., 1996; Kazmin, 1972). Lithologically Taleh Formation contains massive banded anhydrite with interbeds of fossiliferous cherty limestone, with thickness of 450m at its type section near Taleh village in Somalia (Mengesha et al., 1996; Purcell, 1979).

Karkar Formation: this unit has very small aerial extent in the far east of the Ogaden basin and it widens to the northern Somalia. Thus, it represents the last marine water invasion in the Ethiopian Ogaden basin. It is composed of white colored chalky limestone with thin beds of shale and gypsum. Its age ranges from middle to upper Eocene (Purcell, 1979; Kazmin, 1972, 1975; Mengesha et al., 1996).

2.2.4. Tertiary volcanic rocks

Volcanic rocks are rarely outcrop in the basin, and only present at isolated areas and structural features in the Ogaden basin. Thus they are a minor part of the Ogaden stratigraphy. According to Purcell (1979) the oldest volcanic rocks in the basin was recorded at northwestern flank of the basin and it is an Aptian age which occur in Amba aradam Sandstone. Moreover, the volcanic rocks stretched along the Marda Fault and near Fik town, the isolated patches outcropped near Werder and Dolo are all younger and believed to be Tertiary in age. These younger volcanic rocks are mainly related to the Trap series (Purcell, 1979).

AGE		FORMATION	LITHOLOGY	THICKNESS IN METERS
TERTIARY	EOCENE	KARKAR Fm	[Lithology: brick pattern]	100
		TALEH Fm.	[Lithology: brick pattern]	300
		AURADU Fm.	[Lithology: brick pattern]	400
	PALAEOCENE	JESOMMA SANDSTONE	[Lithology: brick pattern]	420
CRETACEOUS	MAESTRICTIAN	FAF FORMATION	[Lithology: brick pattern]	380
	CAMPANIAN	BELEY UEN FORMATION	[Lithology: brick pattern]	250
	CONIACIAN	FERFER GYPSUM	[Lithology: brick pattern]	200
	TURONIAN	MUSTAHIL FORMATION	[Lithology: brick pattern]	200
	CENOMANIAN			
	ALBIAN			
	APTIAN			
	NEOCOMIAN	MAIN GYPSUM (GORRAHEI) FORMATION	[Lithology: brick pattern]	900
JURASSIC	UPPER MALM	GABREDARRE FORMATION	[Lithology: brick pattern]	130
	KIMMERIDGIAN	UARANDAB Fm.	[Lithology: brick pattern]	120
	OXFORDIAN			
	CALLOVIAN			
	BATHONIAN	HAMANLEI FORMATION	[Lithology: brick pattern]	1200
	BAJOCIAN			
	LIASSIC			
	TRIASSIC	ADIGRAT SANDSTONE	[Lithology: brick pattern]	400
PALAEOZOIC	PERMIAN	GUMBORO SANDSTONE	[Lithology: brick pattern]	400+
		BOKH SHALE	[Lithology: brick pattern]	400+
		CALUB SAND	[Lithology: brick pattern]	100
		CRYSTALLINE BASEMENT AND METASEDIMENTS.	[Lithology: brick pattern]	

Fig: 2.2. Generalized Stratigraphic column of the Ogaden basin (after Purcell, 1979)

CHAPTER THREE

3. GEOLOGY OF THE STUDY AREA

3.1. Introduction

The Neocomian deposits of the Korrahe Formation were formerly described by several works as cyclic intercalations of evaporite and carbonate rocks (Kazmin, 1972; Mengesha et al., 1996). However, detail lithofacies variations and petrographical characteristics of this Formation or part of it, have not been studied yet. The present work considers and investigates these aspects, with the aim of depositional environment interpretations.

Accordingly, petrographic and sedimentological investigation along with outcrop lithology logs is conducted in the locality of Korrahe as a studied section, where the widely distributed Korrahe Formation outcropped. The investigated section is located in the Somali regional state, Korrahe zone, Gabridehar wereda. The studied section is along the main asphalt road between Gabridehar and Danan town (Fig. 3.1). During the field work, observations, lithofacies descriptions and graphic logs of the sequence were mainly made by following exposures along the seasonal streams and the main road, due to the scarcity of exposure in the area. Most of the samples were collected along these areas as shown in (Fig. 3.1).

During the field work, rock units exposed in this section were described and different outcrops were logged (Fig. 3.3) according to their stratigraphy, vertical and lateral contact relationships to produce a composite lithostratigraphy of this section. This chapter will present the classification, lithofacies description and graphic logs of the rock successions based on outcrop scale study.

The field classifications, lithological logging and descriptions of the rock units in the Korrahe section are discussed under the following sections, starting by an overview of lithological associations, before proceeding to the lithofacies classifications and their descriptions.

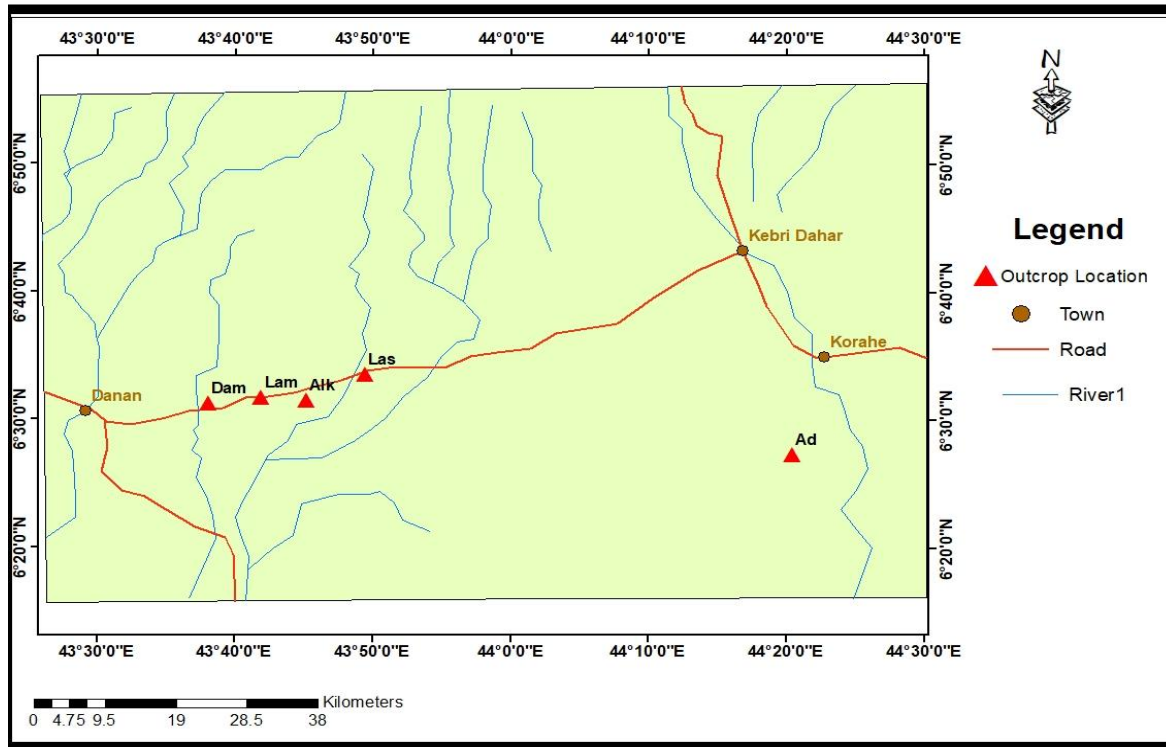


Fig: 3.1. Outcrop and sample location map in the study area (Dam= Damberweine, Lam= Lammaan, Alk=Allakod, Las= Lasdenkeire, Ad= Adalei)

3.2. Overview of the Lithostratigraphy in the Korrahie Section

In Korrahie section two main lithologically different rock units, namely evaporites and carbonates are present in a manner of cyclic intercalation, although the carbonate lithology is subordinate with respect to the evaporite lithology.

Interms of the stratigraphical boundary, the lower stratigraphic control of this carbonate-evaporite succession was not observed in the study area. However, their upper stratigraphic control is present and mostly found on the top of the hills in the southeastern edge of the study area. This upper boundary can be easily observed as a sharp contact by the slope break between the gently formed gypsum below and the directly overlaying, cliff formed limestones (Mustahil Formation). The basal part of the Mustahil Formation consists of thin layers of light grey shale

and yellowish marl intercalations. This basal part graded upward into marl-limestone and grey to light grey thickly bedded limestone.

The exposures of the Korrahie Formation in this area are very limited and they are rare outcrops along the seasonal streams and the main road. The area is characterized by forming a flat plain covered by alluvial sediments and thick weathered gypsum, with only isolated small rounded hills, which are remnants of weathered and eroded limestone and gypsum. A careful inspection allowed describing and measuring the lithologies of the area to provide a detailed bed to bed logging, based on their sedimentary structures, texture, lithology, color and stratigraphic relationships.

Moreover, based on the lithological characteristics and the dominant sedimentological features present within the studied rocks, the vertical and lateral relationships of the outcropped lithologies are described as follows.

Starting from the base of the studied section, it is observable that there is a carbonate dominated lower part and evaporite dominated upper part. Hence, from the base, the succession consists of: laminated white to light grey gypsum which is characterized by very thin discontinuous black and white laminations. These are the occurrence of mm scale fine laminations within thick beds of 40-45cm scale gypsum beds. This unit also displays small sized rosette-like displacive crystal structures, which are sparsely distributed throughout the bed. The thickness of this gypsum layers range from 1 to 1.5m.

Above this unit there is a light yellowish to tan brown and even dark brown colored limestone layers that are thin to thick beds, well consolidated hard rocks with a fine grained muddy texture at the lower part; and thinly laminated medium to relatively coarse grained at the middle part, where it is possible to see even the carbonate grains like shell fragments and showing a graded bedding with a coarsening upward pattern (Fig.3.7A); the upper part is a light grey colored, fine grained lime mudstone. The discernible sedimentary structures in this unit is fine laminations and horizontally planar beds, where the bed thickness irregularly increases from bottom to top of the layer and ranges between 26-45cm, the total thickness of this carbonate layer is upto 6m, but sometimes it is not more than a meter.

Moreover, at some places on the top of this limestone layer there is a thin horizon containing a mixture of angular to sub rounded grey micritic carbonate gravel (upto boulders) embedded within silt to fine sand sized matrix along with white gypsum crystals. The thickness of this horizon is about 30cm, and it can be interpreted as a local erosional surface (subaerial exposure during deposition) or perhaps a solution collapse breccia formed from later stages of evaporite dissolution. However, at other places, especially as one goes from the west to the east of the study area he will find, a nodular gypsum layer resting over a light brown lime mudstone layer that contains a well developed tepee structure and mudcracks. The dominant texture of this gypsum is a nodular texture, where the nodules are either, small in size and elongate, circular or elliptical in shape, or large and form a mosaic-like texture. Sometimes it shows thin interlamination of medium grained lenticular gypsum and carbonate mud alternating with small sized and isolated nodular gypsum dispersed within microbial mat (algal mat). The thickness of this layer is not more than a meter. Vertically and laterally, it gradually changes into laminated, thickly bedded, fine grained white colored gypsum, with a thickness of about 1m. This rarely grades upward into an interlayered clastic gypsum and carbonate mud, which is composed of coarse sand sized lenticular gypsum crystals concentrated along the microbial filaments and/or carbonate mud layers.

In the middle to upper parts of the succession, thick gypsum beds appear to be the dominant lithology with thin interbeds of carbonate layers mainly dolo-mudstone along with associated thin intercalations of lime mudstone, shale and marl layers dominated at the uppermost parts. These interbedded carbonate sediments are mostly found at the base of thick gypsum beds as shown in the graphic logs on (Fig.3.3 and Fig. 3.8) and the outcrop photo in (Fig. 3.2). The sedimentary features observable in these layers range from massive light to dark grey, light yellowish to tan brownish color with thin massive beds or slightly bioturbated calcilutite limestone or dolomitic limestone, to thin planar laminations or rarely cross laminations along with lenticular beds, fenestral fabrics, vuggy pores partially filled with secondary minerals and mud cracks. The other commonly associated minor lithologies are thin intercalations of greenish grey shale and yellowish marl with abundance of fracture filled gypsum crystals and slightly reworked flat pebble fragments at their bottom. Sometimes a carbonate breccia horizon is present which is measurable and traceable for a considerable distance.

Furthermore, the thick gypsum beds found in this part are white to light grey and black colored massive, dome-like shaped with vertically elongated nodules set in argillitic matrix which resemble the bottom growth selenitic crystals (gypsum ghosts) (Fig.3.5E). Planar laminated beds, sometimes alternating with thin laminae of carbonate mud and filamentous microbial micrite is also present. The other common features of these rocks are chicken-wire and entrolithic textures, which are commonly found at the upper parts of the section.

Finally, this alternating, gypsum dominated part is capped and terminated by light yellowish thinly bedded marl-limestone with shale-marl intercalations at the base and light grey thickly bedded cliff forming limestone at the top. Here it is notable that these alternating lithologies (marl, shale/clay and marl-limestone) are considered to be the base of the overlying formation (Mustahil Formation) based on the observed lithological break at the boundary between them and their sharp contact relationship that reflects a depositional change. Moreover, descriptions given by previous works in the basin also confirm this observation. One of those works is that conducted by Russo et al., (1991), in central Somalia near the border between Ethiopia and southern Somalia. In their work on the Mustahil Formation in this area they described the Formation as; basal shale followed by marl, marly limestone and ended by rudistid and coral reef caps, which rests on evaporite-carbonate succession of Korrahie Formation (Neocomian-early Aptian). This point will be more discussed in chapter five of this thesis.

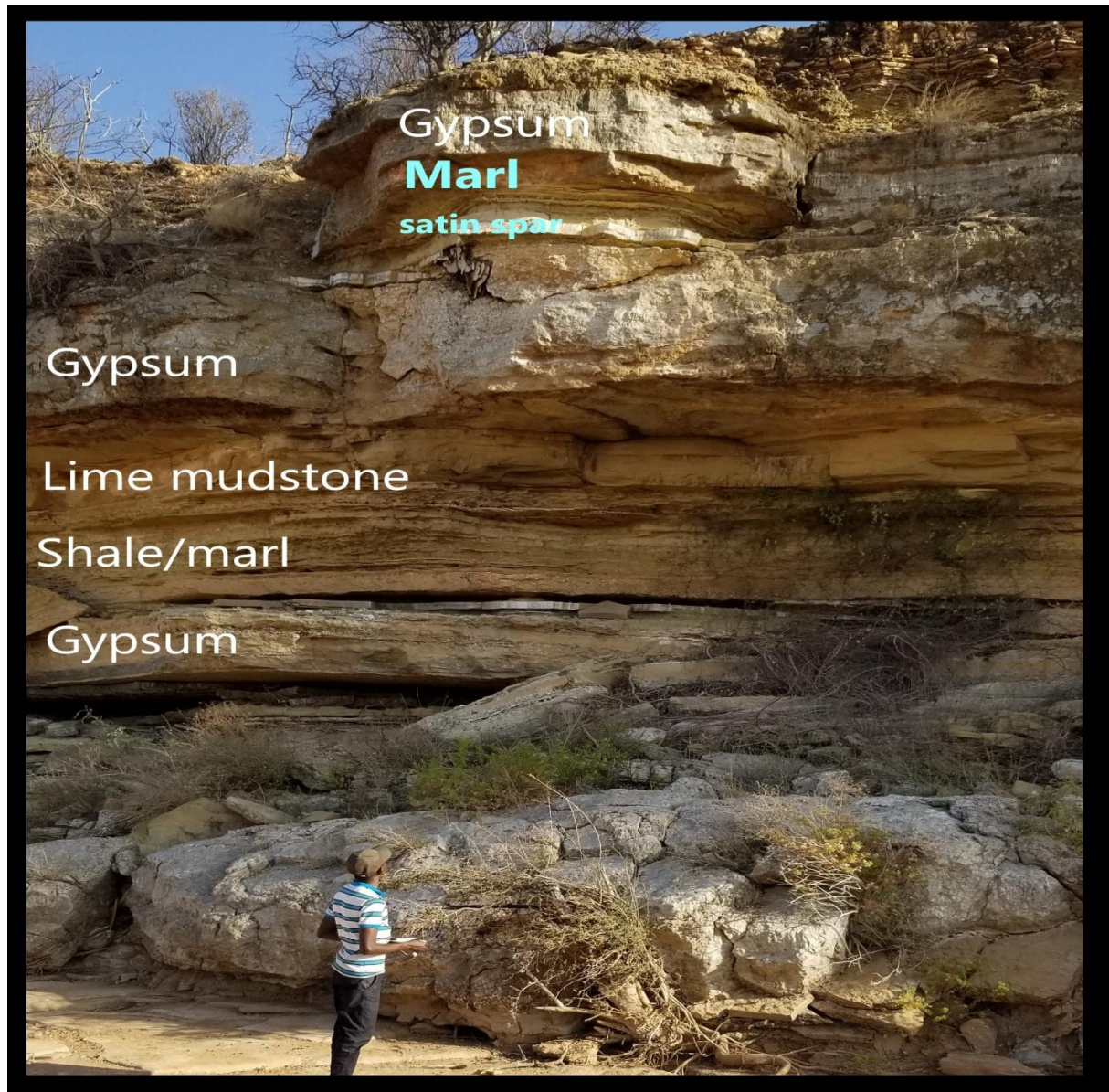


Fig.3.2: outcrop photo showing the vertical sequence of the lithology

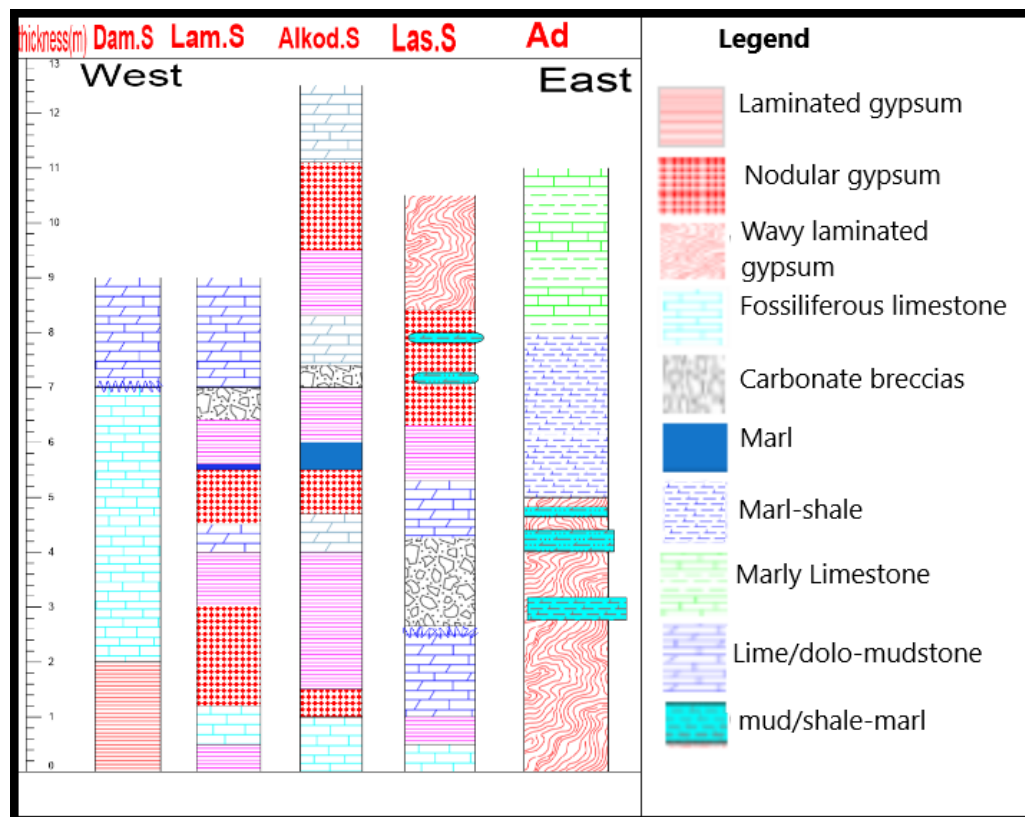


Fig.3.3. Graphic logs of five outcrop sections, namely from west to east (Dam.S= Damberwiene stream, Lam.S= Lammaan stream, Alkd.S= Allakod stream, Las.S= Lasdenkeire stream, Ad= Adaly area).

3.3. Major Lithofacies Analysis

Detailed field investigations on textural, lithological and compositional variations of the rock successions outcropped in the study area, resulted in the recognition and establishment of two main lithologies, namely, evaporite and carbonate lithologies. Based on their observed textures and sedimentary structures the subdivision of these lithologies is possible. Consequently, the evaporite lithologies are subdivided into three lithofacies; and similarly the carbonate is also subdivided into two main lithofacies with minor associated sub-lithofacies.

3.3.1. Evaporite lithofacies

The evaporite lithofacies are the most conspicuous and characteristic lithologies in the study area. It is white, dark grey to light grey and rarely brownish beds. In terms of mineralogy these

lithofacies are commonly composed of calcium sulphate that is highly weathered and altered in outcrops.

In the study area, they are predominantly composed of gypsum with observable macroscopic fabrics (gypsum textures). These fabrics include alabastrine gypsum (fine grained), porphyroblastic gypsum (daisy gypsum), microbial laminated and/or stromatolitic gypsum, fibrous gypsum (satin-spar gypsum), selenitic and enterolithic gypsum textures.

The fine grained gypsum (alabastrine texture) is a secondary type created where precursor anhydrite rehydrated to gypsum. This process occurred in the zone of active phreatic flow (Warren, 2016).

The daisy gypsum (porphyroblastic texture) is formed from fibrous crystals which are arranged into a radial pattern (Fig.3.4A&B) with an average 4-10cm in diameter. It is believed that this type of gypsum is formed under rather homogenous conditions when re-watering of nodular anhydrite unit occurred at depth, as it passes through the stagnant phreatic zone which marks the lowermost parts of the telogenetic zone (Warren, 2006, 2016).

The satin spar gypsum (fibrous texture) is recorded in the studied outcrops with a thickness of 5-15cm and is formed due to transformation of anhydrite to gypsum, which mostly leads the development of fissures or hydration veins, these hydration veins are filled and precipitated later a satin spar and/or selenite gypsum which is an indication of telogenetic alteration and a secondary evaporite texture (Warren, 2016). Nodular texture along with enterolithic structures are also abundant and observed in the outcrops of the study area.

Based on lithological, color, textural and structural variations observed in the field at an outcrop scale, the evaporite lithologies are subdivided into the following lithofacies.

Laminated gypsum (LF1): this facies is the dominant gypsum present in the lower and middle part of the succession and also rarely occurs in the upper part. It is represented by thinly laminated beds and occasionally displays slightly undulating dark grey and white discontinuous laminations which are not traceable with distance. The dark grey, brown or orange laminae represent microbial mat (algal mat) and the white and sometimes black laminae represent

gypsum. The thickness of the laminae within the massive bed of 40-45cm thick is not more than a mm-scale.

Alternating layers/laminations of gypsum and carbonate mud are also abundant and display a graded bedded texture. These beds characterize by fine grained white colored gypsum laminae alternating with white to light brown carbonate mud laminae, with a thickness of about 40-50cm. It grades upward into sand sized clastic gypsum within carbonate mud and/or thin filamentous micrite. The clastic lenticular shaped gypsum crystals appear as they were slightly reworked and entrapped within the microbial micrite as they are oriented and concentrated parallel to bedding and sometimes are randomly oriented and dispersed within the mud.

The other common textures that can be observed in this facies are: extensive fracture filling satin spar and selenitic gypsum, displacive daisy gypsum crystals and enterolithic texture. The daisy gypsum crystals are arranged in a radial pattern with an average diameter of 4-10cm (Fig.3.4 A&B). Such textures are most probably developed as a result of diagenetic processes.

