MICROFACIES ANALYSIS AND RESERVOIR CHARACTERIZATION OF EARLY EOCENE (YPRESIAN) SAKESAR LIMESTONE IN THE EASTERN AND CENTRAL SALT RANGE, UPPER INDUS BASIN, PAKISTAN

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M. Phil Geology

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A thesis Submitted in Partial fulfilment of the requirement for the Degree of Master of Philosophy in Geology, Department of Earth Sciences, Quaid-i-Azam University Islamabad.

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ABSTRACT

Detailed investigations have been carried out for the Early Eocene Sakesar Limestone to evaluate microfacies analysis, reservoir characterization and depositional environment. This work is accomplished of three outcrop sections which are, Dandot village section, Ratucha village section and Sardhai village section in Eastern and Central Salt Range Potwar plateau, Upper Indus Basin. In addition, well-cuttings of Sakesar Limestone were studied from Balkassar-7 well located in the Potwar sub-basin. The main aim of this research work was to investigate the reservoir quality and identify the microfacies of Sakesar Limestone. Based on the relative proportions of bioclasts and micrite, five microfacies were identified which include Calcareous Algal-Miliolidal wackestone, Alveolina-Miliolidal packestone, Assilina-Nummulitic wackestone, Lokhartia Rich-Foraminiferal wackestone and Nummulitic-Heterostegina packestone. The presence of micrite matrix, relative abundance of fossils and their association in these microfacies has proved that the Sakesar Limestone to be deposited in Shallow-marine, inner-middle ramp environment. The porosity types identified in Sakesar Limestone include fracture, moldic, interparticle and intraparticle porosity. The visually estimated porosity values of Sakesar Limestone from thin-section studies ranges from 0.70% to 2.9% while the core plug porosity and permeability values of the outcrop samples vary between 0.66% to 2.98% and 0.05mD to 0.09mD respectively. The well-cuttings plug porosity values ranges from 0.79% to 2.60% and permeability from 0.06mD to 0.44mD respectively. The relationship between plug porosity and permeability shows a reasonable correlation coefficient. The main reservoir quality enhancement factors are fractures on outcrop scale while microfractures and dissolution on microscopic scale which makes the Sakesar Limestone as a secondary reservoir in nature.

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Chapter-01 Introduction

1.1 Introduction

In hydrocarbon industries, the standard indicators of reservoir quality are porosity and permeability. Both porosity and permeability are necessary for a reservoir rock to hold and yield hydrocarbons in commercial amount. The distribution of porosity and permeability in carbonate rocks are mainly controlled by factors like depositional facies, diagenetic modifications, and deformational processes. Approximately 50% of the fossil fuel in the world are extracted from carbonate reservoir rocks (Mazzallo, 2004). Hence, the study of reservoir properties of limestone is of great importance for the new discovery as well as for improving the existing production. The current reserves of oil and gas are on a very steep decline, so, to enhance the production from current conventional reservoirs, we need to know the reservoir properties in detail. The Eocene Sakesar Limestone is a potential and in some oil fields a proven reservoir in Upper Indus basin (Potwar and Kohat sub-basins) which produce hydrocarbons in various oil fields. In the early part of exploration history of Pakistan, approximately 50% of hydrocarbons reserves were added from the Eocene Reservoirs (Athar Jamil 2012).

Porosity is the fundamental property of a reservoir rock and the reservoir is considered as good when it has porosity as well as permeability in the range which produce hydrocarbons in commercial amount. These two properties are the geometric properties of a rock, not genetic (F.K North) and production of hydrocarbons cannot be achieved without these fundamental properties. The distribution of porosity in a rock is dependent on depositional texture, distribution of depositional facies, rock fabric and diagenetic modifications. A rock may have high porosity and permeability when it is initially deposited but it may increase further or decrease with time because of the diagenetic changes, especially in case of carbonate rocks.

The transgression in Paleocene continued in Eocene and deposition of Eocene successions took placed on the Indian-plate (Shah, 2009). The Eocene age sequences have nice exposures in the Trans-Indus Range and Salt Range and they include the Nammal Formation, Sakesar Limestone and Chorgali Formation. The Sakesar Limestone is mainly consisting of light grey to creamy white, medium-massive bedded, nodular, fractured limestone with marls and chert nodules in its upper portion. The Sakesar Limestone is fossiliferous and it contains larger benthic foraminifera fossils of Eocene age as well as calcareous green algae.

