# INTEGRATED CORE BASED AND WELL LOG STUDIES TO BETTER CHARACTERIZE FACIES AND DIAGENETIC PHASES OF EOCENE SAKESAR FORMATION, POTWAR SUB-BASIN, PAKISTAN


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**Session: 2020-2022**

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**A thesis submitted in the partial fulfillment of the requirements for the degree of**

**Master of Philosophy in Geology**

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**MPHIL GEOLOGY 2020-2022**

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## CERTIFICATE

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Dated: __________

# ***Dedication***

***I dedicate my thesis to my beloved parents, Siblings, friends and teachers.***

# ACKNOWLEDGMENT

All praise to Almighty Allah who gave me courage and made me able in completing my thesis work successfully. I offer my gratitude to last Prophet Muhammad (PBUH).

I am also extremely grateful to my honorable supervisor **Dr. Mumtaz Muhammad shah** for their wide knowledge and logical way of thinking have been of great value for me. Their personal guidance has provided a good basis for this study. I must acknowledge the cooperation of all my teachers whose direction and support have been the source of my success.

I would like to highly acknowledge the support of Access to scientific instrumentation program of **HEC**, for providing the research funding. This work could never have been completed without their provided funds.

I would like to acknowledge my seniors and friends for their help and suggestions during my work. I do express my sincere thanks to Muhammad Umais, Waleed Hussan, Anees-ur-Rahman and Muhammad Bilal Malik for their sincere guidance, help, moral support and encouragement.

I am thankful to my parents for moral and financial support. I am indebted to my loving parents, who encouraged and motivated me to face the challenges of life during my academic career. Last but not the least, I am thankful to all my friends and fellows who encouraged and motivated me throughout my academics.

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# Abstract

The Sakesar Limestone of Early Eocene is studied for facies characterization and diagenetic studies using core of Balkasar-7, Potwar sub-basin. The Sakesar Limestone in the studied core is mainly comprised of Limestone, Dolomitic limestone and Argillaceous / Shaly Limestone. For petrographic study 26 samples were selected and on the basis of petrographic obeservation seven microfacies are identified which include, Larger Foraminiferal Wackestone-Packstone, Bioclastic-Nummulitidae Wackestone, Assilina-Nummulitic Packstone, Planktonic Miscellania Wackestone-Packstone, Bioclastic Wackestone, Nummulitic - Lockhartia dolomitic Wackestone-Packstone and Ranikothalia – Assilina dolomitic Wackestone-Packstone. In microfacies, the abundance of the different fossils relative to the matrix ratio suggest that the depositional settings of the Sakesar Limestone are lie in proximal Inner ramp to the Middle ramp, while one facie extends up to the outer ramp settings.

Different diagenetic features are identified during studies which contain compaction, cementation, micritization, neomorphism, dissolution and dolomitization. Micritization is the most common phenomena observed in the diagenetic studies. The dolomitization in the Sakesar Limestone found along fracture veins, stylolites and within matrix indicating the deep burial diagenetic conditions. The presence of fenestral porosity and vugs in the core studies provide evidence of the late stage diagenesis. These features suggest that the Sakesar Limestone has faced early stage diagenetic to late diagenetic changes.

The electrofacies analysis are conducted by K mean Clustering method using well log of Balkasar Oxy-1. The electrofacies shows the dominant lithology of the Limestone in well which is followed by the Shaly limestone and Calcareous shale.  The correlation of both wells and their lithological data shows same pattern of facies distribution.

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# Chapter No. 1

# INTRODUCTION

## 1.1 Introduction

Hydrocarbons are the important natural resource of energy as per its demands in the world. The economic stability of a country revolve around the hydrocarbons reserves and their production. Owing to the excessive exploration activities the hydrocarbon reservoirs are depleting. To fulfill the increasing energy demands, the improvements in the traditional exploration strategies are required to enhance their effectiveness. This will not only aid in the exploration of the new hydrocarbon reservoirs but also improve the production from the existing reservoirs. The understanding of geological parameters like lithology, porosity, permeability, etc. of reservoir rock is necessary for designing the efficient development and production strategy.

Carbonate rocks are the most abundant non-terrigenous sedimentary rocks having high economic importance. Carbonates acts as a good hydrocarbon reservoir, aquifers, also hosts the ores bodies of economical minerals (Prothero & Schwab, 2013). Carbonate reservoirs account for 50-60% Oil reserves around the globe (Burchette, 2012) along with 40% Gas reserves worldwide. In Middle east only, around 70% Oil reserves and 90% gas reserves are present in carbonate reservoir rocks (Missagia et al., 2017).

In Pakistan Carbonates are also reported as a good potential reservoir for hydrocarbons (Jadoon et al., 2005; Dahraj et al., 2018). Eocene carbonates in Pakistan yields highest hydrocarbon production making them highly significant reservoirs (Qadri I, 1995). Eocene "Sakesar Limestone" is one of most important and productive reservoir of Potwar sub basin (Aamir and Siddiqui 2006).

The Current study is an attempt to better characterize the Facies and diagenetic Phases of Sakesar formation in Potwar-Sub Basin using Core and Well log data. Facies are the specific rock characteristics that reflects its particular depositional conditions (Nichols, 2013). The study of facies and diagenesis allows the explorationist to reconstruct the geological history from the formation of rock up to its present form.

The Sakesar Limestone is comprised dominantly of light to dark grey, in places creamy, thin to thick-bedded massive nodular fossiliferous limestone with subordinating marl. It contains mainly corals, mollusks and larger benthic and planktonic foraminifers (Davies and Pinfold 1937). Core study and its subsequent petrographic study enable us to construct Microfacies and paragenetic sequence of diagenesis. Furthermore, Electro facies are characterized by K mean Clustering technique using well log data. The clusters of well logs data classifies the formation in to the electrofacies. Finally, the Depositional and Diagenetic settings are proposed on the basic of the current study.

## 1.2 Scope and objectives of the study

The objectives of this research work are as follows.

- To perform sedimentological analysis of the Sakesar Limestone by studying core.
- To construct the microfacies of the Sakesar Formation by using petrographic study of thin sections.
- To display the depositional model of microfacies.
- To observe the diagenetic modifications and proposed the paragenesis of the Sakesar Limestone.
- To perform electrofacies analysis by using K means clustering technique a machine learning approach.

## 1.3 Study area

The study area of this research work is Balkasar oilfield. It is among major oilfields of the Potwar sub-basin. The Sakesar and Chorgali Formations of Eocene are acting as the main reservoirs in Balkasar oilfield. Balkasar oilfield was discovered in 1944 by Attock oil company. Now It is under Development and Production Lease acquired by Pakistan Oilfields Limited. It is located in district Chakwal of Punjab Province. It is 110 km southwest of Islamabad showing in Fig 1.1.

The objectives of current study were accomplished by using the core of Balkasar-07 and well log data of Balkasar oxy-1. The locations of these wells are shown in the Fig 1.2.


Figure 1.1 Location Map of Balkasar, District Chakwal from Islamabad.

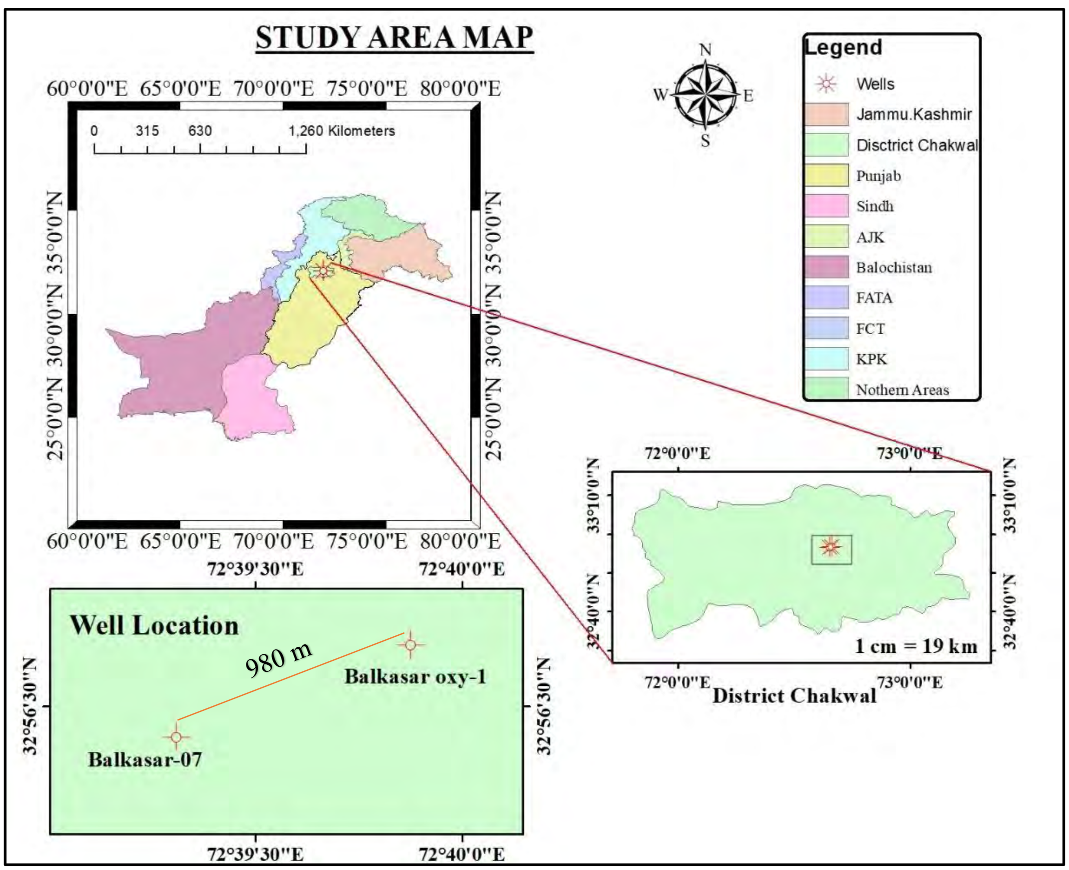


Figure 1.2 Locating Map of current research study area, Balkasar area in District Chakwal, Punjab

## 1.4 Previous Work / Literature Review

(Ishaq et al., 2019) have conducted the study of two outcrop sections for Microfacies and diagenetic studies of Sakesar Limestone in Potwar Plateau. Five microfacies were identified by petrography study. Diagenetic studies show the Sakesar Limestone as a good secondary reservoir. Micro porosity ranges from 0.5 to 2.1% by visual estimation while 0.9 to 2.9% using core plugs. Marine, meteoric, burial and uplift realms were assigned as a depositional and diagenetic settings of the Sakesar limestone.

(Rahman et al., 2017) have attempted study of Sakesar Limestone for Microfacies analysis and reservoir Potential from western Salt Range (Nammal Gorge) along with well cuttings of Pindori-01 well. Bioclastic wackstone microfacies is reported majorly having neomorphic diagenesis. Petrophysical analysis show good hydrocarbon saturation (85.5%). The Environment of deposition is marked as low energy shallow marine shelf environment.

(Ghazi et al., 2014) have studied detailed sedimentological and biostratigraphical characteristics of the Sakesar Limestone from five different field sections within Salt Range. Total nine microfacies are identified, along with several foraminiferal species. Based on these features carbonate ramp platform in designated as depositional setting of Salt Range region. Moreover, isotopic study based on stable carbon and oxygen is conducted ist time which also confirmed the environment as marine settings.

(Ahmad et al., 2013) investigated microfacies, diagenesis and reservoir potential of the Sakesar Limestone in eastern Salt Range, District Chakwal. Nine microfacies were identified from bioclastic wackestone to bioclastic packstone based on petrographic study. The variety of cement types and diagenetic features and observed which concluded the shelf environment of the Sakesar Limestone with good reservoir potential.

In present research work the core study has been adopted for facies characterization and diagenetic studies along with the electro facies analysis of Sakesar Limestone using well log.

# Chapter No. 2

# REGIONAL GEOLOGY AND STRATIGRAPHY

## 2.1 Introduction

This chapter focuses to present the geological knowledge of the study area including tectonics and stratigraphic framework. The regional tectonics plays an important role in architecting the basin which in results impact the stratigraphic framework of an area. Thus, to understand sedimentary processes resulting in filling and modification of the basin, understanding of regional tectonics is a fundamental necessity. The study of basin evolution and its stratigraphic framework gives the information about paleoenvironment of that depositional settings. Thus, the study of geology of an area along with its tectonics and stratigraphy is required to understand the depositional style of rock formations and their relationship which also help in future strategies for economic activities.

## 2.2 Regional Tectonics

Pakistan majorly lies on the north western part of the Indian Plate, having its geological borders with Eurasian Plate in North, Arabian Plate in south while Afghan/Lut Block in the West (Molnar & Tapponnier, 1975). Plate tectonics presents its magnificent features in this region. In North the continent-continent convergence of Eurasian Plate with Kohistan Island Arc (KIA) marks by MKT (Main Karakoram Thrust) while Indian Plate with KIA marks by MMT (Main Mantle Thrust). In south western side, Oceanic-continent convergence results in the subduction of Arabian Plate under Eurasian Plate forming the Makran Subduction Zone. While the Western boundary with Afghan Block is connected through Chaman Transform Zone. The collision of the Indian and Eurasian Plates results in the formation of the Himalayas which developed several foreland basins in India and Pakistan (Acharyaa 2007).

The study area Balkassar lies in Potwar Sub basin which is the north-eastern division of the Indus Basin the largest sedimentary Basin of Pakistan. Structurally Balkassar oil field is located in on the southern limb of the Soan syncline.  The Potwar Sub basin is a fault bounded basin having the MBT (Main Boundary Thrust) in North, Jehlum Fault in East, Kalabagh Fault in west while SRT (Salt Range Thrust) in South. The Potwar Sub basin comprised of four tectonic zones from north to south i.e., NPDZ (Northern Potwar Deformed Zone), Soan Syncline, Southern Potwar Platform Zone (SPDZ), and Salt Range. The structural map of the Kohat-Potwar region encompassing the structural features of the study area and its surroundings is shown in Fig 2.1.

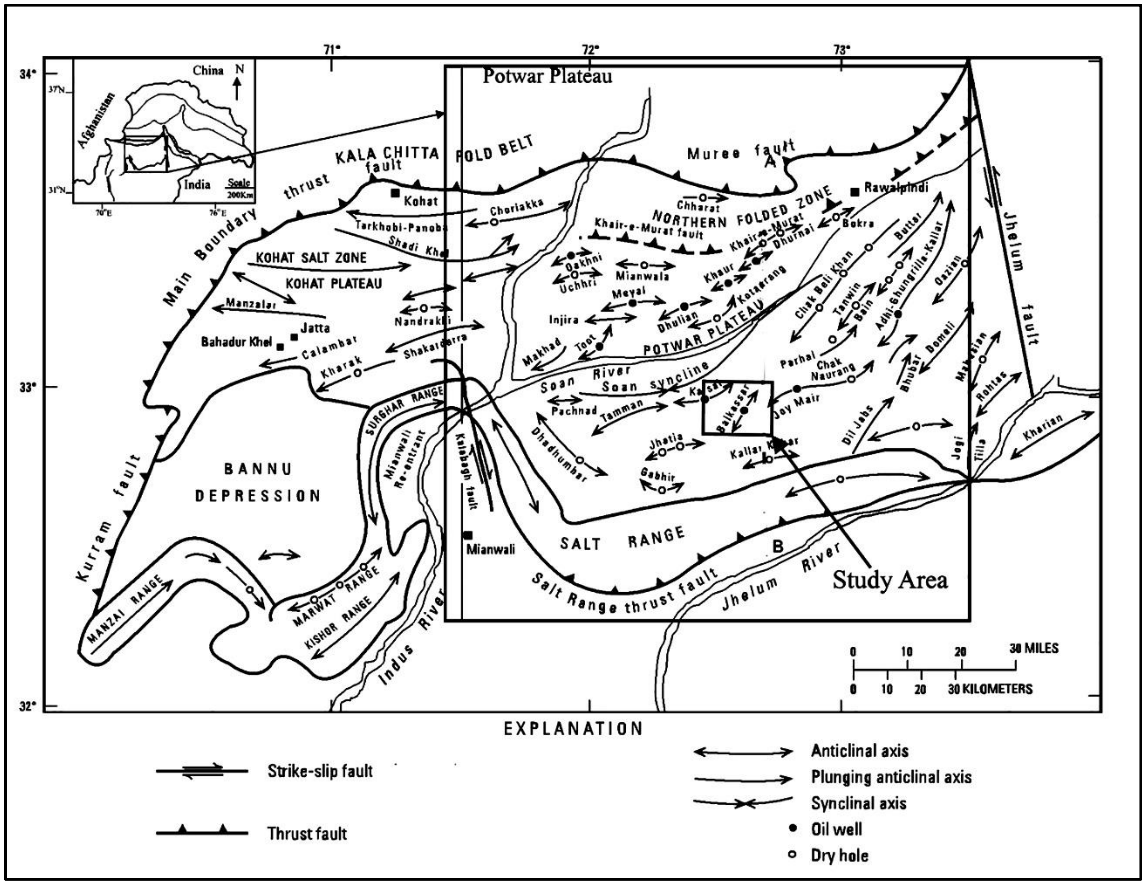


Figure 2.1 Structural Map of Kohat-Potwar region showing major geological features of study area and its surroundings (modified after Khan et al. 1986; Gee 1989)

## 2.3 Hydrocarbon Potential

The Salt Range Potwar Foreland Basin (SRPFB) is categorized under the extra continental down warp basins (Paracha, 2004). The existence of the thick marine sequence, potential source rocks, and good reservoir rocks with the cover of the suitable cap rocks under perfect geometry turn this region in to good hydrocarbon potential zone.

## Source Rocks

The Potwar sub basin encompasses following source rocks resulting in the existence of hydrocarbons in this region:

- Shales of the Patala Formation are considered as the main source rock of Potwar Basin having organic content upto 3.5% (Khan et al., 1986).
- The Khewra Formation, the Kussak Formation and the Jutana Formation are observed with 27 to 36 percent total organic content (T.O.C) due to their woody and coaly content in them (Khan et al., 1986).
- Fair amount of organic matter in the Lockhart Limestone make it as source rock (Qadri, I.B.,1995).

## Reservoir Rocks

Hydrocarbon requires a good reservoir rock for its accumulation. In Potwar Sub basin cumulative thickness of reservoir rocks is 800 to 1000 meters (Qadri, I.B.,1995) and generally belongs to early Eocene Limestone.

- Generally, reservoir rocks of Potwar sub basin belongs to Eocene formations i.e. the Sakesar Limestone and the Chorgali formation in Balkasar, Dhurnal, ChakNaurang, Dakhni fields.
- The sandstone of Cambrian Khewra Sandstone in Adhi and Missa Keswal fields act as a good reservoir.
- The Permian Tobra Formation's conglomerate, Nilawahan and Zaluch Group also give good production in Adhi and Dhurnal Fields.

## Seal Rocks

The main seal rocks of the Potwar sub basin are:

- The Shales of the Eocene Chorgali Formation acts as a good seal to the hydrocarbons.
- In Salt Range Potwar Foreland Basin (SRPFB) Miocene Murre Formation's Shales and Claystone provide significant Lateral and vertical seal to reservoirs (Khan et al., 1986).

## 2.4 Stratigraphy of the Study area

The Stratigraphy of the study area is well developed having the rock formations from Pre-Cambrian to Pliocene. The stratigraphic chart of the Potwar Sub-basin is shown in Fig 2.2.

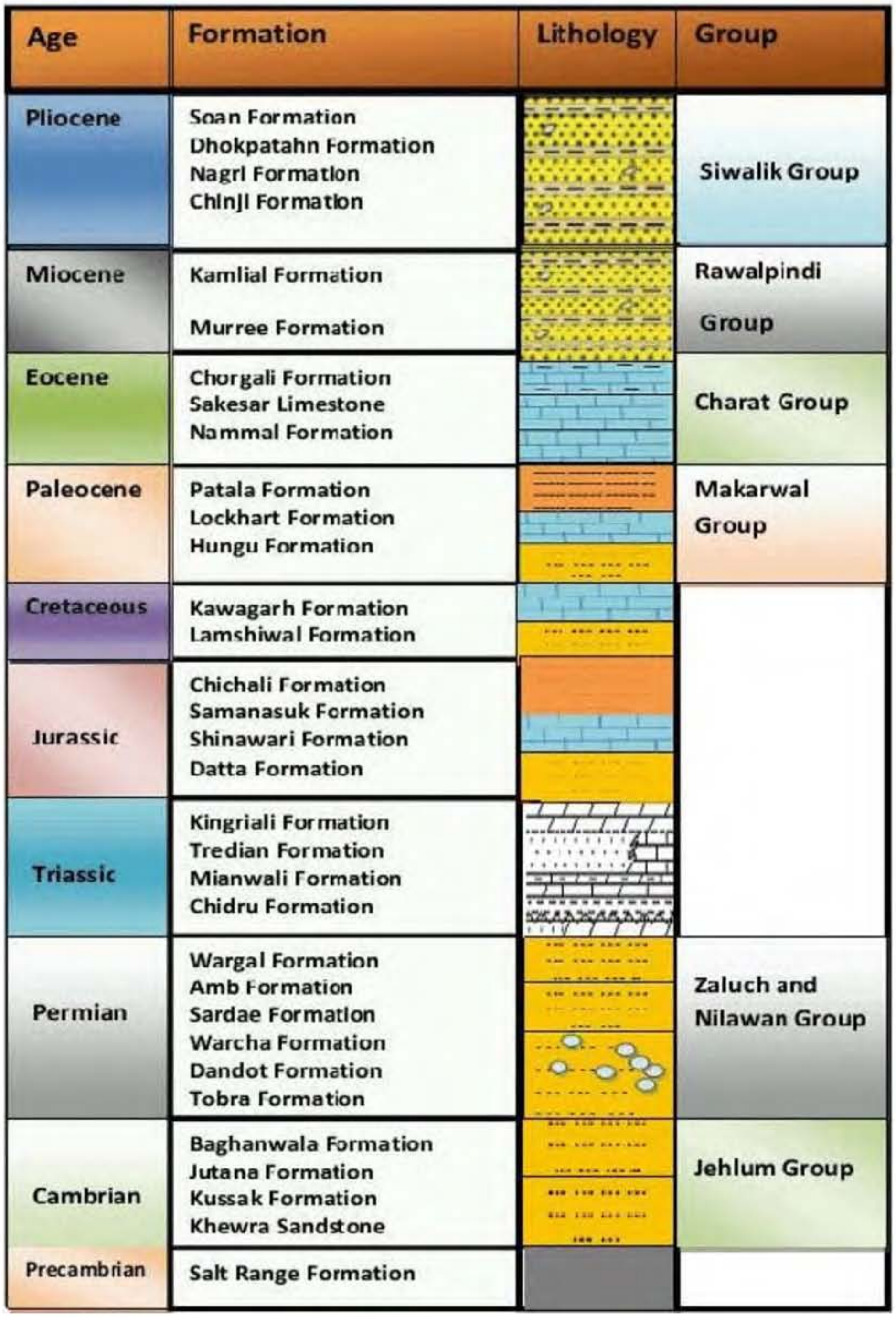


Figure 2.2 Stratigraphic column of Potwar Plateau showing the stratigraphic succession from Pre-Cambrian to Pliocene (after Fatmi 1973; Iqbal et al.2015)

# Chapter No. 3

# METHODOLOGY

## 3.1 Introduction

The current research work is conducted by following data set and data analysis to get insights of the research objectives.

## 3.2 Data Sets

The Data of two wells is used in this research work. Well log data is acquired from the LMKR and Core data from HDIP by the approval of DGPC. The important basic details of wells are shown in table 3.2. The formation tops of wells are shown in table 3.3.
The acquired data set for this research work is as follows:

### Balkasar – 07

- Core Data

The studied number of core sections for this research works are 08, their depths along with thicknesses are shown in table 3.1.

Table 3.1: Showing details of studied cores, their core box numbers, No. of boxes, depth intervals and thickness.

| Core Box | No. of Boxes | Depth intervals (m) | | Thickness (m) |
|---|---|---|---|---|
| **Core-29** | 05 | 2451.81 | 2457.91 | 6.10 |
| **Core-31** | 05 | 2461.87 | 2468.11 | 6.24 |
| **Core-33** | 05 | 2475.59 | 2481.68 | 6.09 |
| **Core-35** | 04 | 2488.997 | 2495.276 | 6.279 |
| **Core-38** | 03 | 2513.69 | 2517.557 | 3.871 |
| **Core-40** | 04 | 2526.79 | 2531.760 | 4.97 |
| **Core-42** | 03 | 2543.251 | 2547.762 | 4.511 |
| **Core-45** | 01 | 2558.491 | 2559.436 | 0.945 |

## Balkasar oxy-01

- Las file of Well Log
- Well Header
- Well Tops

Table 3.2 Showing details of wells including coordinates, status, type and depth.

| Well Name | Latitude | Longitude | Status | Type | TD(m) |
|---|---|---|---|---|---|
| **Balkasar - 07** | 32.94041 | 72.655139 | Oil Producing | Development | 2568 |
| **Balkasar Oxy-1** | 32.944111 | 72.664583 | Abandoned | Exploratory | 3130 |

Table 3.3 Showing the information about depths (MD) of formation tops (in meters) encountered in wells.

| Formation Names | Balkassar – 07 | Balkassar Oxy-1 |
|---|---|---|
| **Nagri** | 0 | 0 |
| **Chinji** | 455 | 478.8 |
| **Kamlial** | 1390.4 | 1408.1 |
| **Murree** | 1497.1 | 1514.8 |
| **Bhadrar / Chorgali** | 2398.7 | 2421.5 |
| **Sakesar** | 2448.1 | 2467.2 |
| **Patala** | 2567.3 | 2602.9 |
| **Lockhart** | ------------ | 2624.2 |
| **Hangu** | ------------ | 2659.3 |
| **Sardhai** | ------------ | 2686.7 |

| | | |
|---|---|---|
| **Warcha** | ------------ | 2796.4 |
| **Dandot** | ------------ | 2938.1 |
| **Tobra** | ------------ | 2999.1 |
| **Khewra Sandstone** | ------------ | 3050.9 |
| **Salt Range** | ------------ | 3129.2 |

## 3.3 Work Flow

The generalized workflow adopted for the completion of the research work is discussed in the following section and adopted workflow is shown in Fig 3.1.