According to Warren (2006, 2016) laminated gypsum is common in subaqueous shallow and deep salina ponds. In such environments, shallowing or deepening upwards sequence can form due to the variation in water fluctuations. However, here the presence of truncation surfaces and intra-sediment layering (Fig.3.4 D) developed as a result of either dissolution on crystal tops, during brine dilution and mixing under holomictic barine (Babel, 2004) or episodic subaerial exposure. The dissolution on crystal tops due to freshening and brine mixing is more possible and attainable in a shallow water and unstratified brine setting than deep water and stratified brine setting (Babel, 2004), and this can be taking as an evidence of subaqueous shallow water origin. Adding to the presence of interlayered microbial filaments (Fig.3.4 C) and intra-sediments also indicate shallower water setting and brining upward with a periodic emergence (Babel, 2004).

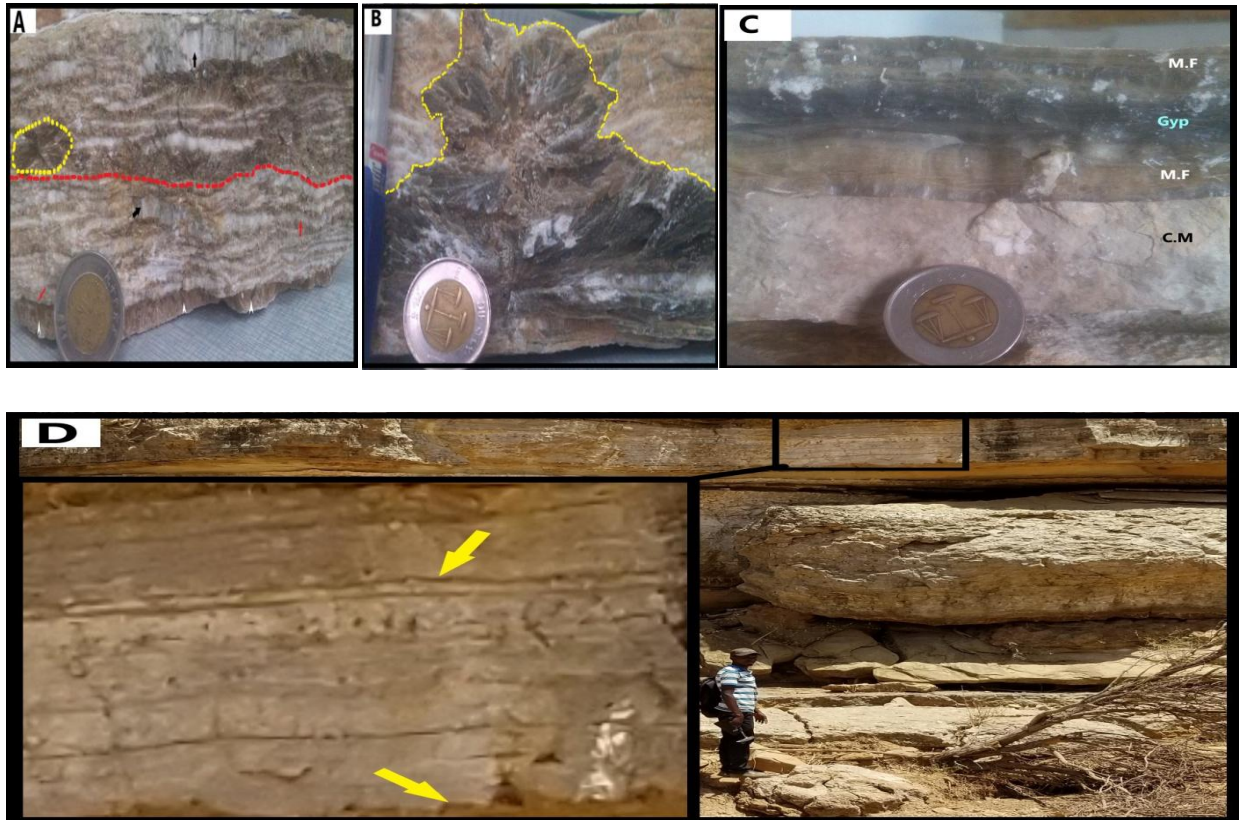
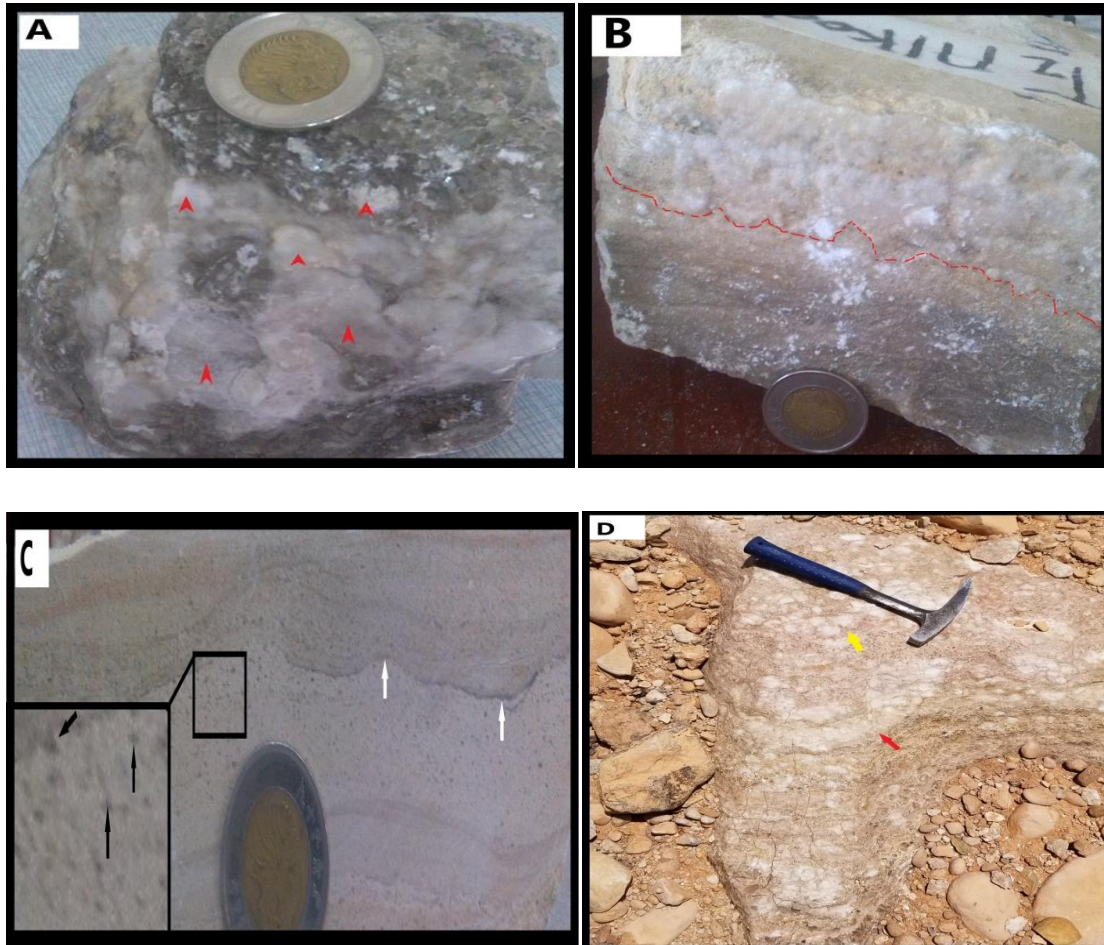


Figure 3.4. Laminated Gypsum facies attributes: **A&B**) showing secondary selenitic (white arrow heads) and satin spar (black arrows) textures along with radial arranged rosette-like gypsum crystals as shown by yellow dashed circle, note also the appearance of entrolithic texture below the red dashed line. **C**) Hand specimen showing planar laminations of alternating carbonate mud (C.M), microbial filaments (M.F) and gypsum (Gyp) laminae. **D**) Magnified view of the outcrop (bottom left corner) showing truncation and partly erosional surfaces between gypsum beds as yellow arrows indicate, some vertical cracks may also indicate vertical desiccation cracks.

Nodular gypsum (LF2): this facies is commonly found in the study area and displays a nodular texture, where the nodule size range from large sized and coalesced nodules, isolated circular and elliptical to lenticular minute crystals. The large sized nodules (Fig.3.5A) are well developed nodules showing preferential elongation or mosaic texture of fine grained alabastrine gypsum. Growth and coalescing of individual nodules into large nodules extensively destroy the carbonate mud matrix, and only thin string between adjacent nodules can be traced (Fig.3.5A). Thus, the depositional structures of the host sediments are completely obliterated by the replacive and displacive growth of these gypsum nodules. However, isolated nodules within microbial carbonate mud display chicken wire-like texture and preserve the host sediments, relatively

banded nodules entrapped within micrite and oriented parallel or sub parallel to the bedding are also observed (Fig.3.5B). On the other hand the minute tiny crystals are imbedded within carbonate mud, and they are only visible in a hand specimen as very fine lenticular shaped crystals as shown in (Fig.3.5C). Due to their appearance they may be vug filled crystals and this can be confirmed by microscopic investigation as will be discussed in the next chapter. Moreover, the rocks containing nodules within the microbial mud and filaments, mostly occur in the lower part of the section while those contain the finer lenticular crystals stratigraphically occur at the upper section, and this may indicate different genetic environments. The large vertically or horizontally elongated nodules within the argillitic matrix shown in (Fig.3.5E) may indicate original bottom growth selenitic gypsum (gypsum ghosts) which is converted to anhydrite nodules (anhydrite pseudomorphs) due to burial and gypsum transformation to anhydrite and then back to gypsum due to uplift process (Schreiber et al., 2007). This complete cycle of the rock history causes the alteration of the depositional texture.



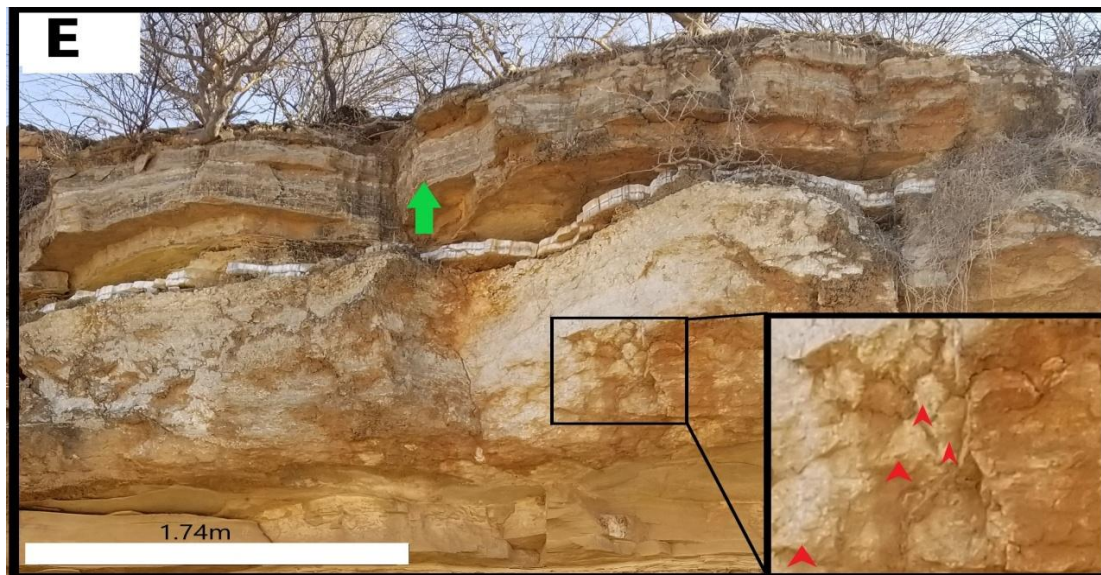


Figure 3.5. Nodular Gypsum facies. **A)** alabastrine gypsum nodules shown by the red arrow heads with coalesced nodules, and the black solid line traces thin string relic of the original host sediments/matrix. **B)** The red dashed line indicates a truncation surface that separates a nodular layer above and crudely laminated layer below. **C)** laminated carbonate mud with extensive displacive/replacive lenticular nodules as shown by the black arrows in the enlarged view (lower left corner), the white arrows indicate truncated surface or eroded surface (probably as a result of subaerial exposure). **D)** isolated nodules as shown by the yellow arrow that display a chicken wire-like texture while the red arrow indicates expanded nodules that grow together and even disturbed the laminations of the host carbonate mud. **E)** outcrop photo showing thick beds with vertically elongated nodules (red arrow heads) and/or horizontally growing into large nodules set in brownish argillitic matrix, and grades up into (green arrow) planar laminated gypsum layer. Note also the thin marl layer sandwiched between the thick gypsum beds. (Scale bar at bottom left).

Wavy laminated gypsum (LF3): this facies is composed of thinly alternating gypsum and carbonate mud along with thin microbial filaments that display wavy and undulating laminar structures which form more or less a laterally close linked morphology of stromatolite type. These stromatolitic wavy laminations are composed of black colored gypsum interlaminated with pinkish to brownish or orange thin microbial laminae and light grey carbonate mud or clay. Small rounded displacive rosette crystals are scattered and densely distributed on the surface of this facies (Fig.3.6A). It is also observed that the presence of thin truncated erosional/flooding horizons that are composed of relatively large reworked and cavity filled material. In some cases this horizon separates the underlying crinkly laminated layer and the overlying planar laminated

carbonate layer (Fig.3.6A &B), composed of pseudomorphic casts of vertically oriented lenticular gypsum crystals along with highly weathered microbial filaments and fenestral fabric. Vertically oriented desiccation cracks which are filled with thin satin spar gypsum are also observable. The aerial extent and distribution of this facies is limited and recorded mostly in the upper part of the section.

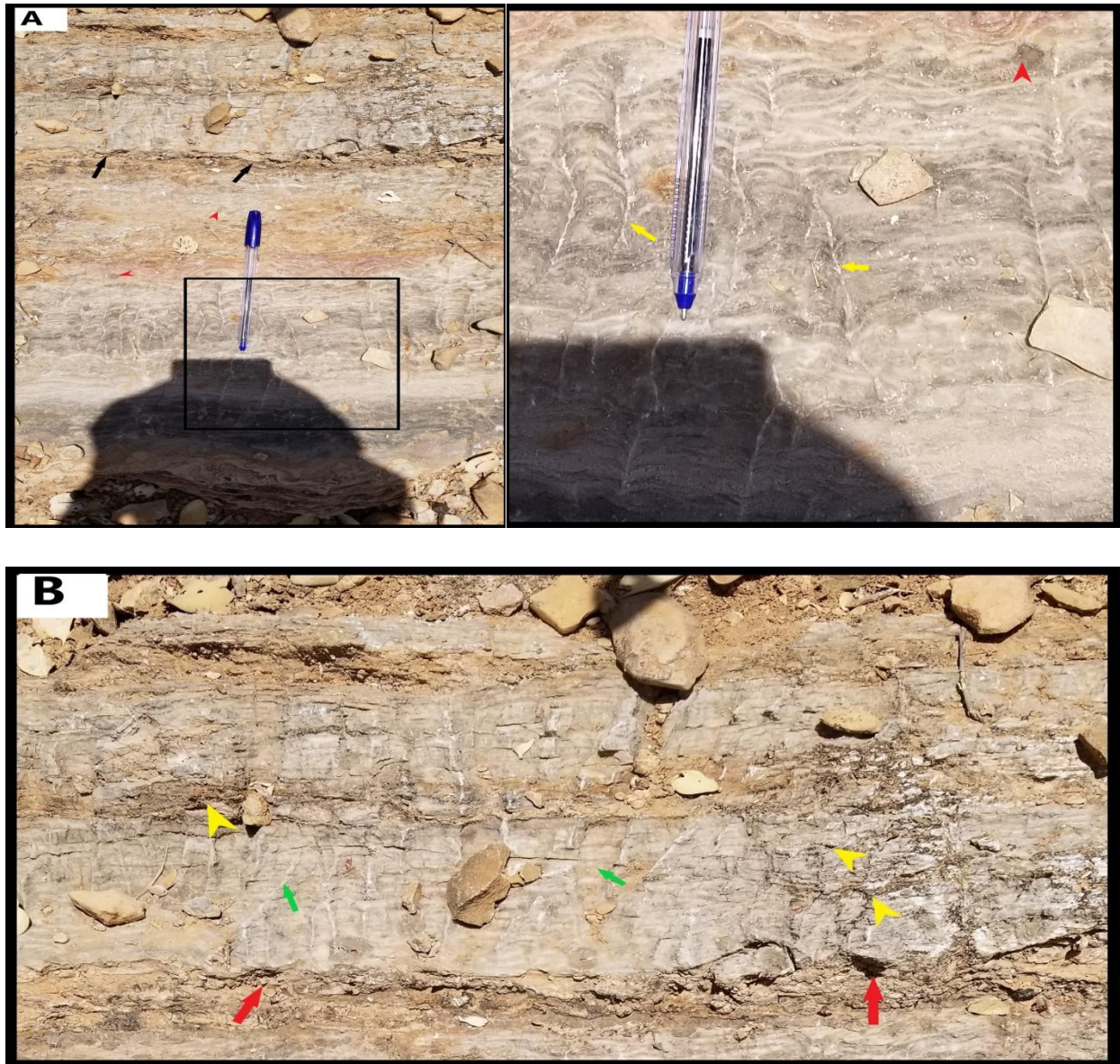


Fig: 3.6. Crinkly laminated stromatolite lithofacies: **A)** undulating light gray, pinkish and brown thin microbial carbonate laminae with thick black gypsum laminae, red arrow heads show small displacive crystals, and the enlarged view box in the right depicts thin vertical dissolution cracks filled with satin spar (yellow arrows). **B)**

details of the upper part in (A) showing the exposure/erosion surface (red arrows) and the overlying thickly laminated lime mudstone containing fenestral fabrics (yellow arrow heads) and vertically oriented lenticular gypsum casts (green arrows).

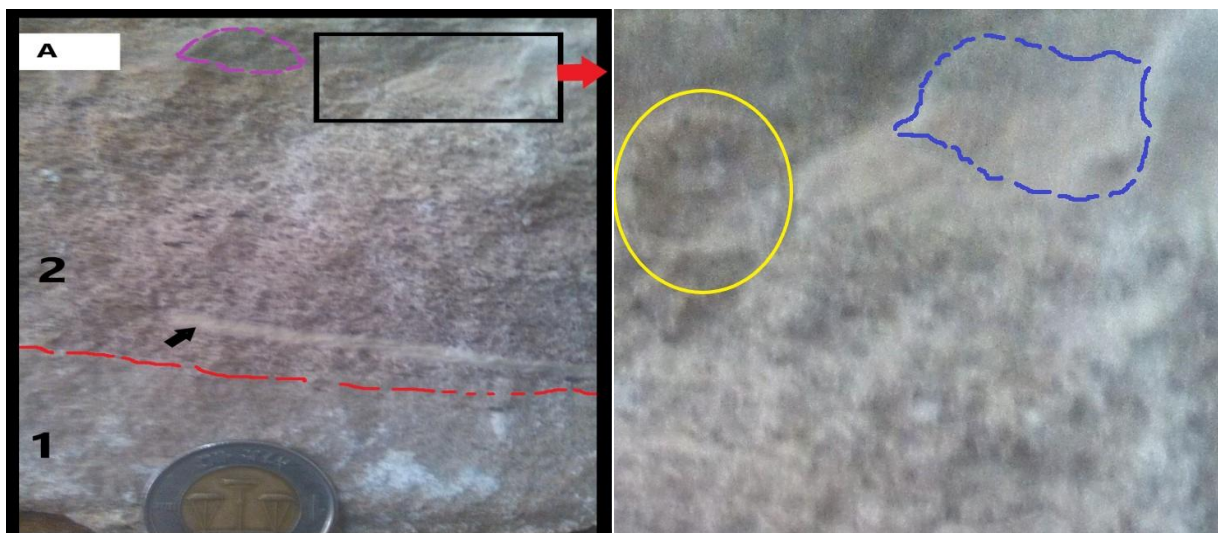
3.3.2. Carbonate lithofacies

The carbonate lithofacies is subordinate in the studied outcrops with respect to the evaporite lithofacies. These carbonate lithologies exhibit tan brown to light brown or dark grey to light grey, yellowish to light yellowish, thick and thinly intercalated beds. Based on the field observations, they are generally classified as fine to medium grained limestones. They contain allochems and very fine grained micritic limestone. At the base of the studied outcrops the carbonates are light brown to yellowish and light grey colored, thin to thickly bedded and calcisiltite to calcarenite fossiliferous limestone which overlies laminated gypsum. It has a variable bed thickness which increases irregularly upward to thick beds of grey colored massive micritic and/or dolomitic limestone, which laterally changes to finely laminated dark grey lime mudstone with shale and marl layers followed by thinly laminated brown to light brown colored fine grained limestone. This micritic limestone has numerous filled and unfilled vuggy porosity, desiccation cracks and fenestral porosity. The whole succession is capped by the Mustahil Limestone which is an alternating lithology of marl and marl-limestone with thin shale's at the base. The following two main lithofacies were recognized in the carbonate rocks, based on their color, textural, structural and compositional variations.

Fossiliferous Limestone (LF 4): this lithofacies is characterized by light brown, yellowish and grey to light grey; thin to thickly bedded intercalations of allochemical, micritic and/or muddy limestone. The dominant lithology among this lithofacies is fossiliferous limestone of fine to medium sand sized grains. Although the carbonate grain types cannot be differentiated at outcrop or hand specimen level, abundant microfossils are observed in thin section samples via petrographic microscope study. This will be discussed and described in the next chapter along with representative photomicrographs. The dominant sedimentary structures observed in this facies are horizontal bedding planes, thin laminations composed of alternating fine and coarse laminae along with graded bedding of either fining up (normal grading) or coarsening up

(reverse grading) as shown in (Fig.3.7A). Generally this facies appear muddy and poorly structured at the bottom, and perhaps this has resulted either by extensive bioturbation subjected to these rocks or by low energy and protected environment origin. This facies is commonly occurring in the lower part of the section and its aerial extent is limited.

Lime/dolo- mudstone (LF 5): this lithofacies is common in the middle and upper part of the section and it is a light brown to tan, yellow and light grey to grey colored; finely laminated to thin massive beds of micritic limestone and/or partially dolomitized limestone. The sedimentary structures observed in this lithofacies are horizontal beds with thin laminations and linear filled and unfilled dissolution features (fenestral porosity), vugy porosity and polygonal mud cracks or desiccation cracks, erosion surfaces, algal stromatolite (thrombolite), vertically elongated burrows and tepee structures as shown in (Fig.3.7 B-F). The other commonly associated minor lithofacies to this facies are thin layers of less consolidated shale and marle along with carbonate breccias. These lithologies, particularly shale layers mostly show vertical to horizontal cracks that are partially or completely filled by clear, white and transparent thin gypsum crystals precipitated perhaps from the overlying gypsum layers. This lithofacies is mostly occurring as thin interbeds/intercalations within thick gypsum layers, as compared to the lower calcarenite limestone lithofacies (LF 4).