1.2 Previous work

Many research work is published by various researchers on Sakesar Limestone which mainly focused on biostratigraphy, diagenesis, and depositional environment of the formation. According to Ghazi et al, (2010), Davies and pinfold (1937) worked out foraminiferal studies on Eocene successions of salt ranges. They described the lithology and reported larger benthic foraminiferal assemblages from Sakesar limestone. Later, paleontological studies were carried out by Gill (1953) and reported various fossil species. The exploration of hydrocarbons in Potwar area, is mainly from shallow lying Eocene and Paleocene rocks and they are mainly producing from the fractures (Jadoon et al 2005). According to Ibrahim Shah (2009), Sakesar limestone, Sheikhan Formation and upper part of the Margalla Hill Limestone are equivalent in Kohat, Kala-chitta and Hazara areas.

Various researchers have contributed to sedimentological and biostratigraphic work on Sakesar Limestone in different parts of the Salt Range. According to Rahman et al, (2017), Boustani (2000), Boustani and Khwaja (1997), Afzal and Butt (2000), Sameeni and Butt (2004), Ghazi et al. (2006, 2010), Nizami et al. (2010) and Ahmed (2013) worked on the biostratigraphy and sedimentology of Sakesar Limestone. These different workers have reported that the Sakesar Limestone is composed of mainly two microfacies i.e wackestone and packestone. They also reported various fossils which include larger benthic foraminifera. The common larger benthic foraminifera include *Alveolina, Assilina, Lokhartia, operculina, Nummulites* and *brachiopods*. These workers also reported some species of green Algae, Echnoids, Mollusks, and sponges. The diagenetic processes reported include cementation, dissolution, neomorphism, micritization, fracturing, filled veins, and open fractures.

1.3 Aim and Objectives

This present work is an attempt to study and evaluate microfacies and reservoir properties including porosity and permeability from plugs of different depositional facies of outcrop samples of Sakesar Limestone collected at three stratigraphic sections in the eastern and central Salt Range along with core-cuttings from the Balkassar-7 well in the Potwar Plateau. Understanding the properties of reservoir rocks is an important task for geologists and reservoir engineers because without the proper evaluation of its properties, oil and gas production cannot be attained. This present research work is an integrated approach to:

- Evaluate porosity and permeability of the Sakesar Limestone
- Understand reservoir properties from outcrop samples and core-cuttings

- Identify microfacies from petrographic analysis to unravel the depositional environment of Sakesar Limestone
- Describe and understand the outcrop features of Sakesar Limestone

1.4 Location and accessibility to the study area

The Sakesar Limestone samples were collected from eastern and central Salt Range Potwar Sub-Basin. Ratucha village section, Dandot village sections in the eastern salt range and Sardhai village section in central salt range. The Ratucha village section is located at 32°41´14.93´ N, 72°58´51.85´´ E and Dandot village section is located at 32°40´12.43´´ N, 72°57´26.60´´ E in the eastern salt range, District Chakwal, Punjab. Sardhai village section is located at 32°41´0.60´´ N, 72°43´1.54´´ E in the central salt range, Punjab, Pakistan. Sardhai village is situated about 90km South of the capital territory. The Ratucha and Dandot villages are about 160km and 166km from the capital area, Islamabad, respectively. The location of the study area is shown on the map in Figure 1.1.