### 3.3.1 Core Study, thin section preparation and petrography:

This research work starts with thorough core logging at 1:6 scale (default scale of Easy Core Software). Core logging is taken on centimeter (cm) scale level. The logging includes the lithological, sedimentological and possible biostratigraphical descriptions along with diagenetic features. The measurements were taken by measuring tape, different intervals were identified and marked according to facies variation and labelled accordingly. 10% Diluted HCL is used to differentiate between limestone and dolomite. Cores and their different features were photographed properly. The sample locations are marked in every different facie observed. A total 26 samples were selected for thin section preparation. Thin section preparation services are also taken by HDIP. The thin sections petrography is carried out at Petrographic lab of Department of Earth Sciences, Quaid.i.Azam University by using Standard Petrography Microscope (Olympus CX-3 and Lecia with Camera mounted DP-21). Petrographic study enables us to create microfacies and observe the diagenetic features present in the Sakesar Limestone encountered in our well core.

### 3.3.2 Electrofacies

The electrofacies represent the specific compositional and physical properties of the rock by electric log suit. In this study, electro facies are marked by using K-means clustering method. The clustering technique divide the identical data points from data set into clusters. Balkasar Oxy-1, Log is acquired by LMKR for marking of the electro facies.

### 3.3.3 Interpretation of data

All of the parameters were utilized to establish the facies and diagenetic modifications of the Sakesar Limestone. These helped in assessing the depositional environment of the studied rock. Diagenetic studies show the changes govern in the Sakesar Limestone. This research work helps to find out the different kind of the facies and diagenetic modifications to get an understanding of the conditions of deposition and all of the changes govern afterwards which are necessary for economical perspective too (i.e. H.C exploration etc.). The obtained results are described in results & discussion section, following by the conclusion of research work.

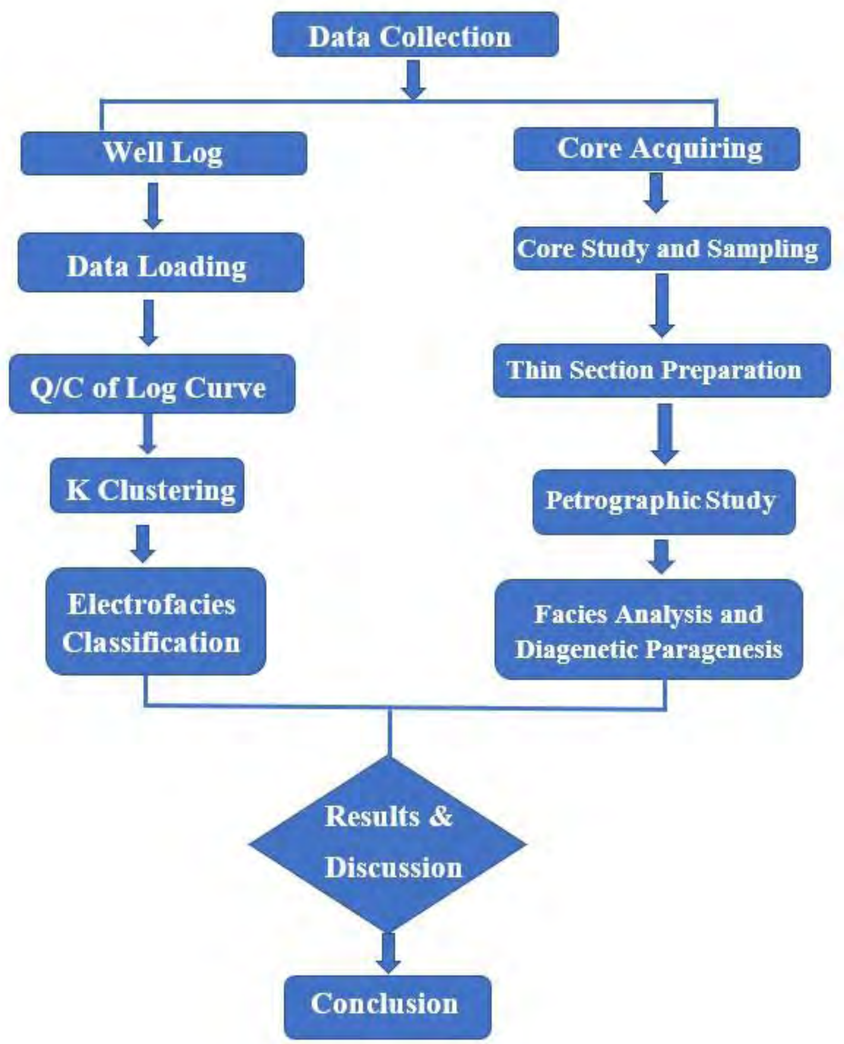


Figure 3.1 Represents the generalized methodological workflow for facies and diagenetic study of the Sakesar Limestone using core and log data.

# Chapter No. 4

# CORE STUDIES

## 4.1 Introduction

In this Chapter the core studies in this chapter are briefed in the descriptive manner. To study the facies and diagenesis of the Eocene Sakesar Limestone, Core of Balkasar-07 Well is studied at Petro Core House, HDIP. The total studied core sections were eight. Core data set availed to study is mentioned in third chapter, Methodology. Core logging has been conducted at 1:6 scale (Easy Core Software) based on lithological and diagenetic properties. The characterizing features observed in this study provide a profound knowledge of information for facies and diagenesis which ultimately helps to generate the depositional style of the Eocene Sakesar Limestone in the Potwar Sub basin.

## 4.2 Description of Core 29

The core 29 marks the top of the Sakesar Limestone in Balkasar Well 7, comprised of total length of 6.096m at depth of 2451.82 to 2457.91 meters. On the basis of sedimentological variation in visual appearance 04 intervals are made, and three samples are selected for studies. The marked intervals and sample location are shown in Fig. 4.1, the features observed in core 29 study, are shown in Fig. 4.2 while the core log is shown in Fig. 4.15.

### 1-*Interval 1 (2451.82 - 2453.945 m):*

This interval is the top portion of the core 29 and composed of the light to medium grey, fine limestone, texture is Wackestone to Packstone. Fossils observed are large benthic forams i.e nummulities along with bioclasts which are randomly oriented. Secondary features include some open and calcite filled vertical fractures and horizontal stylolites. Secondary porosity contains unfilled fractures, fenestral porosity and vugs.

### 2-*Interval 2 (2453.945 – 2455.103 m):*

This interval is also light to medium grey in color but texture get change i.e Mudstone to Wackstone. Fossils content get decreased then previous interval. Stylolites intensity get increased in this interval majorly horizontal stylolites are observed along with one vertical. Fenestral porosity and vertical fractures are also present in this interval.

### 3-*Interval 3 (2455.103 - 2455.347 m):*

This small interval is the repetition of the first interval.

### 4-*Interval 4 (2455.347 – 2457.907 m):*

This is the continuation of the second interval, having light to medium grey color limestone. Texture is Mudstone to Wackestone. Main Secondary feature in this interval are horizontal stylolites, along with some vertical fractures.

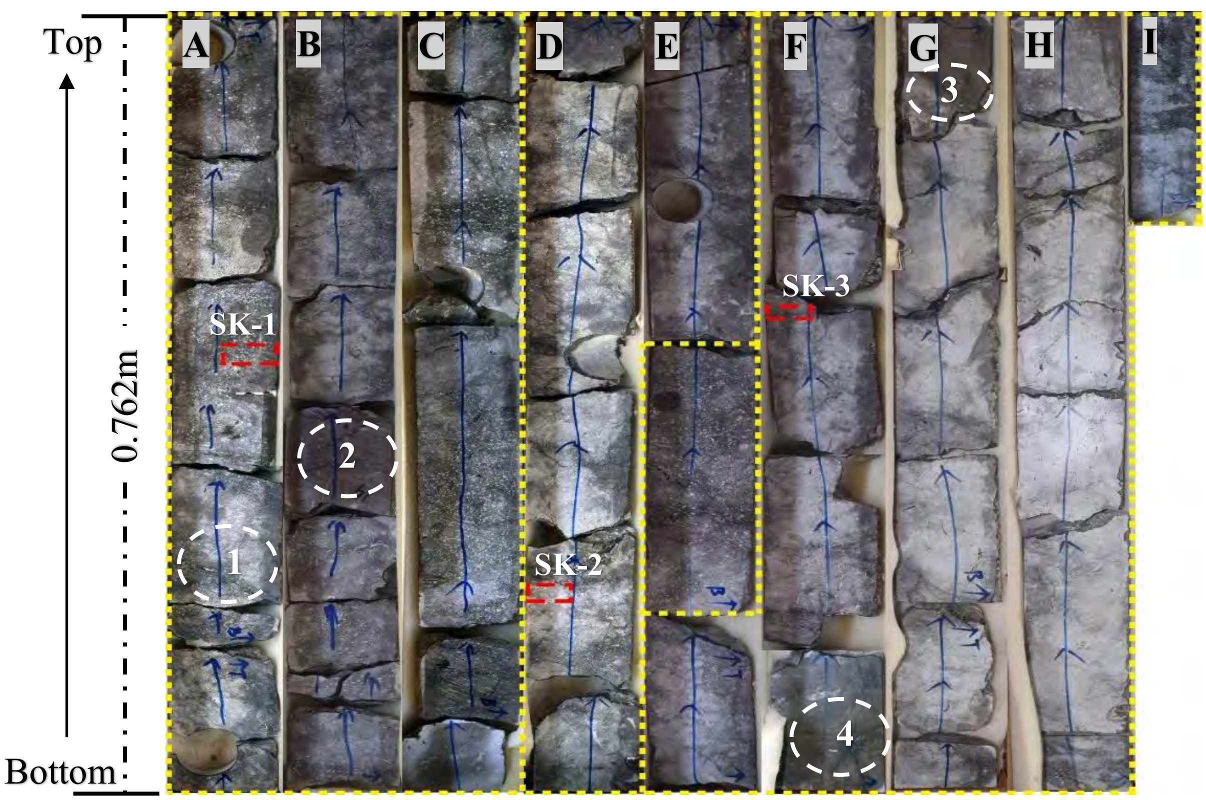


Figure 4.1 Photograph showing core slabs of core-29, labeled A-I represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-1, SK-2 and SK-3) (1-4 circles are features location shown in Fig 4.2)

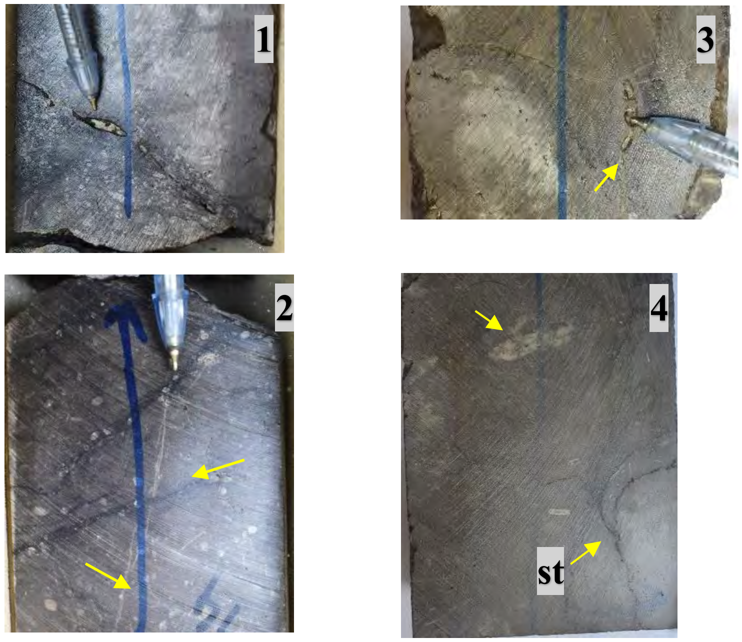


Figure 4.2 Showing key features of Core 29: Partially filled sub-horizontal fracture vein in 1, Vertical calcite filled fractures in 2, Fenestral porosity in 3, Calcite filled vug and Stylolite(st) in 4.

## 4.3 Description of Core 31

This core is of 6.248 m in length and depth is 2461.87 – 2468.118 m. Total seven intervals are made on the basis of difference in visual appearances. For petrographic studies six samples were selected from this core. The core slabs with sample selection and interval labels are shown in figure 4.3, the features are shown in Fig 4.4 while core log is shown in Fig 4.13.

### *1- Interval 1 (24612.87 - 2462.723 m):*

This interval is comprised of light grey highly fossiliferous limestone. The texture of this zone is categorized as a mud dominated Packstone. Fossils are larger benthic foraminifera's Nummulities, assilana's, and skeletal fragments. Vertical fractures filled with blackish material (organic matter) is secondary feature in this interval.

### *2- Interval 2 (2462.723– 2463.516 m):*

This interval exhibits a change in color to medium creamish grey, with texture to wackstone to packstone. The fossils are same as in above interval but their abundance is getting increased downwards. Secondary features such as fractures and stylolites are not present in this interval.

### ***3- Interval 3 (2463.52– 2464.04 m):***

The lithological unit is composed of light to medium grey color highly fossiliferous limestone. Texture of this interval lies in Packstone. Secondary features include vugs and vertical fracture filled with blackish material along with some microscale stylolites.

### ***4- Interval 4 (2464.04 - 2465.38 m):***

This part is composed of medium grey color limestone having Wackestone to Mud dominated Packstone texture. Fossils size get increased in this interval and fossils are larger forams, which are randomly distributed. Vugs, stylolites and calcite filled vertical fractures are also present in this interval.

### ***5- Interval 5 (2465.38 – 2466.66 m):***

This interval is the continuation of the above interval, with the difference of color, which changes from medium to light grey in this part.

### ***6- Interval 6 (2466.66 – 2466.74 m):***

This interval carries dark brown color argillaceous limestone. Visually it does not show any fossils and secondary features as well. The reaction of this portion with HCL (10% diluted) is comparatively low then adjacent intervals.

### ***7- Interval 7 (2466.74– 2468.11 m):***

The repetition of the interval 4 with more secondary features and comparatively high fossils content. Secondary features include horizontal and vertical fracturs, Vugs, and stylolites.

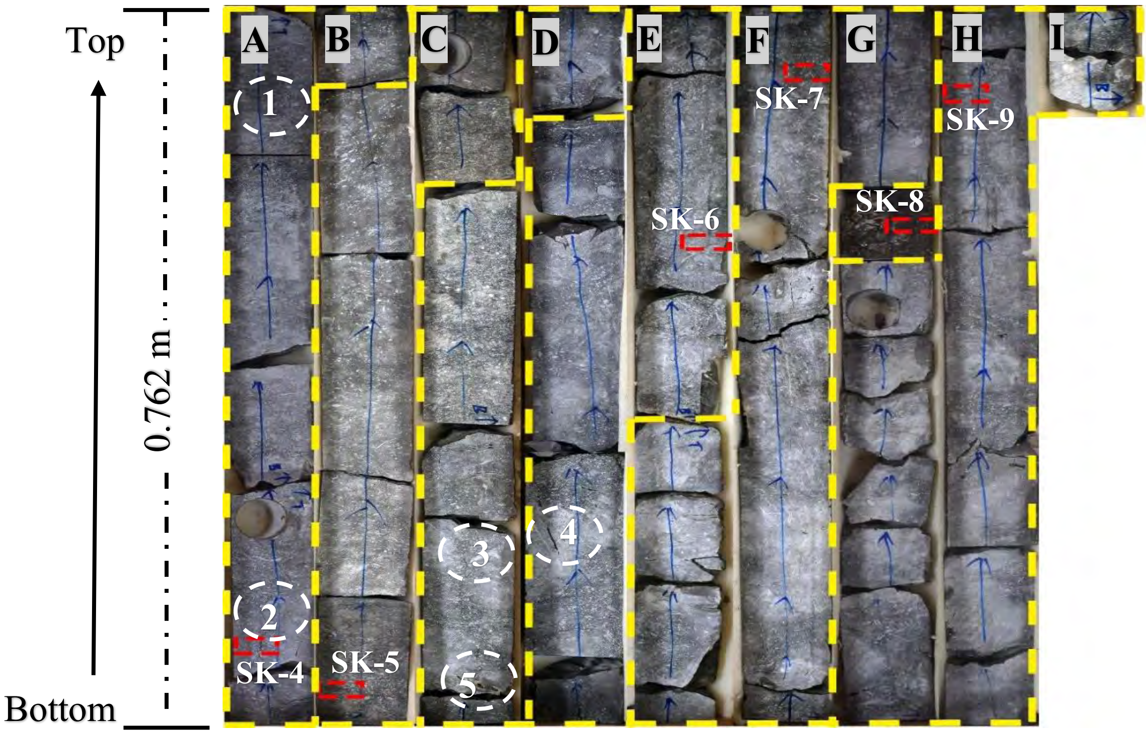


Figure 4.3 Photograph showing core slabs of core-31, labeled A-I represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK- 4 to 9) (1-5 circles are features location shown in Fig 4.4)

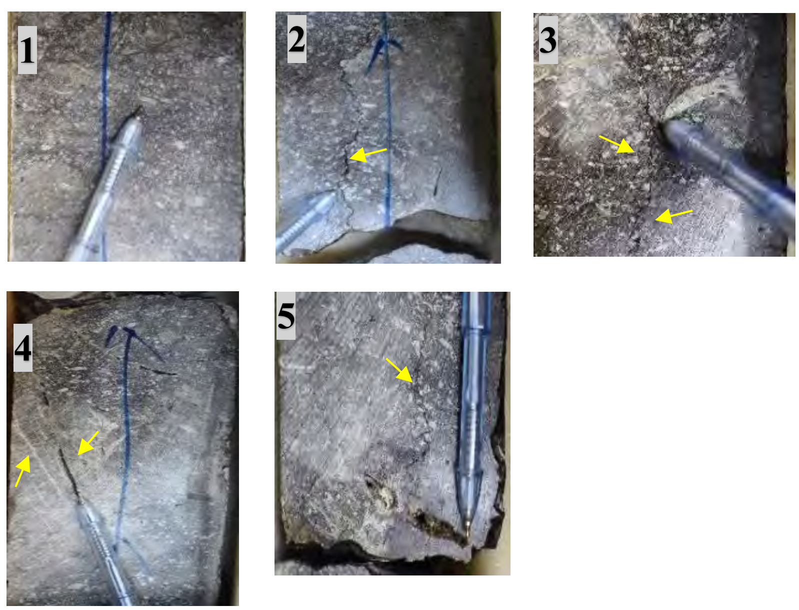


Figure 4.4 Photographs showing Key features of core 31: Larger benthic forams in **1**, Stylolites in **2-3,5**, Bioclastic shell and stylolite in **3**, Calcite filled and unfilled vertical fracture veins in **4,** unfilled pores and stylolite in **5.**

## 4.4 Description of Core 33

This core is from depth of 2475.59 to 2481.68 meters. Total eight intervals are marked in this core section and six samples are selected for thin section preparation. The Fig. 4.5 shows the intervals and samples location, the feature observed while studying are shown in Fig. 4.6 while the core log is shown in Fig 4.14. The description of the core sections intervals are as follows:

### *1- Interval 1 (2475.59 - 2477.11 m):*

This interval is of light grey color limestone of Mudstone to wackestone texture. Fossils are occasionally and randomly distributed forams. A single 4-inch fossils rich unit is also present which is of light brown color. Horizontal calcite filled fractures, vugs and stylolites are also present.

### *2- Interval 2 (2477.11 - 2477.41 m):*

The interval contains the argillaceous limestone, which is of light brownish grey in color and lies in wackestone texturally. Horizontal to sub horizontal calcite fractures are also present in this part of the core section.

### *3- Interval 3 (2477.41 – 2477.45 m):*

This 5-inch portion is the repetition of the interval one.

### *4- Interval 4 (2477.45 - 2477.84 m):*

Interval 2 is repeated here, with some vugs as a secondary feature.

### *5- Interval 5 (2477.84 - 2478.94 m):*

This interval is of light grey color fossiliferous limestone, texturally it is wackestone to pack stone. Secondary features in this interval are vugs, horizontal and vertical unfilled and filled (with blackish material) fractures.

### *6- Interval 6 (2478.94 – 2480.31 m):*

This is again repetition of interval 2, having increase in fossils intensity and size. Texturally lies in wackestone to packstone.

### *7- Interval 7 (2480.31 – 2481.35 m):*

This interval shows change in color majorly, which is light to medium grey fossiliferous limestone. Fossils are larger benthic foraminifera's and bio clasts. In secondary features, well preserved stylolites are observed with minor fracturs.

### *8- Interval 8 (2481.35 – 2481.68 m):*

This is last interval of this core section which shows the repetition of the interval 2 again.

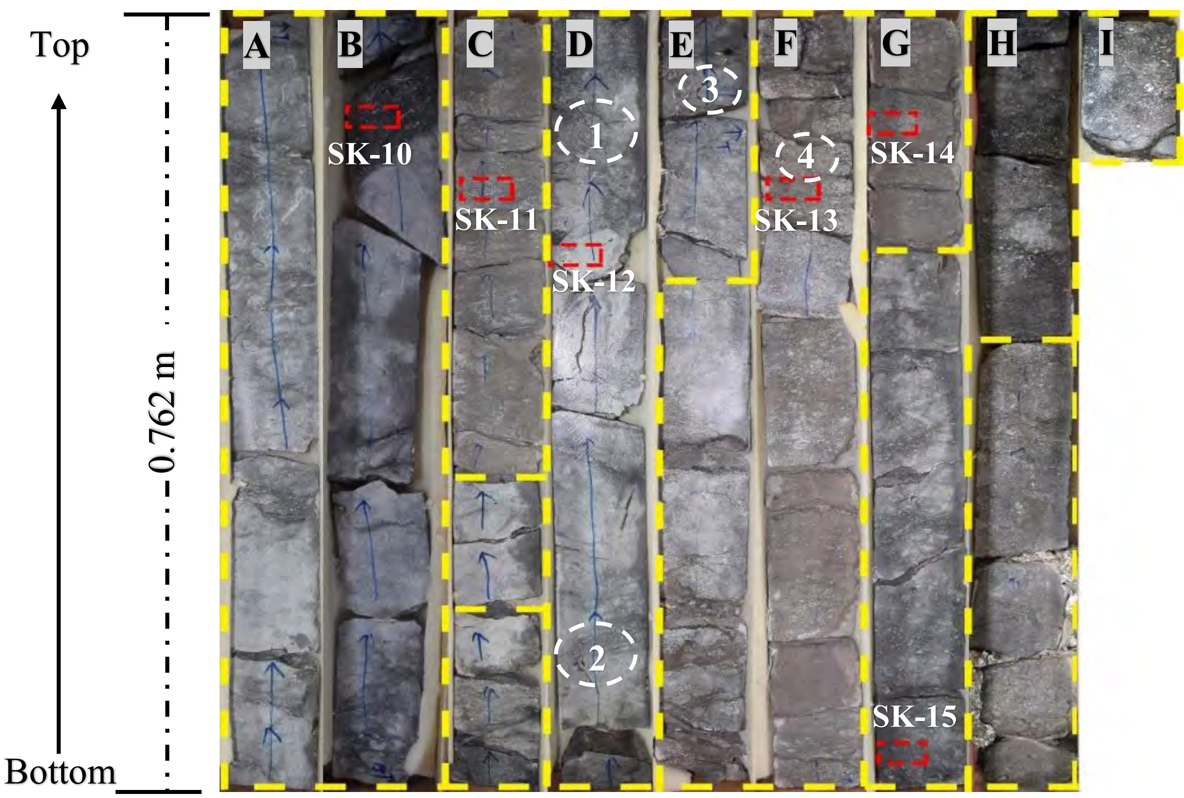


Figure 4.5 Photograph showing core slabs of core-33, labeled A-I represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-10 to 15) (1-4 circles are feature locations shown in Fig 4.6)

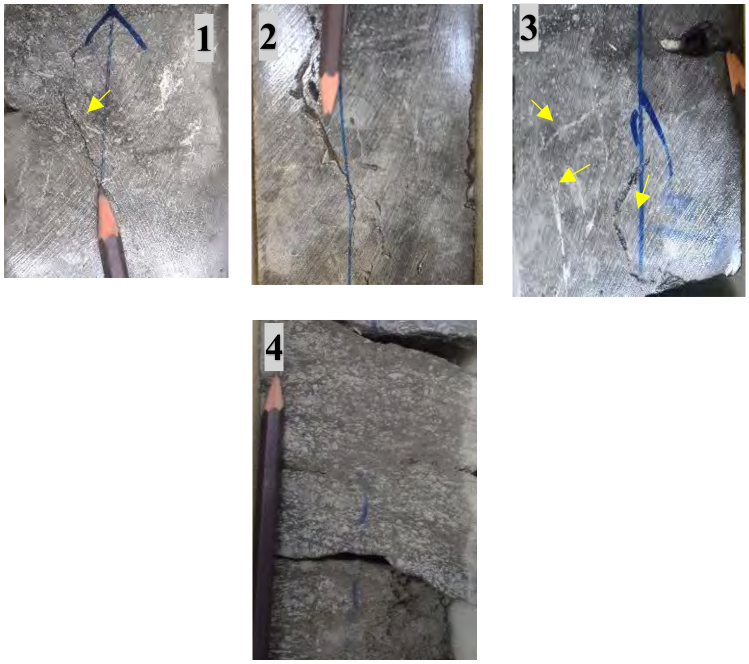


Figure 4.6 Photographs showing the features observed in Core 31: Stylolite and smaller calcite veins in **1**, Unfilled vertical facture in **2**, Stylolite, Calcite filled veins, organic material partially filled fracture and Vuggy porosity in **3**, Larger Benthic foraminifera's in argillaceous limestone **4**

## 4.5 Description of Core 35

This core section is of 6.28 meters in length and depth is 2488.99 to 2495.28 m. Total three intervals are made on the basis of visual observation. For petrographic studies three samples were selected from this core. The core slabs with sample and interval labels is shown in Fig. 4.7, the features present in this core are shown in Fig. 4.8 while the core log is shown Fig 4.14.

### *1- Interval 1 (2488.99 – 2492.17 m)*

The top interval of this core section is comprised of light grey color limestone of mudstone to wackestone facie. The fossils (larger benthic foraminifera's) in this portion is present at different intervals, ranging in 1 to 3 inches. The secondary feature in this interval are vertical fractures some filled with calcite and other are with blackish material, along with some stylolites and vugs.

### *2- Interval 2 (2492.17 – 2493.11 m)*

This interval is also of light grey color limestone with mudstone to wackestone texture. The larger benthic foraminifers present occasionally in this interval but a 9-inch complete fossiliferous interval is also present in this part. The fossils size is comparatively low with good abundance. Vertical stylolite present in this interval as a secondary feature.

### *3- Interval 3 (2493.11 – 2495.28 m)*

The end portion of this core section is the repetition of the interval one with comparatively more fractures and vugs.