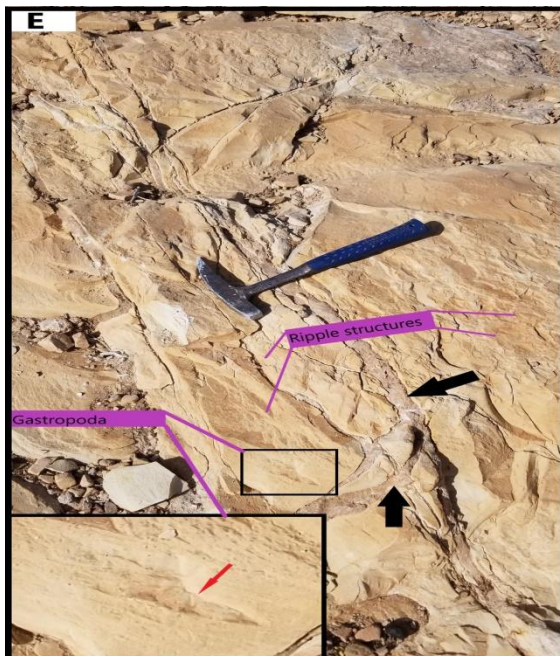
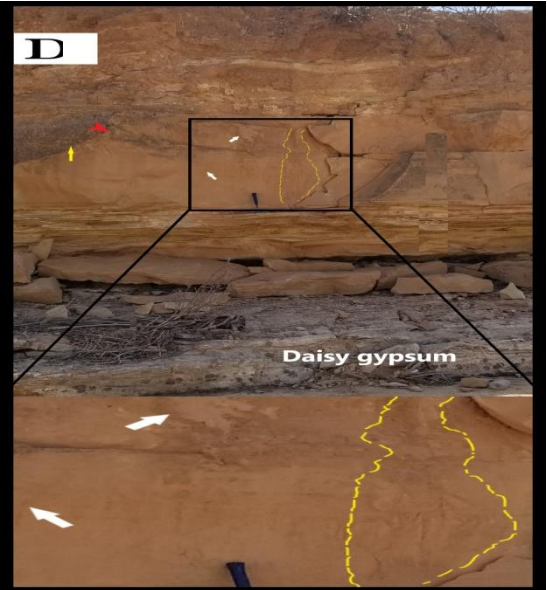
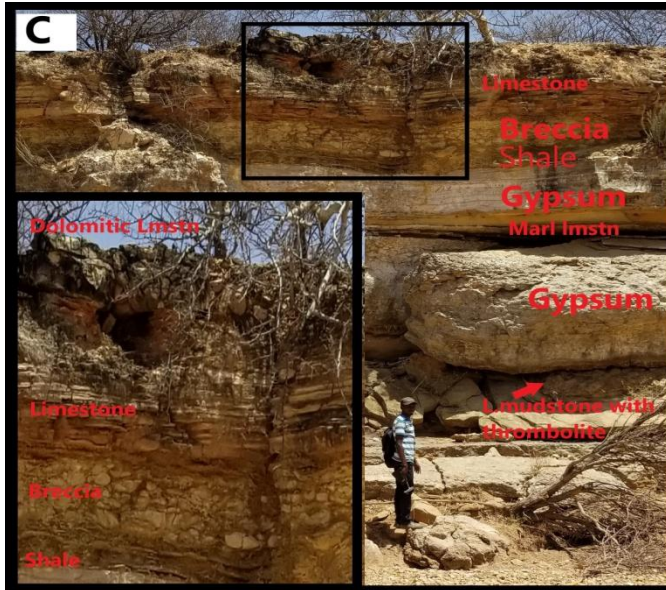


Fig.3.7. Outcrop and hand specimen photos showing different attributes of carbonate lithofacies. **A)** Shows grading bedding (reverse grading), note the fine grains marked by 1 and coarse grains by 2. Note also the red dashed line marked their sharp contacts. The black arrow and the pinkish dashed circle show some visible shell fragments, the magnified view on the right part show details of some carbonate grains as shown by yellow circle (possibly ooid) and blue dashed area, on the right. **B)** Typical tepee structure highlighted by yellow dashed lines. **C)** An outcrop photo showing different kinds of lithofacies and their associations. **D)** Shows different structures in lime mudstone or dolomudstone lithofacies, white arrows indicate desiccation cracks; yellow dashed lines delineate vertically burrowing area. Red arrow head indicate desiccation crack filled by sulphate crystal (note axes head anhydrite crystal shape), and yellow arrow indicate filled karst cavity with evaporite crystal laths embedded within the sediment. **E)** Plan view showing polygonal mud cracks as black arrows show, partially filled by sediments with enclosed or trapped lenticular crystals or their pseudomorphs, gastropod shell filled in burrow is also shown in the enlarged view at lower left. **F)** Limestone with fenestral porosity within algal filaments (the middle yellowish zone) zone along with lenticular gypsum.

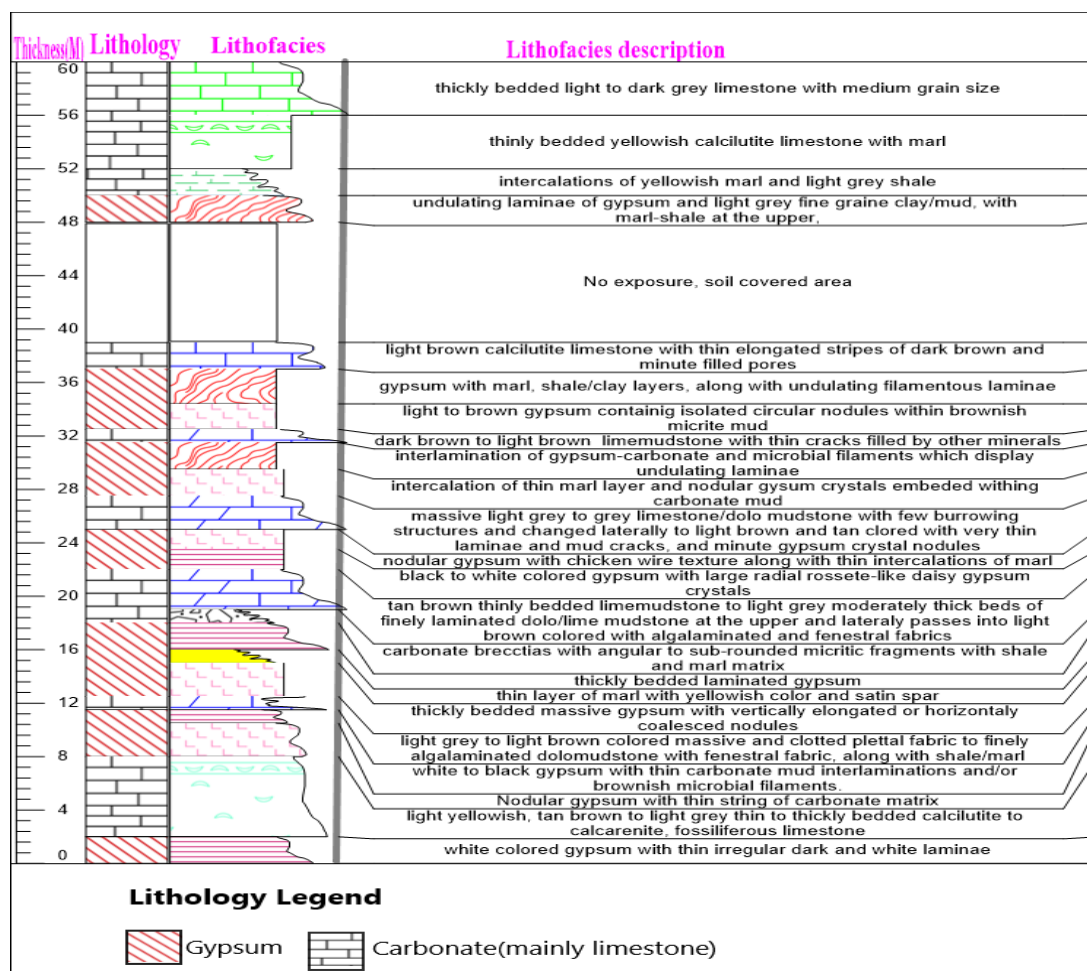


Fig.3.8: Lithostratigraphy log measured in the study area with lithofacies descriptions.

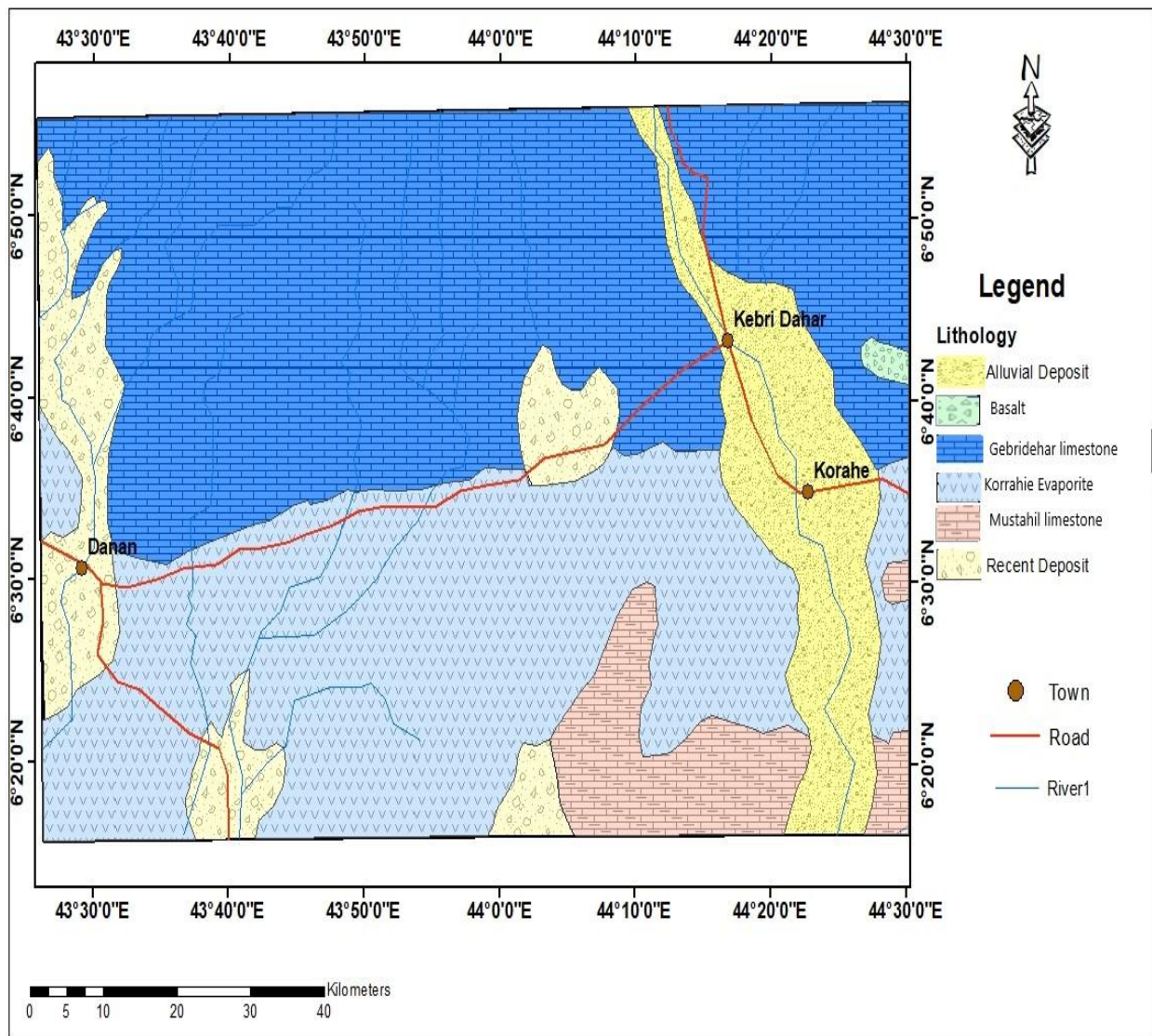


Fig: 3.9. Geological map of the study area and surroundings (modified after National Water Resources Commission (NWRC), 1972)

CHAPTER FOUR

4. PETROGRAPHY AND MICROFACIES ANALYSIS

4.1. Introduction

Apart from the field observations made in the studied outcrop sections in Korrahie area, a total of 29 representative samples of evaporite and carbonate rocks were analyzed and described under the petrographic microscope. Accordingly this chapter will present the petrographical features and microfacies types (for carbonate rocks) of these representative samples collected from the different horizons in the study area. Furthermore by using all these petrographical properties along with their microfacies analysis, the interpretation of depositional environment of the rock units will be discussed in the following chapter.

4.2. Petrographic Analysis

A total of 29 representative samples of evaporite and carbonate rocks collected from the field were prepared and made thin sections, for detailed studies and analysis under petrographic microscope. 20 evaporite (mainly Gypsum) and 9 carbonate samples were studied and analyzed in order to decipher the micro textural signatures for the deposition and diagenetic history of the rock units.

4.2.1. Evaporites

Among the total number of samples, 20 evaporite thin section samples were prepared for petrographical analysis. The microscopic investigation of the analyzed samples has shown that the evaporites of the Korrahie Formation outcropped at Korrahie locality is predominantly composed of gypsum (secondary/diagenetic gypsum) which displays a variety of textures. Other commonly associated components include; anhydrite relic, carbonate mud and/or filamentous micrite. The dominant gypsum textures in this locality are alabastrine, selenitic, porphyroblastic, nodular crystals and satin spar texture, amongst other observed textural variations. Based on this microscopic investigation the following four microfacies types of gypsum were recognized.

Alabastrine gypsum: in most of the analyzed thin sections, alabastrine or microcrystalline textures contained xenotopic to idiotopic crystals can be observed. This texture characterizes fine

grained, interlocking anhedral crystals that sometimes their grain boundaries are almost impossible to define. When viewed under crossed polar the individual grains appear preferentially elongated fibrous and display irregular undulose extinction. It contains fine grained nodular anhydrite (now gypsum) that displacively and/or replacively grew within carbonate micrite. As the nodular anhydrites grow and coalesce the original microbial/carbonate micrite sediment is extensively disrupted and compressed into thin zones between nodules (Fig.4.1.C). Abundant relics of anhydrite crystal laths are present (Fig.4.1 A&B), partial dolomitization and pyritization is also observed within the remaining carbonate material (Fig.4.1D). In some cases it shows a porphyroblastic texture.

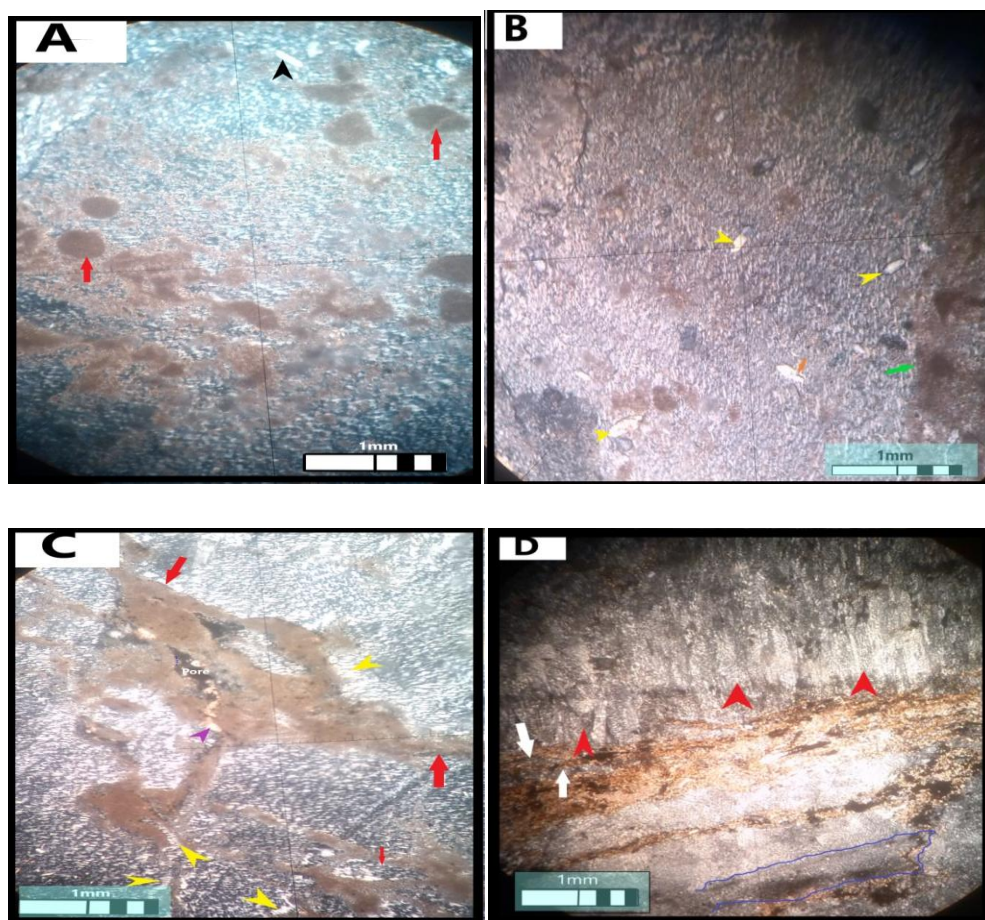


Figure.4.1. Alabastrine gypsum microfacies, showing disrupted original carbonate micrite due to the growth of evaporite nodules. **A)** Alabastrine gypsum showing xenotopic texture along with micritic mud which is extensively replaced by anhydrite (now is gypsum) and relics of peloidal micrite is present (red arrows), and the black arrow head shows some dispersed gypsum laths within alabastrine matrix. **B)** Some displacive anhydrite/gypsum laths within alabastrine and micrite matrix (yellow arrow heads) and some of them show etched and corroded edges as

well as continuing replacement of anhydrite by gypsum as shown the crystal at the center of the photo as red arrow points, the green arrow shows remains of micritic carbonate mud. **C)** The extensive alteration of micrite by gypsum/anhydrite grows that resulted thin string relicts of micrite sediments and the formation of chicken wire like texture. Some lenticular shaped crystals are also present within the filamentous micrite, and may indicate depositional texture as red arrows points, yellow arrow heads indicate relatively coarse fibrous crystals nucleated and concentrated along the envelope micrite and growing outward from it, these are either a late phase cementation or due to recrystallization of earlier formed crystals. **D)** this photo displays the stretched remnants of microbial filaments (dark brown) and the vertically oriented fibrous gypsum crystals (red arrow heads) growing on the top of this filaments perhaps a fracture filling gypsum, while other lenticular shaped crystals (white arrow) are entrapped within the filaments which preserves their depositional morphology, The micritic mat is also subjected partially by recrystallization and pyritization, dark brown patches in the micrite indicate organic matter oxidation.

Selenitic gypsum: in this facies secondary selenitic gypsum is commonly found as interlaminations or as fracture filling within carbonate mud. This gypsum microfacies display a variety of fabrics ranging from large radial rosette-like selenitic crystals (Fig.4.2D) to relatively fine granoblastic fracture filling selenite, where these two fabrics present together their contact relationship is either gradational or sharp, which indicates replacement of coarse grains by smaller grains (degrading processes) and it is a typical feature for telogenetic proceses (Taj, 2012; Aref, 2003). Large euhedral to subhedral elongated pinkish crystals alternating by relatively smaller and less oriented granoblastic selenite crystals (Fig.4.2A), and the vertically oriented swallow tail twin crystal morphology shown in (Fig.4.2D) may indicate relics of pseudomorphs of anhydrite (gypsum Ghosts) after a vertically aligned bottom nucleated selenitic gypsum, which are reduced and crashed as can be seen the corroded crystal edges during the transformation of anhydrite to gypsum. The fractured carbonate micrite display the presence of rhombic dolomite crystals and anhydrite relicts preserved within it (Fig.4.2B&C).

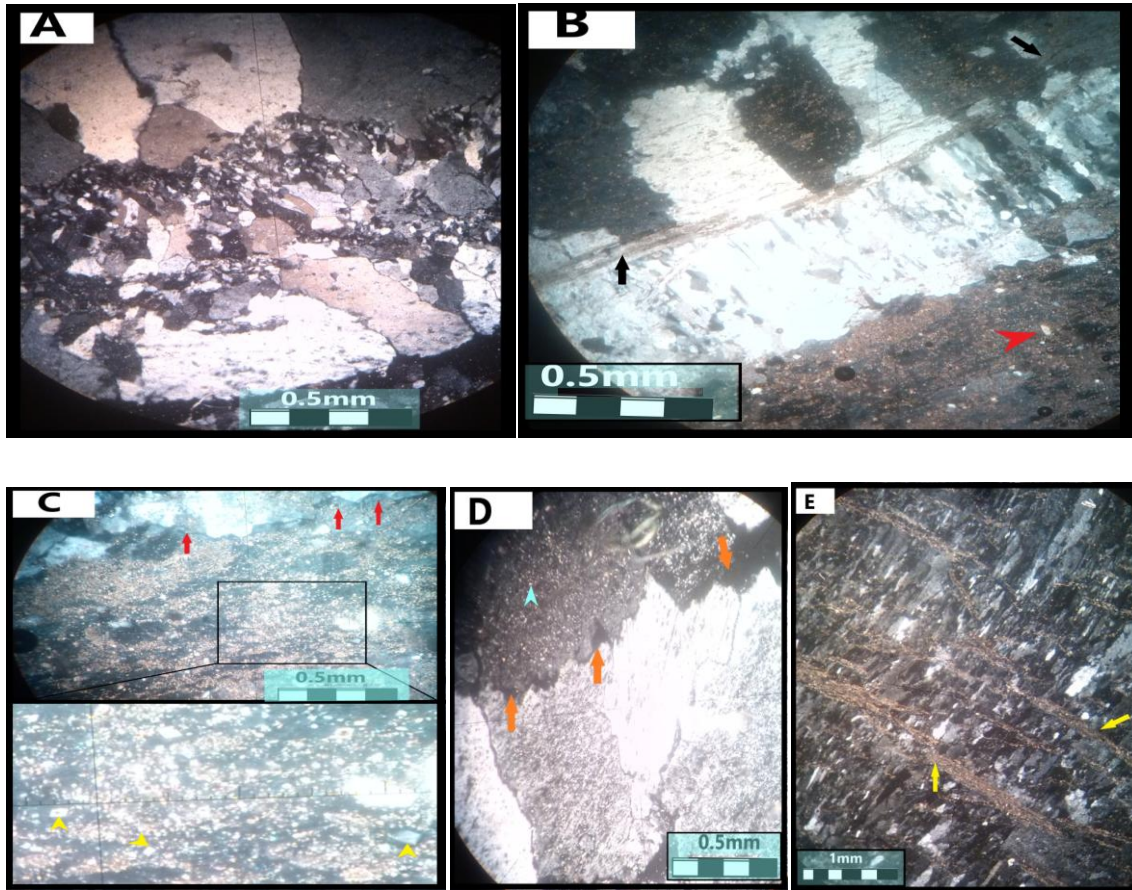


Figure.4.2. photomicrographs of Selenitic gypsum microfacies: **A)** large Euhedral selenite crystals alternating with fine equigranular fracture filling gypsum. **B)** Secondary selenite filling fractures in carbonate mud, note also the presence of fine anhydrite and rhombic dolomite crystals in the mud. **C)** red arrows indicate a rectangular shaped features along the fracture wall which may reflect a pre-existing anhydrite crystals shape, which are dissolved during the opening of this fracture or later solution through this conduit, the enlarged view at the bottom shows details of rhombic dolomite crystals (yellow arrow heads) along with dispersed anhydrite relics, **D)** porphyroblastic selenite crystals showing curved or sutured intercrystalline boundaries (orange arrows) which is termed intercrystalline porosity, the crystal edges near and adjacent to this porosity zone characterize less-inclusion (less anhydrite relics) as compared to the inclusion rich crystal interiors (aqua arrow head). **E)** Vertically elongated prismatic gypsum crystals along with branching microbial filaments (yellow arrows) running across the gypsum prisms.