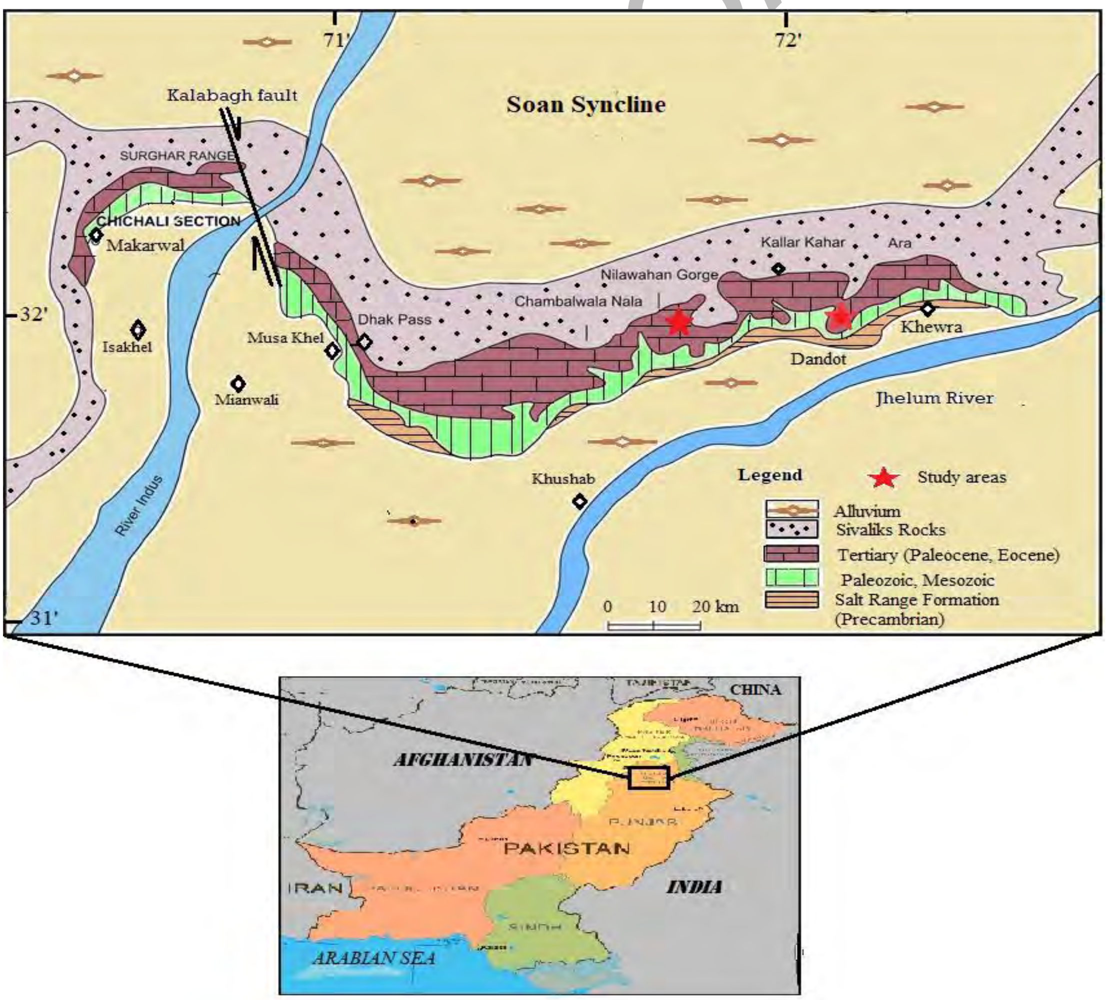

Figure 1.1. Location map of the study area, Salt Range (Modified after Ghazi et. al. 2015).

Similarly, the Balkassar-7 well is located in Balkassar village at 32°55' 00'' N and 72°39' 00''E, Chakwal, Potwar sub-basin onshore Pakistan as shown in the figure 1.2.