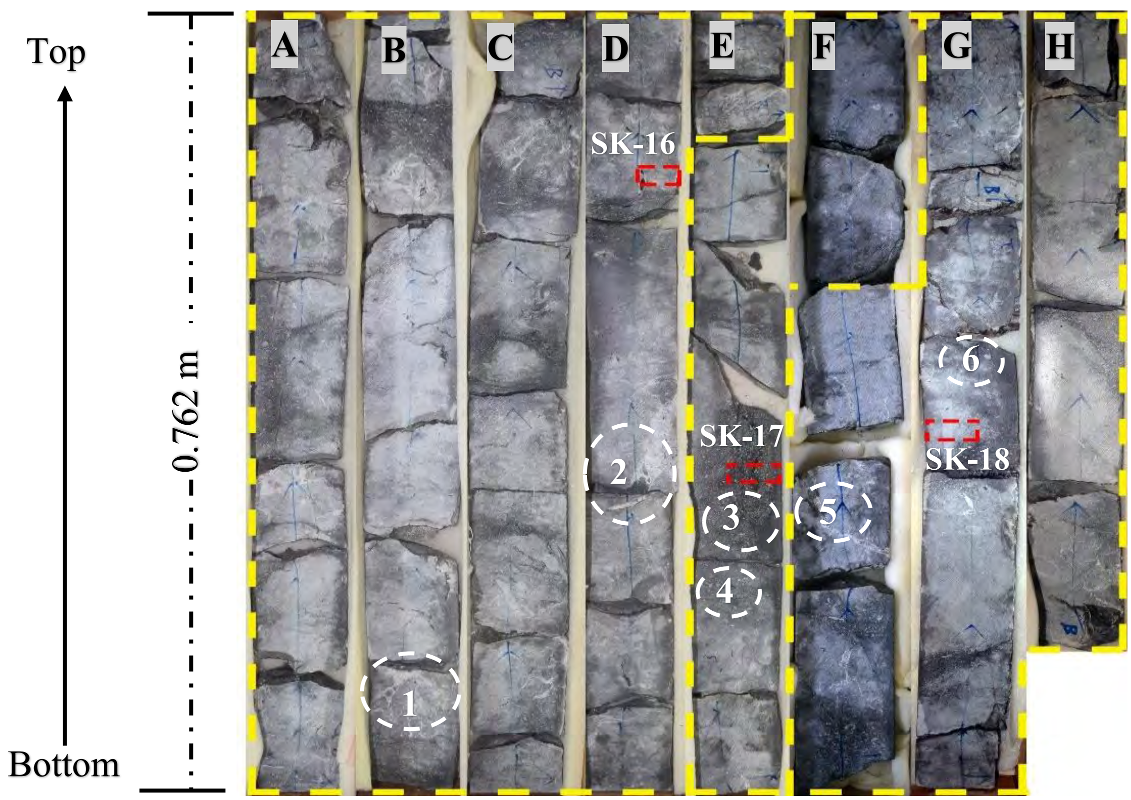


Figure 4.7 Photograph showing core slabs of core-35, labeled A-H represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-16 to 18) (1-6 circles are features location shown in Fig 4.8)

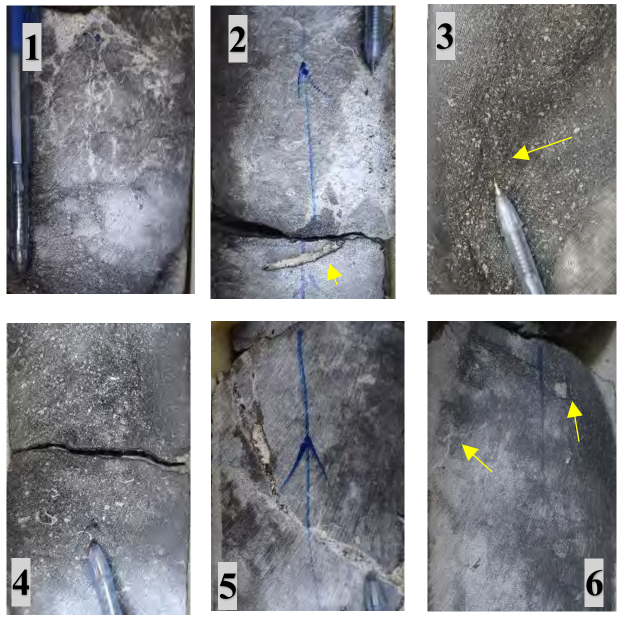


**Figure 4.8** Photographs showing the features observed in Core 35: Calcite filled Channel and fracture in **1-2**, & **5**, Stylolite in **3,** Larger benthic forams and skeletal bioclasts in **4**, Calcite vein and intraclast in **6.**

## 4.5 Description of Core 38

The Core 38 is of 3.871 in length from depth of 2513.69 – 2517.56 meters. The slabs of this core used for study shown in Fig. 4.9 along with main features observed while core log is shown in Fig 4.14. This core shows two intervals, which is described as follows:

### *1- Interval 1 (2513.686 -2514.570 m)*

This interval is light grey color skeletal limestone, texturally Mudstone to wackestone. Fossils are larger benthic foraminifera's, randomly distributed in-places. The secondary features present in this interval are calcite filled and unfilled fractures and horizontal stylolites.

### *2- Interval 2 (2514.570 -2514.935 m)*

The end of the core shows same characteristics as above interval, along with some presence of intra clasts in this interval.

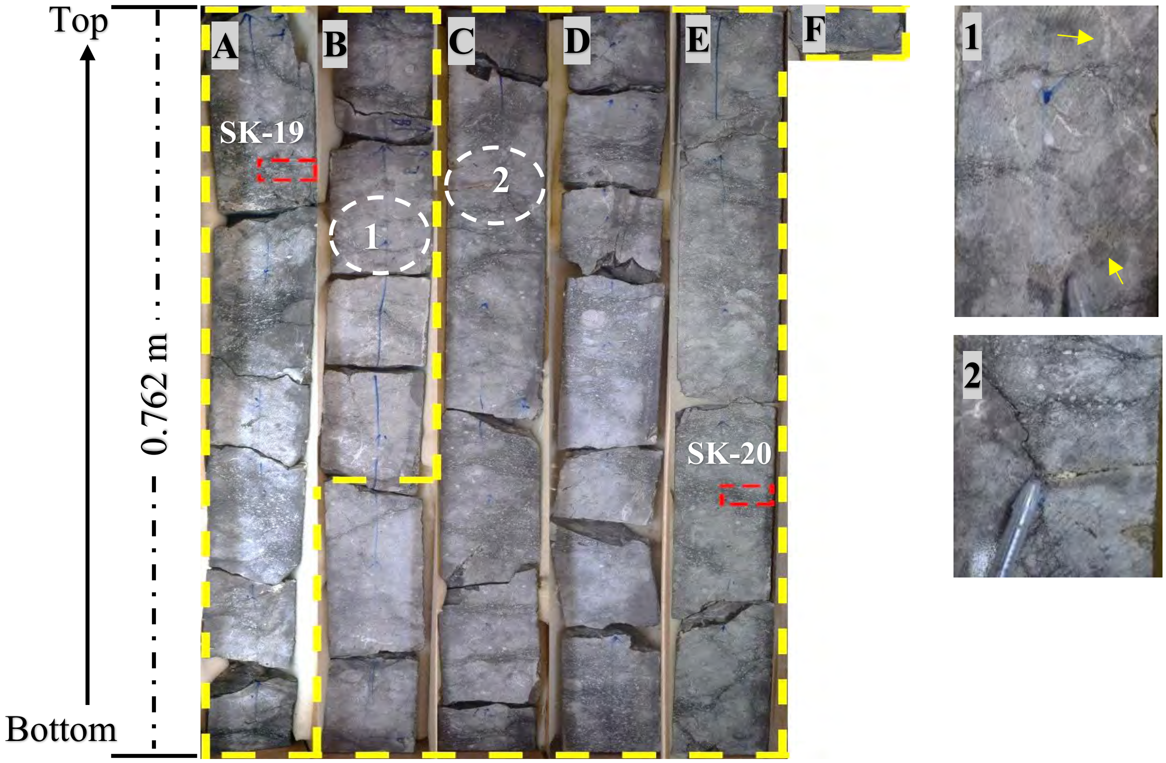


Figure 4.9 Photograph showing core slabs of core-38, labeled A-F represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-19 & 20).(1&2 circles are feature locations) Calcite filled fractures in **1**, Partially filled calcite fracture in **2**.

## 4.6 Description of Core 40

This core section is from depth of 2526.79 – 2531.76 meters. It is divided in to two intervals based on visual appearance. The slabs of this core with their interval division and samples location are shown in Fig 4.10. with representative features observed during the study, the core log is shown in Fig 4.15. The description of the core 40 is as follows:

***1- Interval 1 (2526.79 - 2528.99 m):***

This core section is light to medium grey limestone, and texturally referred as Packstone. Fossils present in good abundance with random to sequential distribution and are foraminifera's, i.e. Nummulities, assilina's and bio clasts as well. The secondary features in this interval include stylolites occasionally, fractures or any pores are not found.

**2-** ***Interval 2 (2528.99 - 2531.76):***

This interval is of medium color highly fossiliferous limestone, texturally it is Packstone facie. The fossils are Larger benthic foraminifera's along with skeletal contents. The secondary features are present in this section.

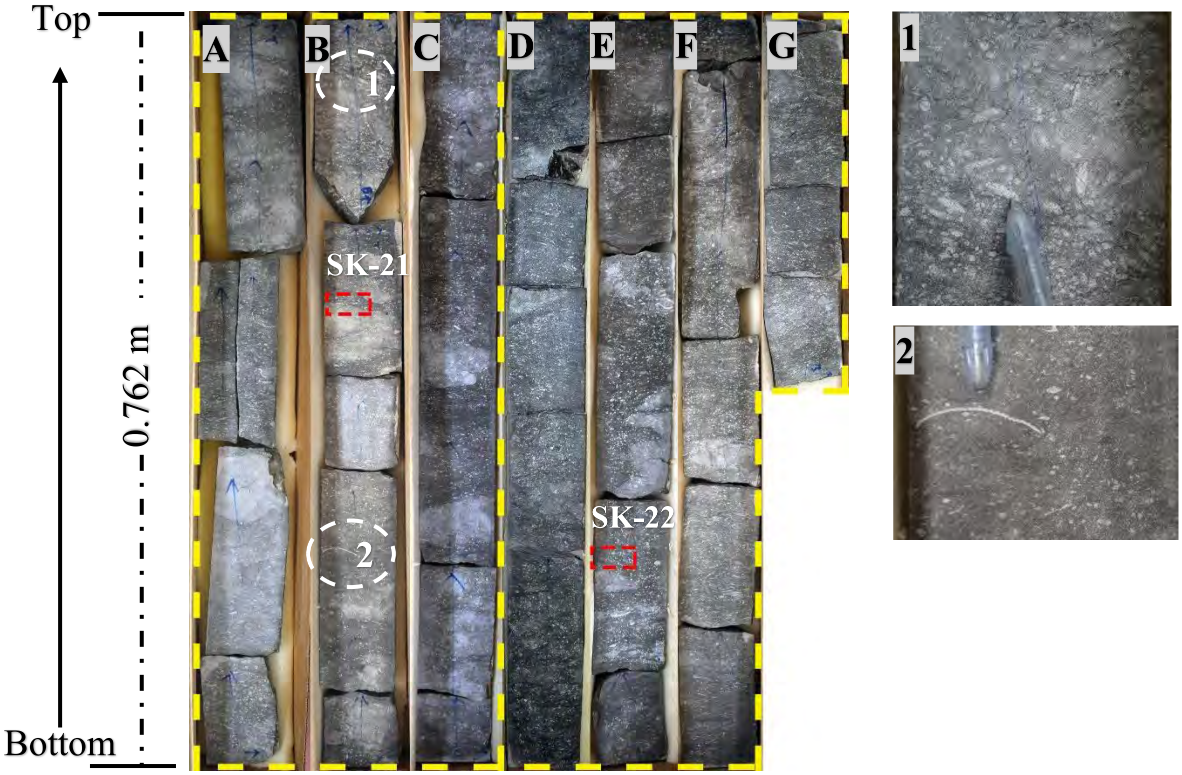


Figure 4.10 Photograph showing core slabs of core-40, labeled A-G represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-21 & 22). (1&2 circles are feature locations) Larger benthic foraminifera's of relatively larger size in **1**, Bioclastic fragment is shown in **2**.

## 4.7 Description of Core 42

This core is from depth of 2543.25 – 2547.76 meters. Total five intervals are marked in this core section and three samples are selected for thin section preparation. The Fig. 4.11. shows the interval and samples location with features of the core observed during study while the core log is shown in Fig 4.15. The description of the core sections intervals are as follows:

***1- Interval 1 (2543.25 - 2543.89 m)***

The top of this core section starts with light grey color limestone, texturally mudstone to wackestone facie. The Eocene larger benthic foraminifera fossils are present occasionally in random distribution. The secondary features of this portion are unfilled vertical fractures, some filled with blackish material and calcite, including few stylolites as well.

***2- Interval 2 (2543.89 – 2544.93 m)***

This interval shows little variation in color from light to medium grey limestone while texturally same as previous one but carries more calcite filled fractures. The fossils distribution changed to, random to sequential with increase in abundance and size comparatively then previous portion.

***3- Interval 3 (2544.93 – 2545.90 m)***

This portion has also light to medium grey color limestone but texturally it shows wackestone to packstone facie. Fossils in this interval are abundant as relative to the above interval. The secondary features of this interval are calcite filled fractures.

***4- Interval 4 (2545.90 – 2546.91 m)***

This interval has light grey color limestone which shows texturally wackestone facie. While the secondary feature in this interval has calcite filled channel and unfilled vertical fractures.

***5- Interval 5 (2546.91 – 2547.76 m)***

The end of this core shows some change with above interval, which is light to medium grey color limestone, Wackestone to Packstone facie. The fossils contents are same as above with presence of calcite filled vertical fracture and vuggy porosity as a secondary feature.

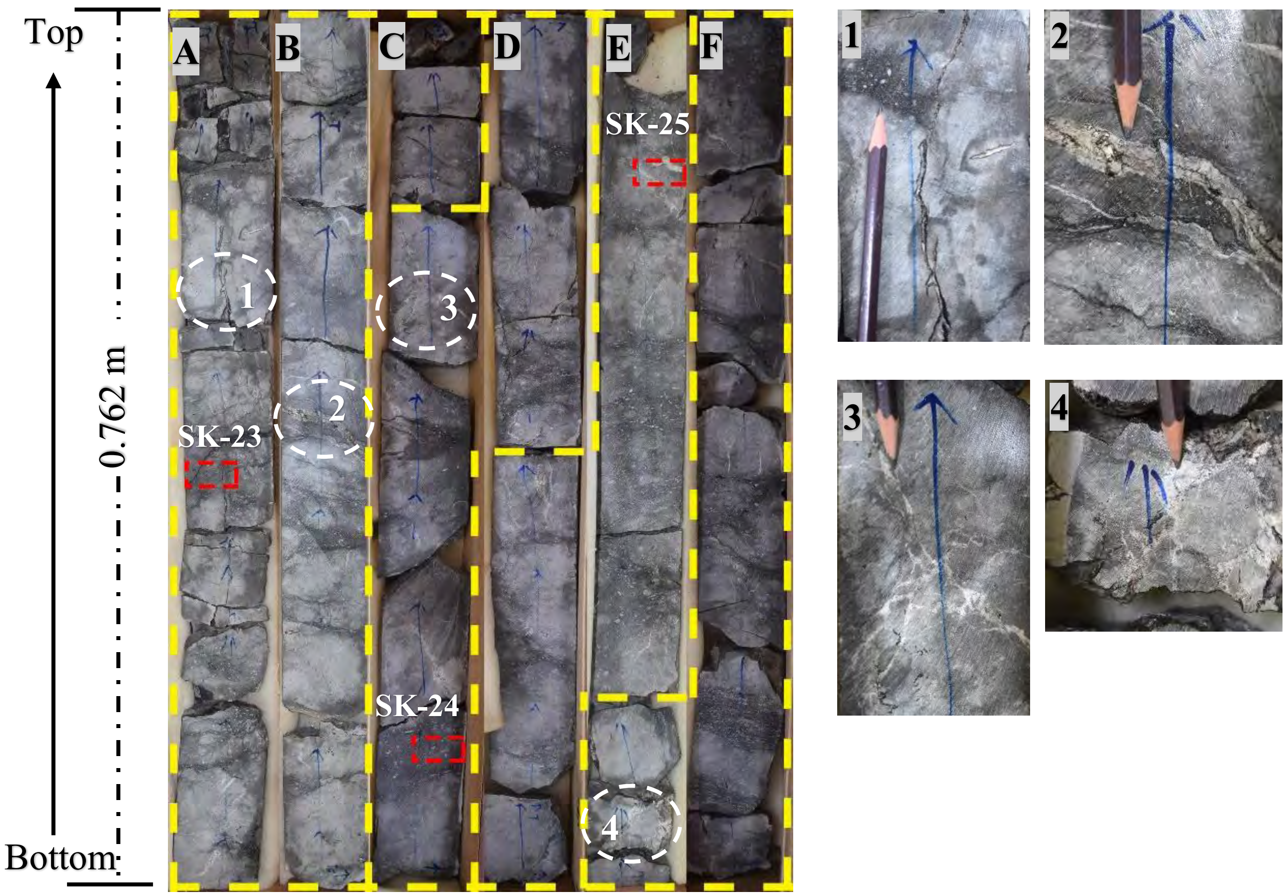


Figure 4.11 Photograph showing core slabs of core-42, labeled A-F represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-23 to 25). (1-4 circles are feature locations) Unfilled vertical fracture in **1**, Calcite filled horizontal fracture veins in **2**, Calcite filled veins in **3**, Calcite filled channel in **4**.

## 4.8 Description of Core 45

This is the last core section of Sakesar formation with depth range of 2558.491 – 2559.436 meters. This three-foot core section marks the lower end of the Sakesar Limestone in studied well core. The slab of this core studied is shown in Fig 4.12 with features observed in the core. The Core log is shown in Fig 4.15. It encompasses one interval, which is described as follows:

### *1- Interval (2558. 491 – 2559.436)*

The interval is light to medium grey highly fossiliferous dolomitic limestone. Fossils size get decreased comparatively to above sections with higher abundance. Texturally it is categorized as Packstone. This interval shows slow reaction with HCL that show presence of dolomite. The secondary features such as fractures, stylolites are not present in this part.

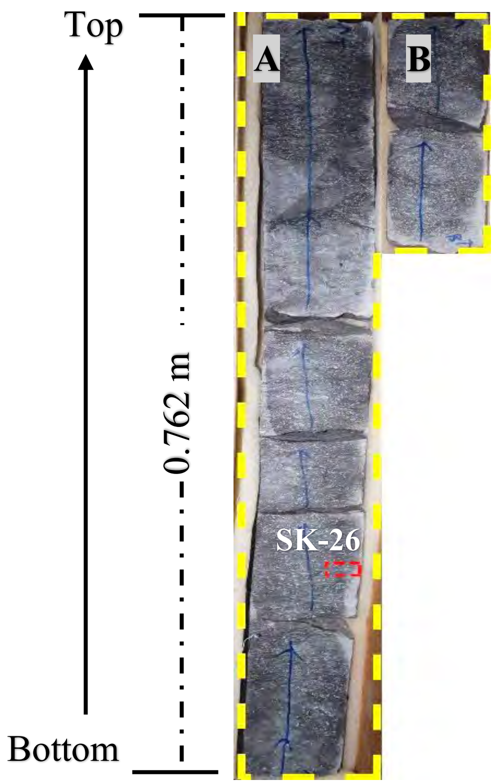


Figure 4.12 Photograph showing core slabs of core-45, labeled A-B represents the top and bottom part of the core slabs respectively, dotted yellow lines marked the different intervals and dotted red lines are the sample locations (SK-26).