Nodular gypsum: this gypsum microfacies displays an elliptical to circular shaped porphyroblastic replacive gypsum nodules set in carbonate mud matrix. In some cases the porphyroblastic gypsum nodules show inclusions of carbonate mud and anhydrite relics (Fig.4.3 B&C) which indicate the replacement of anhydrite by gypsum, that was displacively/replacively

grew within the micrite sediments. Sometimes the lenticular morphology of gypsum is preserved as nodules within carbonate mud (Fig.4.3 A &C)

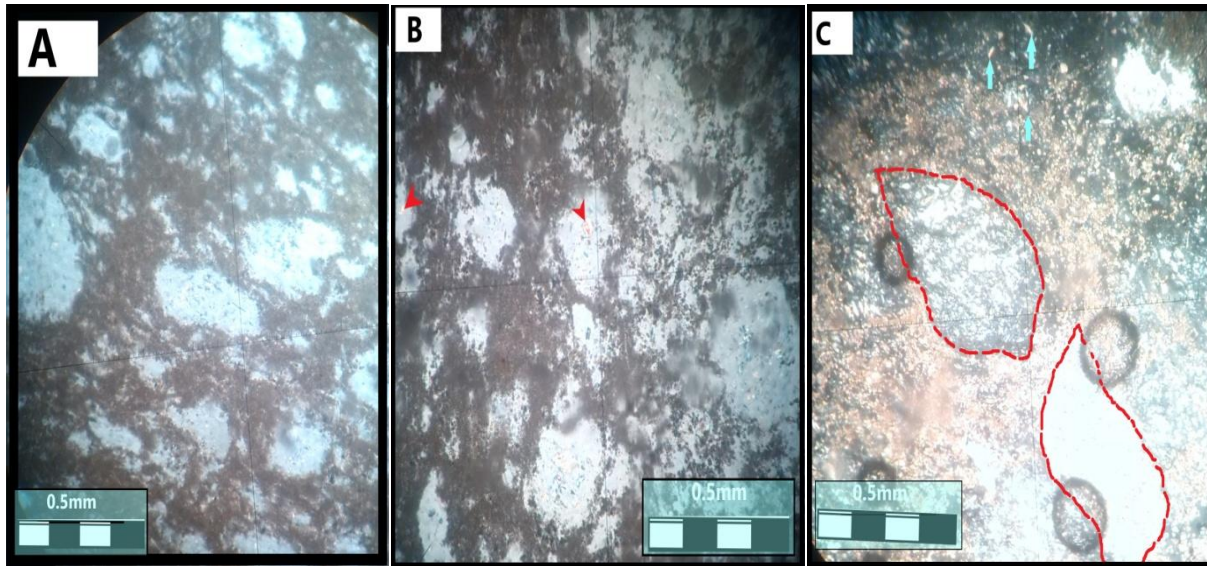


Figure.4.3. Nodular gypsum microfacies: **A)** an elliptical to circular isolated nodules within micrite mud, the core of the nodules also contain anhydrite and/or micrite inclusions. **B)** Details of anhydrite relics at the core of gypsum nodules (red arrow head). **C)** The red dashed features are outlines of original displacive lenticular gypsum crystals enclosed within filamentous micrite which preserved the crystal morphology during the replacement of the gypsum, note also the needle-like anhydrite inclusions at the core of the nodule, other anhydrite laths are also floating on the matrix (aqua arrow), the carbonate is also partially recrystallized

Granoblastic Gypsum: this type of gypsum is more common in the analyzed thin sections and thus the microscopic study of this facies showed that the presence of coarse crystalline euhedral to subhedral crystals with interlocking structure at their margins, and usually planar crystal boundaries. Moreover the crystals are equiangular in size and showing sharp and uniform optical extinction when viewed under Cross polarized light. These crystals mostly occur either as individual or as aggregates. Unlike the Nodular gypsum microfacies, this microfacies characterizes the less occurrence or in sometimes the absence of anhydrite relics and other sediment inclusions.

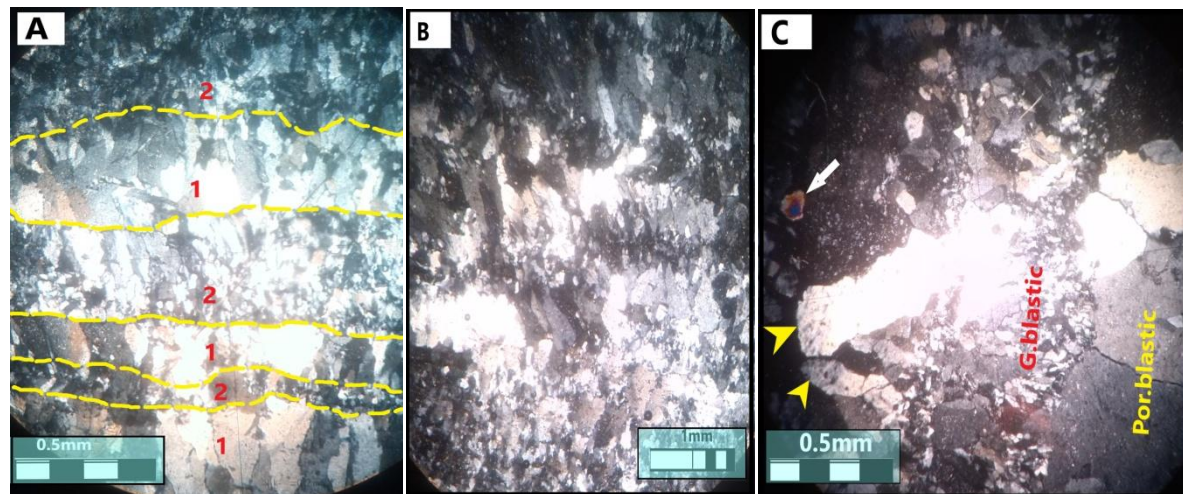


Figure.4.4. Granoblastic gypsum microfacies: **A)** an alternating layers of coarse vertically oriented selenite crystals marked (1) and fine to medium grained equiangular granoblastic selenite marked (2). **B)** Highly altered and reduced radial rosette-like selenite within randomly oriented fine grained granoblastic matrix. **C)** Radial elongated porphyroblastic selenite covered an equiangular granoblastic texture. Note the presence of floating anhydrite relics in the porphyroblastic crystal (white arrow) the extensive alteration is also visible at the crystal edges (yellow arrow heads), where dissolution, replacement and crystal breakdown processes started first and then proceeded to the interior part via cleavage and weak zones.

Since the evaporite minerals are susceptible to burial alteration and can readily altered even on shallow burial, definite identification of depositional features in ancient evaporites is difficult under the microscope. However, the distinction between primary evaporite texture and secondary evaporite texture is an absolute prerequisite to any study of an ancient evaporite deposits.

Although the microscopic investigation of the present study showed that the dominance of diagenetic features over depositional features, the presence of thin algal/microbial filament observed both in the field and under the microscope, can be interpreted as a primary feature formed under restricted shallow marine salina conditions (Taj, 2012; Aref, 1998). The presence of inclusion free lenticular gypsum within filamentous micrite (Fig.4.1C, D&4.3C) indicates the precipitation of gypsum on or within the microbial mat surface was took place during the living mat (Perri et al., 2017). The occurrence of regular evaporite bedding and their interbedding with marine carbonates observed in the field is additional evidence that supports the primary origin of this vertically oriented bottom growth and lenticular gypsum crystals. The presence of carbonate

mud around replacive gypsum nodules with anhydrite relic inclusions (Fig. 4.3A&B) can also indicate primary anhydrite nodule formed under supratidal sabkha (Warren, 2006, 2016; Warren and Kendall, 1985).

On the other hand the petrographical result of the analyzed evaporite samples revealed the dominance of secondary and/or telogenetic evaporite textures like the alabastrine, granoblastic, porphyroblastic and satin spar textures displayed by the gypsum microfacies discussed above, are the result of precursor anhydrite rehydration. This means that all such textures seen at micro and macro scale in gypsum beds are indicative of telogenetic processes.

According to Warren (2016), although the gypsum porphyroblast and finer alabastrine microcrystalline, xenotopic gypsum generally formed under phreatic zone, they differ in terms of the operating hydrological conditions. Hence, porphyroblastic gypsum is favored by sluggish or relatively stagnant water cross flow, slow crystallization rate and near equilibrium hydration conditions, whereas alabastrine gypsum tends to form under supersaturated active phreatic zone with rapid crystal growth rates. Thus porphyroblastic gypsum is the response of anhydrite rehydration as it re-enters the lowermost part of the Telogenetic realm, and changes to alabastrine gypsum when this massive nodular anhydrite reaches the more diffusive active phreatic zone. The presence of intercrystalline polyhedral porosity in coarse crystalline (selenitic) gypsum (Fig.4.2D), is an evidence of precipitation and dissolution of precursor anhydrite (Gindre-Chanu et al., 2015, Warren, 2016). The presence of coarse granoblastic gypsum is also an evidence of relatively homogeneous hydration and slow crystallization (Warren, 2006).

4.2.2. Carbonate

Petrography is the most effective way of identifying the mineralogical and other components of rocks, especially carbonates, as it is one of the methods used to classify carbonate rocks. Hence, among the total number of collected samples, 9 representative samples collected from the carbonate beds in the study area were prepared for thin sections. In order to conduct detail petrographic investigation and study their micro scale features, with the aim of deciphering the nature of various carbonate constituents and to classify the carbonate rocks. Moreover the

proportions among different carbonate components (allochems and interstitial materials) were determined under the microscope. Finally the rocks were classified according to the famous carbonate classification schemes set by Dunham (1962) and Folk (1962).

The major constituents of limestone are grouped as allochemical components (e.g; Intraclasts, Fossils, Ooids, Peloids), microcrystalline calcite matrix (micrite) and sparry calcite cement (spar). Petrographical study of the representative samples, showed that different carbonate textures ranging from mudstone to wackstone-grainstone limestone. Based on the various textures observed under the microscope, the following six carbonate microfacies were recognized.

Peliodal-bioclastic wackstone/packstone microfacies (MF.A): this microfacies represents an extensively micritized/bioturbated limestone, where the individual bioclastic grains are mostly difficult to recognize. Except a few shell fragments preserved their outline shape, either by thin layer of micrite (micrite envelope) or sparry calcite. The common carbonate grains observed in this facies are small sized peloids, bioclasts such as; brachiopods, foraminifera, bivalves and few ooids which are embedded in micrite matrix and rarely very fine sparry calcite cements. Some grains and their outer thin micrite envelope layers show recrystallization of micrite into microspar along with dissolution porosity inside the grains (Fig.4.5A). This microfacies is found in the lower and uppermost parts of the studied sections.

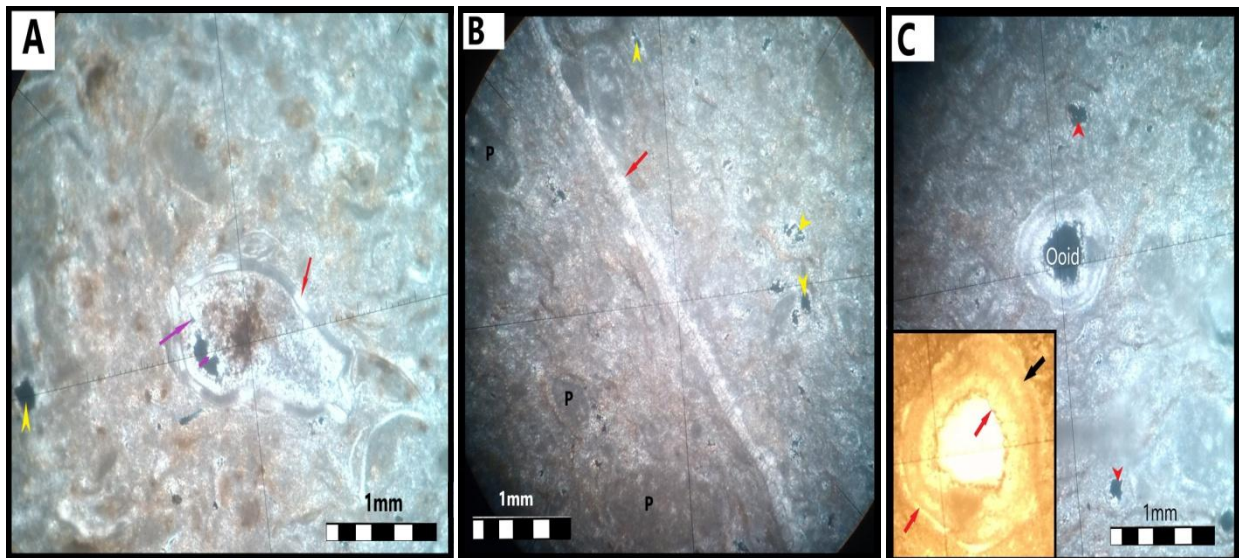


Fig.4.5: photomicrographs of pel-bioclastic wackstone/packstone. **A)** bioclastic packstone showing the extensive bioturbation of the allochems, the core as well as the micritic rims of the shells are replaced by neomorphic calcite crystals, as the red arrow indicates the replacement of micritic envelope by fine microspar, and the pinkish arrow shows replacement of internal micrite sediments by coarse blocky calcite crystals and the formation of intragranular porosity, also note the distortion of the shell and its mottled appearance at the center, the yellow arrow head also shows moldic porosity as the core of the grain is leached. **B)** Radial fibrous calcite cement preserves long brachiopods shell (red arrow), the internal structure of most bioclasts are not preserved due to extreme alteration and converted to peloids although many of them display a foraminiferas outline, like those marked by (p). **C)** internal structure of an ooid displaying concentric laminae, and leached core, the originally micritic lamination is partially replaced by neomorphic calcite crystals, shown by black(micritic laminae) and red (spar laminae) arrows in the close-up and plan polarized view at the lower left. Most of the other grains appear muddy and poorly preserved.

Ooid-bioclastic grainstone microfacies (MF.B): this microfacies characterizes the presence of an abundant but less diversified fossil content. It composed mostly of an ostracode shells and radial structured ooids, along with bivalves, foraminifers and peloids, cemented by thin isopacheous sparry calcite cement. The grains of this facies experienced some sort of compaction as evidenced by their grain contacts (concavo-convex), other grains are penetrating one to another and display truncations, fractures or breakages and overlapping (Fig.4.6 A-C). The ostracode shells are preserved by their calcified prismatic shells with micrite sediment infill in the shell cavity. This allowed it to resist the compaction effect, whereas the elongated bivalve shells show fractures and breakages. In some cases skeletal shells show more or less preferential orientation (Fig.4.6A) which perhaps either due to compaction or current generated structure. It also exhibit poorly to moderately sorted along with sub rounded grains. Other microscopic features depicted from this facies are the presence of diagenetically precipitated evaporite minerals filling the pore spaces remained after the initially precipitated isopacheous sparry calcite cements (Fig.4.6 B&C). Intergranular as well as intragranular porosity is also observed (Fig.4.6A).

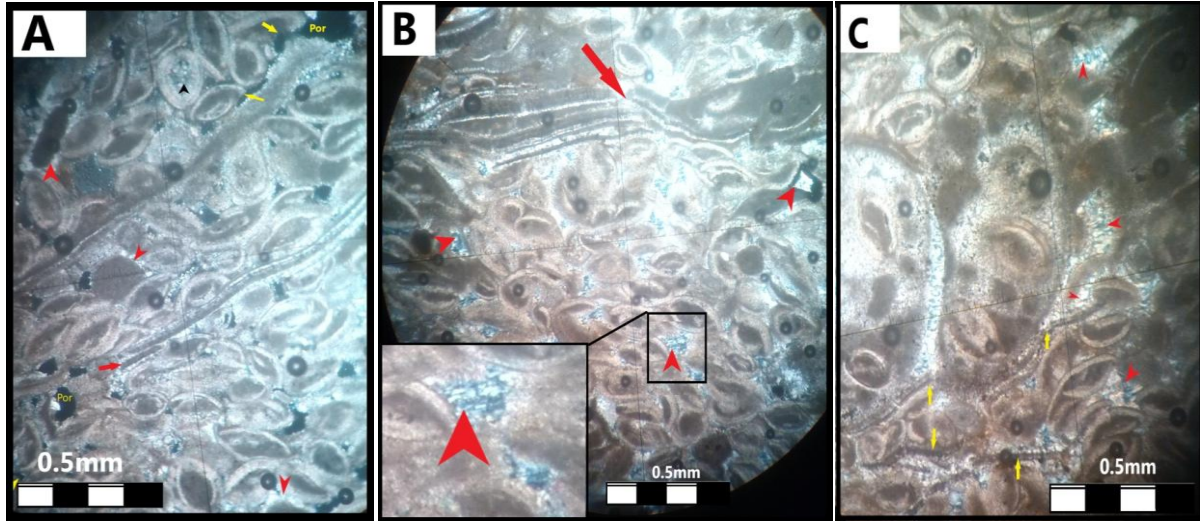


Fig.4.6. **A)** photomicrograph of ooid-bioclástico grainstone, containing predominantly by two valved ostracode shells, ooids, foraminifers, and peloids along with elongated bivalves and brachiopods cemented together by thin fibrous (isopacheous) sparry calcite cement as shown by the red arrow heads, some of the shells are fractured and broken (red arrow), note also the grain imbrications and their preferential orientation, and also the radial/tangential structure on the concentric lamination of ooids as the black arrow head shows at the top part and at the bottom of the photo. **B)** showing the presence of diagenetically precipitated pore filling gypsum crystals (red arrow heads), and shell fractures (red arrow), the magnified view at the lower left box shows details of pore space filling by fibrous needle-like gypsum crystals. **C)** This photomicrograph shows the partial replacement of skeletal grains and blocky sparry calcite cement by secondary gypsum (red arrow heads) and segmentation of the elongated shells into pieces as shown by yellow arrows.

Interlaminated micrite-packstone microfacies (MF.C): this microfacies is composed interlaminations of micrite dominated laminae and fine grained ostracode shell dominated packstone layer. The contact between these alternating laminations is either sharp or gradational as shown in (Fig.4.7A&B). Most shell fragments are relatively aligned their long axis in a direction parallel to the bedding, and the grain sorting ranges from moderate to well sorted. Similar to the previous microfacies (MF.B) the grain contacts are intruded and penetrating to one another, displaying the concavo-convex grain contact relationship. Moreover in the skeletal dominated layers both micrite matrix and sparry calcite cements are present and thus given the name ‘grain supported bioclástico packstone laminae’. The most common bioclástico grains in this layer include: fine grained ostracodes, ooids, elongated fragments of bivalve shell, gastropods

and foraminifers. Some intraclasts along with few peloids are also present (Fig.4.7 A-D). These interlaminations of micrite and packstones finally culminate a gastropod-bearing micrite layer at the upper part of this microfacies. This layer composed of principally micrite sediment; however, some skeletal (gastropod) grains less than 10% are floating in the micrite matrix. The preservation of the shell fragments is either as moldic or cast, where the shells are outlined partly by thin sparry cement and partly by thin micrite envelope (Fig.4.7 C&D). The internal shell cavities are filled by micrite sediment lining by thin fibrous sparry calcite cements (isopachuous cement). Some incomplete shell fragments have been totally leached and left behind nothing, but only a biomoldic porosity outlined by thin calcite cements (Fig.4.7 D). Although there are some complete gastropod shells in this layer (Fig.4.7 C), most shells are fragmented and oriented randomly. This thin sparsely fossiliferous micrite layer culminates the skeletal-rich microfacies and grades upward into micrite and microbial dominated microfacies.

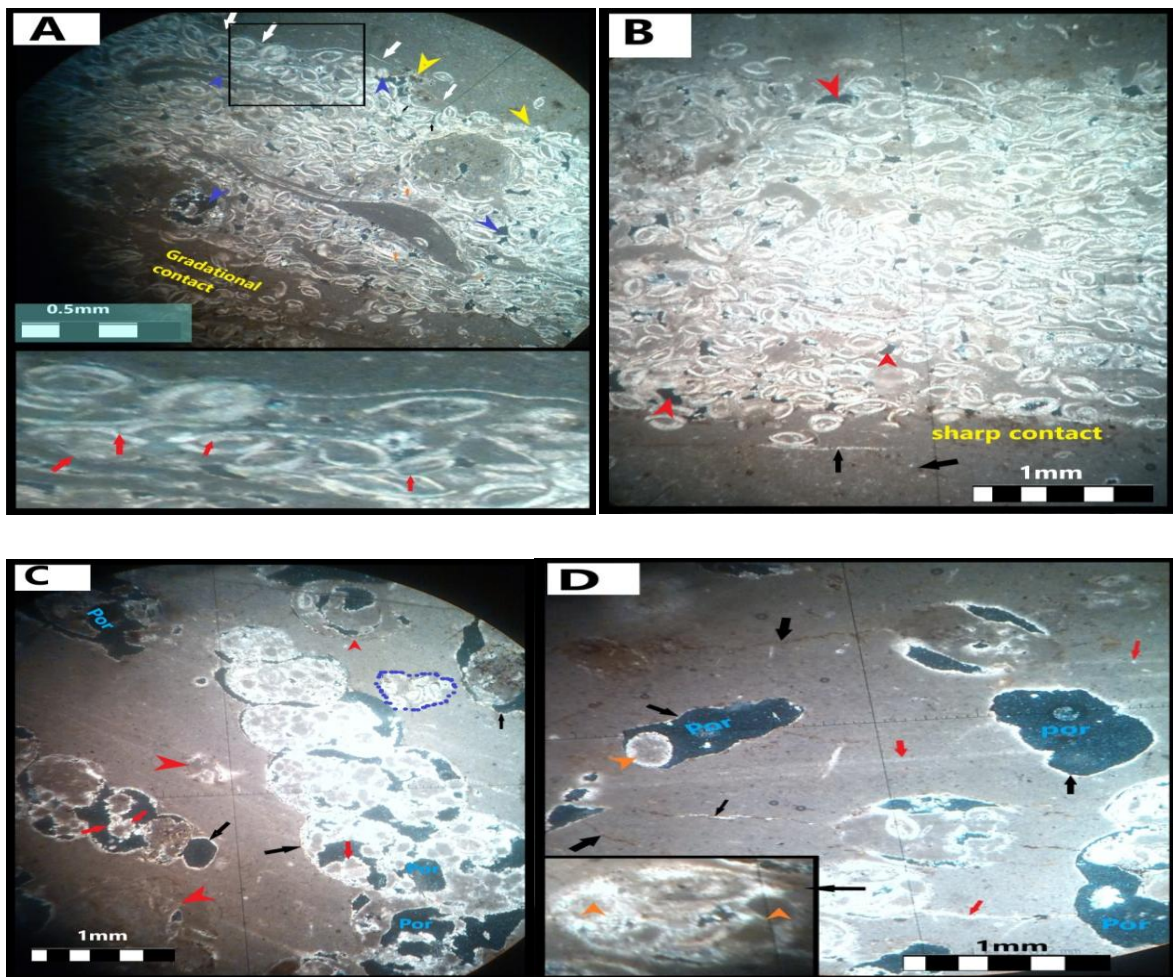


Fig.4.7. photomicrograph of laminated microfacies: **A&B**) interlaminated microfacies displaying the gradational and sharp contact relationship between micrite dominated laminae and skeletal dominated laminae. Note also the truncation and thin crust formation (white arrows) running on the top of skeletal grains in (A), the presence of some eroded and partly leached grains (yellow arrow heads) which may indicate subareal exposure, the magnified view at the lower part shows intruded grain contacts and concavo-convex relation. The sharp contact in (B) also displays linear exposure line (indicated by black arrows), marked by the presence of micro cracks filled either by micrite mud or thin white sparite, and the dominance of grain dissolution along/near to this surface (red arrow heads). **C**) Showing gastropod shells floating in micrite matrix. The internal micrite sediment in the shell is partially cemented by isopachous calcite cement (red arrows) and partially dissolved (por), some shells are completely filled by micrite mud and preserved their outline by thin micrite envelope as shown in red arrow heads. **D**) complete to partially leached gastropod shell fragments and the preservation of the mold by thin calcite cement and/or micrite envelope (black arrows), red arrows indicate micro cracks filled by white calcite crystals, the lower left enlarged view shows details of peloidal micrite (orange arrow heads) cemented together by isopachous cement spar.