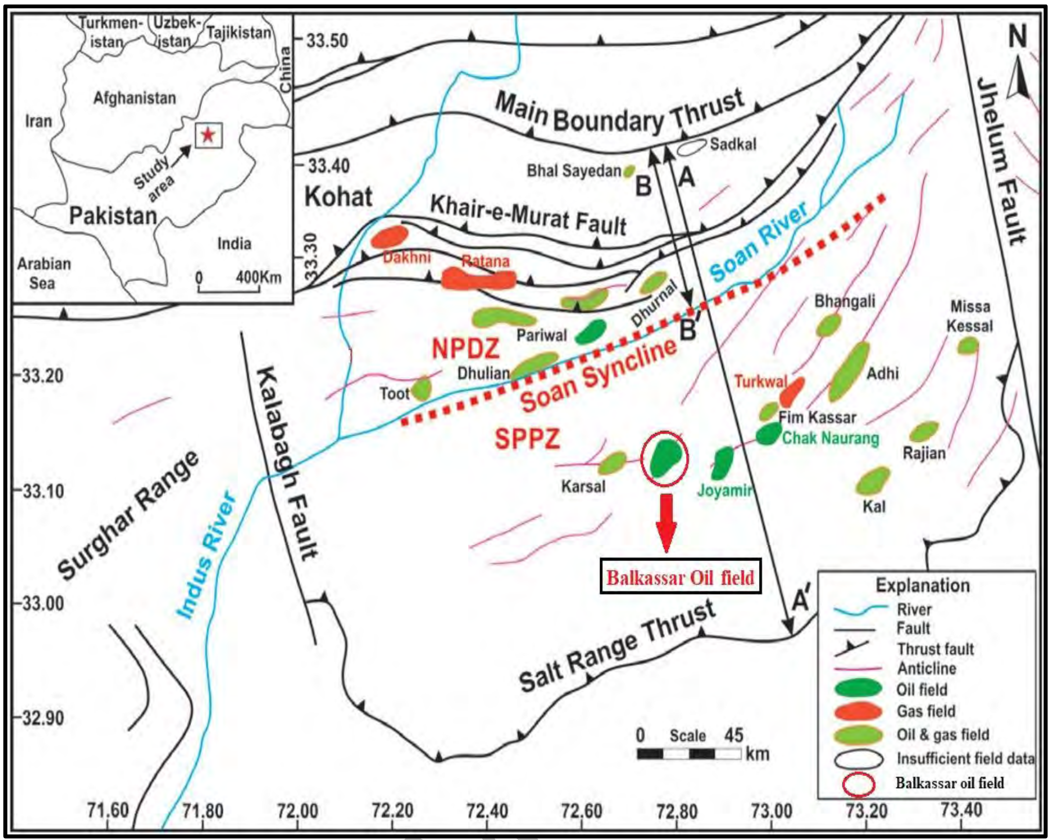

Figure 1.2. Location map of Balkassar oil field in potwar plateau (Modified after Riaz et al. 2019).

1.5 Methodology

The methodology followed in this research work is comprised of field work and laboratory analyses for detail assessment of porosity, permeability and microfacies analysis of the Ypresian Sakessar Limestone at eastern and central Salt Range Potwar sub-basin, Pakistan. As mentioned earlier, the Sakessar limestone is well exposed in the Salt Range in different areas including eastern, central, and western Salt Range. Detailed and informative Geological field were conducted to eastern and central Salt Range for data collection, sampling and observing the field features of Sakesar Limestone. The details of methodology are given in the flowchart (Figure 1.3).