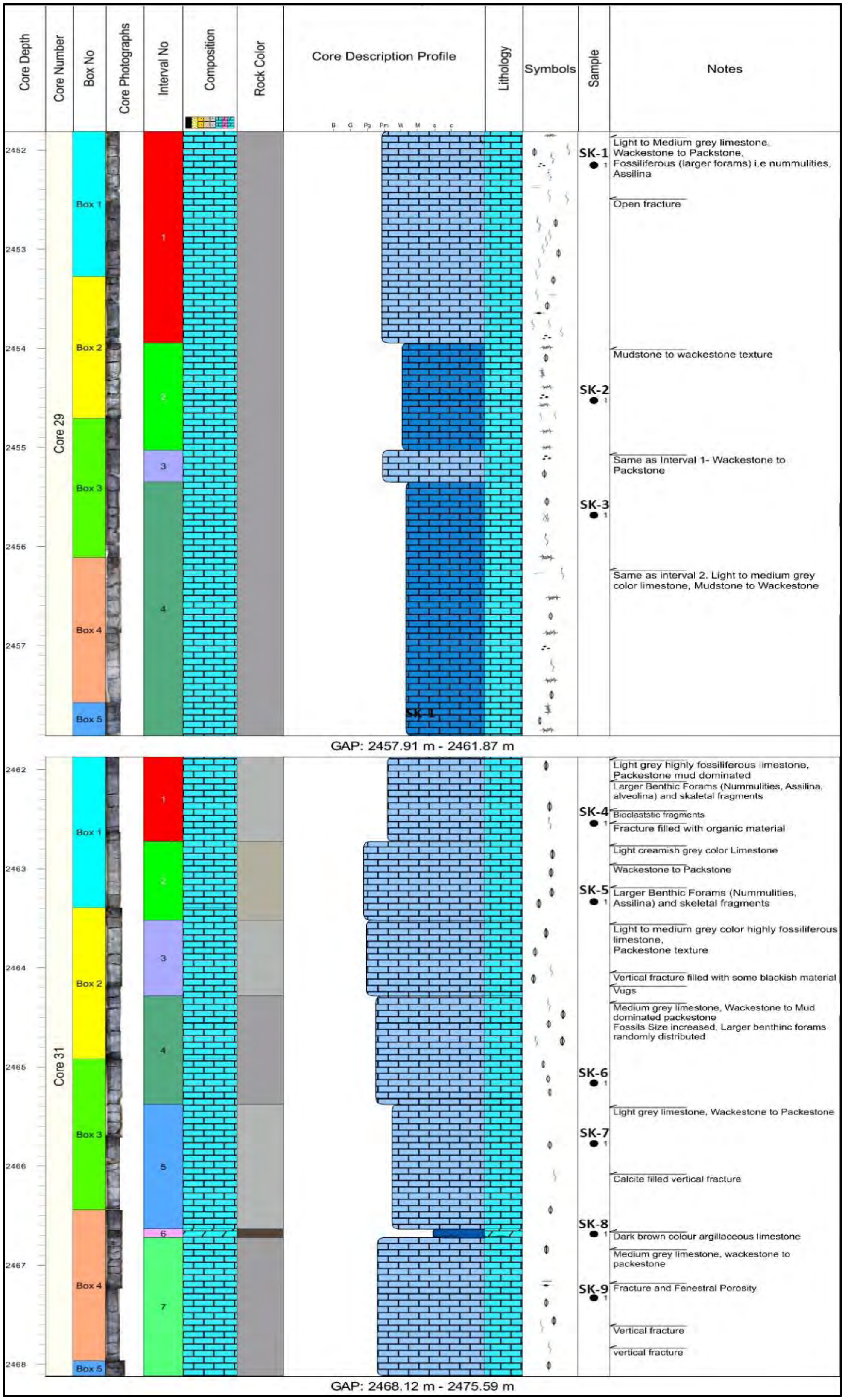


Figure 4.13 Photograph showing Core Log of Core 29 & Core 31

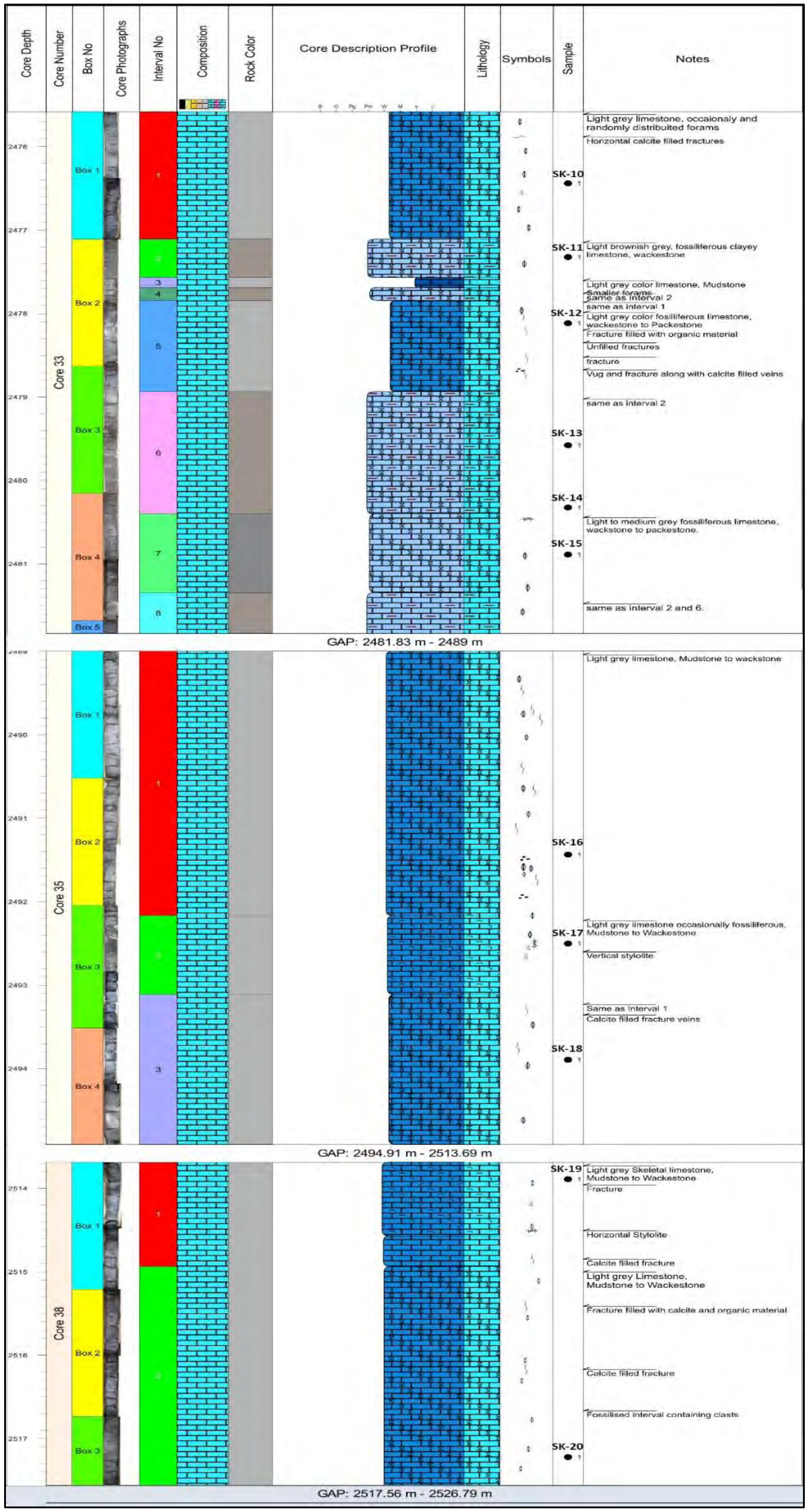


Figure 4.14 Photograph showing Core log of Core 33, Core 35 and Core 38

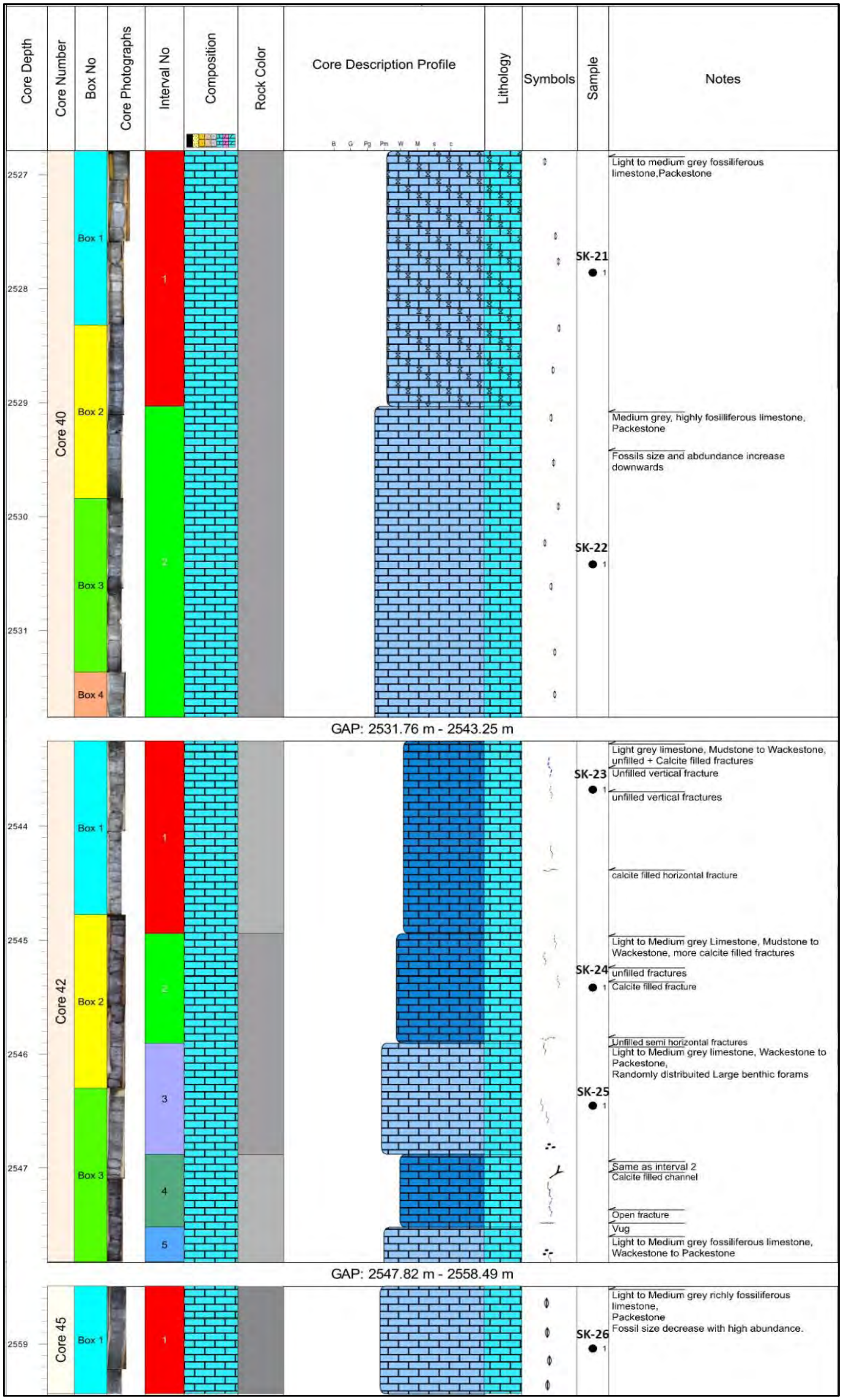


Figure 4.15 Photograph showing Core log of Core 40, Core 42 and Core 45

# Chapter No. 5

# PETROGRAPHIC STUDIES

## 5.1 Introduction

Petrographic studies of carbonate rocks are the key indicator of their environment of deposition (James & Jones., 2015). It is the microscopic analysis of thin section slides of rock samples. For petrographic examination, 26 representative samples were taken from core. The samples were acquired from Petro Core House HDIP and thin section preparation were also prepared at HDIP Lab. The objective of the petrographic study is to identify and construct microfacies on sedimentological and micro paleontological characteristics to develop depositional model. Furthermore, the diagenetic features are to identified for diagenesis and then paragenesis to explore the diagenetic studies.

## 5.2 Depositional Texture

Many classification schemes were proposed for limestone studies. Amongst all of them, two most well-known classifications are Folk (1959, 1962), and Dunham (1962). The latter one classification is used for rock typing, while the former scheme is also been used for description of constituents. Dunham (1962) Fig 5.1. classified the texture on whether the grains are in self-supporting framework or enclosed in matrix (micrite).

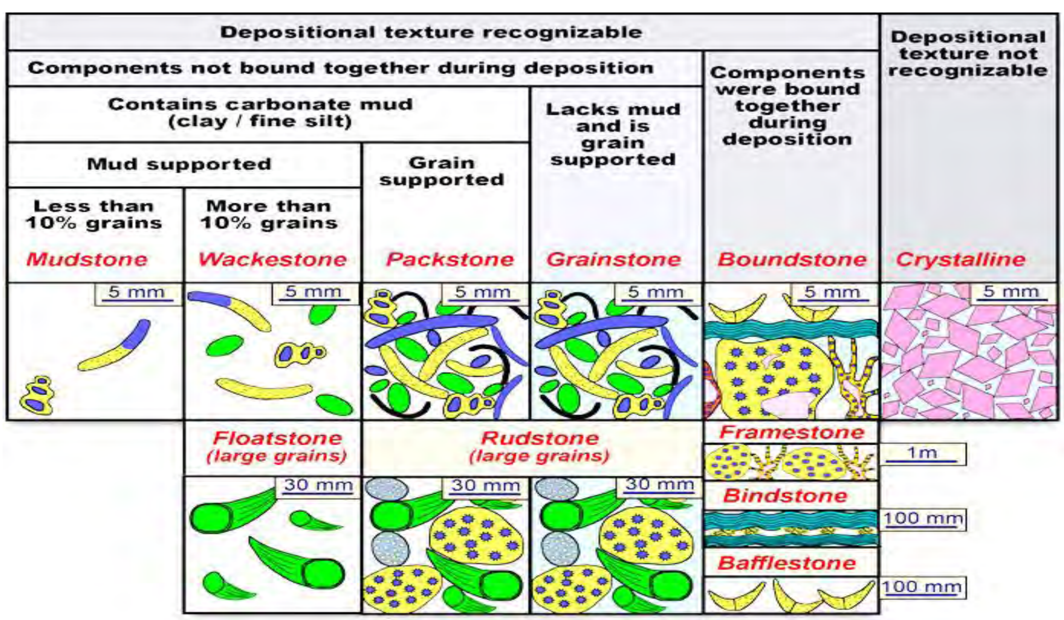


Figure 5.1 Dunham (1962) Classification based on the depositional texture of Limestones

## 5.3 Microfacies study of the Sakesar Formation

The rock typing of the carbonate sequence is considered as microfacies analysis (Gubler et al., 1967). To identify variety of fossils, cements and diagenetic phases, Erik Flügel (2010), Scholle & Ulmer scholle (2003), A.E Adams & Mackenzie (1998), Afzal, J., et al., (2011) are used. The petrographic observations are conducted to establish the microfacies of the Sakesar formation. On textural bases three major textural facies are identified which are Wackestone, Wackestone to Packstone, and Packstone. While on bases of allochems component's along with texture, total five microfacies are constructed which are as follows:

1. Larger Foraminiferal Wackestone-Packstone
   1.1. Nummulitic - Assilina Wackestone-Packstone
   1.2. Assilina - Nummulitic Wackestone-Packstone
2. Bioclastic - Nummulitidae Wackestone
   2.1. Bioclastic - Nummulitic Wackestone
   2.2. Bioclastic Assilina Wackestone
3. Assilina - Nummulitic Packstone
4. Bioclastic Wackestone-Packstone
5. Bioclastic Wackestone
6. Nummulitic-Lockhartia dolomitic Wackestone-Packstone
7. Ranikothalia-Assilina dolomitic Wackestone-Packstone

The pre-fixes of the above establish facies shows the dominance of the types of allochems over other constituents.

### 5.3.1 Larger Foraminiferal Wackestone-Packstone (SKMF-1)

The SKMF-1 micro facie is the most dominating microfacie found in the studied sections. Different genera of Larger benthic foraminifera are found in this facie i.e. Nummulities, Assilina, Lockhartia, Ranikothanlia e.t.c. On the basis of these genera's four further sub-microfacies are classified under this Microfacie (SKMF-1). The thin sections included in this microfacies are SK (1,4,5,6,11,19,20,21). Their description is as follows:

### 5.3.1.1 Nummulitic - Assilina Wackstone-Packstone (SKMF-1A)

This is dominating facie with representation of four petrographic thin sections having depositional texture of Wacke to Packstone. The main constituents, micritic matrix and allochems are in difference of only 2.5% average. The matrix of this facie is 43-67% with averaging value of 51.25%. The Skeletal allochems are in 33-57% while on average these are 48.75%. The major allochems constituting are, Nummulite sp., Assilina sp., Lockhartia sp., Miscellanid sp., Gastropods and rotalia. Miliolid, planktons, and discocyclina species are present in lesser amount (<2%). The algae is 1-5% with broken fragments of fossils which are 2-5%. The secondary features present in this microfacies are filled fractures, with calcite and blackish material. Dolomitization, micritization and pyritization are also observed in this microfacies. This microfacies is observed in four thins section which includes SK- (1, 5, 6, 21). The Fig 5.2 represents this microfacie.

### 5.3.1.2 Assilina-Nummulitic Wackestone-Packstone (SKMF-1B)

This sub microfacie is similar to the above one but with more matrix %age and assilina sp., contents. This is representative of four thin sections. The depositional texture of this microfacie is observed as Wackestone to Packstone. The main constituent of this facie is matrix ranging from 55-75% with an average of 65%. The dolomite rhombs are present in some sample with average of 25 while sparry calcite is upto 10% on average. Allochems show their presence in range of 25-45% having average of 34%. The major portion of the allochems contains Assilina sp., and then Nummulites sp., Lockhartia sp., and Miscellanid. Minor amount (<2%) of Miliolid, Planktons, Rotalia, Gastropods and Algae are also present in this specie. Discocyclina sp., show their presence in one thin section which is upto 4%. Bioclasts of different fossils are found with an average of 5% (2-9% range). Clacite filled fractures, stylolites, pyritization and dolomite crystals are also found in this facie. The thin section samples of this microfacies are SK- (4, 11, 19, 20). The representative photomicrographs of this is show in Fig 5.3.

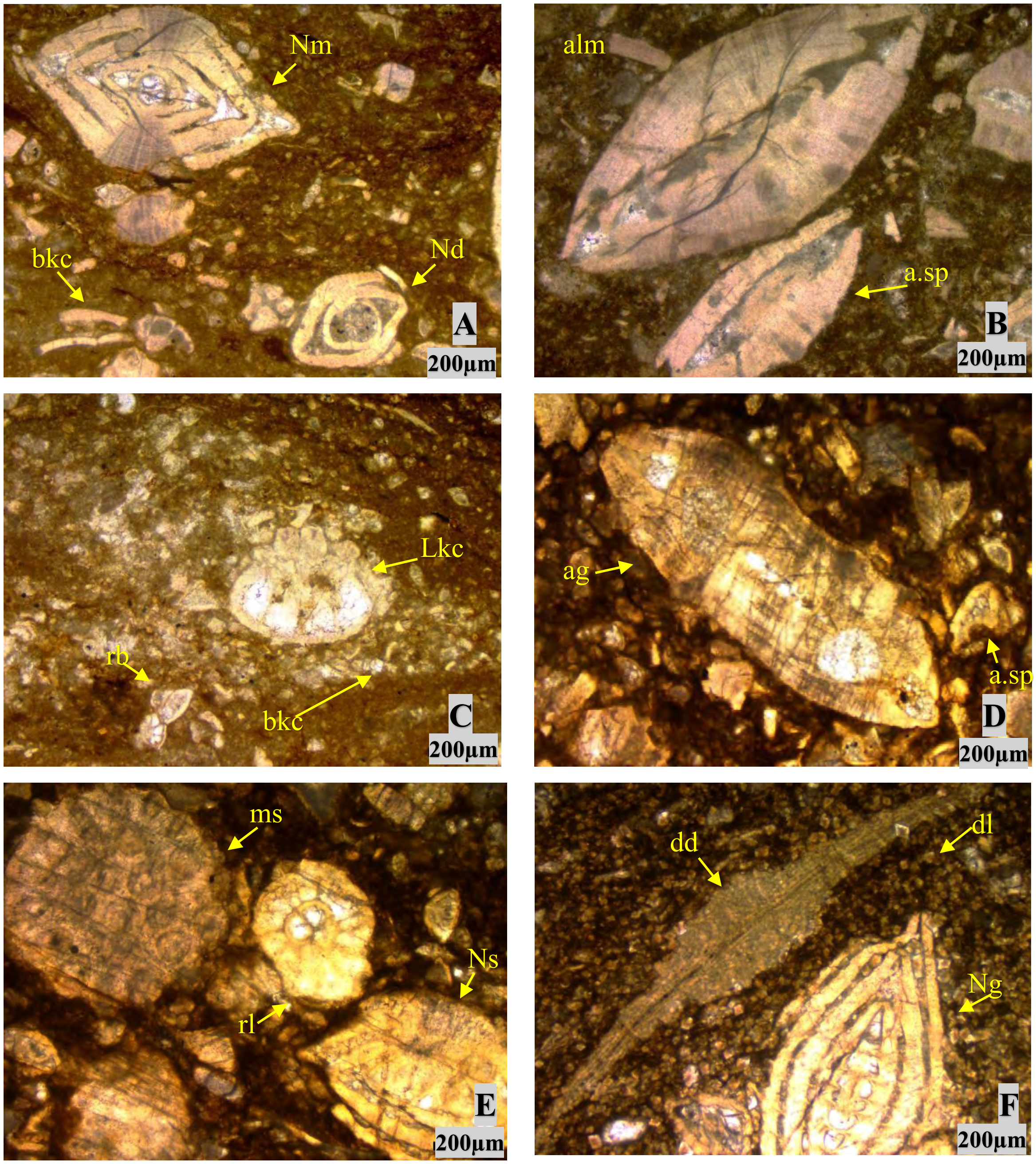


Figure 5.2 Nummulitic-Assilina Wackestone-Packstone (SKMF-1A): Skeletal allochems majorly include LBF (larger Benthic foraminifera) i.e Nummulites mamilatus (Nm in A), Nummulites djodjokartae (Nd in A), Nummulites globulus (Ng in F), Nummulites specie (Ns in E), Assilina Laminosa (alm in B), Assilina granulosa (ag in D), Assilina sp. (a.sp in B & D), Lockhartia coniditi (Lkc in C), Discocyclina dispensa (dd in F), Miscellanea sp. (ms in E), Laffitteina bibensis (smaller rotaliid) (rl in E), broken rotallid clast (rb in C), broken bio fragments (bkc A & C), Dolomite rhombs (dl in F). Photomicrographs are from samples (SK -1, 5, 6, 21)

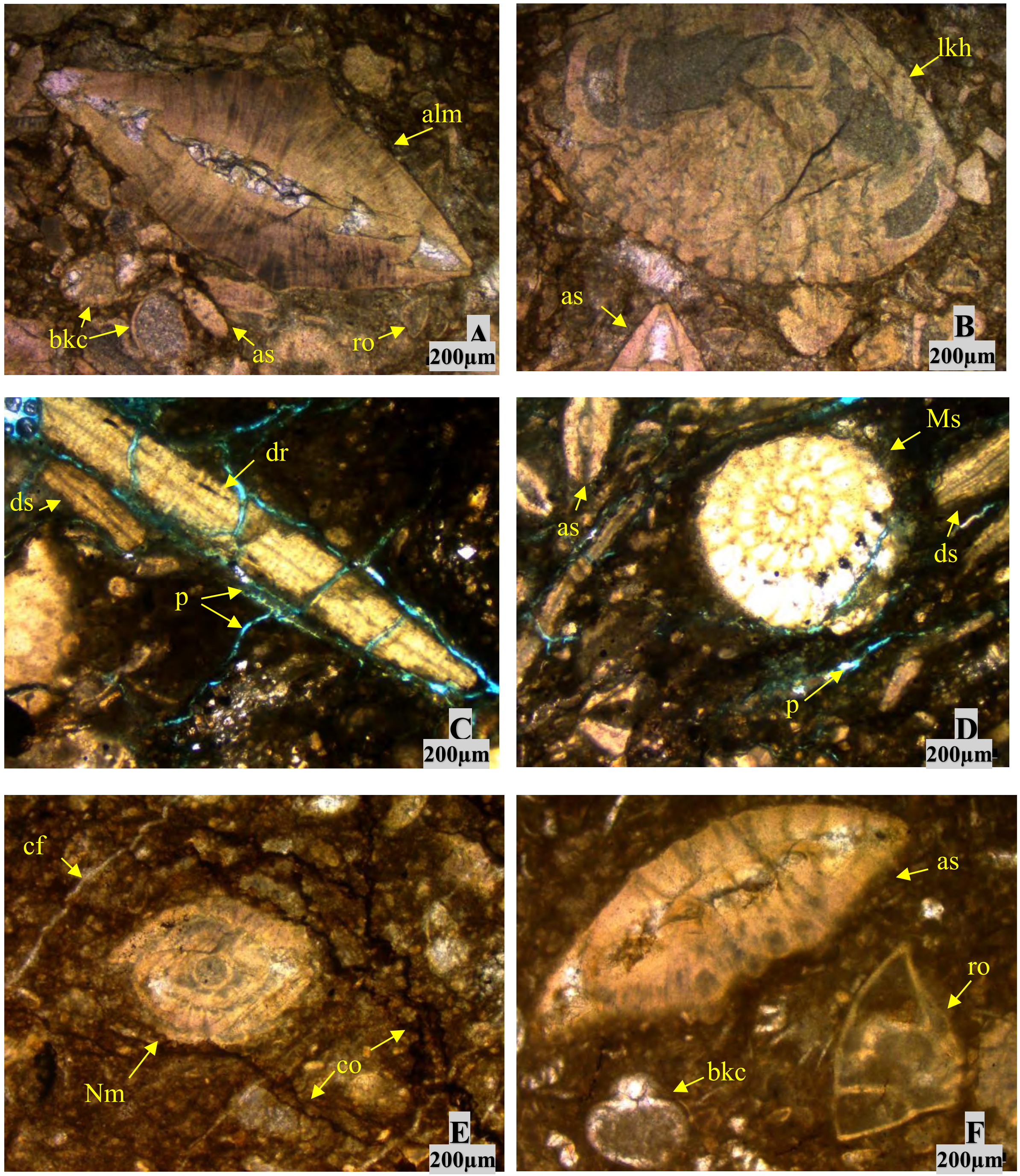


Figure 5.3 Assilina-Nummulitic Wackestone-Packstone (SKMF1-B): the allochems in this facie includes Assilina Laminosa (alm in A), Assilina sp. (as in A,B,D,F), Lockhartia heimei (lkh in B), Discoclyclina ranikotensis (dr in C), discocyclina sp., broken fragments (ds in D), Miscellanea sp. (Ms in D), Nummulites mammilatus (Nm in E), broken and altered bio fragments of different species (bkc in A ,F), fracture filled with calcite (cf in E), fracture filled with blackish material (co in E), rotalidae (ro in A, F), Porosity (P in C,F) Photomicrographs are from samples (SK - 4, 11, 19, 20)

### 5.3.2 Bioclastic – Nummulitidae Wackestone (SKMF-2)

The SKMF-2 is the second dominating mircofacie in the studied section. The show higher content of the bioclastic fragments dominates over Nummulitidae allochems i.e Nummulites and Assilina, in this facie with the depositional texture as Wackestone. It also has two sub categories of the microfacies owing to the percentage content of the genera observed in thin section. The thin sections included in this microfacies are (SK-2,3,7,8,9,15,16,24,25). Their descriptions are as follows:

#### 5.3.2.1 Bioclastic – Nummulitic Wackestone (SKMF-2A)

This Sub microfacie is represented by Seven thin sections. The depositional texture of these thin sections is observed as Wackestone. The main constituents of this facie are micritic matrix and allo chems. As the name suggest in allochemical components, the major portion of this facie is represented by the bioclasts which are in range of 10-24% with average of 14.8%. The allochems of different familie, range lies in 30-40% with average of 35 which includes Nummulite sp., Assilina sp., Alveolina sp., Lockhartia sp., Milliolid sp., Algae sp., Discocyclina sp., ranikothalia sp., and planktons, rotalia, miscellanid, marginipora sp., with few gastropods. Marginipora is only found in this facie. The algae presence on average is 2.5% and is green algae in this facie. The matrix of this facie range between 60-70% with average of 65%. Sparry calcite ranges from 5-20% with average of 12%. Stylolites, calcite filled fractures and bio-lithite bioclast are observed in thin sections. The Fig 5.4 & 5.5 are showing the thin section photographs of samples SK- (2,3,,8,,15,16,24,25) of this facie.

#### 5.3.2.2 Bioclastic Assilina Wackestone (SKMF-2B)

The submicrofacie is comprised of two petrographic thin sections. The main dominating constituent of this facie is matrix 70-74%. The allochems constituents the 26-30% of this facie. The bioclasts are dominant individually in allochems over other components with average of 10%. The other allochems components contains Assilina sp., Nummulites sp., Alveoloina sp., Miliolid., Planktons., and miscellanid. The algae in this facie lies between 1-5%. The fractures filled filled with blackish material (organic matter) are observed. The Fig 5.6 showing the photographs of this facie, the thin section are SK- (7,9).

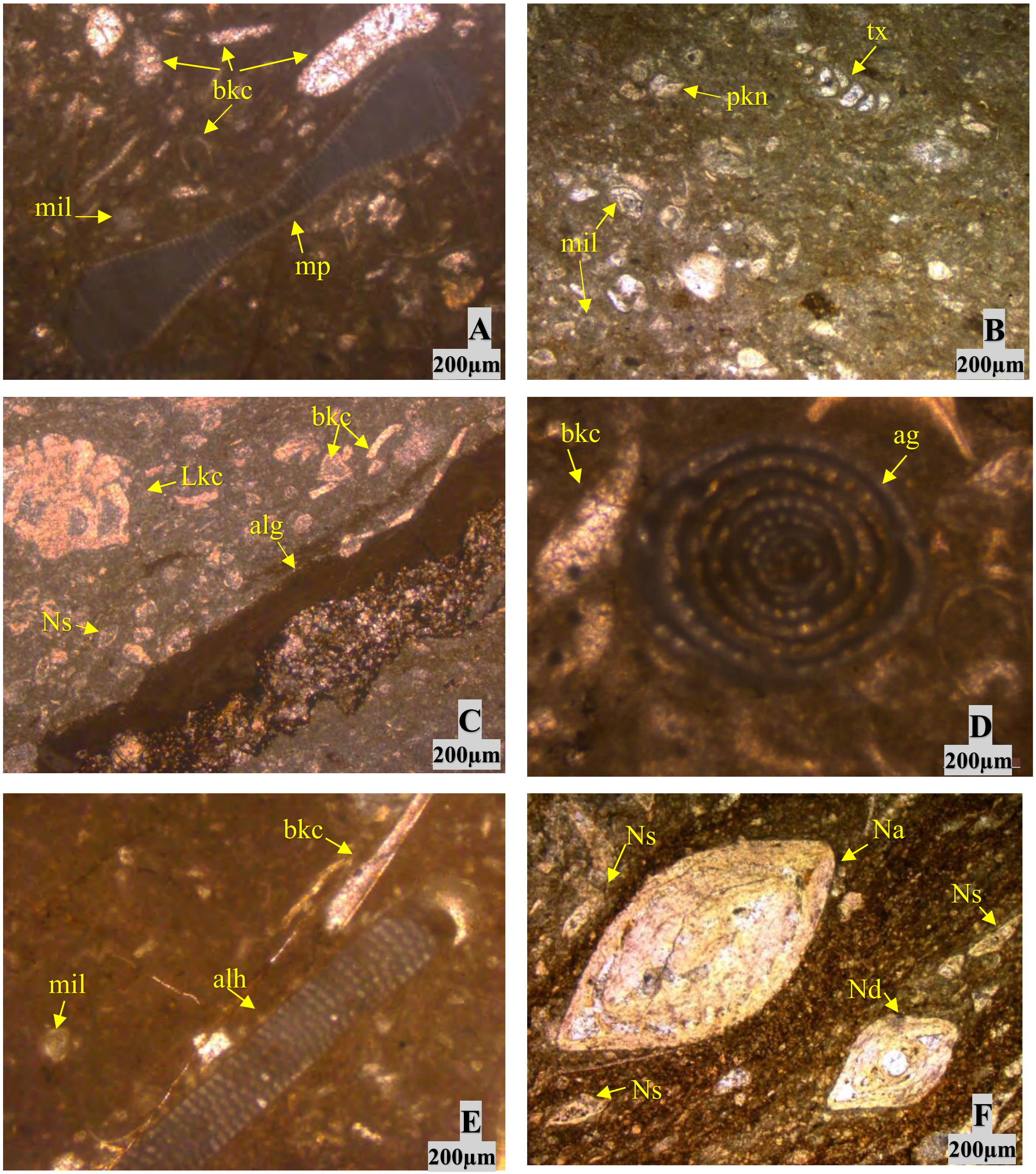


Figure 5.4 Bioclastic–Nummulitic Wackestone (SKMF-2A): Variety of Skeletel components comprised of,Nummulites atacius (Na in F) Nummulites djodjokartae (Nd in F), Nummulites sp. (Ns in F), Lockhartia Coniditi (Lkc in C), Larger Benthic foraminifera sp. Marginiopora (mp in A), Milliolid sp. (mil in A,B,E), Alveolina globula (ag in D), Algae halimeda (alh in E), Algae sp. (alg in C), Broken / altered bio clasts (bkc in A,C,E),Smaller plankton sp(pkn), texturalia (tx in B). Photomicrographs are from samples (SK- 2,3,8,15,16,24,25)