Dolomudstone microfacies (MF.D): this microfacies composed of finely crystalline dolomite with sugary texture and dense micrite matrix. Dolomite crystals display anhedral crystal shape with xenotopic texture. The prominent feature of this microfacies is the presence of both pseudomorphs of gypsum after dolomite crystal rhombs and ‘swallow tail twin’ selenite crystals amongst other evaporite crystals dispersed and displacively grow in the carbonate matrix (Fig.4.8 A&B), while few anhydrite/gypsum crystals are also filled along the dissolution and fenestral cavities. Some scattered micritic allochemical (mainly hard micritic peloids) grains as well as organic matter are also observed, which are present either as dark black or stained spots perhaps due to oxidation and dolomitization (Fig.4.8A- C).

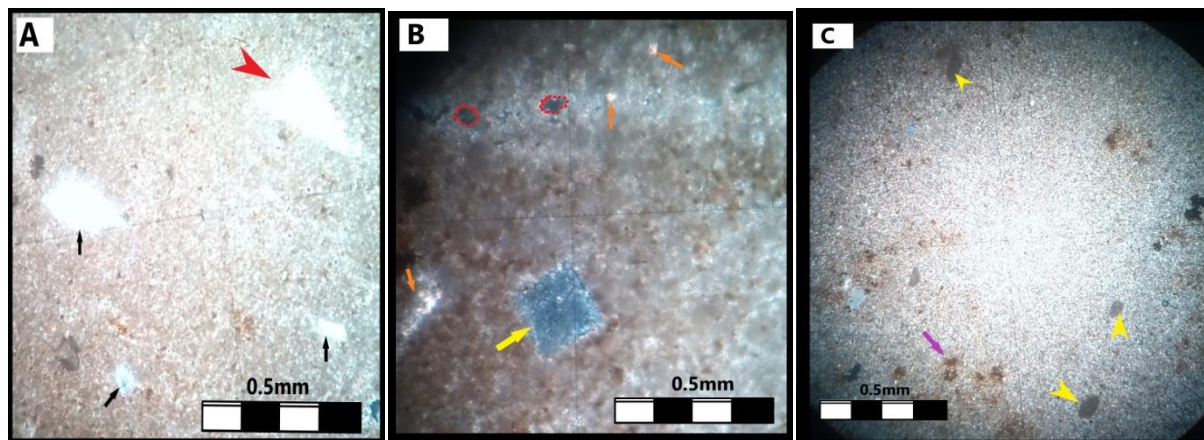


Figure.4.8. Photomicrographs of dolomudstone microfacies showing; (A) well formed displacively precipitated swallow tail twin selenitic crystal (red arrow head) along with other displacively grew lenticular/tabular gypsum crystals (black arrows) set in a dolomitized sugary matrix, (B) pseudomorphy of gypsum after rhombic dolomite crystal as shown by the yellow arrow and some anhydrite relics as indicated by orange arrows, in a clotted micrite matrix, structures marked by red dashed circle are fenestral pores (Birdseye) partially filled by anhydrite and/or gypsum. (C) Fine crystalline sugary dolomite showing the presence of hard elongated/flatened pelmicrite grains which are not dolomitized due to their resistant of dolomitization processes or were transported elsewhere by storms and currents (yellow arrow heads) the pinkish arrow shows red/brown spots of oxidized peloids and/or microbial relics.

Microbial laminated boundstone microfacies (MF.E): this microfacies characterizes the presence of microbial boundstone, which contain laminated stromatolite structures. The stromatolite shows sub-millimeter thick planar lamination, which mostly composed of micritic filaments and clotted micrite and/or peloids along with fenestral fabrics alternating with relatively thick gypsum laminae (Fig.4.9B). Sometimes the planar laminations produced by microbial mats are extremely disrupted by lenticular gypsum crystal growth. Even though it is difficult, if not even impossible to identify the internal structures of the microbial organisms, some filamentous micrite shows filament bundles with preserved segmentation (Fig.4.9.C.). Moreover, this microfacies displays heterogeneous dolomitization/replacement pattern. The dolomitization is more concentrated and shows euhedral to subhedral dolomite crystals along with intercrystalline porosity in some areas (possibly in dissolution cavities and leached grains), while in other areas it only occurs as fine microcrystalline anhedral crystal fabric (Fig.4.9 A). Perhaps this is due to the presence of permeable burrows through which a dolomitizing fluids moved preferentially and replaced materials within and adjacent to these fluid passages. Postdated gypsum and/or anhydrite cements which are replaced to one another are also observed within this zone.

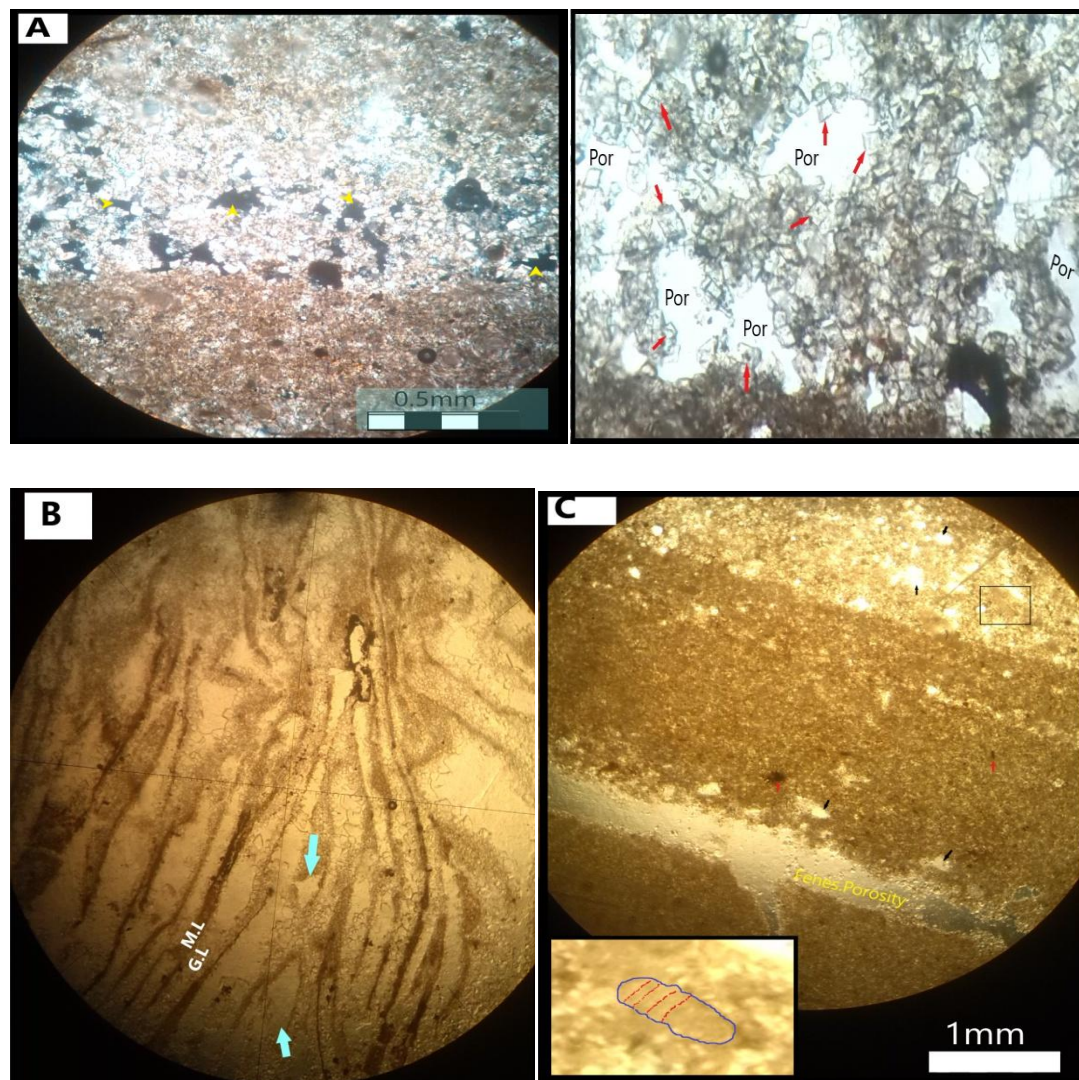


Figure.4.9: Photomicrograph of microbial laminated boundstone. **A)** Microbial boundstone showing highly dolomitized zone marked by euhedral rhombic dolomite crystals, as showing by red arrows. Note also the yellow arrow heads indicating intercrystalline porosity developed from leached undolomitized matrix, (the right side in (A) is the same field of view under plane polarized light). **B)** Interlaminated microbial mat and gypsum laminae, with preserved lenticular gypsum as arrows pointing. Extensive recrystallization/neomorphism of the micrite sediment is also observable in this view (full field view under PPL, with magnification of 4X). **C)** Fenestral laminated stromatolite boundstone with alot of micritic filaments and clotted peloidal micrite microfabric. One of such micritic filaments is shown in the enlarged view at the lower left corner (blue line enclosed area), the parallel red dots show the internal transversal segmentation of the filament, the black and red arrows indicate porosity and sparsely distributed organic matter remnants respectively.

Micritic Limestone microfacies (MF.F): this is a micrite dominated microfacies lacking other carbonate components. However, it characterizes the presence of dispersed opaque mineral crystals, possibly pyrite crystals replaced by dolomite, as it observed the pseudomorph of pyrite after rhombohedral dolomite and anhydrite/gypsum lath crystals (Fig.4.10 A&B). The fine grained micritic sediment is later partially recrystallized into microspar calcite and/or (dolomite??). It also contains some laminae of brownish clay with elongated bioturbation features and floating gypsum laths (Fig.4.10C).

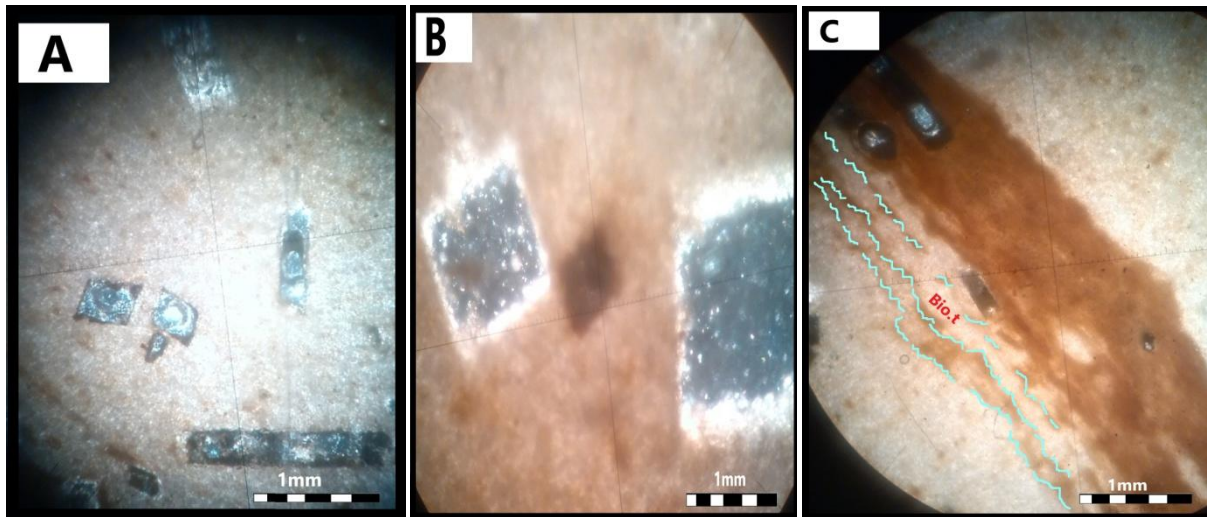


Figure.4.10. photomicrograph of micritic limestone microfacies: **A&B)** pseudomorphs after anhydrite/gypsum blades and dolomite rhombs dispersed in micrite sediments, note the corroded edges of the crystals due to the alteration process. **C)** Brown colored clay laminae along with preferentially oriented, rectangular shaped crystals, and long narrow, burrowed zone (shown in cyan dashed line) filled by white microspar and micritic sediments.

CHAPTER FIVE

5. DISCUSSION

5.1. Introduction

The various recognized macro and micro structures and textures described in the previous chapters (Chapters-3 & 4) will be discussed and more elaborated in this chapter in the light of depositional environment. Moreover the combination and integration of outcrop observations and detailed thin section analysis, with the aim of carbonate microfacies categorization and characterization of their succession geometry, heterogeneity, lateral continuity and vertical facies successions, will be a step by step approach towards the interpretation of the origin and depositional paleoenvironments of the different lithofacies outcropped in the study area. These reconstructions of paleoenvironment will be finally considered under a paleogeographical setting that will be discussed under this chapter. The chapter will also contain a detailed discussion on lithostratigraphy and the correlation with other sections in the basin. In addition to the depositional settings and lithostratigraphic sections, a discussion about the diagenetic processes that have been operated throughout the history of these rock successions will be presented.

5.2. Depositional Environments

A depositional environment is a place on the earth's surface in which accumulation of sediments takes place. It can be interpreted and categorized through the study of these sediments, in terms of lithology, color, texture, sedimentary structures, fossil content and bed geometry both in outcrop and laboratory scale. As far as the depositional setting of an evaporite-carbonate sequence is concerned, they have been generated in different depositional settings such as peritidal sabkhas, along coastal lagoons, intracratonic and basin wide (subaqueous Salina) environments and non marine/ continental (playa) settings (Makhlouf and El-Haddada, 2006; Warren, 2006; Kent, 2003; Schreiber and EL-Tabakh, 2000; Warren and Kendal, 1985). These varied sub-environments characterized by evaporite deposits can be generally grouped into two main generic environments namely: evaporites formed under subaqueous conditions (shallow to

deep) and those formed under subaerially exposed sediments (Kent, 2003; Warren and Kendal, 1985). Due to such a wide depositional spectrum for evaporites along with their higher susceptibility to diagenetic alterations, which at times completely obliterate the depositional textures, often makes their environmental interpretation problematic.

Moreover, the characteristics of evaporite-carbonate sequences outcropped in the study area (Korrahie locality) were investigated both in outcrop and petrographic scale. Although there are a limited number of outcrops, that can provide a clear relationship between the vertical and lateral facies succession. An attempt of the interpretation of depositional environments and origin of the sequence was made based on their recognized/identified depositional signatures. Since every primary micro and macro texture and structure reflects and symbolizes a specific environment of deposition. Accordingly, the significant variations of macro and micro facies of evaporites and carbonates in the study area will be discussed as follows:

Outcrop based studies made during the field work of the study area resulted in the establishment of five lithofacies in the evaporite and carbonate stratigraphic interval. These lithofacies have been described in chapter three, and they are repeating many times in a cyclic manner, as seen the stratigraphical column in (Fig.3.8 & 5.2). Similarly microscopic investigations revealed that the presence of six microfacies types within the carbonate lithofacies. Detail descriptions and photomicrographs of some thin sections for each of these carbonate microfacies types were given in chapter four of this thesis.

The lithofacies textures and sedimentological features recognized during the field and their microfacies (for carbonate rocks) analyses during the petrographic investigation, determined that the evaporite-carbonate sequences of the Korrahie Formation in the study area were generally deposited in a low energy shallow marginal marine environments interrupted by episodes of desiccation and/or subaerial exposure phases.

Furthermore, the evaporite-carbonate sequences exposed in Korrahie locality was a result of cyclic deposition originated on a broad, low relief shallow subtidal lagoon to intertidal-supratidal evaporitic mudflat environment. The cycles are arranged in a shoaling upward pattern, and each cycle contains a basal carbonate unit overlain by an evaporite unit. Therefore, these sequences

record a shallow subtidal to intertidal-supratidal signature. The cyclicity pattern observed from these facies can be interpreted in relation to the presence of minor relative sea level fluctuations, or basin subsidence that provides an accumulation space in this shallow transitional setting. The individual cycles and the overall succession show mostly an upward shallowing pattern, which in turn reflect a shoaling brine body or an upward salting. An alternating climatic condition (cold to warm episodes) that existed in the depositional environment is also another possible mechanism.

The various evaporite textures (gypsum in this case) present in the studied samples and outcrops are mainly falling under nodular texture and rarely wavy or planar laminated textures. The presence of laminated gypsum facies with microbial filament interlaminations (Fig.3.4C&D) is an evidence of shallow water subaqueous Salina deposits (Aref, 1989; Taj, 2012; Babel, 2004; Warren, 2016). The fining upward or shoaling-up of such succession indicates shallowing of the brine body and at the same time increased salinity of the brine. The presence of a truncated surface (Fig.3.4D) represents either subaerial erosion or dissolution, which resulted from brine dilution and mixing as a result of new influx of fresh water into the brine body. This mixing process is more possible in shallow unstratified brine water body than deep and stratified brine water (Warren, 2006, Warren, 2016; Warren and Kendall, 1985; Hardie et al, 1985). The presence of clear and inclusion free lenticular shaped gypsum crystals within the algal/microbial mat (Fig.4.1C&D, 4.3C, 4.9B) indicates that gypsum was precipitated within or on the mat surface while the mat still alive (Perri et al., 2017) along the upper intertidal zone. The occurrence of thick gypsum beds composed of vertically elongated and/or horizontally bedded nodules set in argillitic matrix (Fig.3.5E) can be interpreted as they were formed originally as vertically aligned bottom nucleated selenitic gypsum which is known to form under shallow subaqueous conditions (Warren, 1999, 2006; Babel, 2004), and that now present only as a gypsum ghost (anhydrite pseudomorphs) as it retains some traces about the primary depositional morphology.

Moreover, depositional signatures indicating sabkhas origin are commonly observed on the evaporite unit. The existence of displacive and/or replacive growth of nodular anhydrite and/or gypsum in a micritic carbonate matrix (Fig.3.5A-E, 4.3A-C) along with enterolithic and chicken wire textures as well as the presence of tepee structures, mud cracks, fenestral fabrics,

stromatolitic structures, deflation and erosion surfaces within the associated carbonate rocks as shown in (Fig.3.7B, C, D, E,F), are all unequivocal evidences of supratidal sabkha deposition (Warren and Kendall, 1985; Warren, 1991; Schreiber and EL-Tabakh, 2000; Schreiber et al., 2007; Muray, 1964).

On the other hand the interbedded carbonates within the evaporite sequence are generally composed of thin to thick beds of limestone and dolomitic limestone which also display vertically stacked cycles. Furthermore facies analysis is very crucial for depositional environment interpretation of carbonate deposits. Thus, the reconstruction of their paleoenvironment requires investigation of the compositional and textural constituents of carbonate rocks under the microscope to establish microfacies types. Most microfacies analysis used to discriminate ancient depositional environments are qualitative and refer to compositional and textural variations (grain size, sorting) as well as bioturbation features (Flugel, 2004).

Moreover, petrographical analysis of carbonate samples collected from the field has revealed six microfacies types, which include: peloidal-bioclastic wackstone/packstone, ooid/bioclastic grainstone, interlaminated micrite-bio packstone, dolomudstone, microbial laminated boundstone and micritic limestone microfacies types. These microfacies types generally represent low energy environments with localized high energy settings.

The first three (pel-biowackstone-packstone, ooid/bioclastic grainstone and interlaminated micrite-to biopackstone) microfacies types are dominated in the lower part of the succession, while the last three microfacies types (dolomudstone, micritic limestone and microbial laminated boundstone) are more common in the middle and upper parts of the stratigraphy interval. These microfacies types, particularly the last three microfacies are repeating many times in a more or less shallowing-up cyclic manner. This cyclic pattern of the facies relates most probably small changes of relative sea level in the depositional setting.

Pelbiowackstone-packstone (MF-A) occurred at the base of the section and it characterizes the presence of obscured skeletal shells which are extensively micritized and embedded within micrite matrix, and fine peloidal carbonate grains along with brown to red stained spots on the

grains which may indicate an alteration due to bioturbation or high Mg-clay minerals. Common recognizable biota assemblages of this facies are mollusks, brachiopods, foraminifera and ostracoda which are mainly in a growth position (Fig.4.5 A-C). These characteristics determine the deposition of this microfacies under low energy shallow marine environment of open-restricted shelf lagoon, mid-to inner ramp (subtidal) settings, as these features have strong resemblance and comparable to facies belts 8 and 7 of Wilson (1975).

Ooid/bioclastic grainstone microfacies (MF-B); the main features of this facies are the abundance of sand sized ostracode shells and tangential structured ooids with peloids, foraminifera and bivalves within sparry calcite cement. The relative similar orientation of skeletal shells, the moderate sorting, the imbrications and/or overlapping of the shells and their slightly mechanical fracturing (this may also occur by means of compaction), reflects short distance transportation of the sediments from subtidal to lower tidal flats and/or tidal bars, most probably by storms or tidal currents. The presence of fractured or distorted concentric ooid laminae with radial structures (Fig.4.6A) is an indication of relatively high energy environment and shallow water setting (Flugel, 2004).

According to Tucker (2001) tidal flat carbonates characterize most commonly by fine sediments mainly lime mudstone and peloids. However, there are local lenses and/or layers of coarse grained skeletal subtidal sediments (grainstone) transported onto the tidal flats by storms and occur as tidal-channel fills. Flugel (2004) also suggests the occurrence of such facies in bars, channels and sand shoals heaped up by tidal currents, and assigned to inner ramps and shallow lagoons in restricted platform interior settings, accordingly compared facies belt 8 of Wilson (1975).

This microfacies passes up on the section into interlaminated micrite-to biopackstone microfacies (MF-C), which characterizes planar, fine to coarse millimeter thick alternative laminae that differ in internal composition and texture. The finer lamina mostly shows micritic fabric while the coarser lamina displays packstone and rarely wackstone. Fossil assemblages in the coarse laminae are dominated by fine to medium sand sized ostracode shells and Ooids (Fig.4.7A&B) with some large foraminifera, gastropods and bivalves. These skeletal shells exhibit moderate to good sorting with occasional poor sorting patches and generally oriented sub

parallel to the bedding. Signs of storm reworking and re-sedimentation of the shells are common. All these properties indicate tidal related processes were resulted the deposition of this facies, where the energy level shifting rapidly. At times some large gastropod shells are floating in a micrite matrix, and these gastropod shells are partly or completely leached and fragmented along with very thin cracks partly filled by cements. This situation was observed at the upper part of this facies. The boundary relationship of these couplets is either sharp or gradational as shown in (Fig.3.8A, 4.7A&B). This microfacies is comparable to facies belts of 8 and/or 9 of Wilson (1975) (near coast platform interior), inner ramps and tidal flats (Flügel, 2004).

Dolomudstone microfacies (MF.D), exhibit finely crystalline sugary dolomite of anhedral crystal shape with xenotopic texture and scattered large rhombic shaped features now filled by gypsum. Other evaporite nodules are dispersed in the matrix or filled elongated fenestral-like features (Fig.4.8). It also contains pelletal grains, organic matter relics and clotted micrite. In the field this facies appears as massive with no discernible structure except some burrow-like features, fine grained in texture and light grey to dark grey in color. Therefore, these attributes indicate most probably in restricted shallow to sub emerging lagoon or upper subtidal to intertidal evaporitic setting. The dolomitization of this microfacies can be taking as a penecontemporaneous origin, owing to its fine crystalline texture, presence of gypsum/anhydrite nodules and the absence of skeletal grains.