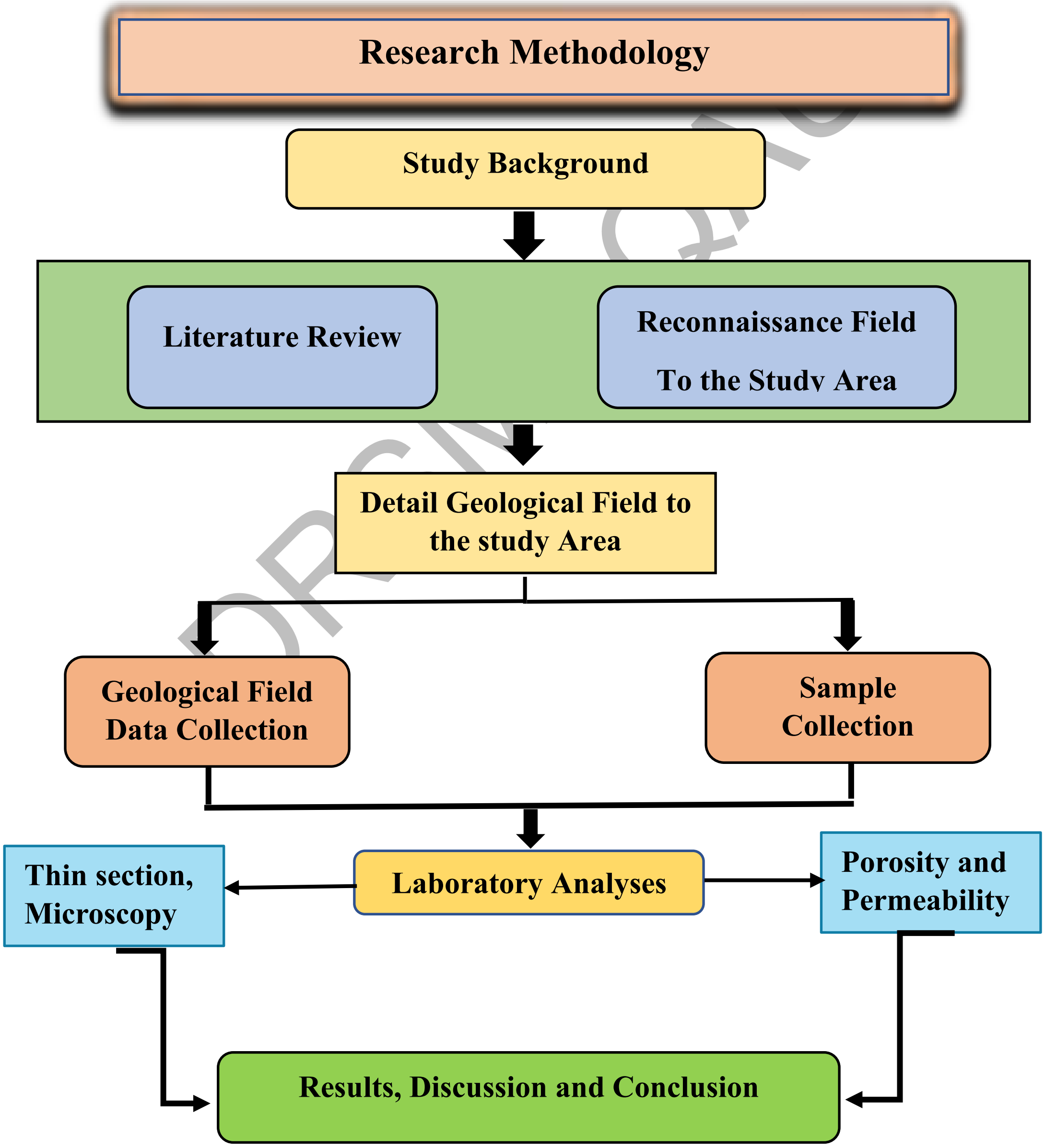

Figure 1.3. Flowchart showing methodology followed in the research work.

1.5.1 Field Instruments

The instruments used in the field work include Geological Hammer for sampling, Measuring Tape for measuring the thickness of strata, Brunton compass for recording orientation of beds, Global Positioning System device (GPS device) to locate and record the coordinates of the studied sections, and Hand lens for observing fine details in the rock units.

1.5.2 Sampling

Based on the lithological variation, bed thickness, equal intervals or fossil variations, a total of 43 samples were collected systematically from bottom to top using conventional methods and tools of geological field work. Upper and Lower contacts of the Formation were marked and a scaled photograph were taken. Each sample orientations were recorded and photographs were taken from the sample location. In eastern Salt Range, 15 fresh samples were collected from the FWO (Frontier Work Organization) quarry near Ratucha village, East of Choa Saidan Shah. Lithological log was prepared for the entire section and all the observable features were noted. The samples collected were named as SLR (Sakesar Limestone Ratucha village) and wrapped in sample bags to protect them from weathering and each bag were marked with sample number and locality to avoid confusion. Similarly, 10 Samples were collected from the Dandot village section at interval of 1m with the help of geological hammer and named as SKD (Sakesar Limestone Dandot village). Orientation of strata were recorded and thickness of the beds were measured using measuring tape and field features of the Sakesar Limestone were recorded. In the Central Salt Range, Sakesar limestone is well exposed Sardhai village section having both the contacts with upper and lower formations. 18 samples were collected systematically from different beds based on variation in thickness and coded with SLC (Sakesar Limestone Central Salt Range). These samples were packed in sample bags and photographs were taken of all the observed features including sample's location, bedding, chert nodules, fossils, and contacts.

1.5.3 Core Study (Well-Cuttings)

Directorate General of Petroleum Concessions (DGPC) approved the application for the study of Core from the Balkassar-7 well. Balkassar Oil Field is a conventional oil field located in the central part of the Potwar plateau, Balkassar village District Chakwal, Punjab. The available core interval of about 8.25m (from 8032ft to 8064ft) from the Balkassar-7 well were displayed at Hydrocarbon Development Institute of Pakistan. The core was studied systematically using conventional methods of core studies from top to bottom and all the features were noted including color, fossils, structures present and texture of the Sakesar Limestone. Zones were marked for core plugs porosity and permeability assessment. These zones were marked based on the change in texture, fossils, fractures, and relatively low fractured zones in various depth intervals. A total of seven plugs were collected for porosity and permeability analysis and their depth were noted.

1.6 Laboratory analyses

1.6.1 Thin-section preparation

A total of 43 unstained thin sections were prepared at Department of Earth Sciences Quaid-i-Azam University. All the collected samples were cut and grinded in rock cutting laboratory and the grinded slabs were then placed on hot plates to remove the moisture content because it causes bubbles during attachment. The thin grinded rock sample were then polished and attached to slides with the help of Epoxy resin. After attachment to slide, they were again polished and thinned to standard thin sections size.