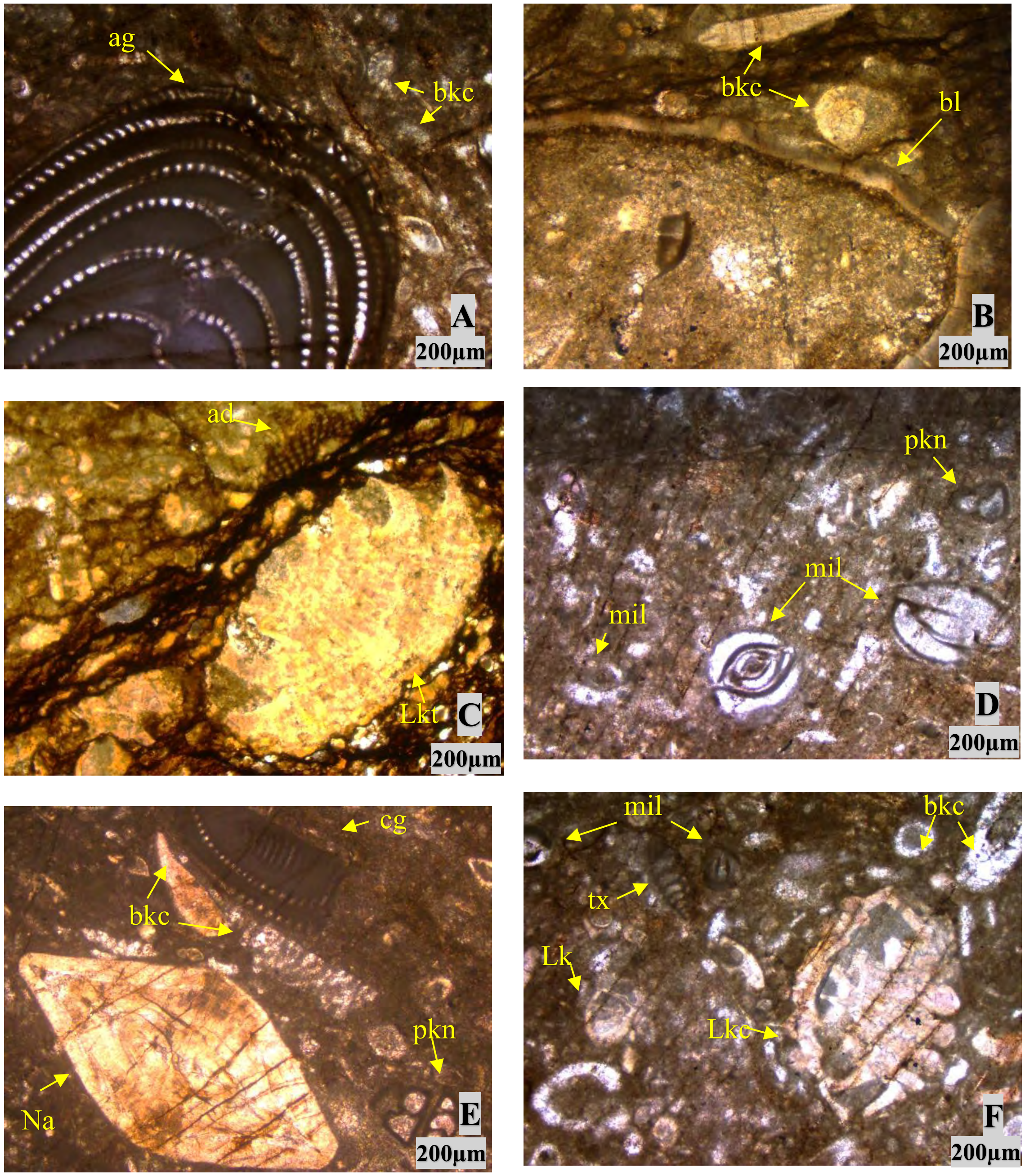


Figure 5.5 Bioclastic-Nummulitic Wackestone SKMF-2A: the skeletal allochems are Alveoline globula (Ag in A), Nummulites atacius (Na in E), Lockhartia Coniditi (Lkc in F),Lockhartia tipper (Lkt in C), Lockhartia sp. (Lk in F), Miliolidae sp (mil in D & E), Smaller planktonic foraminifera (pkn in D-E), textularia (tx in F), Biolithite (bl in B), Algae coralline green (Cg in E) Algae dascyladean (ad in C), broken / altered bioclastic fragments (bkc A, E-F). Photomicrographs are from samples (SK-2,3,8,15,16,24,25)

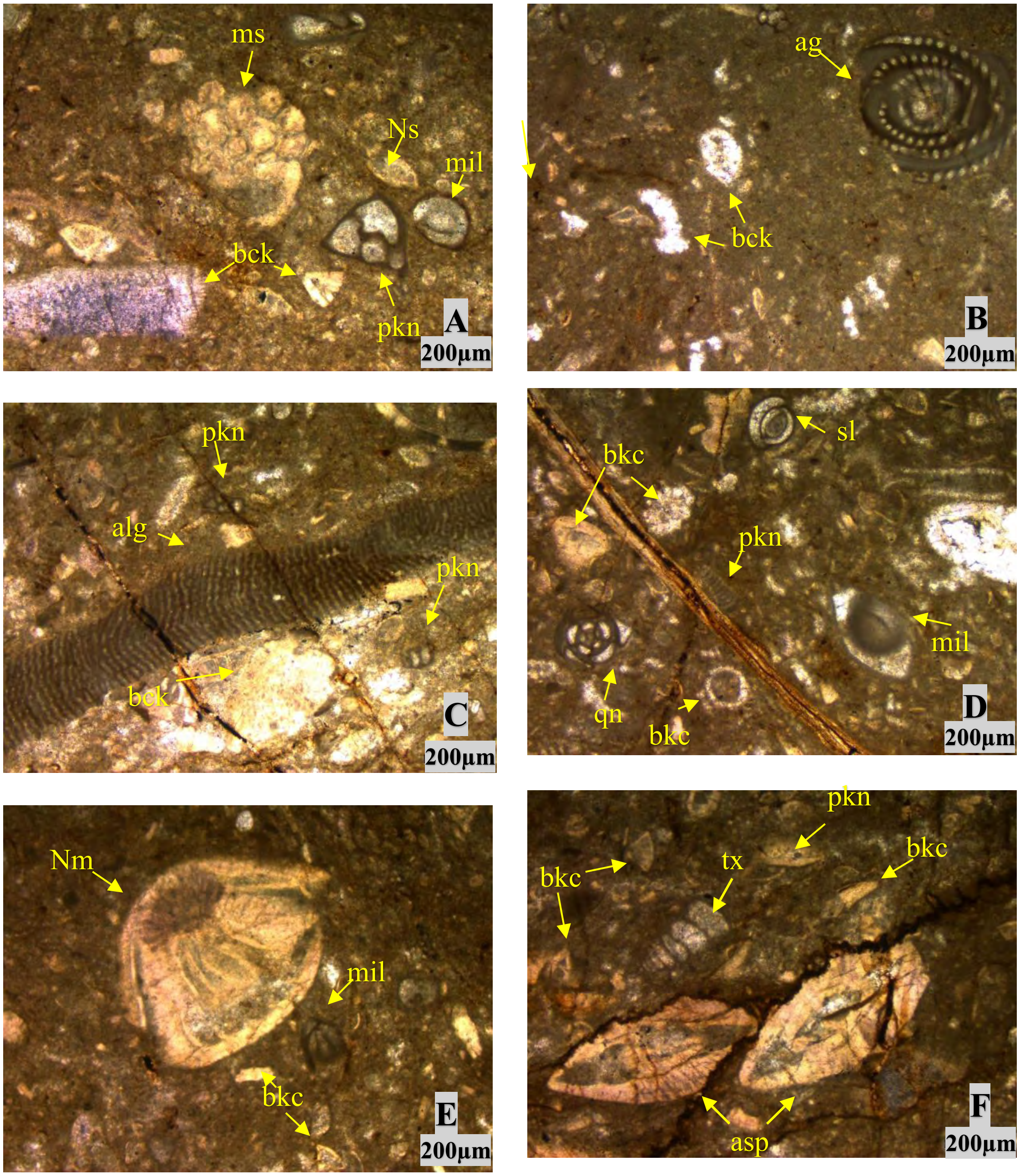


Figure 5.6 Bioclastic-Assilina Wackestone (SKM2-B): skeletal allochems found, includes Nummulites Mamillatus (Nm in E), Nummulites sp. (Ns in A), Assilina Spinosa (asp in F), Miscellanea sp. (Ms in A), Alveolina globula (ag in B), Milliolid (mil in A,D,E), Quiqueloculina (qn in D), Spiroloculina (sl in D), Smaller planktonic foraminiferas (pkn in A, C-D, F), Textularia (tx in F), broken / altered bioclastic fragments (bkc A-F), Algae (alg in C). Photomicrographs are from samples (SK- 7,9)

### 5.3.3 Assilina - Nummulitic Packstone (SKMF-3)

The SKMF-3 microfacie shows the depositional texture of Packstone and is present in three consecutive thin sections showing the well-developed range of this facie. These three thin sections are blue-dyed stained thin sections. The matrix of this facie lies in range of 30-50% having average of 41%. The allochems range between 50-70% with average of 58%. The dominating allochem component is Assilina sp., over Nummulites sp., then Discocyclina sp., Miscellanid and Lockhartia. The algae is present in one thin section which is 4% while the fragments of different fossils as a bioclasts constitutes upto 5-6% in this facie. Dolomite crystals are up to 8 percent in this facie. So, this facie is dolomitized limestone facie. Fracture porosity (4-5%) is present and shown best due to staining. The Figs 5.7 & 5.8 are showing the thin section photomicrographs of samples SK- (12, 13, 14) of SKMF-3.

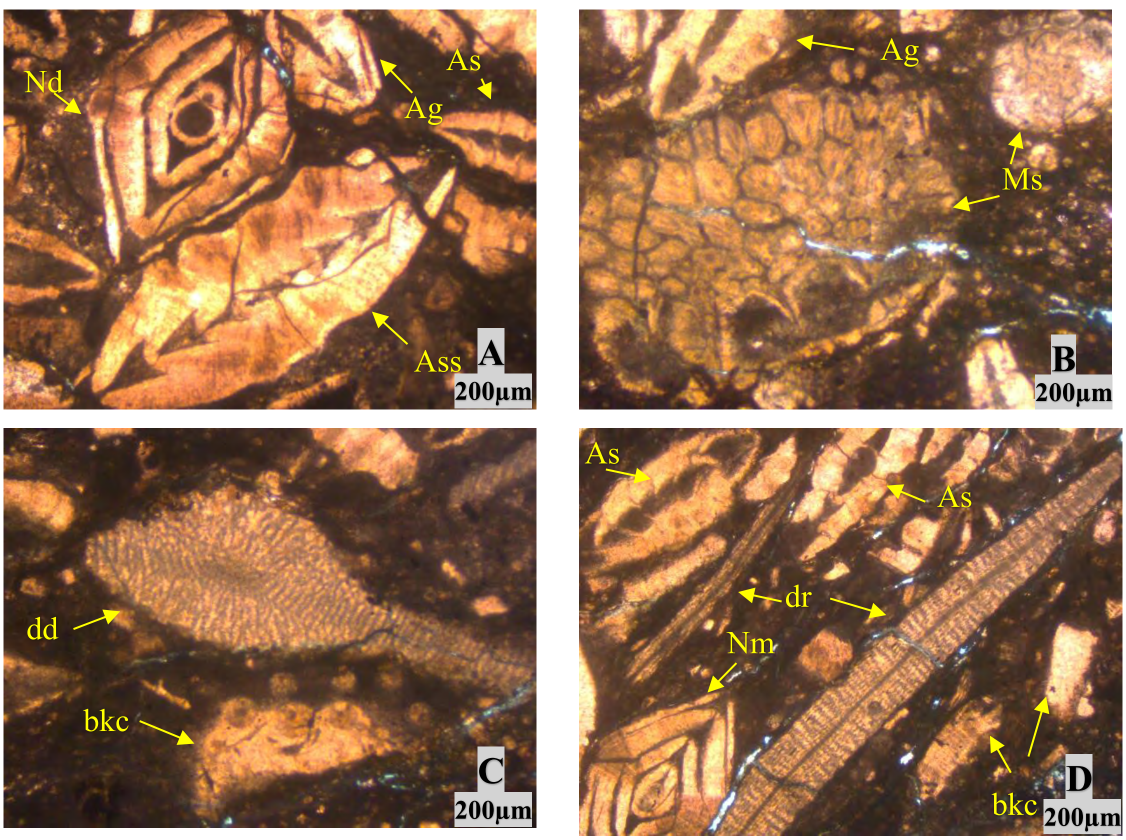


Figure 5.7 Assilina Nummulitic Packstone (SKMF-3): the skeletal allochems are dominated by Larger benthic foraminifera which include Nummulites djodkokartae (Nd in A) Nummulites Mamillatus (Nm in D), Assilina granulosa (Ag in A-B), Assilina subspinosa (Ass in A), Assilina sp. (As in A,D), Discocyclina Dispensa (dd in C), Discocyclina ranikontensis (dr in D), broken / altered bioclasts of different fossils (bkc in C-D). Photomicrographs are from samples (SK- 12, 13, 14)

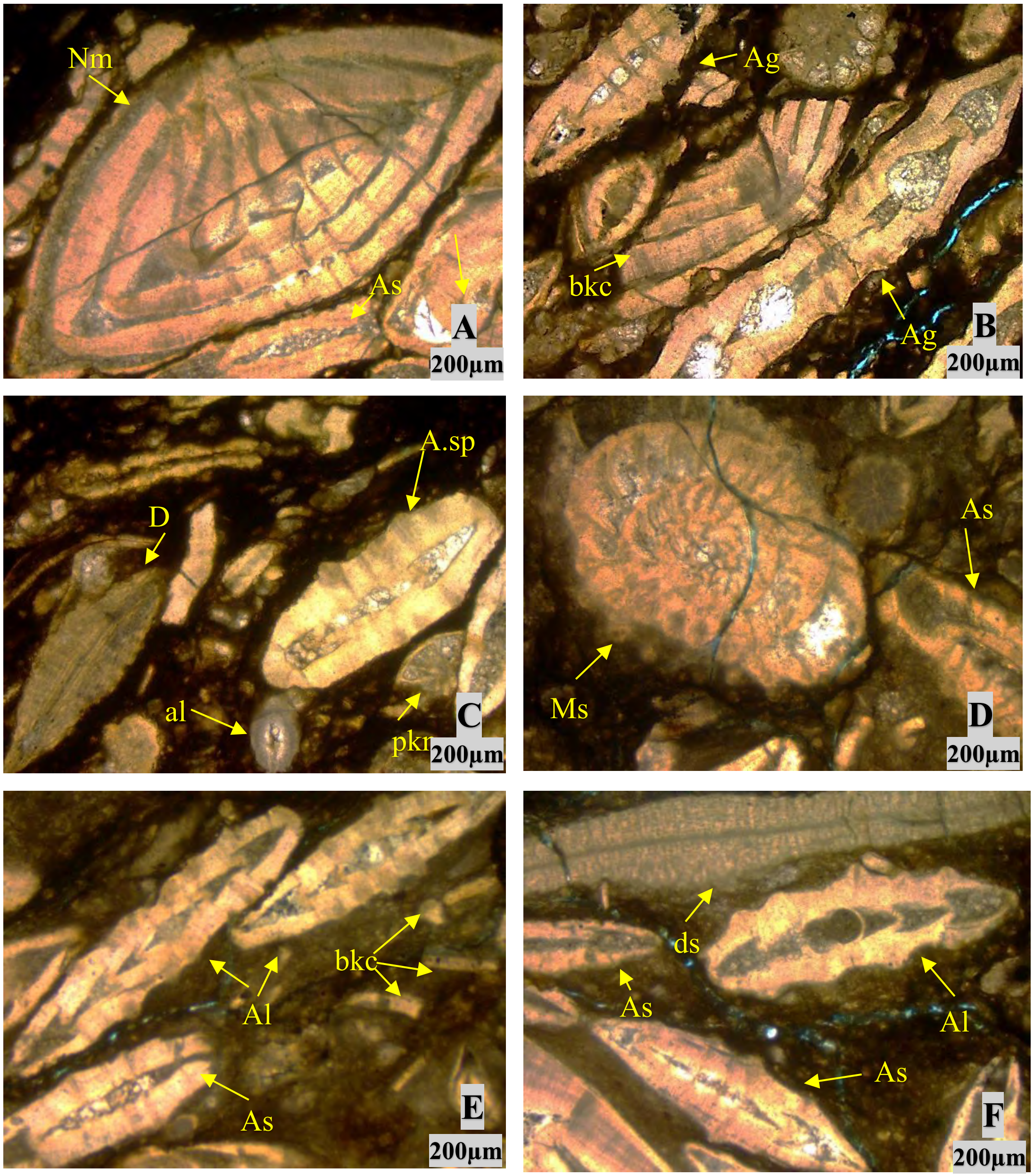


Figure 5.8 Assilina-Nummulitic Packstone (SKMF-3): the skeletal allochems in this facie are Nummulites Mamillatus (Nm in A), Assilina granulosa (ag in B), Assilina spinosa (A.sp in C), Assilina lamionsa (Al in E-F), Assilina sp. (A, D-F), Discocyclina sella (ds in F) algae (al in C), Broken / altered clasts of different fossils (bkc in B, C), Planktonic foraminifera altered (Pkn in C). Photomicrographs are from samples (SK- 12, 13, 14)

### 5.3.4 Planktonic Miscellania Wackestone-Packstone (SKMF-4)

This microfacie has also Wackestone to Packstone depositional texture. This microfacies is the representative of three thin sections. The main constituents of the facie are matrix and allochems which are 60% and 40% on average, respectively. Matrix contain dolomite rhombs upto 15%. In allochems, the main constituents are comprised of the bioclasts. The bioclasts are of different fossils (up to 10%) including planktonic foraminifera's, Mollusks and bivalves' shells. The planktonic foraminifers are also up to 10%. Miscellanid species are also present up to 10%, Gastropods are upto 4-5%. Lockhartia is showing good presence in one thin section upto 10%. The Nummulities, assilina, rotalia and algae are restricted to 2% each in this facie. The Fig 5.9 and 5.10 showing the thin sections photographs of samples SK- (10,17,18) of this microfacie.

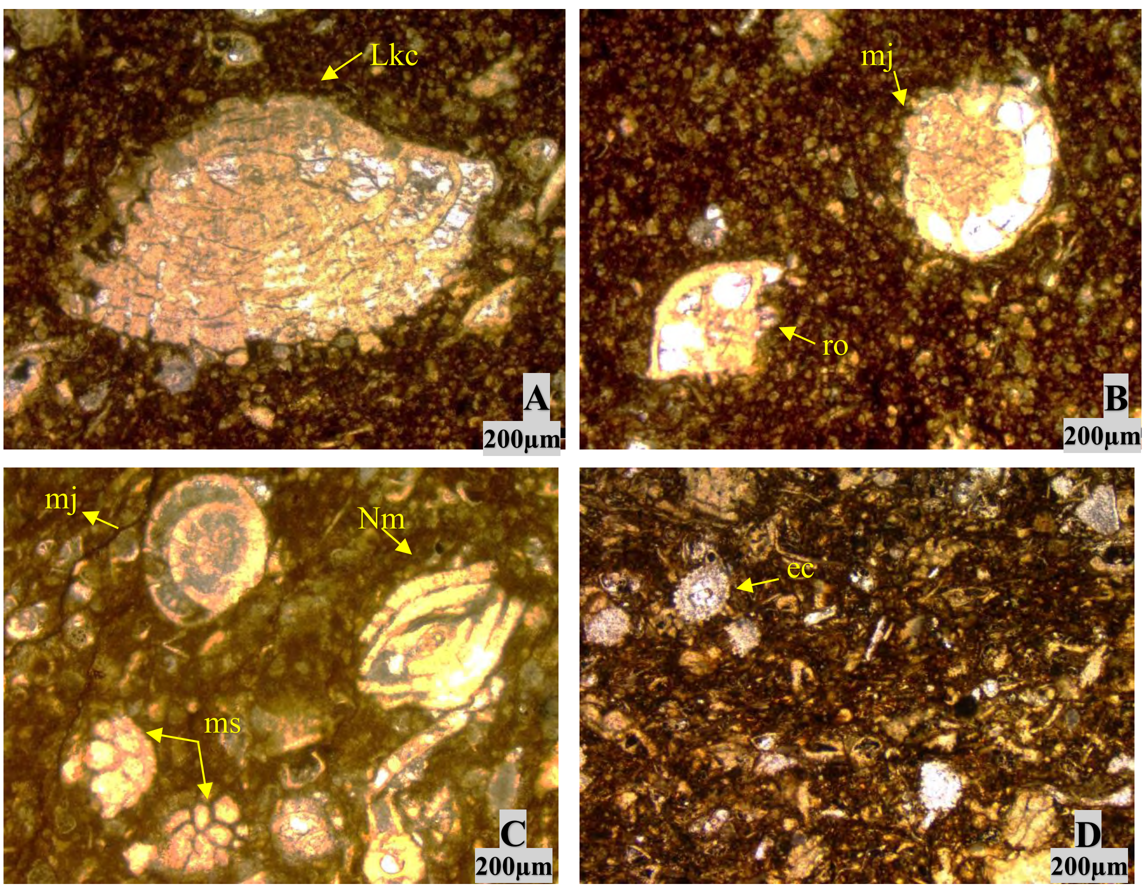


Figure 5.9 Planktonic Miscellania Wackestone–Packstone (SKMF-4): the main allochem constituents are Nummulites mammilatus (Nm in B) , Lockharita Conica (lkc in A), Miscellanea juliettae (mj in B-C), Miscellanea sp (ms in C), Rotalia (ro in B), Dolomite rhombs in A & B, Echinoderm (ec in D), Planktons smaller in A, C-D, Dolomite rhombs are in A&B). Photomicrographs are from samples (SK – 10,17,18)

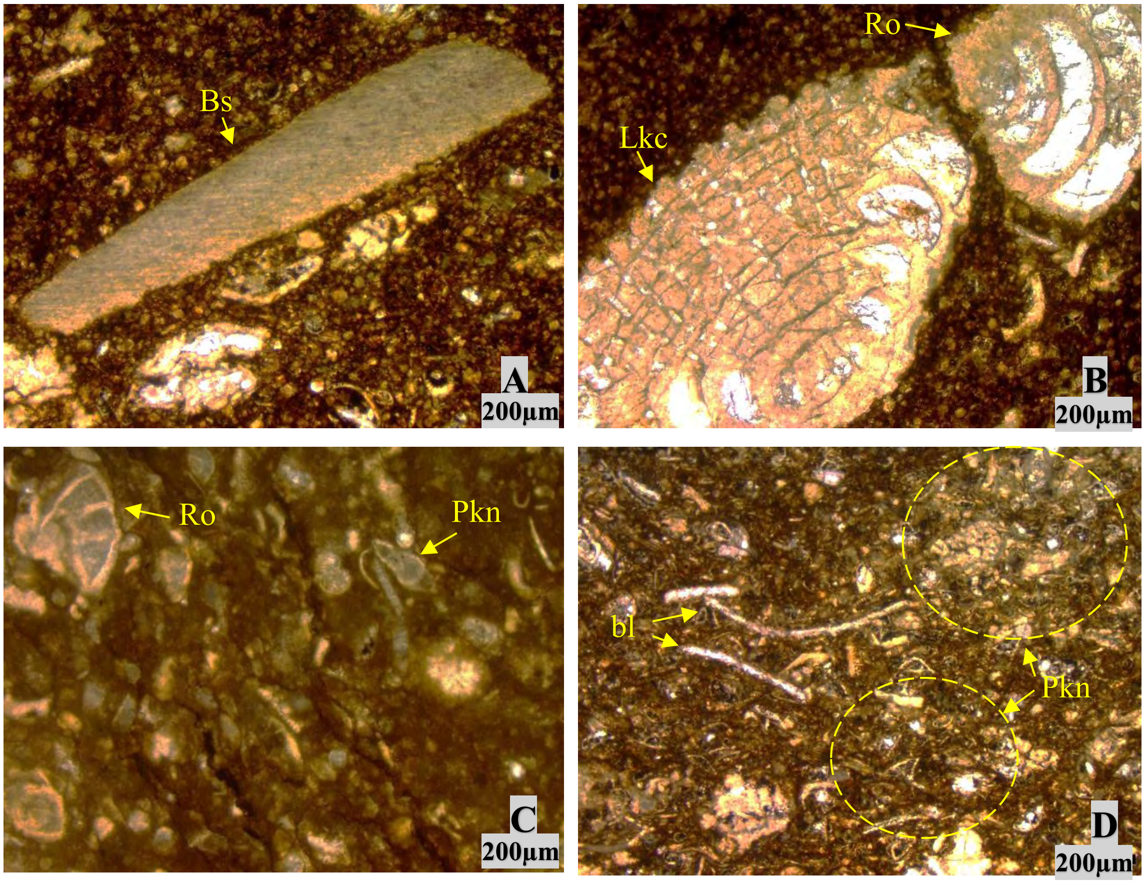


Figure 5.10 Planktonic Miscellania Wackestone–Packstone (SKMF-4) Lockhartia Conica (Lkc in B), Rotalia (Ro in B-C), Mollusks shell (Bs in B), Bioclasts (bl in D), Planktons smaller (Pkn in C-D, Dolomite Rhombs are in A&B. Photomicrographs are from samples (SK - 10,17,18)

### 5.3.5 Bioclastic Wackestone (SKMF-5)

The SKMF-5 microfacie has Wackestone depositional texture. One thin section is included in this micro facie. The main constituent's matrix and allochems are 55 and 45 % respectively. In allochems the main component is bioclastic fragments of different fossils benthic and planktonic foraminiferas (3%) along with some gastropod shells, bivalves and echinoderms, bio debris which are collectively up to 33%. Other main components are Nummulite, Assilina and planktons. Algae is upto 2%. The facie shows good diagenetic effects such as micritization and calcitation in fossils, organic material filled fractures, dolomitized and pyritized dissolution seam. The Fig 5.11 shows photograph of the thin section SK-23, of this facie.