According to Kaldi (2016) four textures typical for penecontemporaneous supratidal dolomite are: **1)** very fine crystalline, sucrosic texture **2)** lack of skeletal grains **3)** close association with algal matter and **4)** the presence of displacive evaporite crystals. All these textural characteristics were observed in this microfacies (Fig.4.8 A-C).

The microbial laminated boundstone microfacies (MF.E) displays microscopic microbial/algal mat structures and scattered gypsum/anhydrite crystals along with few carbonate clasts in the groundmass micrite matrix. It contains microbial laminations and fenestral fabrics with clotted micrite and peloids. The micrite matrix is partially or completely affected by neomorphism and the microbial laminae are extensively disrupted by lenticular gypsum crystals and filled the fenestral porosity (Fig.4.9B). Some samples show heterogeneous dolomitization/replacement pattern (Fig.4.9A), in which euhedral rhombic dolomite crystals along with intercrystalline

porosity are common and concentrated along the dissolution and fenestral cavities developed probably as a result of decaying microbial organisms and/or leaching micritic grains. This type is perhaps a later stage dolomitization processes, caused by dolomitized fluids moved preferentially along these permeable structures. Postdated gypsum/anhydrite cements are also present in these zones.

Some filamentous microbial micrite shows filament bundles with preserved segmentation (Fig.4.9C). During the field it was observed the presence of tepee structures, desiccation cracks, fenestral and dome-shaped thrombolite structures (Fig.3.7B-F). The observed macro and micro textures and structures of this microfacies are equivalent to the Standard Microfacies Types (SMFT 20 and 21) of Wilson (1975), which is named “laminated stromatolitic bindstones/mudstones” and “fenestral packstones and bindstone” of Flugel (2010). It is assigned its depositional setting mostly in intertidal zone but also in supratidal and shallow subtidal settings, open platforms (subtidal, FZ7), tidal zones of restricted lagoons (FZ8) and arid coasts (FZ9A, supratidal). Filled or unfilled fenestral fabrics associated with stromatolite structures are a diagnostic feature to tidal flat settings (Lasemi et al., 2012).

The micritic limestone microfacies (MF-F) represent non laminated pure micrite with some scattered pseudomorphs of pyrite after rhombic dolomite and/or gypsum/anhydrite crystal laths along with lenses of brownish clay. The micrite is partially recrystallized into microspare. This microfacies also characterizes the absence of skeletal and other carbonate grains. Compared this microfacies to the Standard Microfacies Types of Wilson (1975), it is more or less akin to ‘non laminated pure micrite’ microfacies of Wilson. As a result its depositional setting corresponds to either Tidal flats (FB-8) or arid evaporitic coast (FB-9) facies belts in the Wilson model. However, in the case of the study area, due to the presence of evaporite nodules and lack of fossils makes its depositional setting more likely on arid evaporitic coast and specifically in (FZ-9A).

From the above discussed carbonate microfacies types with their corresponding Standard Microfacies Types (SMFT) suggested by Wilson (1975) and its modified type adopted by Flugel (2010). The depositional setting of the carbonate rocks in the study area corresponds to the Facies belts ‘8’ and ‘9’ in Wilson facies model (1975). The former belt characterizes shallow

marine water on platform interior and/or inner ramps (lagoon), where water circulation may be restricted. The latter belt favors deposition on platform interior/inner ramps, where evaporative conditions exist.

Adding to the presence of widespread gypsum beds in the study area both depositional belts (FZ-8 and FZ-9) is possible for the deposition of the whole sequence (evaporite-carbonate), given that the appropriate climatic conditions. This means that during hot season and higher evaporation rates, consequently much water lost from the basin the formation of evaporites is favored, whereas during cold and humid season along with enough water in the depositional basin, carbonate deposition is preferred. Thus these carbonate-evaporite sediments originate a generally low energy peritidal environments ranging from; subtidal lagoon through intertidal to supratidal sabkha setting (Fig.5.1).

As evidenced by the presence of peloidal-bioclastic wackstone/packstone (MF-A) of subtidal facies passing upward into beach barrier/ridge or tidal island facies of ooid-biograinstone (MF-B) and interlaminated micrite-biopackstone (MF-C) which represents a wash-over facies, passing laterally through dolomudstone into laminated algal boundstone (MF-E) with fenestral fabrics along with tepee structures of intertidal zone to non-laminated pure micrite (MF-F) of supratidal setting.

Generally the lithofacies and microfacies data of the carbonate and evaporite rocks in the study area shows, shallow marginal marine depositional environments ranging from low energy open-restricted platform interiors (lagoonal shelf) through periodically high energy setting of tidal bars to low energy arid evaporitic environments of intertidal to supratidal setting, as the figure below shows (Fig.5.1).

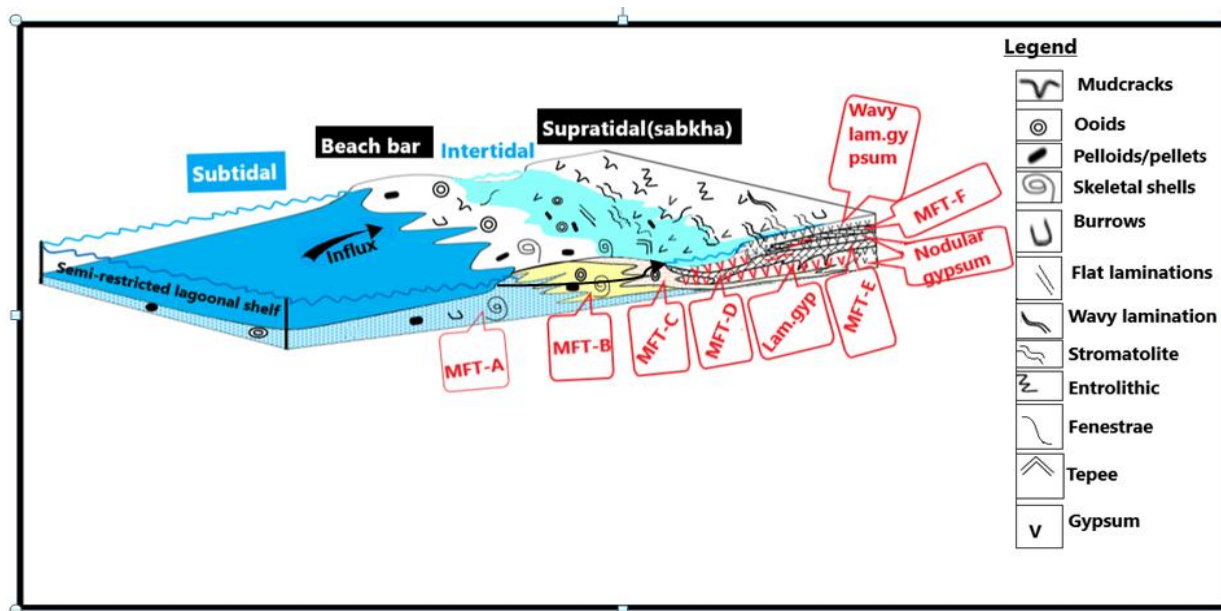


Figure: 5.1. Proposed schematic model showing the depositional setting of the studied carbonate-evaporite sequences along with subenvironments and their respective position of carbonate microfacies types (MFT-A, B, C, D, E, F) and evaporite lithofacies (Laminated gypsum, Nodular gypsum, Wavy laminated gypsum), structural and sedimentological features are also illustrated.

5.3. Lithostratigraphy and Facies associations

The evaporite-carbonate succession analyzed in this study is part of the Korrahie Formation (Neocomian) in the Ogaden basin. Although the lower stratigraphic control was not observed or not outcropped in the study area, the upper stratigraphic control was observed in the southeastern edge of the study area. This is marked and recognized geomorphologically, as a sharp contact by the slope break between the gently formed gypsum (Korrahie Formation) below the boundary and the directly overlying, cliff formed limestones (Mustahil Formation). Moreover, the white colored very fine grained massive alabastrine gypsum layers along with extensive fibrous satin spar is overlain by thin layers of loose shale/clay and marle. This passes up section, into well consolidated thinly bedded light yellowish limestone or marly-limestone, which in turn overlain by thickly bedded dark to light grey fine to medium grained limestone.

A sample took from the light yellowish limestone at the lower part of the Mustahil Formation was investigated under the microscope. The observed skeletal assemblages in this sample include: brachiopods, foraminifers and crinoids amongst other carbonate grains like ooids and

peloids, which embedded in muddy matrix. These bioclasts exhibit the impression of intensive bioturbation. Texturally it is a skeletal wackstone to packstone similar to MF-A recorded at the bottom of the studied evaporite-carbonate rocks (Korrahie Formation). Therefore, this facies indicates regeneration of normal open marine depositional environment, after a period of restriction and evaporitic conditions that allowed the deposition of the underlying sequence (Korrahie Formation).

Moreover, based on the previous works in the Ogaden basin these lithologies represent the bottom part of the Mustahil Formation as many works in this area were reported and mapped. According to Russo et al., (1991); Mengesha et al., (1996); Purcell, (1979); Bosellini et al., (1999) and John, (2016), the Mustahil Formation characterizes basal shale followed by marly limestone and ended by rudistide and coral reef caps. This formed under inner to outer shelf environment and directly rests on evaporite-carbonate succession of Korrahie Formation (Neocomian-early Aptian). The description given by the previous works are similar to the observations of this study. Thus, the lithostratigraphic section log, presented here is a part of the Korrahie Formation. The correlation given in the following section is also confirms this conclusion.

The stratigraphic succession of the Korrahie Formation outcropped in the study area (Korrahie section) is measured a total thickness of about 50m. It consists of generally flat lying beds of alternating limestone, dolomitic limestone, gypsum and minor marly and shale layers as well as thin horizons of carbonate breccias (Fig.5.2). The vertical succession of this sequences reveal a meter scale repetitive stratigraphic cycles (parasequences). These cycles are most probably developed as a result of minor relative sea level fluctuations or tidal related processes. Accordingly, a complete cycle of carbonate-evaporite sequence is as follows:

From the base of the studied succession, the microfacies association of the fossiliferous limestone lithofacies (LF4) display shallowing upward pattern (stacked facies), that reflects specific depositional setting. Consequently the vertical succession of this unit consists of light yellowish thin to thickly bedded muddy (calcilutite) limestone, with bed thickness ranging from 26-30cm and horizontally planar bedding. Microscopic texture of this microfacies ranges from

wackstone to packstone, and composed of mainly bioclastic and peloidal carbonate grains which are relatively bioturbated and micritized. The mottled appearance of this pel-biowackstone-packstone microfacies (MF-A) represents possibly bioturbation with no clearly recognizable burrows. Identifiable skeletal grains of this facies predominantly contain bivalves and ostracode along with brachiopods, algae, foraminifera and other unrecognizable fossil fragments which are converted to peloids due to extensive micritization. The micrite matrix is partially crystallized into microspar. This microfacies represents deposition under shallow open-restricted lagoonal shelf environment where energy is relatively low and/or below the wave base.

This facies passes up on the section into light grey to tan brown colored, thinly laminated medium to coarse sand sized fossiliferous grainstone (MF-B), with a bed thickness ranging from 15-25cm. Microscopically it contains primarily ooids and ostracode shells, flat to rounded peloids along with foraminifera, elongated bivalves, brachiopods and crinoids are also present. Sorting is relatively medium to well sorted with bimodal grain size distribution, and cemented by fibrous sparry calcite. Some diagenetically precipitated intergranular evaporite cement is occasionally observed. Based on the underlying muddier facies, this facies suggests an upward change of energy from relatively lower to higher energy settings. The presence of grain imbrications, overlapping, truncated and/or intruded along with concave-convex contact relationship between grains (Fig.4.6) as well as the occurrence of tangential (radial structured) sand sized ooids are also other features indicating the energy level of the depositional setting. This sediment were reworked and redeposited (Flügel, 2004; Tucker, 2001) on to a beach barrier or tidal bar setting by storm and/or tidal currents. Moreover this microfacies (MF-B) has a limited areal extent and forms a narrow long ridge-like structure.

The overlying microfacies (MF-C) characterize an alternating fine and coarse grained laminations. The coarser lamina contains predominantly by sand sized ostracode shells and ooids along with other scattered large shells like some bivalves, foraminifera and gastropods ranging in size from 1-2.5mm, whereas the finer lamina contains predominantly by micrite/mud. Texturally it is a micrite to packstone. These alternating laminae can be interpreted as rapid fluctuations of energy level caused by periodic storm or tidal currents. The poorly sorted character and the grain composition of this facies also may suggest a proximal beach barrier and/or presence of patch

reefs/shoals in the lagoon (Nimegeers and Qing, 2002). Thus it can be interpreted as a back barrier/wash over facies, and its sediments are transported by periodic storms and waves from the mid lagoon/seaward through the barrier and deposited as wash over behind the tidal barrier.

Moldic porosity developed by leaching skeletal shells mainly gastropod shells along with thin cracks occur in the uppermost part of this facies. This may indicate meteoric influence and vadose alteration/leaching due to subaerial exposure. Thin layer (30-35cm) composed of angular to sub rounded boulders of micritic limestone and loose sand sized matrix along with whitish gypsum crystals observed on top of this microfacies also point out this subaerial exposure event. This microfacies (MF-C) is laterally (eastward) changed into thin, light brown limestone. That contain tepee and rippled structures along with polygonal cracks and burrow filled by gastropod shells (Fig3.7B&E), which indicate intertidal to supratidal environment.

On top of this microfacies (MF-C), thin layer of nodular gypsum is present. This nodular gypsum changes vertically its thickness and texture, and displays relatively thick, horizontally bedding with thin black and white discontinuous laminations as well as brownish microbial filaments (Fig.3.4C). Passing up an alternating carbonate mud and sand sized lenticular gypsum layers of about 0.8 to 1m thick in the seaward direction, and to the landward it exhibit an isolated nodules forming a chicken wire-like texture with abundance of radially arranged rosette-like displacive crystals.

Microscopically this unit shows lateral textural variation. From west to east (seaward-landward), it contains remnants of micritic algal mat strips within the gypsum nodules. Due to extensive replacement of evaporites (anhydrite/gypsum), the algal mat structures were extremely destroyed and obliterated, and the micritic sediments of algal mat relics were crystallized into microspar and partially dolomitized or pyritized. This gypsum facies formed in shallow evaporitic pond (intertidal pond) that floored by algal mat, and existed behind the established beach barrier/ridge (Fig.5.1), under peritidal environment.

As the relative sea level falls on/or below the barrier/ridge, and the ridge crest exposed to the surface. The salinity of this shallow evaporitic pond increase due to high evaporation, as a result of this high salinity and brine concentration the microbial mat growth ceased, and gypsum crystals formed on or within the mat surface (Aref, 1989; Taj, 2012;), as observed lenticular

gypsum crystals embedded within microbial filaments (Fig.4.1D, 4.9B). On the landward direction beyond this isolated pond, it formed under supratidal sabkha condition within the carbonate mud as nodular form and exhibit chicken-wire and enterolithic textures (Fig.5.1).

Therefore the sub-aerially exposed surface on the beach ridge/barrier crest can be considered a local exposure surface that developed on relatively topographic highs due to rapid falling of relative sea level; whereas areas of topographic lows are under shallow water condition (brine pond) and the deposition of microbial/algal mat and gypsum continuous. The presence of microscopic leaching of the skeletal grains observed in the upper part of microfacies (MF-C), which is exposed on the barrier, also supports this conclusion, as these leaching features may develop as a result of meteoric invasion. According to Lasemi et al., (2012) Long time subaerial exposure in arid to semiarid conditions results the partial dissolution of carbonate grains and porosity enlargement by meteoric water. The formation of iron oxide stained envelope around the grains is also caused by this emergent event.

This vertical succession shows a shoaling upward or brining up, as it starts a subtidal carbonate facies and ends an evaporite facies. Thus a new influx of sea water due to relative sea level rise will repeat the cycle by depositing subtidal/intertidal facies on the preceding supratidal evaporite. Finally a major sea level rise (Transgression) causes the re-establishment of normal marine with the deposition of the overlying Mustahil Formation in an open marine setting, and the evaporative condition in the area is terminated by this event.

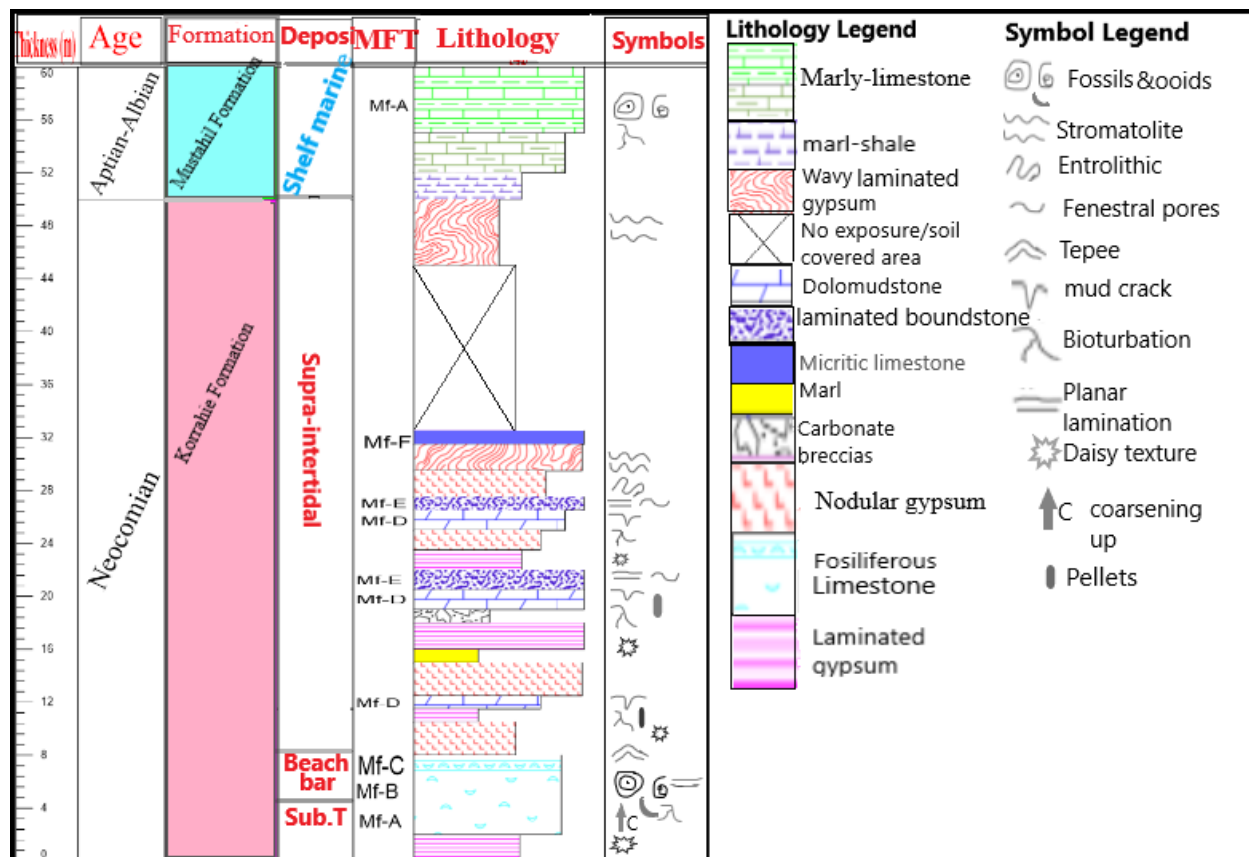


Figure.5.2.Stratigraphic log showing lithofacies and microfacies sequence along with their textures, structures and faunal components and their interpreted depositional environment, (subtidal-beach bar/ridge, intertidal-supratidal). (MFT=microfacies types)

5.3.1. Correlation with other studied sections in the Basin

The Neocomian Korrahie Formation is well known in the subsurface of the Ogaden basin. As many wells drilled by oil companies encountered this Formation in different depths at different localities in the basin (Purcell, 1981). The thickest part of the Formation is found in the basin center, as recorded from Bodle-1 Well, 1680m thick succession of interbedded shale, limestone, dolomite and sandstone with anhydrite and salt (Purcell, 1979, John, 2016). Further to the west from Bodle-1Well, the sandstone content increases, as thick section of shale, sandstone and limestone with gypsum in the upper part was reported from El-kuran well (Purcell, 1979). On the eastern side, a significant thickness was recorded at Calub-Wells, which is about 1104m of gypsum-anhydrite intercalations with dolomite at the base. Further to the east from the Calub

Wells, the thickness of the Formation decreases, from Gumburo Well to Galadi it changes from 123m to 104m respectively (John, 2016, Purcell, 1981), beyond Galadi the Formation is not present, as reported from Bokh-1 Well.

In addition to this subcrop data, the Formation is also outcropped on the surface at different localities in the basin. However, no recent detailed lithostratigraphic data is available. As a result an older data found in the gray literature of the Ogaden basin will be used here for correlation purpose, to confirm the stratigraphical position of the present study. Although the original work of this study is not in hand, it is cited from other works. This work was done by Elwerath (1967, as cited in Purcell, 1979), and he correlated the Cretaceous outcrops in 9 sections within the basin as shown in (Fig.5.3). One of these sections is in Korrahie area (Gorrahie section(1)) which is very near the present study area, two other sections are also close to the present study area (AGerre(8) and Anfodpile (9)) as shown in (Fig.5.3).

As shown in the figure below, the graphic log section constructed at AGERre (8), which is located to the northeastern direction of the present study area, do not contain Cretaceous lithology and thus the exposed unit in this section is below Korrahie Formation. It is most probably Gebrideharre Formation as the age indicates (U.malm-Kimmeridgian). The other nearby section is Anfodle (9) in the eastern direction of the present study. As the graphic log of this section shows, both the Kimmeridgian and the overlying Neocomian rocks are outcropped with gradational contact but no Aptian lithology. Going to the type section at Gorrahie (1), the Neocomian and the directly overlying Aptian unit is outcropped with sharp contact relationship, but not Kimmeridgian unit which is buried now. Here the present study is more or less correlatable to this section. Going further to Lazzal (2) section an Albian unit is coming to exist and finally a Cenomanian unit at Marehan (3) section.

As the trend shows the age of the outcropped lithology becomes younger towards southeast. A similar trend is observed on the other side from Goja (7) all the way to Ascraft (4) along the Wabi Shabele valley with the thickest outcropped section is at El-Kere (5). Therefore, the stratigraphical position of the present study is confirmed as it is correlable to the Gorrahie section as shown in (Figure. 5.3).