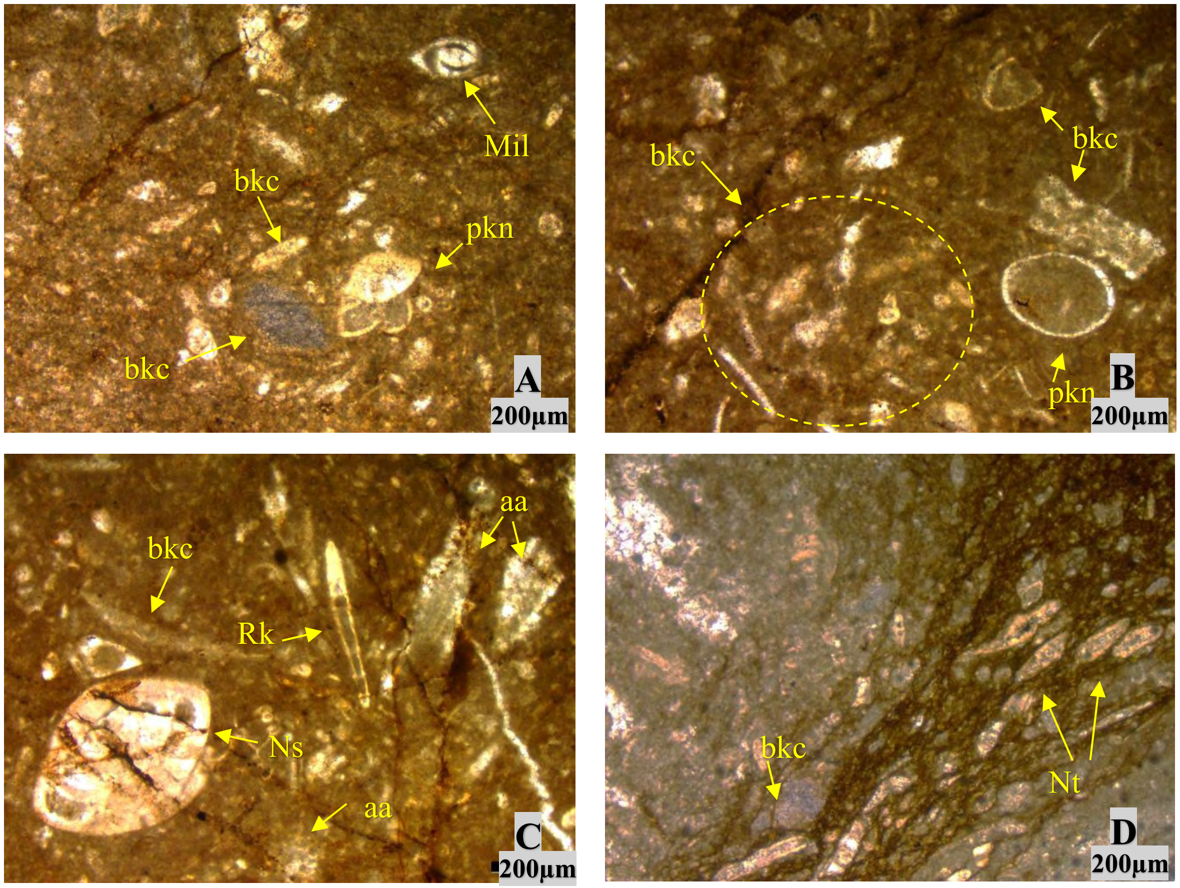


Figure 5.11 Bioclastic Wackestone (SKMF-5): the skeletal allochems of this facie contains Nummulites sp. (Ns in C) Nummulitidae sp. - Nummulites and Assilina (Nt in D), Algae (aa in C). Milliolids (Mil in A), Planktonic foraminifera (pkn in A-B), Ranikothalis sp. (Rk in C), Broken / altered bioclastic fragments (bkc in A-D). Photomicrographs are from sample SK-23.

### 5.3.6 Nummulitic–Lockhartia dolomitic Wackestone-Packstone (SKMF-6)

This microfacie has also Wackestone to Packstone depositional texture. The main constituents of the facie are matrix and allochems which are 60% and 40% respectively. Nummulitic species and lockhartia are dominating over other components with 15% and 10% of their weightage individually. Other allochems include Discocyclina sp., Assilina sp., Miscillanid sp., and planktons. The bioclastic debries are constituting by 2% in this facie. The dolomite rhombs are well preserved in this facie which are upto 40%. The Fig 5.12 showing the thin sections photographs of the microfacies of sample SK-22.

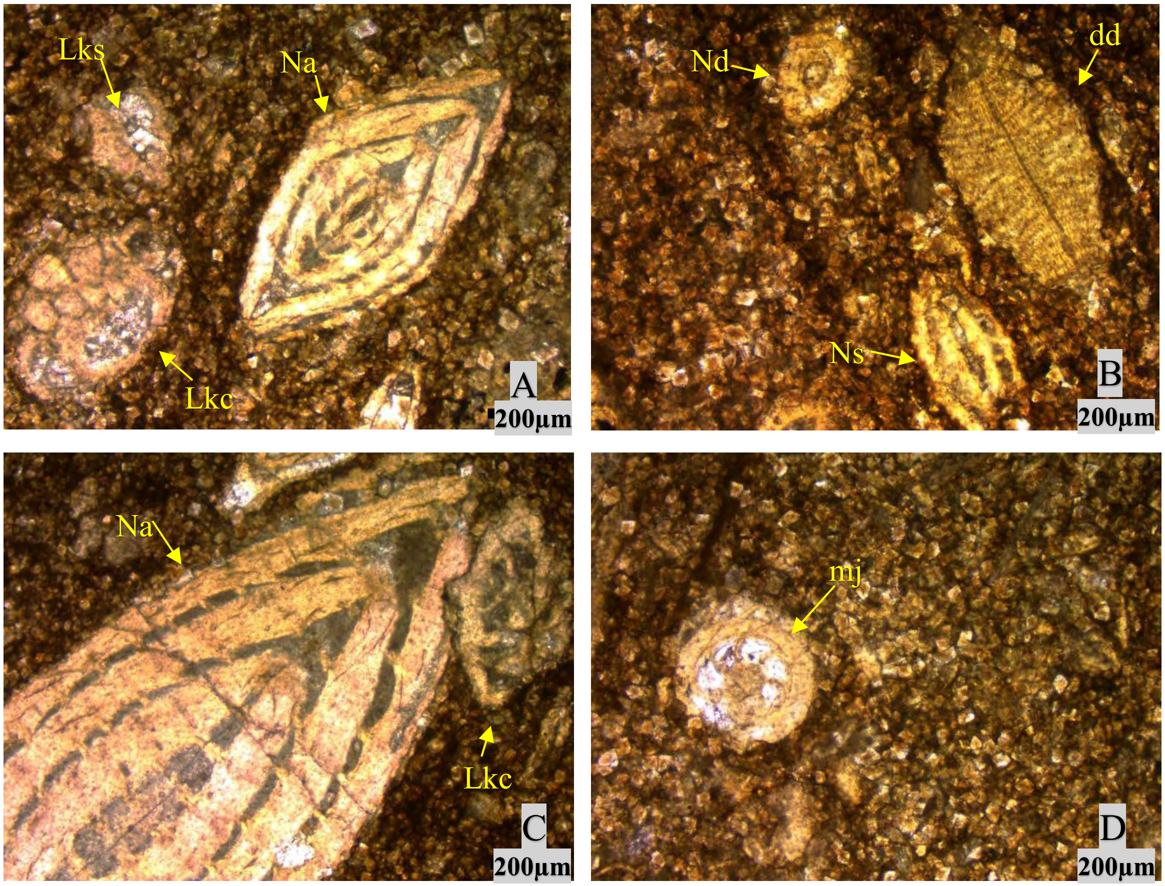


Figure 5.12 Nummulitic–Lockhartia dolomitic Wackestone-Packstone (SKMF-6): the skeletal allochems of this facie include Nummulites Atacicus (Na in A, C), Nummulites djodjokartae (Nd in B), Nummulites sp. (Ns in B), Lockhartia Coniditi (Lkc in A, C) Lockhartia sp. (Lks in A), Miscellanea juliettae - equatorial section (mj in D). Photomicrographs are from samples (SK – 22)

### 5.3.7 Ranikothalia-Assilina dolomitic Wackestone-Packstone (SKMF-7)

The sub microfacie is observed at the lower contact of the Sakesar Formation. It also has the Wackestone to Packstone depositional texture. The main constituents of this microfacie matrix and allochems are 55% and 45% respectively. The allochems are dominated by Ranitkothalia sp., and Assilina. Other allochems include Nummulites sp., Lockhartia sp., Gastropods and Planktons. The green algae is 2% while the bioclastic fragments are upto 8% in this microfacies. Dolomite crystals are upto 25% in this facie. Micritization and calcitation are also present. The Fig 5.13 showing the photographs of this facie.

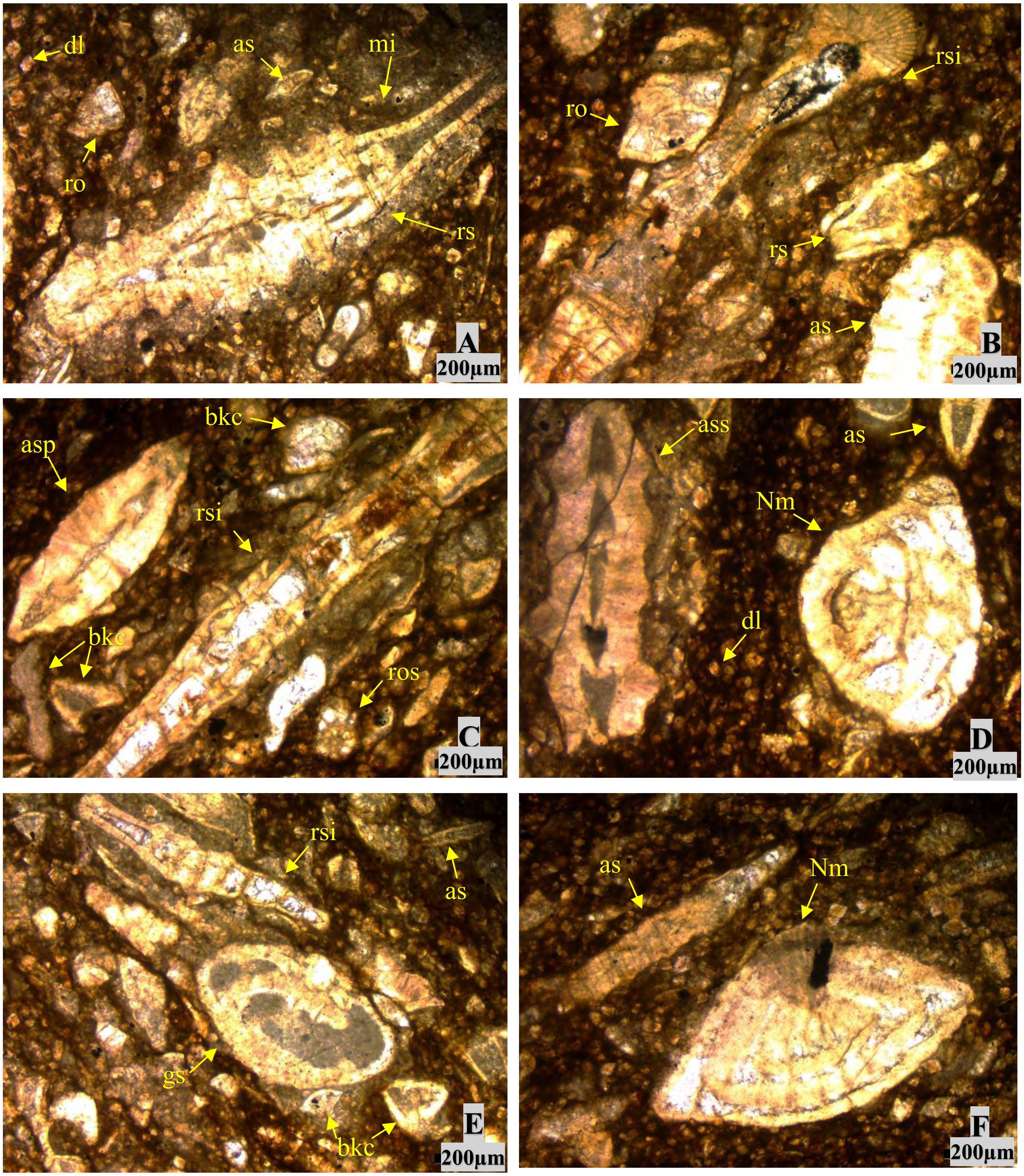


Figure 5.13 Ranikothalia–Assilina dolomitic Wackestone-Packstone (SKMF-7):The main skeletal components are : Ranikothalia sindensis (rsi in B,C & E), Ranikothalis sp. (rs in A-C), Assilina subspinosa (ass in D), Assilina spinosa (asp in C), Assilina sp. (as in A-B, D-F), Nummulites mamilatus (Oblique section, Nm in D and F), Broken / altered fragments (bkc in C, E), Gastropod (gs in E), Rotalia (ro in A & B), rotalia smaller sp. (ros in C), Dolomite rhombs are common present in every slide (dl in D), Micrite around foram (mi in A). Photomicrographs are from samples (SK-26)

# Chapter No. 6

# DIAGENETIC STUDIES

## 6.1 Introduction

Diagenesis refers to all type of changes either physical, chemical or biological govern in a rock just after deposition till the metamorphic starts. Carbonates are composed of calcite, dolomite and aragonite which are highly susceptible to diagenetic modification. In carbonates, diagenesis affects the composition and depositional texture of the rocks (Dawson & Carozzi, 1993). It is essential for understanding the history and evolution of rocks, and for predicting their behavior in different environments.

The prime diagenetic processes are compaction, cementation, micritization, neomorphism, dissolution and dolomitization. These diagenetic modifications take place in three environmental conditions, Marine, Meteoric and deep burial diagenetic settings (Tucker, 2009). In this chapter, all of the observed diagenetic changes are discussed and diagenetic conditions are proposed in Results and Discussion Chapter. The diagenetic features observed in Sakesar formation during petrography, are mentioned in table 6.1.

## 6.2 Diagenetic features:

### 6.2.1 Compaction

Compaction is the reduction in the volume of the rock mass owing to different sources. This reduction in the volume of the rock is either by Chemical or mechanical mechanism.

#### 6.2.1.1 Mechanical Compaction

Mechanical or Physical compaction is subjected by the continuous tectonic stresses or by the overburden pressure on the rock sediments, which ultimately affects (reduce) the physical parameters of the rocks such as thickness, porosity and permeability. Mechanical compaction finally yields compressed fabric of rock due to distortion and breakage of the grain particles (Flügel, 2010).

In the Sakesar Limestone the Mechanical compaction is results in the form of fractures and broken bioclasts of different species. The Fig. 6.1 show the representative pictures of mechanical compaction observed in thin sections.

### 6.2.1.2 Chemical Compaction

Chemical compaction is the result of pressure solution phenomena. It yields the grains dissolution at point of stress. In Sakesar formation, the observed features of chemical compaction are solution seams and stylolites (Fig. 6.1).

In Sakesar formation both chemical and mechanical compactions are well preserved and observed in both core studies and thin section petrography. These are present in almost every thin section.

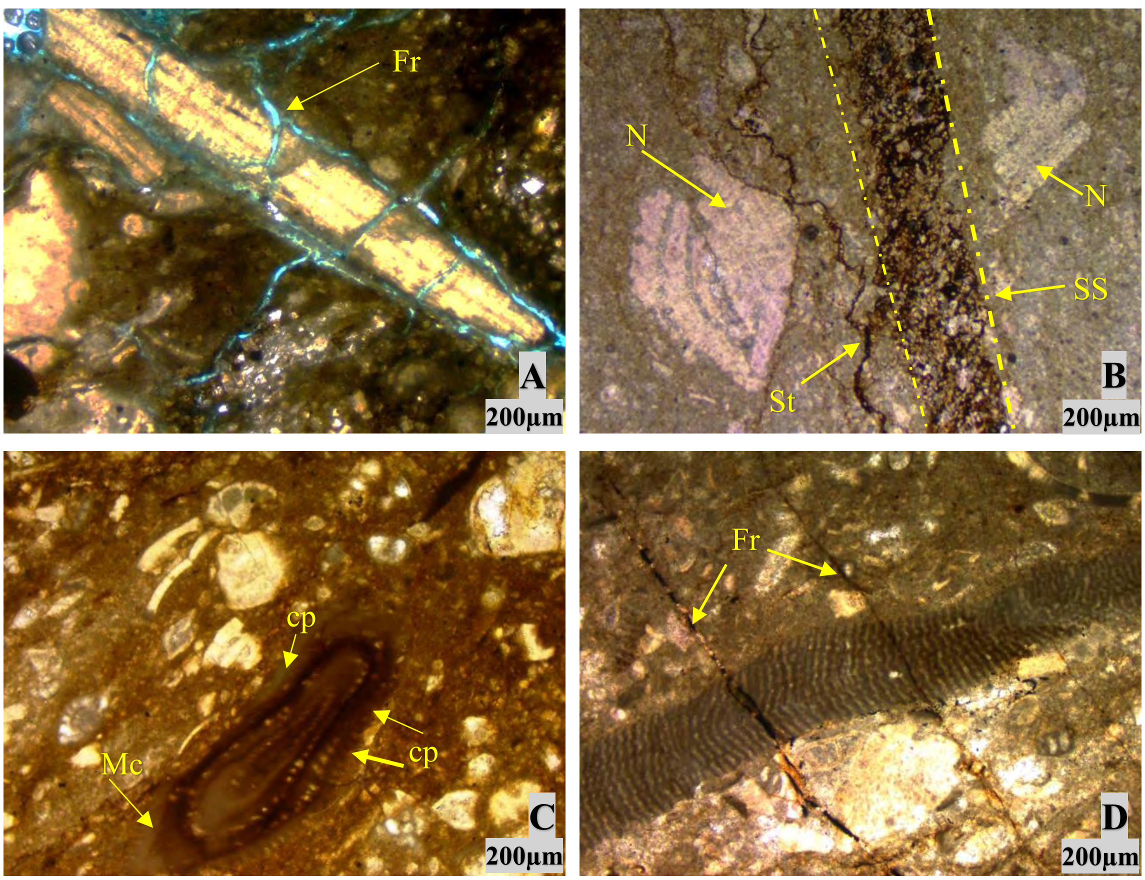


Figure 6.1 Thin section photomicrographs Showing Diagenetic changes: **Fr**- fracture in A around and within all component grains, in D fracture veins, **N** in B showing Neomorphism, **Cp** in C showing Compaction which squeezes the allochem, **Mc** - in C showing Micrite around the allochem, **SS** in B -pyritizied dolomite solution seam, **St** – Stylolite filled with blackish organic material. (Photomicrograph A is of SK-11, B & C is of SK-2, D is of SK-7)

### 6.2.2 Micritization

Micritization is the process of grains degradation of skeletal and non-skeletal constituents in to complete micritized grain or devoid of allochem structure (Khalifa 2005). It is an Eogenetic (early diagenesis) process, starts just after deposition of sediments (Adams and Mackenzie 1998). The organisms which results in this degradation are endolithic microbes such as fungi, bacteria and algae (Harris et al., 1979). Micritization process usually take place in low-energy conditions (Flügel, 2010).

In Sakesar formation, micritization is present in almost every thin section and observed in allo chem grains and around the skeletal grains. The Fig.6.2 shows the micritization of the Sakesar formation.

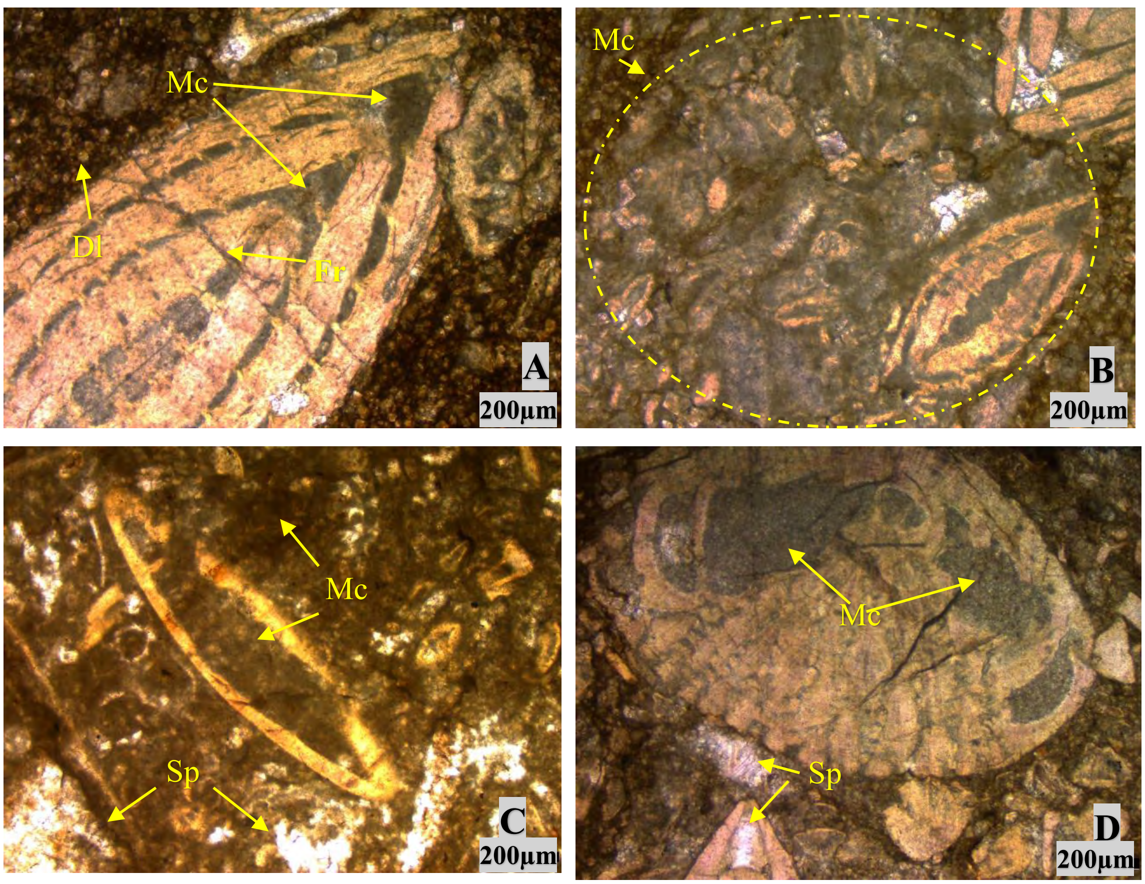


Figure 6.2 Thin section photomicrographs Showing Diagenetic changes: MC - Micrite in A-D, Micrite is developed in both with in clast and around the clast. Sp - Sparry calcite in C-D, Dl – Dolomite Rhombs in A, Fr – Fractured nummulite in A. (Photomicrograph A is of SK-22, B is of SK-7, C is of SK-25, D is of SK-4)

### 6.2.3 Cementation

Cementation is one of the principal diagenetic process of the carbonate rocks. Cementation is result of the precipitation. The cement type relies on the water chemistry and supply rate of carbonate. The source of $CaCo_3$ in marine realm is seawater, while in meteoric and burial conditions it is sediment dissolution (Tucker, 2009).

The identified type of cement in the current study is blocky calcite cement.

### Blocky Calcite

The blocky calcite cement observed, has no proper orientation. It shows its presence in intraskeletal pores of perforate foraminiferas, in the molds of early dissolved allochem grains and in the fracture fillings. This type of blocky calcite cement is formed during the meteoric-phreatic and burial environment and rarely in marine environment (Moore et al., 1981, Flügal 2010, Khalifa et al. 2005; Abu-El Ghar et al. 2015)

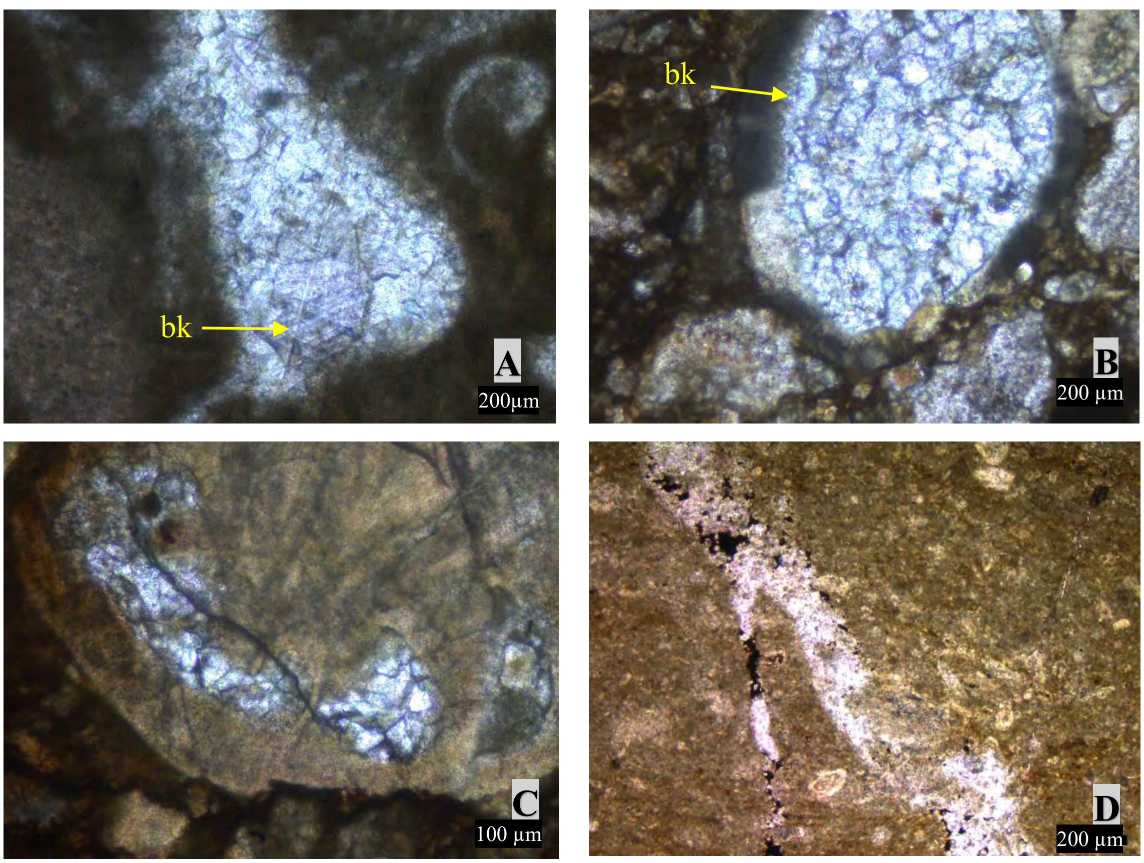


Figure 6.3 Photograph is showing blocky calcite cements observed during study. (A-B) shows blocky cement in pore space, C shows blocky cement in intraskeletal, D shows blocky calcite cement along fracture. (Photomicrograph A is of SK-3, B is of SK-4,C is of SK-19, D is of SK-2)

### 6.2.4 Neomorphism

Neomorphism includes the processes of replacement and recrystallization of mineral with or without change in mineralogy (Folk, 1959). The replacement is in-situ replacement (Calcitation), while the recrystallization involves the modification of carbonate minerals (Adams & Mackenzie 1998). In Sakesar formation the Neomorphism is also frequently observed diagenetic feature (Table 6.1) and Fig. 6.4 shows some features observed.