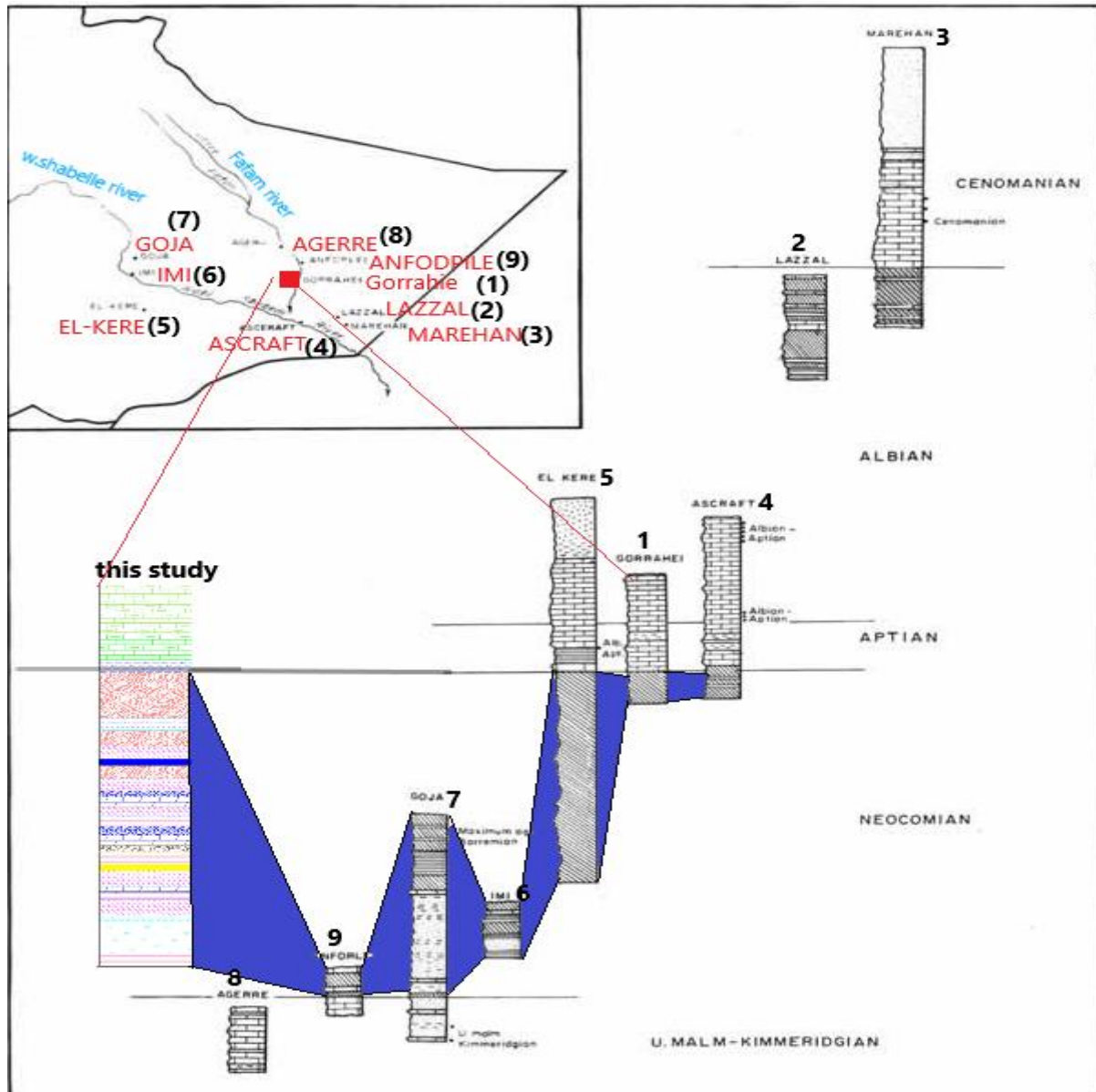


Fig.5.3. Correlation of the present study with other sections in the Ogaden basin. The red rectangle shows the location of Korrahei (Gorrahei) village near the study area. The numbers (1-9) in the bracket refer, names of their respective section columns, which are rewrite here as red colored names over the original sketch, to make clear and readable (after Elwerath, 1967, in Purcell, 1979).

5.4. Diagenetic evolution

Sulphate and carbonate sediments are more susceptible to diagenetic alteration than in terrigenous siliciclastic sediments, because their constituent minerals (calcium sulphate and

calcium carbonate) are more easily soluble. These diagenetic alterations took place at different diagenetic stages (during early, late and uplift stages) throughout the history of the rocks. It is important to note that carbonate and evaporite rocks response differently to each of these diagenetic stages.

In this study an integration of field sedimentary and petrographic data has been utilized to identify the major diagenetic features overprinted on the studied rocks. The observed diagenetic signatures are discussed in the following pages, and some representative photomicrographs and field photo will be present in Appendix one.

A) Carbonate rocks

The various diagenetic features of carbonate rocks are the result of different diagenetic processes. These occur at different diagenetic realms, ranging from near surface marine and meteoric realm and down to burial realm. The major diagenetic processes subjected to the studied carbonate rocks include: micritization, cementation, neomorphism, compaction, dissolution and dolomitization. These processes and their product are discussed as follows and summarized in (Table 5.1)

Micritization: is the process by which carbonate grains are partially or completely altered by the activity of microbes (commonly endolithic algae) at or just below the sediment-water interface, mostly in shallow marine environment (Flugel, 2004). The process involves boring on the grains by microbes and the subsequent filling of micritic cement in the small holes on the grains, which ultimately leads the formation of thin micrite envelopes around the grains. In some cases the original carbonate grains are completely converted to peloids, as a result of extreme micritization. Therefore this process is either constructive or destructive; it is constructive as it maintains the shape of an original bioclastic grains after their complete dissolution during diagenesis (Plate 1-E), due to addition of thin carbonate (micrite envelope) on the exterior of the grains, in a low energy environment or during shallow burial (Taj, 2012). At other times it is destructive, as the repeating borings and fillings destroy the peripheral zone (Plate 1-A) or even the whole grain, and finally results in the production of peloids (Flugel, 2004; Tucker, 2001; Taj, 2012; Adams and Mackenzie, 1998)

Cementation: cementation is the process by which carbonate crystals precipitate into pre-existing (depositional and/or secondary) void spaces. It is the diagenetic processes that converts a loose sediment into lithified solid carbonate rock, and mostly taking place where there is a significant pore-fluid saturated with respect to the cement phase (Tucker, 2001). The recorded cementation on the studied carbonate rocks is early diagenetic isopacheous (fibrous) cements, which indicate early marine cementation that precipitated where pores are filled with water. It is a diagnostic feature of early diagenetic cementation in lower intertidal and subtidal settings in hypersaline conditions (Adams and Mackenzie, 1998). This type of cement is observed around the carbonate grains as sparry calcite cements, that lining both the intragranular and intergranular porosity (Plate 1-D&E). Meteoric phreatic cements were also observed. This type of cement characterizes a crystal size increase towards the center of the pores and exhibits a drusy mosaic fabric (plate 1-C). Although the mineralogical composition of these cements are carbonate, occasional evaporite (mainly gypsum) cements were also observed (Plate 1-H), which indicates the effect of pore water chemistry on cement mineralogy.

Neomorphism: is an in situ process of recrystallization and replacement of one mineral to the same mineral or another of similar composition. It comprises the increasing crystal size in micrite to microspar or pseudospar, and the transformation of aragonite shells and cements to calcite and/or dolomite (Tucker, 2001; Adams and Mackenzie, 1998). The observed neomorphic fabrics are mostly growth of dense, dark micrite into clear fine crystals of microspar or pseudospars, some aragonite skeletal grains partially replaced by calcite microspar and aggrading neomorphism of dolomite/calcite are also observed (Plate 1-F). This diagenetic process indicates the effect of burial diagenesis on this rocks, meteoric diagenesis is also possible cause of this fabric.

Compaction: in carbonate sediments compaction occurs during burial, resulting varying degree of grain packing, grain deformation and grain contact dissolution depending on burial depth and sediment nature. This process involves either the mechanical or chemical effects on sediments. The diagenetic physical compaction results the overall reduction of the rock porosity by readjusting loose grain fabrics into more tightly packing grains, fracturing the weakened and uncemented grains and dewatering of carbonate mud, which result cracks and fractures (Plate 1-

D). As burial exceeds many hundreds of meters of overburden chemical compaction leads the formation of stylolites and dissolution seams (Tucker, 2001). In the studied rocks, it was observed a good example of mechanical compaction, through grain fracture and breakage (Plate 1-H). Much of the intergranular depositional porosity has been lost by close packing of the grains and some by squashing of the grains together. Some of the outer margins of the grains along with their early marine cemented rims have flaked or spilled off the grains, others changed their original grain point contacts to line contacts and many of the grains penetrate one another. Dissolving at the grain contacts due to further compaction and/or deep burial of the sediments is also rarely observed.

Dissolution: dissolution in carbonates occur, as a result of pore fluid passage passing through the carbonate rocks, which are undersaturated with respect to the existing carbonate phases. This diagenetic process leads the formation of new porosity and the enlargement of the pre existing voids, by dissolving mostly aragonite and high-Mg calcite carbonate grains (Taj, 2012). Moldic porosity formed from selective dissolution of aragonite and high-Mg calcite of gastropod shells is observed (Plate 1-E). These moulds were later filled and/or lined either by micrite sediments or by isopachuous (fibrous) calcite cements and occasionally by gypsum crystals (Plate 1-C). This dissolution process took place in either a meteoric diagenetic environment during short period of subaerial exposure of the carbonate rocks at the margin of the subtidal/lagoon or burial/uplift diagenetic environment.

Dolomitization: this process is mostly found in ancient limestone rocks, and usually has either partial or complete effect of the original rock fabrics. It can form at almost any diagenetic stages from symsedimentary to burial diagenesis.

The effect of dolomitization in the studied carbonate rocks is more pronounced and observed in the tidal flat facies than in lagoonal bioclastic facies. The predominant fabrics of these rocks are microcrystalline groundmass of dolomite with sparsely distributed coarse euhedral to subhedral dolomite rhombs set in the groundmass and/or concentrated along elongated burrow shaped and fenestral cavities (Plate 1-F). Some large rhomb shaped crystals are now filled and contain gypsum pseudomorphs (Fig.4.8B).

It is believed that recent dolomitization occurs in a wide variety of settings ranging from evaporite associated intertidal-supratidal to normal saline lagoonal settings, as penecontemporaneous replacement of aragonite and calcite sediments (Tucker, 2001; Kaldi, 2016). Some modern examples include Trucial coast in the Persian Gulf, Florida, Bahamas, and the Coorong districts (Tucker, 2001 and others). Several models have been forwarded for dolomite formation and all stressed the importance of three basic factors for dolomite formation; which are the source of Mg ions, the mechanism by which the dolomitized fluids are transported through the sediments and a way to diminish kinetic factors inhibiting the precipitation of dolomite (Tucker, 2001). The presence of fine microcrystalline dolomudstone with algal matter and the presence of displacive and void filling evaporite crystals in the studied rocks indicate a penecontemporaneous mechanism for the dolomite origin. This mechanism strongly depends on hypersaline brine for which Mg/Ca ratio is higher than the normal seawater.

The supratidal dolomitization of the studied rocks is more or less resembles present sabkha dolomitization in the Trucial coast. In this area dolomitization occurs as a result of brine concentration in the sabkha surface by evaporation of storm generated seawater, and the subsequent aragonite and gypsum precipitation leads the removal of Ca ions from the brine solution and the elevation of Mg/Ca ratio in these brines. The increased Mg/Ca ratio results the early dolomitization of the supratidal sediments either by replacement or direct precipitate (Moore, 1989; Tucker, 2001). Therefore the fine grained dolomicrite sediments in the study area were formed in similar situation (evaporative model).

The presence of coarse dolomite rhombs within the microcrystalline matrix suggests later and subsequent episode of dolomitization. Large euhedral dolomite rhombic crystals can develop as a result of mixing meteoric and marine water (Ulmer and Laury, 1984). Kaldi (2016) interpreted the formation of such large dolomite rhombs in dolomicrite matrix as a result of fresh water flushing and dilution, lowering salinity while Mg/Ca ratio remained high.

Seepage reflux is also another possible mechanism for their formation, providing that the presence of limited film of Mg-rich brine fluids, generated in tidal flats and sabkha by evaporation, and moving downward through density contrasts with marine pore fluids. As this

fluid with high Mg/Ca ratio moved preferentially through the permeable burrows the materials within and adjacent to these fluid conduits will be altered and dolomitized. The common occurrence of these coarse rhombic dolomite crystals along the linear burrow-shaped or dissolution cavities (plate 1-F) as well as their limited extent and restriction in the supratidal to lower intertidal sediments indicate their precipitation from small volume of dolomitized fluids which losses its Mg content as it moves downward through the porous and permeable cavities.

Sulfatization: sulfate and other evaporite (eg. Chloride) minerals can occur in carbonate sediments as displacive and/or replacive nodules and cement precipitates. These minerals precipitate from evaporative brines that migrate through the adjacent or underlying strata. In the analyzed carbonate samples sulfate minerals occur diagenetical in a variey of ways; as displacive crystals or nodules, carbonate replacements (Plate 1-G) and as pore filling cements. The replacement of carbonate by sulfate minerals can happen as sulfate-saturated solutions migrate through carbonate rocks, when this situation took place at depth under high temperature and pressure the resulting sulfate mineral is likely anhydrite rather than gypsum (Makhlouf and EL-Haddad, 2016; Murray, 1964).

In the case of this study the observed gypsum mostly contains relics of anhydrite and micrite, but also inclusion free lenticular gypsum crystals was observed which represents direct replacement of carbonate by gypsum under near surface conditions. Gypsum/anhydrite also found as pore filling cements (Plate 1-D, H) which formed from downward percolating brines that precipitate gypsum and/or anhydrite in the open pore spaces and biomoldic porosity of the underlying carbonate rocks. Sulfate can also occur in fractures across carbonates as vein filling (Plate 1-I)

B) Evaporite Rocks

Petrographical investigation of the evaporite (gypsum) rocks in the study area shows the presence of various diagenetic features. These features were developed at different diagenetic stages of the rock's history; from early diagenesis related to syndepositional processes through burial to uplift stages.

Moreover, like the carbonate rocks, evaporite rocks experience various diagenetic processes and alterations during early diagenetic stages. The major fabrics and textures that can be attributed to eogenetic modifications are displacive and replacive gypsum/anhydrite nodule formations and carbonate dissolution.

The formation of evaporite nodules at this early diagenetic stage have been interpreted in several ways; such as a replacement of earlier formed swallow-tail gypsum crystals by anhydrite, or displacive growth of gypsum nodules in the soft sediment layer, due to upward capillary movement of groundwater as the evaporation processes continuously operating on the surface, which ultimately leads increasing brine salinity (Murray, 1964). Or transformation of gypsum to anhydrite due to higher surface temperature that result the dehydration of gypsum and the formation of primary anhydrite, which can be interpreted a syndepositional diagenesis under sabkha setting (Warren, 2006, 2016).

In the study area the anhydrite nodules formed at this stage were found as relic crystals in the cores of gypsum. This indicates the rehydration of the anhydrite nodules during exhumation and uplift, and regeneration of gypsum with anhydrite relic inclusions. Dissolution cavities in carbonate rocks, later filled by gypsum are also an indication of supratidal environments (Rahimpour-Bonab et al., 2010).

From field observation and petrographic analysis, it seems that the evaporite rocks were more affected during burial and the subsequent exhumation diagenetic stages (mesogenetic-Telogenetic), where partial to complete alterations of both primary mineralogy and their depositional crystal morphology occur. Although the conversion of gypsum to anhydrite can occur at the earth's surface by extreme solar heating in arid regions similar to that described by Aref et al., (2003) in the Miocene evaporites from the red sea, or in the capillary zones of sabkha and evaporitic mudflats due to flushing of high salinity brines (Warren, 2016). An effective and pronounced anhydritization (gypsum to anhydrite) took place during burial of primary gypsum deposits. Thus, most thick beds of anhydrite in ancient evaporites were initially deposited as gypsum (Murray, 1964).

Moreover during burial, both temperature and brine salinity increases, and based on the stability field of gypsum and anhydrite, gypsum is not stable at temperatures above 50-60C° under

atmosphere pressure (Taj, 2012). As a result it will convert (dehydrated) to nodular anhydrite and loses its lattice water as well as original crystal morphology, unless preserved within microbial laminae (Taj, 2012). The transition depth of gypsum to anhydrite is variable depends on lithostatic pressure, local geothermal gradient and salinity of the pore brines, however, mostly it is in the range from few meters to over a kilometer (Warren, 2006; Taj, 2012).

The presence of chicken wire-like structures and enterolithic texture which are observed in the studied rocks are the results of early stages of burial diagenesis. The occurrence of anhydrite pseudomorphs after gypsum and the common presence of secondary satin spar gypsum (Plate 2-A, C&F) observed in the studied evaporite (gypsum) rocks, is an evidence of sulphate-rich fluids produced during gypsum dehydration processes and/or dissolution of pre-existing evaporites. These fluids act as hypersaline pore fluids and precipitate fracture filled satin spar gypsum, which is interpreted an indication of the end of burial diagenesis and the beginning of telogenetic processes (Gindre-Ghanu et al., 2015; Warren, 2006; 2016).

Microscopic analyses indicate that the predominant uplift (telogenetic) textures overprinted on the evaporite rocks and the widespread occurrence of secondary gypsum in the study area. Most gypsum fabrics observed in outcrop and under petrographic microscope are the result of exhumation. As evaporite rocks were uplifted and entering the telogenetic realm, the anhydrite nodules formed during early and burial stages as a result of compaction and gypsum dehydration, is now rehydrated and reconverted to gypsum (secondary gypsum). The following is a discussion of the petrographical characteristics of the observed types of diagenetically regenerated gypsum (secondary gypsum).

Rehydration fabrics were observed both in the field and petrographic study and include: fine grained gypsum (alabastrine gypsum), daisy gypsum (porphyroblastic gypsum), fibrous gypsum (satin spar gypsum) and granoblastic selenitic gypsum. Moreover pseudomorphs and microscopic relics of anhydrite crystals floating in gypsum are also the petrographical properties of the observed secondary gypsum.

Four different types of secondary gypsum textures were identified in the samples collected from the study area which include; alabastrine, porphyroblastic, granoblastic and fibrous satin spar.

All these types were formed at different telogenetic stages and varied hydrologic conditions during exhumation history of the rocks.

Microcrystalline xenotopic mosaic crystals of fine grained alabastrine gypsum textures were observed under the microscope (Fig.4.1A), which contain scattered gypsum or anhydrite laths floating in alabastrine matrix and carbonate mud. The presence of this texture can be interpreted as a result of pervasive re-watering of precursor anhydrite under the active phreatic zone, where rapid reactions and recrystallizations took place due to extreme hydrologic disequilibrium conditions created by the seasonal groundwater changes, and possibly occurred in the late stages of the exhumation history of the rock (Gindre-chanu et al., 2015; Taj, 2012).

The coarse displacive clusters of porphyroblastic with smooth straight or curved boundaries and sometimes interlocking gypsum crystals (Fig.3.4A&B, Fig.4.2D) with corroded anhydrite relic inclusions (Fig.4.4C). Indicate the rehydration of anhydrite at near equilibrium conditions under stagnant phreatic zone with sluggish cross-flow, where hydration reactions and recrystallization took place slowly. This process occurs in the lower part of the telogenetic realm (Taj, 2012; Gindre-chanu et al., 2015; Warren, 2016). The presence of intercrystalline porosity (Plate 2-E) (Fig.4.4D) was interpreted by Gindre-chanu et al., (2015) as a micro-scale dissolution and/or replacement front that runs across the precursor crystals, dissolving its way and precipitating by clear gypsum in the created pore spaces.

The relatively coarse equigranular subhedral to euhedral granoblastic gypsum crystals occur as aggregates or as patches within porphyroblastic gypsum (Fig.4.4C), with euhedral crystal faces toward the porphyroblastic gypsum. Indicate the replacive origin of granoblastic gypsum from porphyroblastic gypsum which in turn, a replacive from precursor secondary anhydrite (Mandurah and Aref, 2010). The lack of anhydrite inclusions in the granoblastic gypsum interpreted as an advanced stage of anhydrite rehydration (Makhlouf and El-Haddad, 2006).

The widespread occurrence of fibrous (satin spar) gypsum in the study area, which presents as veins interbedded between carbonate and evaporite rocks of the Korrahie Formation, indicates the telogenetic origin of the secondary gypsum. It is believed that the formation of this type of gypsum is mainly from a sulfate-rich water developed from the rehydration processes of

anhydrite (Makhlouf and El-Haddad, 2006; Zeljko et al., 2018). Thus, it characterizes clear fibrous gypsum crystals without anhydrite inclusion and morphology. Satin spar gypsum formation could also occur during late burial at depth within the mesogenetic realm from concentrated and overpressured burial waters (Gindre-Chanu et al., 2015). According to Warren (2006) satin spar gypsum developed from the action of passive and active hydrological processes, with available episodes of undersaturated water input at different stages in the uplift.

The presence of carbonate mud parallel to the fracture (vein) walls (Plate 2-F), indicates the simultaneous occurrence of episodic opening of the fracture and filling with gypsum crystals (Mandurah and Aref, 2010). The formation of karstified voids and cavities along with solution collapse breccias (Plate 2-D) is attributed as the continued exhumation and uplift processes ultimately reach in the vadose zone (Gindre-Chanu et al., 2015; Warren, 2006, 2016).

The different textural types of the secondary gypsum have showed a mutual relationship as they occur in the same sample; this relationship infers the development of one crystal type as the expense of the other (Zeljko et al., 2018; Mandurah and Aref, 2010). The associated occurrence of porphyroblastic and granoblastic or alabastrine gypsum textures indicates this relationship. They have gradational interpenetrating contacts evidenced the replacement of coarse porphyroblastic gypsum by finer granoblastic (Fig.4.4C) or even alabastrine gypsum crystals. The presence of corroded anhydrite relics within the porphyroblastic gypsum indicative of replacement origin during early exhumation stage, and the absence of anhydrite inclusions in the granoblastic gypsum also confirm these sequential replacements (Mandurah and Aref, 2010; Makhlouf and El-Haddad, 2006).

Table.5.1.summary of the major diagenetic processes with their respective diagenetic products along with their probable diagenetic environments

Diagenetic Processes	Diagenetic Features	Diagenetic Stages			
		Early stage		Late stage	
		Syndepositional	Meteoric	Burial	Telogenetic
Micritization	This diagenetic process caused by microbe organisms resulted the formation of micrite envelope	█			
Early cementation	Thin isopachuous (fibrous) cement represents the product of early cementation process	█			
Neomorphism	The enlargement of dense dark micrite matrix and aragonitic shells into microspar and pseudospar is the effect of this processes		█		
Compaction	Fracturing, close packing and squashing of the grains along with concave-convex contacts are caused by the mechanical compaction	█	█		
Dissolution	The formation of biomoldic porosity by the dissolution of aragonite skeletal shells	█			█
Late cementation	the presence of coarse drusy mosaic calcite cement indicates late stage cementation processes		█		
Dolomitization	The presence of euhedral dolomite rhombs concentrated along the elongated permeable features may represent the effect of this processes	█			
Sulfatization	The occurrences of gypsum/anhydrite in carbonates as cements or fenestral cavity fill	█		█	
Anhydritization	The formation of secondary anhydrite due to dehydration of gypsum		█		
gypsification	The presence of different diagenetic gypsums caused by rehydration of precursor anhydrite as well as the replacive and displacive forms of gypsum				█
Satin spar gypsum formation	The widespread occurrences of satin spar gypsum in the sequence			█	
Karstification	The development of solution collapse breccias is the result of this diagenetic processes				█

5.5. Palaeogeographical Setting

The extensional rifting and faulting processes that operated so far within the Gondwanaland supercontinents from Late Paleozoic through the Triassic and into the Jurassic, ultimately led the fragmentation of this supercontinent (Guiraud et al., 2005). From the west of this supercontinent, the separation of South America from the western Gondwana (present day Africa) commenced in the middle Jurassic. The Atlantic Ocean developed and fills the gap created by this continental splitting. Similarly in the eastward, the Gondwana split into two as western Gondwana separates from the eastern Gondwana (present day India/Madagascar/Seychelles/Australia/Antarctica and

Sri Lanka), and as a result the ancestral Tethys Sea developed and occupied the created void of the eastern coast of the western Gondwana, as the eastern Gondwana moved away (John, 2016). At the beginning the subsidence of the newly formed African continental margin commenced in the north, consequently marine incursion progressed from north to south along the rifted zone (Purcell, 1981). This marine water directly affects sedimentation in the east Africa and surrounding regions. As the continental block of east African margin subsides and tilted towards east, the sea began to proceed into the northwest through the Ogaden basin and deposited the earliest Triassic shoreline clastics known as Adigrat Sandstone (Purcell, 1979).

During the Jurassic time, further subsidence or thermal related subsidence as stated by Guiraud et al (2005) affected the former troughs of the continental margin of the east African region, this accompanied by global eustatic sea level rise eventually leads the transgression of the sea from east and southeast. Consequently flooding large areas in the region and generally deposited marginal marine facies including thick evaporites. As the sea advances into the western and northern parts of Ethiopia, depositing mixed terrigenous and marine clastics in the Blue Nile basin. The Ogaden basin was under shallow warm water and deposited carbonate shelf sediments (Purcell, 1979, 1981; John, 2016).

At the late of Liassic time the circulation between Ogaden Sea and the open ocean was silled, which eventually leads the development of evaporitic basin and the precipitation of anhydrite/gypsum. This hydrographic isolation was probably caused by a regional uplift on the Bur Fault in coastal ridge, it is also suggested an uplift of the Marda Fault zone can be another factor that can cause this barrier (Purcell, 1981).

A later subsidence event happened during Bajocian and leads the Sea water to cross over the basement sill. Shallow water, flooded across the basin, deposited a fine grained limestone and reached again into the Abbai basin, where limestone with gypsiferous beds was deposited. This water further extends into northern Ethiopia, mainly along the narrow Blue Nile trough (Guiraud et al., 2005). As the shallow carbonate platform progrades into northwest, deposited limestone in the Tigre region, and together with other seas advanced westward from Yemen, ultimately reached to Eritrea and near to central Sudan by the end of the Bathonian. At the Oxfordian time the marine conditions prevailed whole over the Horn of Africa, and thick marine sediments

consisting of marl, shale and limestone were formed (Guiraud et al., 2005). In the Ogaden basin, reefs were developed along the elevated platforms like the Marda Fault (Purcell, 1979).

After the Jurassic Sea reached its maximum extent across the Horn of Africa and the Arabian platform, it starts to withdraw in the Kimmeridgian as evidenced by the lagoonal shale deposits in northern Ethiopia, and the shoreline siliciclastic facies of Garbaharre Formation in the southeast (Purcell, 1981). The Sea in the Ogaden basin became shallow, as a result of major tectonic events commenced in the late Oxfordian such as the diapiric structures formed in Mendera-Lugh basin and the uplift in Chercher massif and Nogal arch. Due to this, the entire area north of Nogal arch was eroded, as reported in the Migiurtinian basin of northeastern Somalia, where lower Cretaceous limestone unconformably rests on Hamanlie Formation. The origin of this uplift is uncertain, however it is suggested that the initial rifting of the Gulf of Aden was a major control on this uplift (Purcell, 1979, 1981), as simultaneous rifting and doming occur in the adjacent regions (Arabian-Somalia).

The uplifted northern margin of the Ogaden basin, and the continued regression of the Sea from northwest during Portlandian to near Neocomian time led a progressive shallowing of the Ogaden basin, where carbonate sediments deposited (Gebridehar Formation) at the center of the basin and grading into near shoreline terrigenous clastics in the western and northern basin flanks (John, 2016; Purcell, 1979, 1981).

Moreover, from the end of Portlandian to early Neocomian evaporitic ponds separated by carbonate banks were developed in the basin center. At this time an uplifting occurred on Bur fault and hydrographically silled the Ogaden basin. Another uplift and block movement also occur in northern Somalia which led subsidence of the basin center (John, 2016; Purcell, 1979, 1981), consequently the basin became more hypersaline and decreases in size. Finally in the Barremian the evaporite deposition within the basin concentrated in two sub-basins namely: the western Ogaden sub-basin and the eastern Ogaden sub-basin; which are separated by a basement ridges related to the Marda Fault and Bur massif (Purcell, 1979) as shown the isopach map in (Figure 5.5).

Due to this restriction of water circulation, but with possible periodic replenishment or subsurface seepage and possibly basin subsidence, led to the formation of a thick 1600m evaporite unit, dominated by gypsum/anhydrite in the center of the basin (Bosellini et al., 1999). Carbonate sediments mainly limestone was deposited on the basin flanks, as a result of salinity segregation (John, 2016) and merged into shoreline clastics (Amba aradam Formation) as shown in (Fig.5.5).

This evaporite unit is termed Korrahie Formation in Ethiopia and main gypsum Formation in Somalia; it is equivalent to the lower Cretaceous limestone of cotton Formation in northeastern Somalia. In the central coastal Somalia, an abyssal lower Cretaceous mudstone was reported, which is deposited in the down throw side of the Bur Fault (Purcell, 1979). This indicates the Bur Fault acts as a barrier structure during the deposition of Korrahie Formation in the Ogaden basin (Purcell, 1976, 1981).

By the Aptian major transgression overflowed the barrier, flooded across the basin, and deposited the overlying limestone unit (Mustahil Formation). According to Bosellini et al (1999) this event happened before any desiccation in the evaporitive basin. In other words the evaporite deposition continued in the Ogaden basin up to the Aptian transgression, without unconformity or depositional interruption as seen the correlation sections in (Fig. 5.3), and the two units have a sharp contact as observed in the study area.

The extent of the Aptian Sea transgression in Ethiopia was limited up to Harar, as recorded an Aptian limestone in Gara Mulatta Mountains near Harar, such as Grau limestone, which interbeds a thick sandstone unit (Amba aradam Sandstone). However, the event was a regional scale as recorded similar events in East Africa and Northeastern margin of the Afro-Arabian craton (Bosellini et al., 1999). This transgression event inundated across the Horn of Africa re-establishes the shallow shelf carbonate deposition after a Neocomian-Barremian evaporite deposition (Bosellini et al., 1999).

Based on the previous studies and the available paleogeographical maps, the geological time interval between Neocomian-early Aptian best explains the paleogeographical framework

prevailed during the deposition of the Korrahie Formation and the overlying Mustahil Formation. Hence, the following three maps will summarize the whole story about the paleogeographical setting of the Ogaden basin and the surrounding regions.

The first map (Fig.5.4) is a palaeogeographical map that reveals the early Jurassic Sea invasion into the continental cratons through the existing troughs or rifted basins and its progressive advancement into the continental interiors, its ultimate coverage over the whole east Africa and part of southeastern Arabian platform during the late Jurassic period.

The second map (Fig.5.5) is an isopach map of Korrahie Formation, which displays the extent of the Sea during Neocomian-Baaremiian, and the prevailing conditions in the Ogaden basin and surrounding regions.

The third map (Fig.5.6) is a palaeogeographic map which depicts the short lived pulse of the early Aptian Sea transgression and its invasion to east African craton and southern Arabia. This marine water pulse terminates the evaporite deposition in the central Somalia and the Ogaden basin, as the depositional environment was converted to a shallow water carbonate shelf.

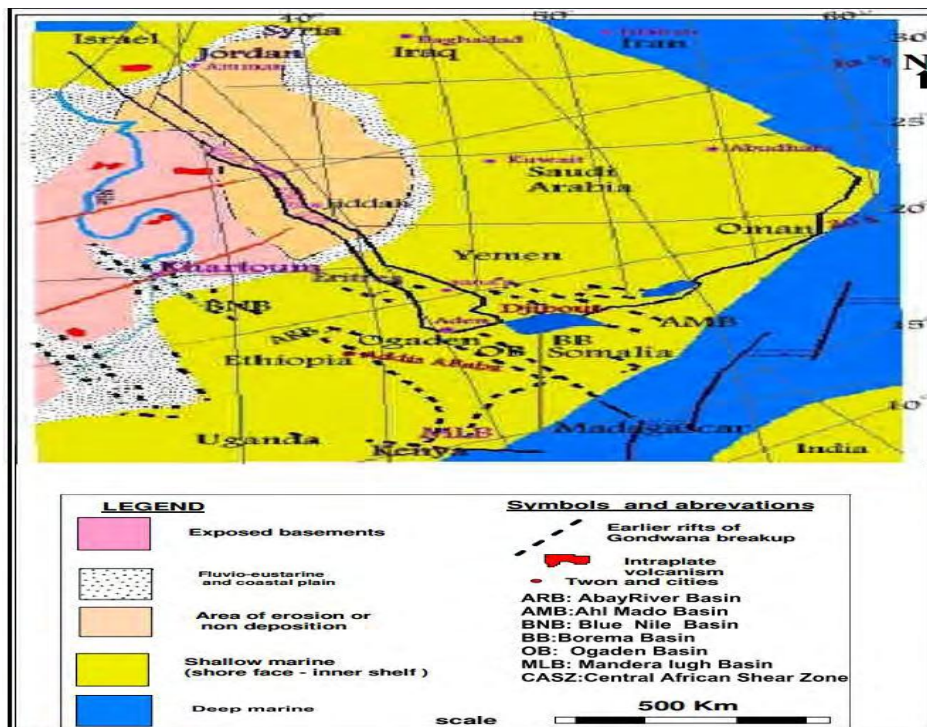


Fig.5.4. Palaeogeographic map of Northeastern Africa and southeastern part of Arabian platform during late Jurassic period, showing the areal extent of the late Jurassic sea (after Reynolds et al., 1997 in Bekssa Amente, 2017)

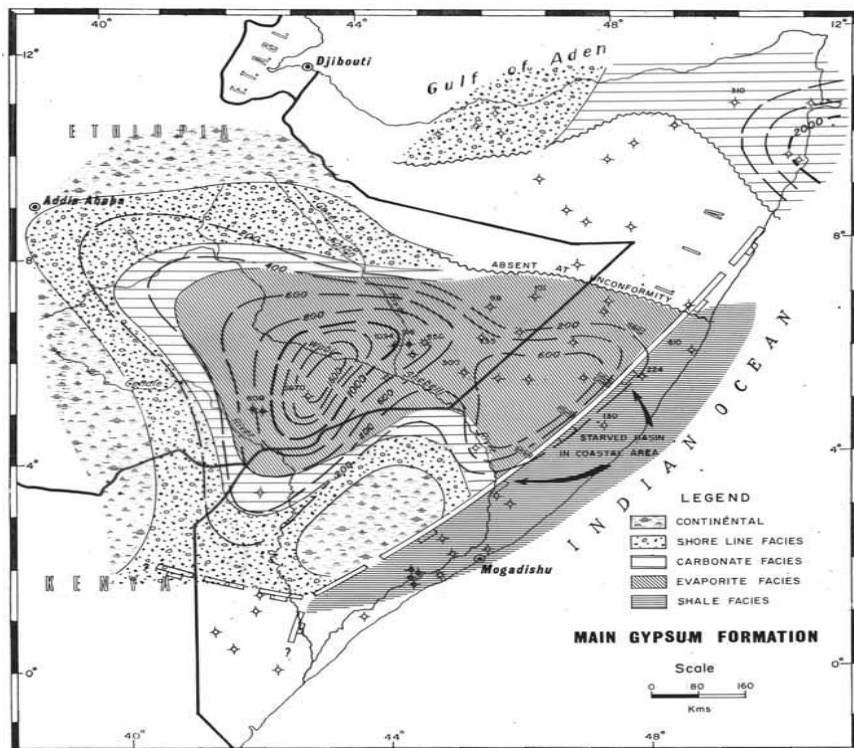


Fig.5.5. Isopach map of Korrahie formation showing facies distribution in the Ogaden basin and surrounding region, particularly it depicts two sub-basins where evaporite deposition concentrated and the NW- trending Marda ridge separating the two evaporitive sub-basins (After Purcell, 1979).

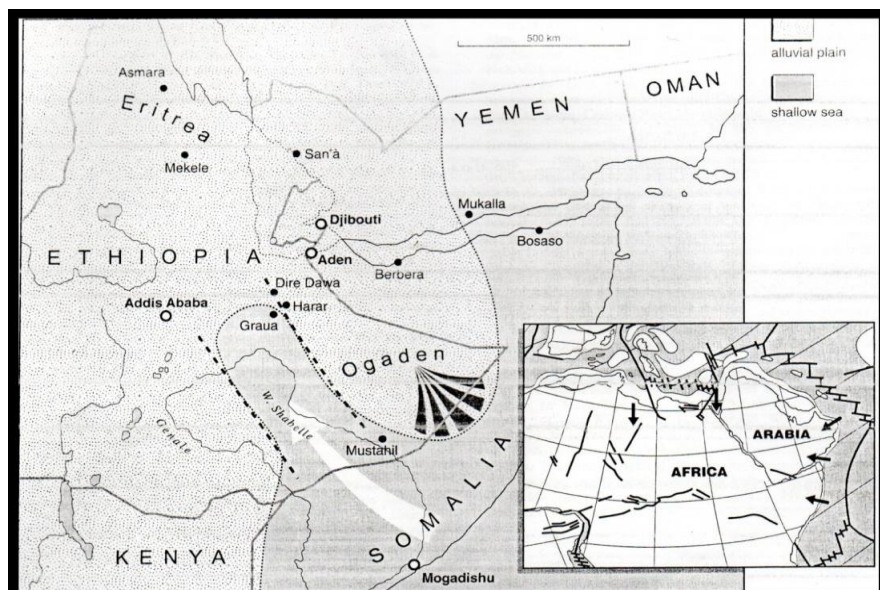


Fig.5.6. Palaeogeographic map of East Africa and southern Arabia for the early Aptian, and showing the incursion of the Aptian Sea into east African craton through pre-existing structural depressions. (Adopted after, Bosellini et al., 1999)

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

Outcrop based field study and petrographic investigations of the evaporite-carbonate rocks of the Korrahie Formation in the study area (Korrahie locality) have led to the following conclusions about the depositional environment and the diagenetic characteristics of the sequence.

The depositional signatures of the evaporite (gypsum) lithofacies indicate generally supratidal evaporitic mudflat with rare occurrence of subaqueous origin. As identified from their textural characteristics, the presence of nodular textures forming chicken wire and enterolithic structures which are a typical signatures for subaerially deposited sulfates, the planar or wavy laminated gypsum with microbial filaments and abundant intra-sediment layering suggesting brine mixing and seasonal subaerial exposure under unstratified holomictic brine conditions, the occurrence of lenticular shaped gypsum crystals within carbonate micrite and the regular bedding and their interbedding with marine carbonates are all indicators of deposition under either subaerial or shallow subaqueous restricted conditions.

The carbonate lithofacies exhibit various depositional setting according to their petrological and microfacies type investigations. They are compared with the Standard Microfacies Types of Wilson (1975) and its modified type adopted by Flugel (2010). The carbonate lithofacies originate in a generally low energy peritidal environment ranging from subtidal lagoon through intertidal and to supratidal setting. This is evidenced by the following microfacies associations:

- ✚ The presence of peloidal-bioclastic wackstone/packstone(MF-A) of subtidal facies
- ✚ Passing upward into barrier island/tidal bar facies of Ooid-bioclastic grainstone (MF-B) and interlaminated micrite-biopackstone (MF-C) which represents barrier to back barrier facies and
- ✚ Passing into dolomudstone (MF-D) and microbial laminated boundstone (MF-E) with fenestral fabrics along with tepee structures, thin planar laminations, erosive surfaces,

mud cracks and displacive lenticular gypsum crystals which are all indicating an intertidal to lower supratidal setting.

- ✚ Finally culminated into micritic limestone (MF-F) of non-laminated, pure micrite with gypsum/anhydrite nodules of supratidal setting.

The studied section, which is the exposed part of the Korrahie Formation, does not represent the whole unit because the underlying part of the Formation is not exposed in the area. The logged lithostratigraphic section is of about 50m thick. The lower part of the profile is dominated by carbonate lithofacies, which is predominantly composed of bioclastic limestone of about 10m thick. This occurs below an alternating sequence of thick bedded gypsum and dolomitic-limestone along with marl and shale intercalations. The whole sequence is capped by a 10-15m thick, composed of thin to thickly bedded cliff forming limestone with a very thin shale and marl at the base of the cliff that marks the start of the stratigraphically overlying unit (Mustahil Formation).

The petrographic investigation in this study shows that the outcropped evaporite rocks of the Korrahie Formation in the study area are predominantly composed of secondary gypsum, which has formed from the rehydration of precursor anhydrite. Secondary gypsum textures observed under the petrographic microscope in this study include: porphyroblastic, alabastrine, granoblastic and fracture filled fibrous (satin spar and selenitic) gypsum. All these textures are the result of telogenetic processes subjected to the evaporite rocks during their uplift stage. The presence of corroded anhydrite relics within the gypsum indicates a precursor anhydrite which transformed into gypsum via rehydration, as it re-enters into the low temperature and low salinity environment of phreatic zone. Therefore, diagenetic textures overprinted on gypsum, ranges from syndepositional through burial to telogenetic (uplift) textures. It experiences a complete cycle of diagenetic processes that caused extensive obliteration of its primary texture.

Post depositional diagenetic alterations recorded on carbonate rocks mostly show early diagenetic alteration (both marine and meteoric influence) and to a lesser extent on late (burial and telogenetic) diagenesis.

6.2. Recommendation

This study considers the identification and interpretation of depositional environments for the evaporite-carbonate succession by utilizing petrological and petrographical approaches. However, due to limited outcrops in the current studied section, may affect precise determination for the depositional environment model of the Formation, hence detailed lithostratigraphy studies in well exposed areas in other localities of the basin is recommended to provide a complete depositional model and lithostratigraphy of the Formation.

Field and petrographic investigations of this study show extensive diagenetic alteration on evaporite rocks that obscure their primary depositional textures, and again this makes difficult on depositional interpretation of evaporites using only petrography, hence future studies on this Formation is recommended to utilize and/or integrate other approaches such as elemental geochemical, and isotope geochemical analysis. On this aspect the present study also provides an opportunity for the future researches to study thorough diagenetic attributes of these rocks.

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APPENDIX

Plate -1:

Photomicrographs showing the various diagenetic features overprinted on the studied carbonate rocks. (A) It shows a mulluska shell with micritic envelope due to micritization and partly destroys the periphery of the shell as red arrows indicate. (B) Extensive micritization can cause unrecognizable grains as shown in this microphoto, the red arrow points thin micrite envelope around the shell, the yellow arrow head shows micrite matrix changed into microspar due to neomorphism. (C) This microphoto depicts the presence of drusy mosaic cements lining around gypsum filled moldic porosity as black arrow head points, the yellow arrow head shows gypsum with anhydrite relics as pore filling cement, and the red arrow indicates moldic porosity outlined and preserved by thin micrite envelope. (D) The effect of mechanical compaction in weakened grains as shown by black arrow and yellow arrow shows a hard peloidal micrite which resists the compaction processes. (E) Dissolution creates biomoldic porosity and then thin isopacheous (fibrous) cements of early marine to meteoric origin lining around the pores as shown by the yellow arrow heads, the red arrow indicates early formed micrite envelope around the margins of the shell. (F) Typical aggrading neomorphism of dolomite rhombs as marked by the black arrows inside the yellow dished features. (G). Replacement of carbonate by sulfate minerals as shown by the red arrows with full of inclusions. (H). Extensive compaction causes the breakage of the long elongated shell fragments like that of bivalves. (I). The effect of compaction on fine grained (micritic) carbonate rocks leads cracks and fractures as the rock dewateres, this crack or fracture is filled (vein) by gypsum in later stages.

Note photomicrographs (A, B ,C, D) are a full field of view under 4x magnification and Plane polarized light for (A), all the other photomicrographs are under cross polarized light.

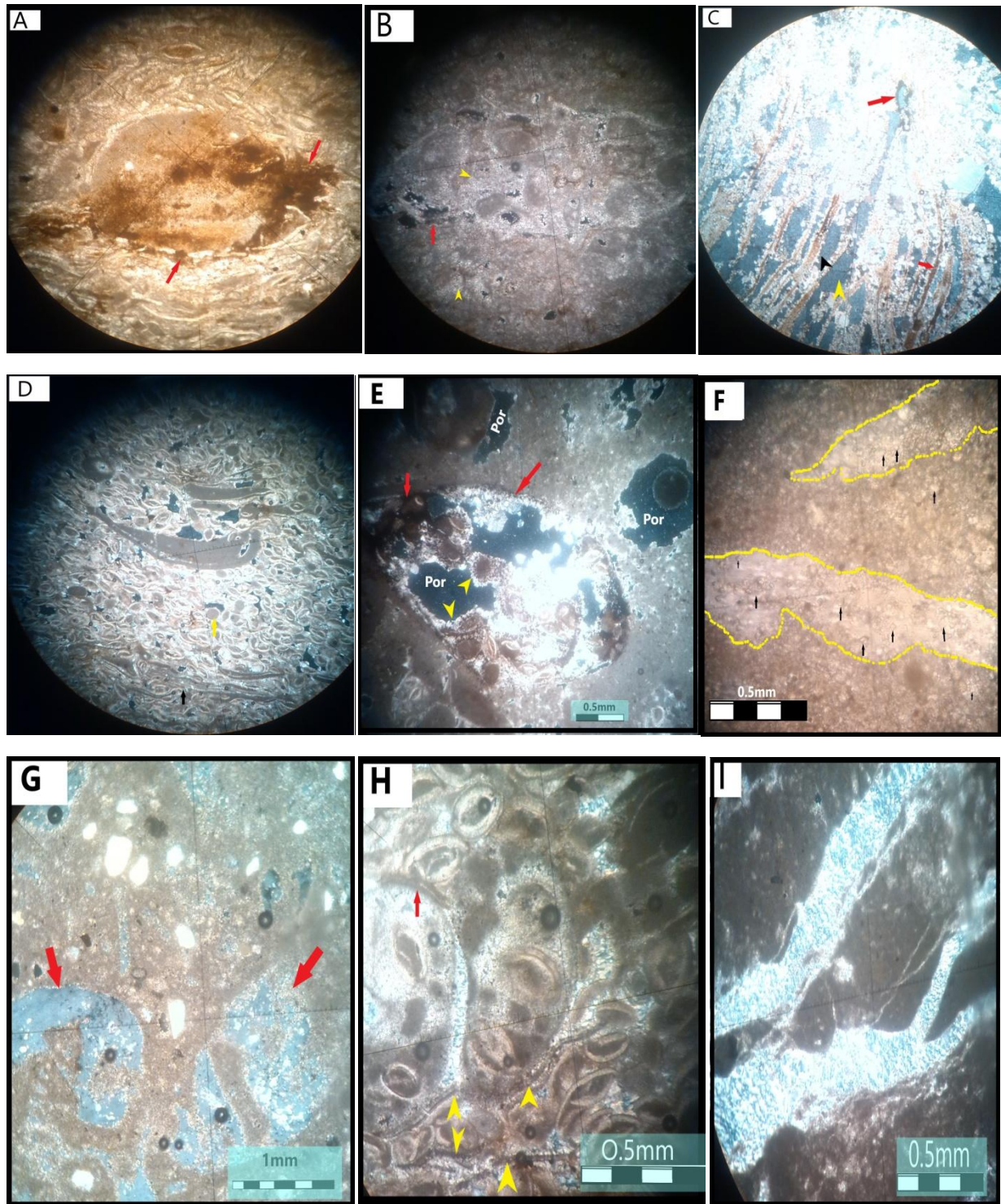


Plate-2

Field photo and Photomicrographs showing the various attributes of the diagenetic effects recorded on gypsum rocks, which mostly indicate Telogenetic signature. (A) Hand specimen of interlayering fracture filling selenitic gypsum and fibrous satin spar along with displacive crystals. (B) Radial rosette-like daisy gypsum crystals displacively forming within alabastrine gypsum. (C). Satin spar gypsum within shale bed and displaying microfolds (enterolithic) structures. (D). Cavity developed as a result of evaporite dissolution in the vadose zone and the formation of solution collapse breccias in the upper part of the photo. (E) Photomicrograph showing the development of polygonal intercrystalline porosity running across the photo. (F) Microscopic fracture filling satin spar gypsum.

Note both photomicrographs are taking full field of view under 4 x magnifications and under the cross polarized light.