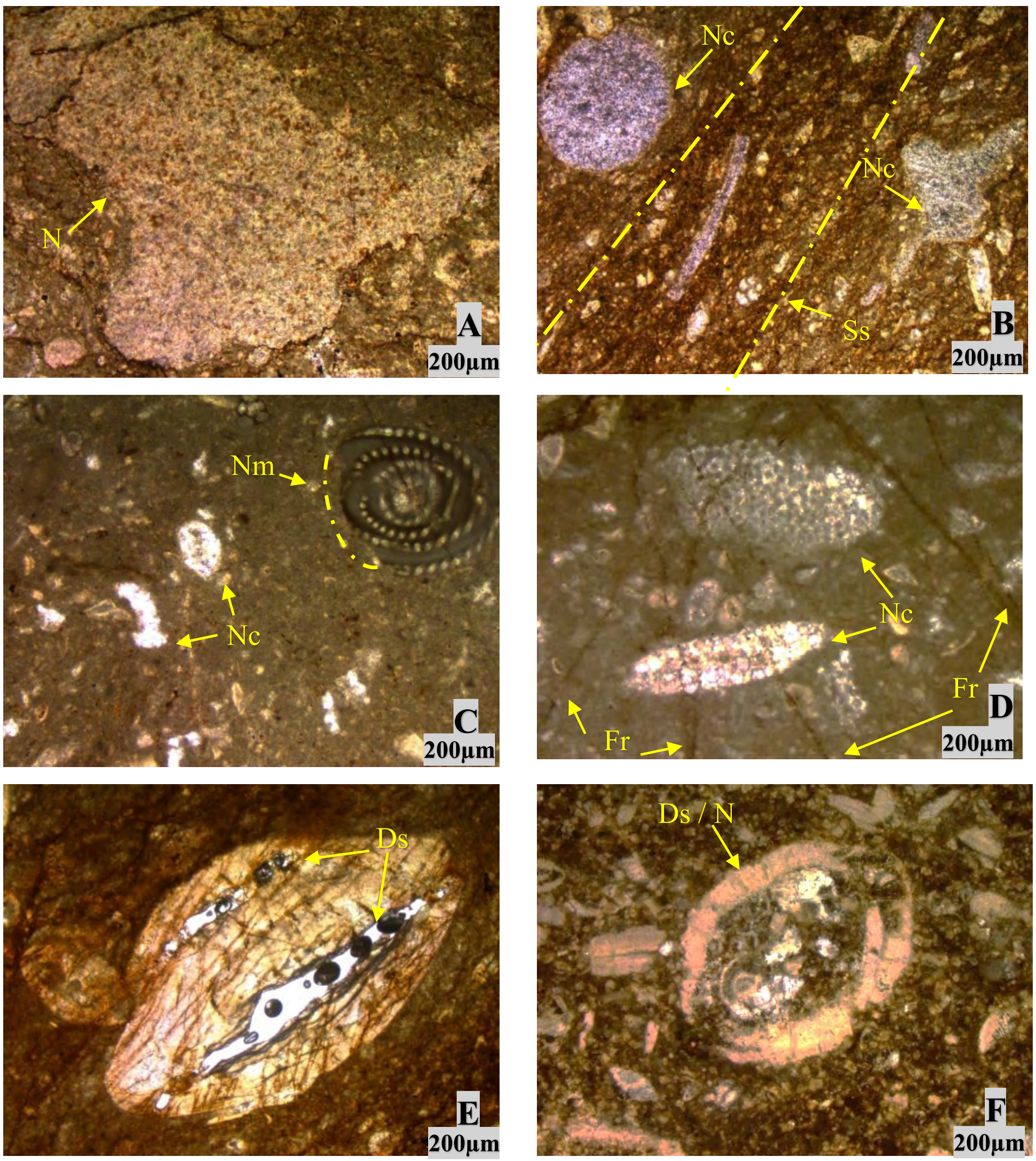


Figure 6.4 Thin section photomicrographs Showing Diagenesis: **N** - Neomorphism by micrspar in A, **Nc** – Neomorphism by Calcitization in B-D, **Nm** – Neomorphism of bioclast boundary by micrite, **Ss** partially pyritized dolomite Solution seam in B, **Fr** – Fracture two sets in D, **Ds** – Dissloution within bioclasts in E, **DS/N** – Dissolution first and then neomorphism of deposited constituents (A-SK.2, B,E,F-SK.24,C-SK7, D-SK.9)

### 6.2.5 Dissolution

Dissolution is the dissolving out process of the limestone constituents due to undersaturated fluids with respect to surrounding carbonate minerals. The minerals like aragonite which are less stable usually get completely dissolved out. In Sakesar formation Dissolution is observed at different levels and Fig 6.4 E-F, Showing the representative photomicrographs.

### 6.2.6 Dolomitization

Dolomitization is one of the most important diagenetic process of Carbonates, in which Calcite is get replaced by Magnesium due to Mg-rich precipitating fluids in undersaturated rocks. As the Mg ion is comparatively smaller then Ca, this volume reduction increased porosity in carbonates (Weyl, 1960). In Sakesar formation, dolomitization is frequently observed phenomena. The dolomite grains present's rhombs in the thin section slides, rhombs perfect geometry indicate their resistance to physical compaction during mesogenetic stage (Murray, 1960). Based on petrographic studies the dolomitization in Sakesar formation are categorized into three categories which are as follows:

#### 6.2.6.1 Dolomite-I (Matrix Supported)

The type-I dolomite exhibits texturally planar euhedral dolomite crystals. The crystals size of this type is between 17-92µm. This type is fabric and grain selective dolomitization. The skeletal allochems are also partially dolomitized. Fig 6.5 (A-C) shows the type-I dolomitization.

#### 6.2.6.2 Dolomite-II (Fine crystalline)

The type-III dolomite are comparatively fine crystalline as their crystal sizes range between 8-41µm. This type shows matrix supportive presence and along fractures. The crystals textures are an-hedral to sub-hedral in type-II. The Fig. 6.5 (D-F) shows the type-III dolomitization.

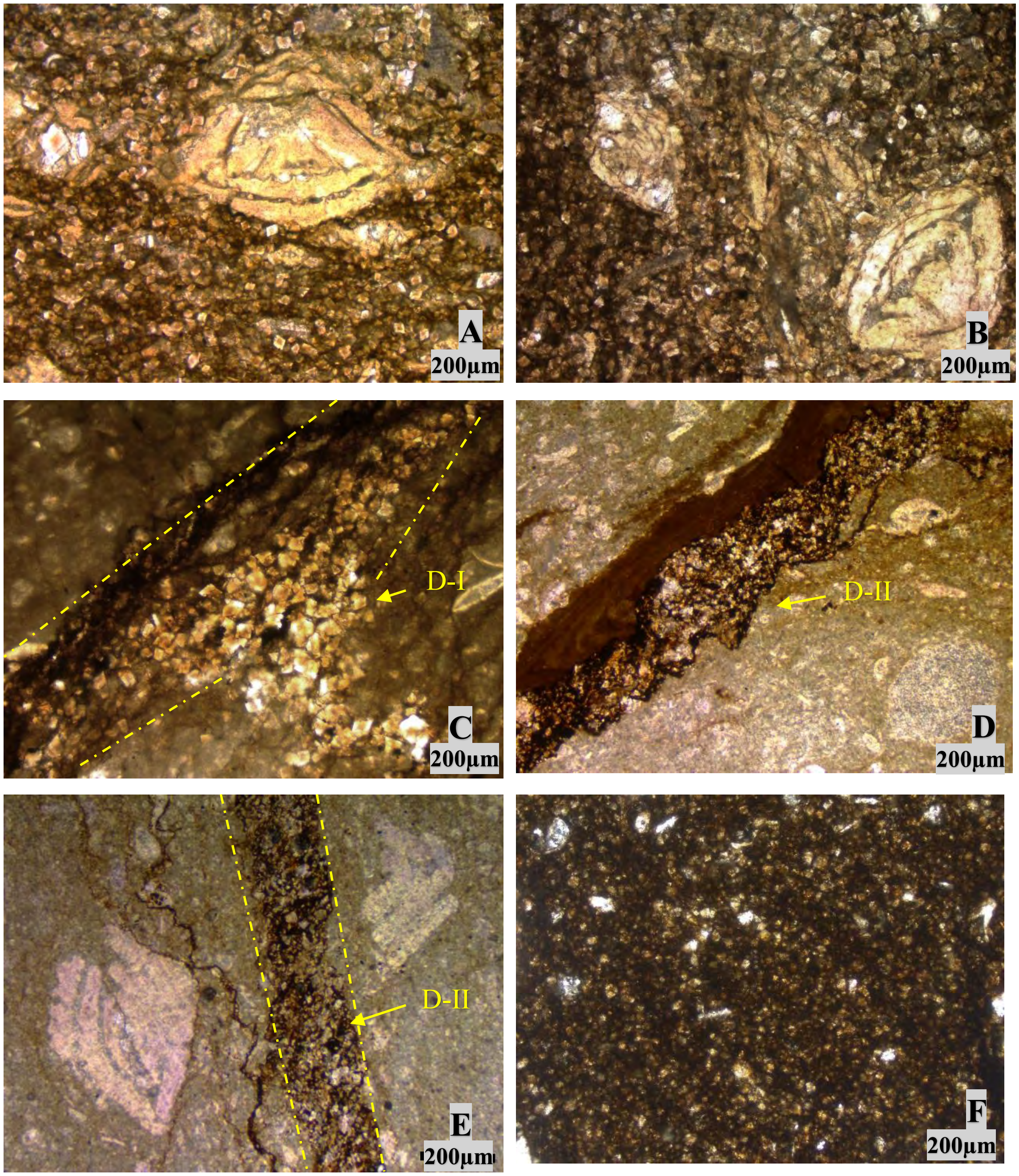


Figure 6.5 Photographs showing types of dolomitization on base of crystals shapes and sizes. Type-I in A-C, A-B shows partial replacive and grain selective dolomitization, C shows dolomite along fracture, Dolomite Type -II in D-F, D-E shows dolomite type-II in fracture filling, F shows fine matrix supportive dolomite. (A-SK.21, B-SK.22, C-SK.21, D&E-SK2, F-SK.10 )

## Calcite Phases

Following types of Calcite phases are observed during study of the Sakesar Formation.

C-I Calcite phase includes the calcitation in the pore fillings.

C-II Calcite phase formed after the initial fracture formation and cuts the initial fractures as shown in Fig 6.6 (A).

C-III Calcite phase post docs the Type-2 calcite vein as shown in Fig 6.6 (B).

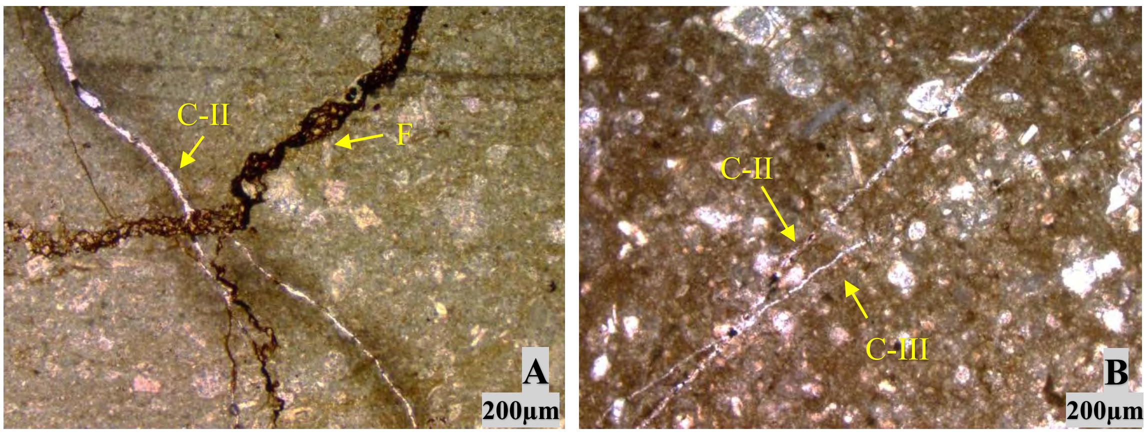


Figure 6.6 Photograph showing the calcite phases, C-II and C-III. (A-SK.2, B-SK8)

Table 6.1 Diagenetic features observed in Petrographic thin sections along with Microfacies of Sakesar Formation.

| Sample I. D | Microfacies Name | Diagenetic Features |
|---|---|---|
| SK(1, 4, 5, 6, 11, 19, 20, 21, 22, 26) | **(SKMF-1, SKMF-6 & SKMF-7)** | Dolomitization, Micritization, Compaction (Fractures & Stylolites), Cementation, Neomorphism |
| SK(2, 3, 7, 8, 9, 15, 16, 24, 25) | **(SKMF-2)** | Fracturing, Stylolites, Neomorphism, Micritization, Dolomitization |
| SK(12, 13, 14) | **(SKMF-3)** | Dolomitization, Fracturing |
| SK(10, 17, 18) | **(SKMF-4)** | Stylolites, Micritization, Neomorphism, |
| SK-23 | **(SKMF-5)** | Mechanical Compaction, cementation |

# Chapter No. 7

# ELECTRO FACIES

## 7.1 Introduction

Facies are the certain characteristics of the rock that reflects its forming conditions along with distinguishing it from its surrounding rocks (Reading, H.G. 1996). Lithological characterization of a rock accounts as lithofacies analysis. The term "Electrofacies" was firstly introduced by Serra and Abbot (1982) placing it as as alternative for lithofacies. Electrofacies are Unique set of petrophysical log responses that reflect the specific compositional and physical properties of the rock by Log suit (Euzen and Power, 2012). Petrophysical analysis is one of the important parameters to know physical properties of the subsurface geology. Petrophysicist's using numerical models evaluate reservoirs based on their knowledge and experience (Ali and Sheng-Chang, 2020).

In this research work, electrofacies analysis is performed by using K-mean clustering technique. Cluster analysis is a multivariate machine learning technique which classify the large data sets based on some specific characteristics into groups and sub groups (Cornish, 2007). The data points in a cluster are identical with one another as compared to the points of other cluster groups. Facies classification of carbonates is a challenging task for the explorationists dealing with the carbonate reservoir rock. Machine learning provides the tool for carbonate facies analysis on the basis of log data. In this research work the K mean Clustering technique of machine learning is utilized for the carbonate facies classification of the Sakesar Limestone encountered in Balkasar oilfield.

## 7.2 Clustering techniques

There are different techniques to classify the data points in to groups, listed as follows (Estivill-Castro,2002).

### 7.2.1 Hierarchical Clustering

It is a type of unsupervised machine learning that generates a hierarchy of clusters. The technique of this model is based on connectivity. The distances between the data points of the data sets classify them in to different groups (Kattan et al., 2018).

### 7.2.2 K mean Clustering

K mean clustering is well known unsupervised machine learning technique. K mean clustering is preferred for this research work because it interprets the data on the basis of classification of data according to mean values. The log data consists of measurements of geophysical properties at particular depth. The values of geophysical properties give the information about the rock facies present at that depth. The group of data represents the specific facie which can be interpreted using geological knowledge of the area.

### 7.2.3 Biclustering

Biclustering technique is also known as two-mode clustering or co-clustering. It separates the No. of observations in to the sub categories based on some identical observations. This technique fit for the text data and image data.

## 7.3 Workflow

K means clustering segregates $n$ number of numerical data / observations in to $K$ number of cluster groups. K mean clustering classifies the data into groups around the central point representing the mean of group (Wang et al., 2012).

This technique starts with the random selection of the No. of clusters from the available data set. Based on these assigned number of clusters, the subsets of data points are formed. Then all data points of the same cluster are assigned by mean value of their centroid. These steps are repeated until the mean values assigned to centroid get similar values upon iteration (Ali and Sheng-Chang, 2020).

The Workflow scheme adopter for K mean Clustering is shown in Fig 7.1.

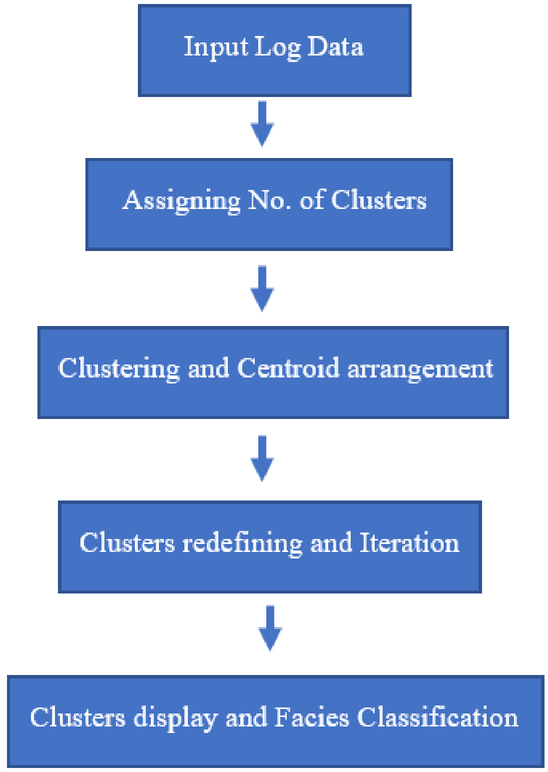


Figure 7.1 Photograph showing Workflow steps of K mean clustering for Electrofacies characterization of Sakesar formation

## 7.4 Cluster Analysis of the Sakesar Limestone

The Sakesar Limestone is one of the major proven reservoir for hydrocarbon exploration in Potwar sub-basin (Aamir and Siddiqui, 2006). The Sakesar Limestone is mainly consists of the limestone with marl and dolomite at some localities (Fatmi, 1973). The identification of different intervals in a rock unit is very important task and petrophysical logs are very useful to resolve this issue. Electrofacies are placed as alternative for lithofacies (Serra and Abbot, 1980).

The log data of Balkasar Oxy-1 well is used to perform K means cluster analysis for the carbonate facies classification of the Sakesar Limestone encountered in the wellbore. The log curves utilized for performing the K mean Cluster analysis included the GR, RHOB, NPHI and DT.

### 7.4.1 Selection of cluster numbers

Three numbers of clusters were selected for performing the cluster analysis on the basis of variation among the data. The selection of number of clusters is entirely based on the variation present in the log data. In this research work limited variation is present within the log data so, three number of clusters are considered as optimum for performing the K means cluster analysis. Fig 7.2 is showing the data points in form of crossplots. These crossplots are illustrating the relationship between different curves as well as frequency of datapoints. The colored points in crossplots representing the clusters points over the total data points.

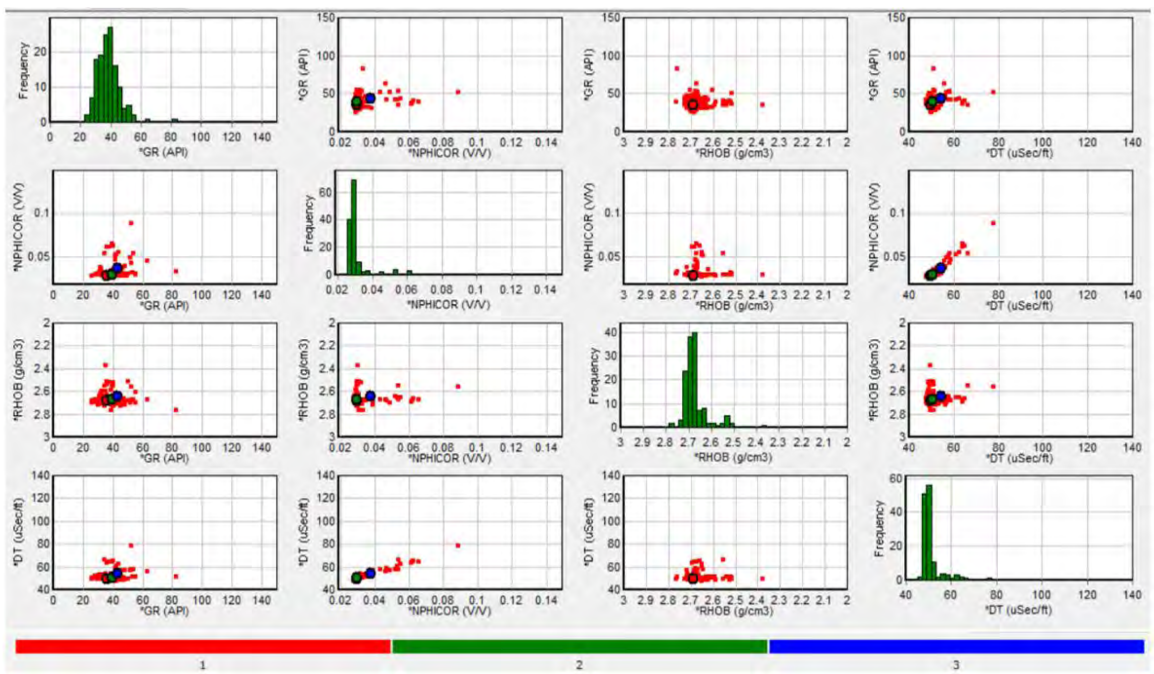


Figure 7.2 Photograph showing the cross plots of the combination of log curves and frequency diagonally. The red points are the data points while the colored points are the centroid of the clusters group.

### 7.4.2 Classification of data

The classification of data is performed on the basis of initially identified clusters. The data points are assigned to clusters on the nearest cluster. Each cluster of data points is indicated with a specific color. Mean of the cluster is indicated by the bold point of same color. The mean value or center point initial mean of each initial cluster is shown in Table 7.1.

Table 7.1 Showing the values of log curves based on their cluster group.

| Cluster | # | Cluster | *GR | | *NPHICOR | | *RHOB | | *DT | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | Points | Spread | Mean | Std Dev. | Mean | Std Dev. | Mean | Std Dev. | Mean | Std Dev. |
| 1 | 0 | | 35.729 | | 0.02907 | | 2.6867 | | 49.434 | |
| 2 | 0 | | 39.415 | | 0.02958 | | 2.671 | | 50.331 | |
| 3 | 0 | | 42.786 | | 0.03753 | | 2.648 | | 54.231 | |

Once, the data points are assigned to their relevant clusters. The clustering technique iterate the steps of mean value collection until it gets same. This mean value of the data sets named this technique as K means clustering. After iteration, the finalized mean values of the data set with their representative cluster group are shown in Table 7.2.

Table 7.2 Showing the statistical details of every cluster, their total encompassing data points, spread, Computer mean value after iteration and their standard deviation

| Cluster | # | Cluster | *GR | | *NPHICOR | | *RHOB | | *DT | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | Points | Spread | Mean | Std Dev. | Mean | Std Dev. | Mean | Std Dev. | Mean | Std Dev. |
| 1 | 110 | 0.9564 | 38.657 | 7.287 | 0.03003 | 0.00202 | 2.6847 | 0.02596 | 50.457 | 1.548 |
| 2 | 13 | 1.049 | 39.684 | 6.258 | 0.02988 | 0.00081 | 2.5384 | 0.05872 | 50.157 | 0.9038 |
| 3 | 14 | 1.843 | 45.045 | 8.316 | 0.05645 | 0.01141 | 2.6553 | 0.04337 | 62.115 | 5.686 |

The results show the details of each cluster such as number of points in a single cluster, the spread of cluster, finalized allocated mean value and standard deviation of each input data set. The mean value is the arithmetic mean of the specified data set of the cluster group. The spread of the data is indicator of tightness of cluster. The lesser the spread values of a cluster show the data points are nearer along their mean value. The standard deviation shows deviation of selected data points from the mean value of their cluster.

The finalized K mean clustering results based on above data is shown in Fig 7.3. The data points are now classified under three clusters representing their own color code. The colored central points in the cross plots shows the mean value of their cluster set. The data set is now categorized under three cluster represented by different allotted color.

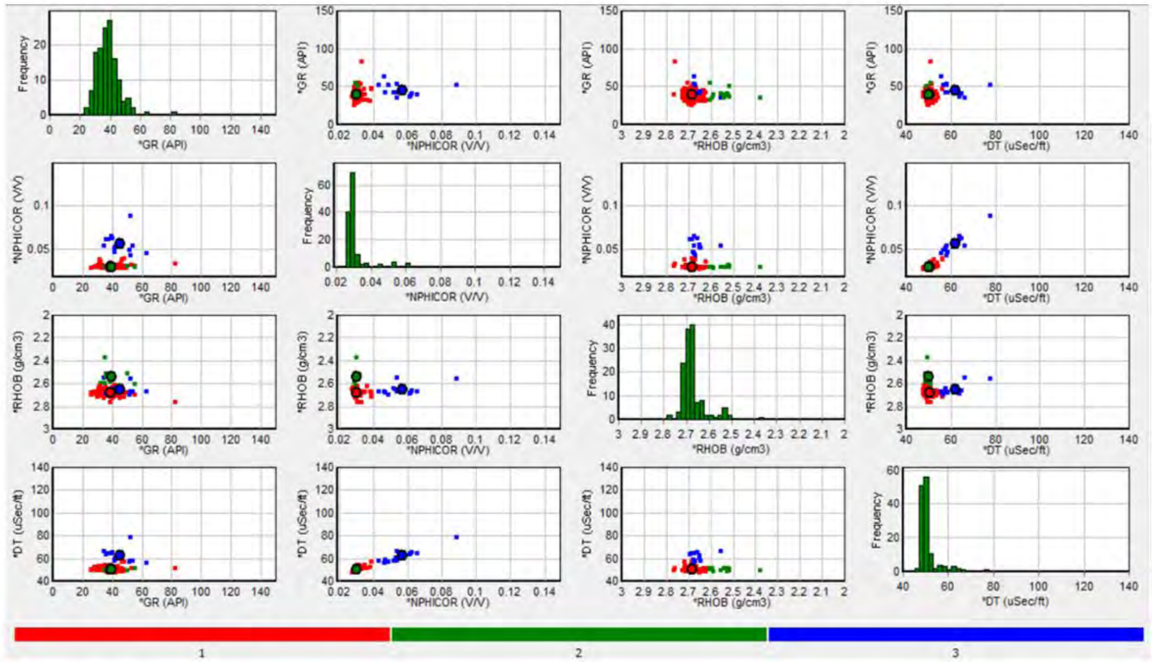


Figure 7.3 Photograph of crossplots representing clusters datasets. The input data (Log Curves) are plotted in crossplots. The Colored points in the plots are the cluster of the log data. The bold points are centroid (mean) of each cluster.

### 7.4.3 Consolidation of Clusters

The consolidation is the merging process of identical clusters in to groups, and the hierarchical method of cluster grouping is used for consolidation. Cluster consolidation is performed on the basis of randomness present within the clusters. The cluster consolidation can be best visualized by the dendogram, which is the tree diagram based on the closeness relationship among the clusters (Doveton, 1994). The dendogram showing the cluster consolidation of the Eocene Sakesar formation using K mean clustering technique is shown in Fig. 3 illustrating the relationship among clusters on the basis of nearness. In this research work the linear relationship is observed among clusters due to smaller number of clusters so, the number of clusters before and after consolidation is same.

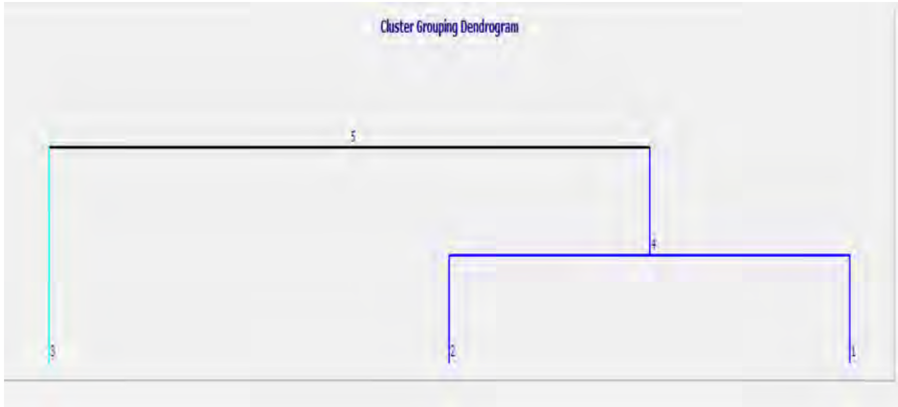


Figure 7.4 Photograph showing Dendogram based on consolidtaion of the cluster groups. Final groups are same due to smaller number of clusters and data.

The randomness of clusters data to total number of clusters are visualized by randomness plot. The number of clusters in groups are plotted in x-axis while y-axis shows the randomness of the data in clusters. The randomness plot is shown in Fig 7.5. Randomness Index is calculated by Devton, 1994. Randomness index Eq.7.3. is based on the average thickness 7.1. and random thickness Eq. 7.2.

$$Average\ Thickness = \frac{Number\ of\ depth}{Number\ of\ cluster\ layer} \qquad (7.1)$$

$$Random\ Thickness = \sum Pi\ /(1 - Pi) \qquad (7.2)$$

Pi is the depth level proportion given to $i^{th}$ cluster.

$$Randomness\ index = \frac{Average\ Thickness}{Random\ Thickness} \qquad (7.3)$$

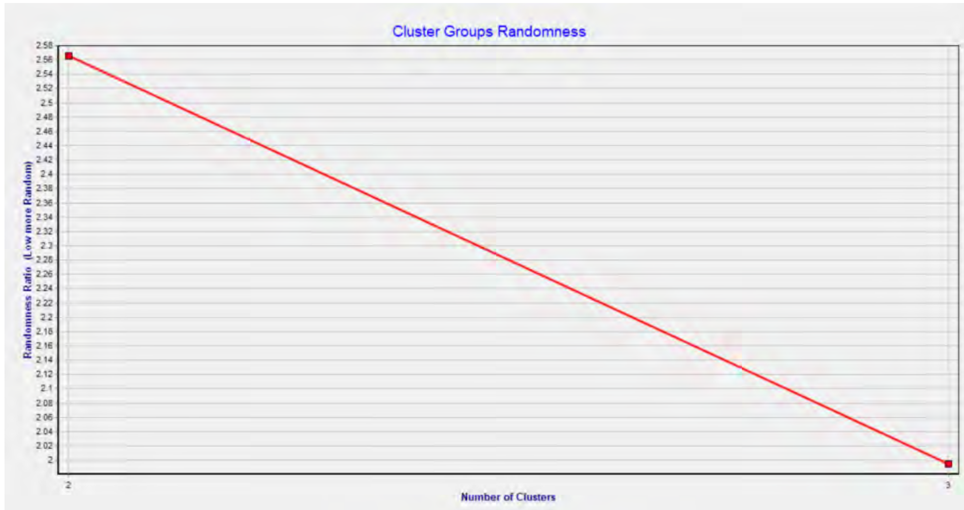


Figure 7.5 Photograph showing the Randomness Plot based of cluster groups. The randomness plot shows the relationship between the randomness of data in clusters and number of clusters.

## 7.5 Classification of Facies

The final step of K mean clustering is to give the geological explanation of the consolidated clusters. Three facies are identified in the Sakesar Formation encountered in Balkasar Oxy-1 well as a result of k means cluster analysis of well log data. The facies identified are plotted against the raw log curves in the Fig 7.6. The details of identified facies are as follows.

### 7.5.1 Limestone

It is the major facie constituting most of the Sakesar Limestone interval in Balkasar Oxy-1 well. It is shown in blue color Fig 7.6. it is marked by low GR values and relatively low DT values.

### 7.5.2 Shaly Limestone

Thin beds of shaly limestone are present within the lower intervals of the Sakesar Limestone interval in Balkasar Oxy-1 well. It is shown in brown color in Fig. 7.6. It is marked by slightly high GR values and relatively high DT values. The variation in log curves indicate the increase in shale content within the limestone.

### 7.5.3 Calcareous shale

Lower contact of the Sakesar Limestone is with Patala Formation which is mainly composed of shale. The bottom interval of Sakesar Formation in Balkasar Oxy-1 well is marked with calcareous shale. It is indicated with green color Fig. 7.6. This facie is marked by slightly high GR values and relatively increased DT values.

| Numeric | Text | Shading |
|---|---|---|
| 1 | Limestone | |
| 2 | Shaly Limestone | |
| 3 | Calcareous Shale | |

Figure 7.6 Color code of Electrofacies formed by cluster consolidation step of K mean clustering

## 7.6 Facies Classification of the Sakesar Limestone

Facies of the Eocene Sakesar Limestone in Balkasar Oxy-1 in response of the log curves are plotted in Fig 7.7. The limestone is the most dominant lithology of the Sakesar Limestone. The other two lithologies marked are shaly limestone and calcareous shale.


Figure 7.7 Electrofacies of the Eocene Sakesar Limestone in Balkasar Oxy-1. The blue color is representative of the limestone, the most dominant lithology of the formation in the well.

# Chapter No. 8

# RESULTS AND DISCUSSION

## 8.1 Introduction

This chapter finally discusses about the results and outcomes of the current research work. The Sakesar Limestone of Eocene age using core analogue is studied. The study focuses on microfacies analysis and diagenesis of the Sakesar Limestone which ultimately suggest the depositional and diagenetic settings of the Sakesar Limestone.

## 8.2 Depositional Settings

The microfacies formed by the petrographic studies of thin sections are the representative of the certain depositional condition, which are interpreted on the basis of their faunal association and sedimentological characteristics. The suggested depositional settings of the Studied microfacies of the Sakesar Limestone based on current study are shown in Fig. 8.1. The Depositional environment interpretation of microfacies are as follows:

The SKMF-1, SKMF-6 and SKMF-7 facies in major proportion, consists of Larger benthic foraminifera's Nummulities, Assilina, Lockhartia, Miscellanid and Ranikothalia. The larger benthic foraminiferas are the main constituents in the time of Later Pleocene to Early Eocene carbonates (Hottinger, 1997). The SKMF-1A and SKMF-1B are Nummulites and Assilina rich, over Lockhartia, clasts of forams and algae. One thin section SKMF-1C is Ranikothalia dominant followed by Assilina. The Nummulites sp. along with Assilina sp. indicate the deep inner to middle ramp settings of depositional environment settings (Racey 2001; Beavington-Penny and Racey 2004). The Lockhartia sp. with algae is the indicator of the ramp's inner settings (Racey 1994; Beavington-Penny et al. 2006). The Miscellanid represent shallow warm water depositional conditions (Levin, 1957). Ranikothalia with the association of the Assilina is the indicator of the deeper setting on carbonate platform (Hottinger, 2014). The micrite rich matrix along with the above mentioned larger benthic foraminiferas's suggest that this facie is deposited in inner ramp to middle ramp settings (Table 8.1).

The SKMF-2 facie allochems are enriched with bioclasts of larger benthic foraminifera's usually Nummulitdae's clasts, few planktonic forams, gastropod shells, over whole fossils of Nummulites and Assilina's. The Nummulites represent the mid ramp environment settings and with association of Assilina sp. indicates the comparatively deeper settings (Racey 1994; Anketell and Mriheel 2000; Racey 2001; Ishaq et al. 2018). The few Alveolina's and Miliolid's are present in some thin sections. The Alveolina sp. are the representative of the Warm water depositional conditions (Hohenegger et al. 1999). While the Miliolids present in low turbulence waters (Geel 2000; Brandano et al. 2009). So, the abundance of the bioclastic of larger benthic forams and planktons with whole clasts of Assilina, Nummulites and Miliolids indicate that SKMF-2 is deposited in Inner ramp to distal Middle ramp settings (8.1).

The SKMF-3 shows the abundance of the Assilina and Nummulites along with presence of Discocyclina sp. and Miscellanid (Upto 5%). The Assilina with association of Nummulites shows relatively the deeper setting of the middle ramp environment (Racey 1994; Anketell and Mriheel 2000; Racey 2001; Adabi et al. 2008; Ishaq et al. 2018). The Discocyclina is reported from the outer ramp settings (Racey, 1994). The Miscellanid represent shallow warm water depositional conditions (Levin, 1957). The higher percentage of the Assilina and Nummulites with micrite suggest that this facie SKMF-3 is deposited in middle ramps with low energy conditions (8.1).

The SKMF-4 has the abundance of bioclasts of different fossils majorly Planktonic fossils, shells of bivalves, gastropods, and mollusks along with few calcishperes. The completely preserved species of Lockhartia, Planktons and Miscellanid are up to 10% each. The calcishperes are the indicators of the low energy depositional settings (Frank, 2010). The presence of planktonic foraminifera's with calcishpere's represents comparatively deeper marine conditions (Bertle & Suttner, 2005). Miscellanea species suggest the warm shallow water settings (Levin, 1957), while Lockhartia presence in one thin section represents inner to Middle Ramp settings (Racey, 1994). The Nummulites and assilina associations shows the deep inner to middle ramps settings (Racey 2001; Beavington-Penny and Racey 2004). The existence of these skeletal allochems and their bioclasts suggest the deep inner Ramp to Outer Ramp settings of deposition by this microfacie.

The SKMF-5 has the abundance of bioclasts of larger benthic foraminiferas and planktonic forminifers along with shells of gastropods, bivalves and biodebris. The other main constituents are Nummulities and Assilina. The Nummulites sp. with association of Assilina sp. indicate the deep inner to middle ramp settings of depositional environment (Racey 2001; Beavington-Penny and Racey 2004). These allochems with micritic fabric and other constituents such as planktons, bivalves and gastropods suggest the depositional settings are majorly proximal to distal middle ramp settings (8.1).

Table 8.1 Table showing the Microfacies, their encompassing thin section slides and proposed depositional settings

| Sample I. D | Microfacies Name | Depositional Settings |
|---|---|---|
| SK (1, 4, 5, 6, 11, 19, 20, 21) | Larger Foraminiferal Wack-Packstone **(SKMF-1)** | Inner Ramp to Proximal Middle Ramp |
| SK (2, 3, 7, 8, 9, 15, 16, 24, 25) | Bioclastic - Nummulitidae Wackestone **(SKMF-2)** | Inner Ramp to Distal Middle Ramp |
| SK (12, 13, 14) | Assilina - Nummulitic Packstone **(SKMF-3)** | Middle Ramp |
| SK (10, 17, 18) | Planktonic Miscellania Wackstone-Packstone **(SKMF-4)** | Proximal Inner Ramp to outer Ramp |
| SK-23 | Bioclastic Wackestone **(SKMF-5)** | Distal Middle Ramp |
| SK-22 | Nummulitic-Lockhartia dolomitic Wackestone-Packstone **(SKMF-6)** | Inner Ramp to Proximal Middle Ramp |
| SK-26 | Ranikothalia–Assilina dolomitic Wackestone-Packstone **(SKMF-7)** | Inner Ramp to Proximal Middle Ramp |

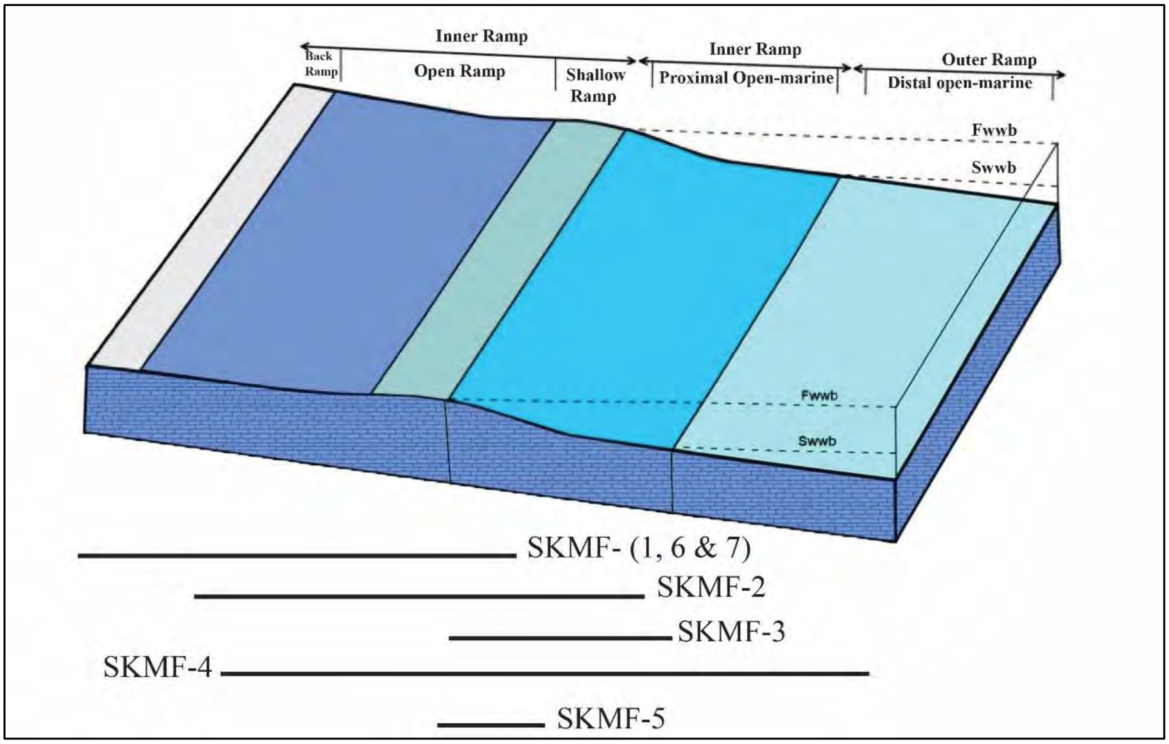


Figure 8.1 The suggested Depositional settings of Microfacies of Sakesar formation

## 8.3 Facies Correlation

The lithofacies and electrofacies are correlated to observe the facies distribution in the studied wells. The lithofacies of the Balkasar-7 are marked by using core of well, while the Electrofacies are categorized using well log of Balkasar-Oxy 1. Both well are less then 1 km apart. The thickness of the target formation in both well are in difference of 10 meters while the formations tops are 20 meters. The lithofacies are discussed in Chapter-4, while the Electrofacies are in Chapter-7.

Both lithofacies by core studying and Electrofacies by using well log shows the similar patterns of lithology in studied wells. The limestone is the most dominant lithology preceding by Shaly limestone and Dolomitic limestone as shown in Fig 8.2. The results show that these both methods can be used as an efficient tool for facies analysis and their distribution.

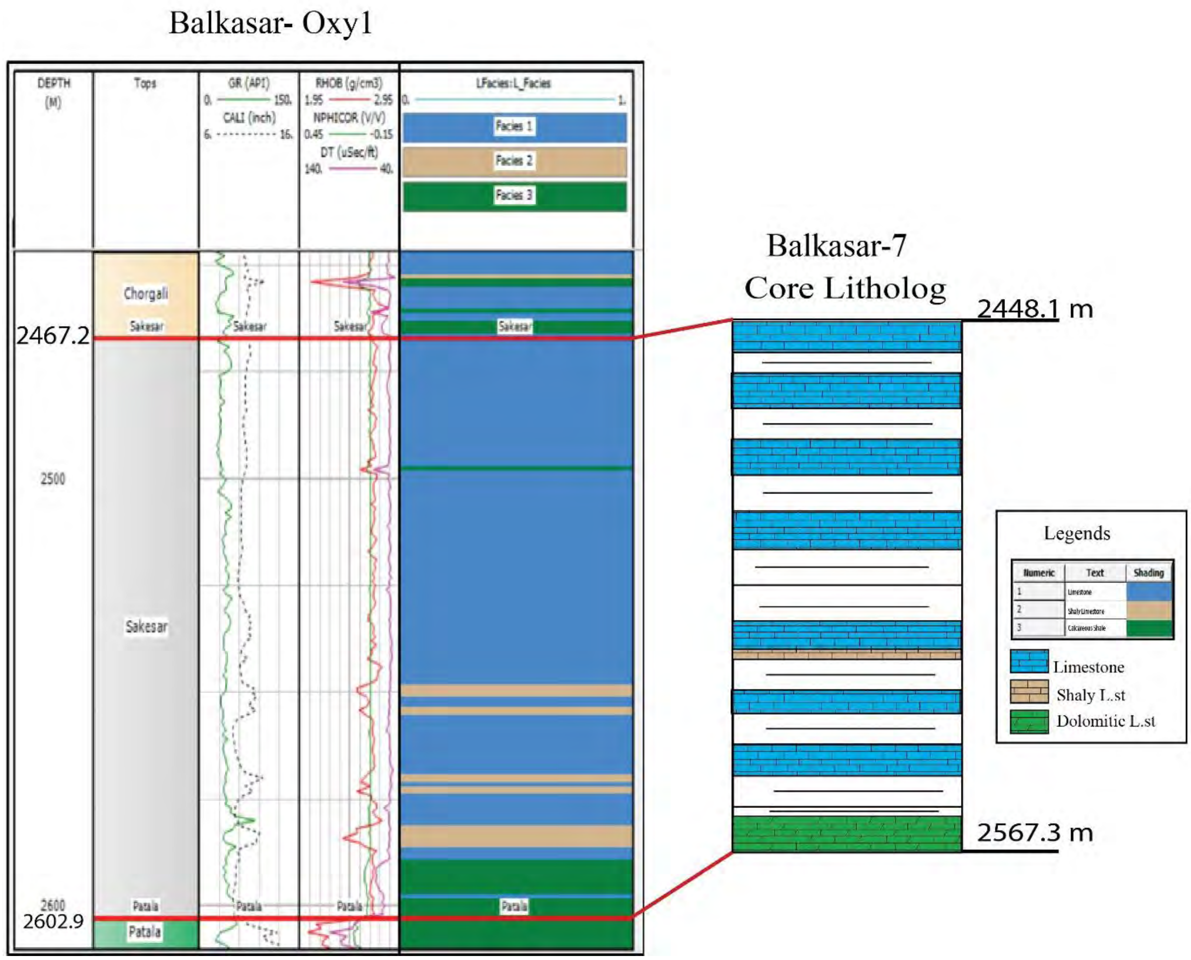


Figure 8.2 Well correlation of Balkasar Oxy-1 and Balkasar-7. The lithology in Balksar-Oxy1 is calculated by using well log as shown in Clusters group last track correlated with Core litho-log of Balkasar-7.

## 8.4 Paragenetic Sequence

The paragenetic sequence of the Sakesar Limestone is established on the basis of core study and thin section observations shown in Fig. 8.3. The diagenetic environments proposed for the Sakesar Limestone in current studies starts from marine environments to late stage diagenetic burial and uplift realms.

- The early stage diagenetic changes govern in the Sakesar Limestone are lithification and compaction which is followed by the micritization. Micritization is commonly observed during current study and present in the form of micritic envelops and skeletal alteration. The micritization is the result of the microbial activities, and it take place during marine phreatic environment (Flϋgel, 2010; Beigi et al., 2017).
- Then in middle stage diagenesis, the dissolution of the skeletal and non-skeletal grains take place and is followed by the neomorphism, mostly blocky cements C-I type, which represent the phreatic condition of meteoric diagenesis during (Khalifa 2005, Khalifa et al., 2009, Ishaq et al., 2018).
- The D-I dolomitization is planar eu-hedral and medium crystalline, it is fabric selective as it is present in matrix and allochem grains too, also found along fractures.
- The D-II dolomitization is an-hedral to sub hedral and it also shows its presence in matrix and fracture fillings with fine crystals sizes.
- The telogenetic events in the Sakesar Formation are fractures, calcite veins and dissolution which results in the form of porosity creation such as fenestral and vugs (observed and mentioned in Core study).

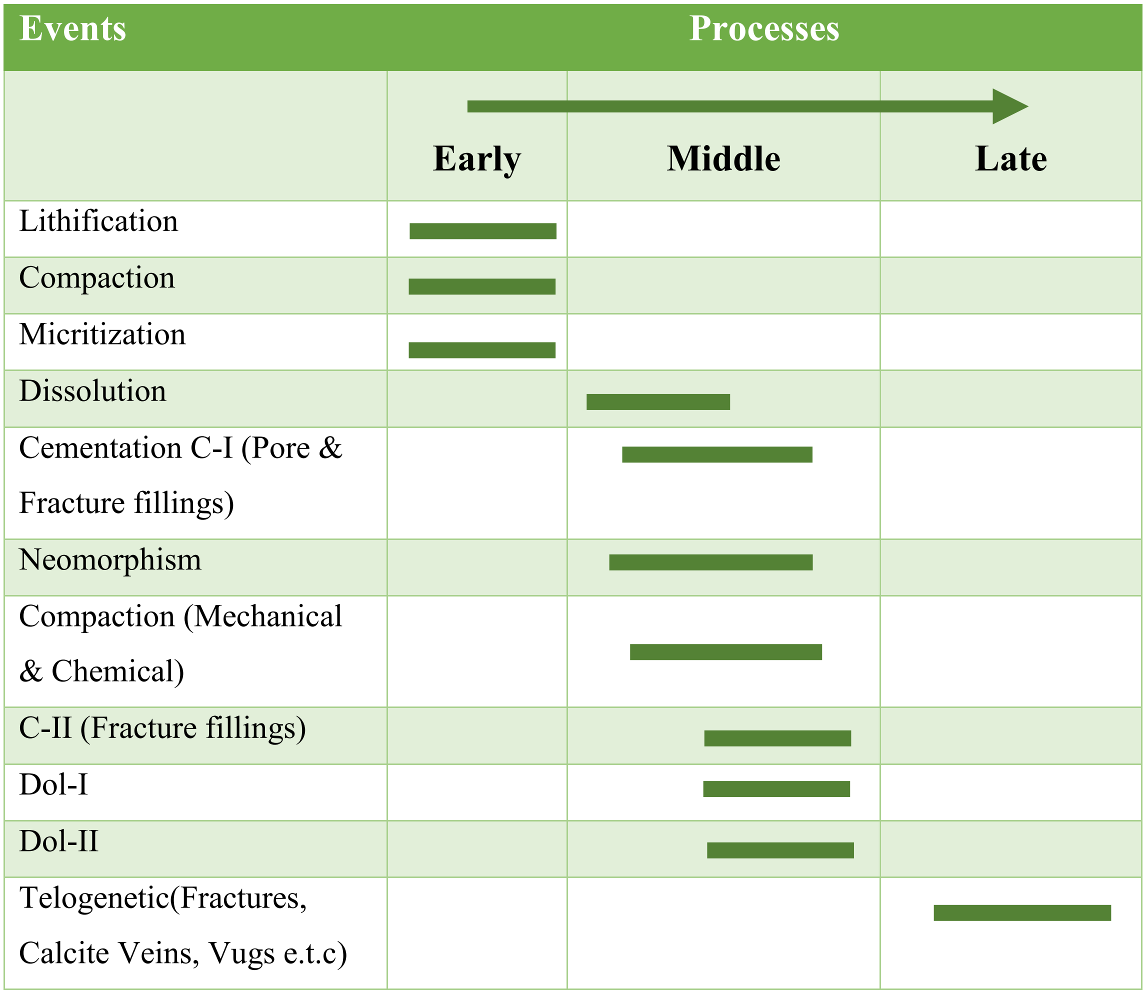


Figure 8.3 The proposed paragenetic order of the Eocene Sakesar Formation.

## Chapter No. 9

# CONCLUSION

The Eocene Sakesar Limestone is studied for facies and diagenetic studies. following conclusions are drawn from current research work.

- Based on detailed petrographic thin section studies seven microfacies are identified of the Sakesar Limestone studied sections.
- Seven microfacies are: Larger Foraminiferal Wackestone-Packstone, Bioclastic - Nummulitidae Wackestone, Assilina - Nummulitic Packstone, Planktonic Miscellania Wackestone-Packstone, Bioclastic Wackestone, Nummulitic-Lockhartia dolomitic Wackestone-Packstone, and Ranikothalia–Assilina dolomitic Wackestone-Packstone.
- These microfacies show Wackestone to Packstone texture.
- These microfacies suggests that depositional settings of the Sakesar Limestone are proximal Inner ramp to Outer ramp settings.
- The diagenetic features observed during studies include compaction both mechanical and chemical, micritization, cementation, neomorphism, dissolution and dolomitization.
- Micritization is the most common and dominant diagenetic feature found in the Sakesar formation studies.
- In thin section studies, only one cement type is found i.e. Blocky calcite cement in pore fillings and in fracture fillings.
- Dolomite in the observed thin sections present as a matrix supported, along fracture and stylolites.
- Diagenetic studies suggest that the Sakesar Limestone has experienced the early to late diagenetic phases.
- Electrofacies of the Sakesar Limestone are generated by K mean clustering method which shows dominant facie is Limestone, followed by shaly limestone and calcareous shale.
- Well correlation shows the similar pattern of facies in the studied wells.

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