1.6.2 Petrographic Microscopy

The petrographic analysis of thin-sections prepared, were carried out in the petrographic laboratory at Department of Earth Sciences, Quaid-i-Azam University, Islamabad. The polarizing microscope Leica with attached camera were used. Different resolution powers of 200µm and 100µm were used and photographs were taken for petrographic analysis. To study the fine details of all thin-sections, photographs were taken with 40X and 100x magnification lenses.

1.6.3 Porosity and Permeability Analyses

For porosity and permeability assessment, the samples were carried to Hydrocarbon Development Institute of Pakistan (HDIP), Islamabad. The rock samples were cut and core plugs were prepared of the selected samples. The plugs were cut parallel and some were perpendicular to bedding. Each plug of known dimensions (1×1 inch) was then further processed for porosity and permeability assessment.

Plug-Porosity Measurement

Porosity of rocks can be measured by several methods. These methods include Direct Measurement, Mercury Injection Method, Imbition Method, Density Method, Petrographic Method, and Gas Expansion Method. The method used in this work is based on the Gas Expansion method, *Helium Porosometry.*

Helium Porosometry (HEP)

The Helium-Porosometry method is purely based the Boyle's law or Ideal gas law. The core plugs were cleaned and placed on hot plates to remove the moisture content and other contaminations.

The core plugs are then closed in a container at atmospheric pressure P_1. The volume of container is known represented by V_1. This container is connected to another container of known volume V_2 having pressure P_2. When the valve of two connected containers are opened slowly, the pressure equalizes to P_3. The volume of grains V_S can be calculated from the equilibrium pressure. According to Boyle law, pressure times volume is constant for a system. So, we can write PV before the opening of valve is equal to PV when the system is at equilibrium.

$$P1\,(V1 - Vs) + P2\,V2 = P3\,(V1 + V2 - Vs)$$

$$\text{Volume of grains, } V_s = \frac{P_1 V_1 + P_2 V_2 - P_3 (V_1 - V_2)}{(P_1 - P_2)}$$

The bulk volume of the rock sample is determined by using instruments like vernier callipers. The bulk volume and grains volume of the rock sample then can be used to calculate the *connected porosity* of the selected samples.

Plug Permeability Measurement

For permeability measurement, the dry gas has been traditionally used due to the reasons that it minimizes the rock-fluid reaction, easy to use and inexpensive. Before the measurement procedure of permeability, the sample must be cleaned and dry before the measurement. Air is flowed through the sample of known diameter and length in laboratory. The differential pressure and rate of flow is measured, and using Darcey's equation, the permeability of the respective sample can be calculated. The resulting permeability values are valid if there is no reaction between the rock sample and the flowing fluid.

Chapter-02 Geology and General Stratigraphy

2.1 Geological setting

The Indian plate was part of a single super-continent Pangea which was surrounded by the single gigantic ocean known as the Panthalasa ocean. The tectonic evolution of the Indian plate, which started about 167 million years ago (Late Jurrassic) indicate a very an exceptional case history with different events of plate tectonics including sea-floor spreading, continental-breakup, generation of new oceans, volcanism, generation of new faults, subduction and obduction, orogeny and collision of tectonic plates (Chatterjee 2013).

During Permian age, the Indian and Atlantic oceans were closed so that all the continents constituted into a single supercontinent Pangea (Dietz and Holden, 1970). The pangea started splitting in Jurrassic and consequently divided into two parts i.e Gondwana and Laurasia. The breakup of Gondwana about 167-Ma ago lead to the evolution of the Indian ocean (Royer and Coffin, 1992).

The Indian plate separated from Gondwana during Jurrassic age and throughout most of the cretaceous it was a separate continent but in contact with Africa (chatterjee and Scotese, 2010). In its long voyage, the Indian plate experienced both the convergent as well as divergent tectonic boundaries. The possible age of India, Antarctica and Australia is between 124-Ma and 130-Maa (Gaina et al., 2007). The Indian plate drifted as an island to the North and collided with Asia in Eocene which slowed down its motion to about 5cm/year (Copley et al., 2010). During the drifting of Indian plate, due to the intra-oceanic subduction the Kohistan-Island Arc (KIA) formed which divided the ocean into Paleo-tethyan and Neo-tethyan oceans. The Kohistan-island Arc collided with Eurasia during cretaceous followed by India-Eurasia collision during the Early Eocene (50-Ma) (Molnar and Tapponnier, 1977; Allègre et al., 1984). The collision between India and Eurasia is type of continent-continent collision which resulted in the shortening of crust and formation of the highest mountain peaks of the world, the Himalaya (Dewey and Bird, 1970). The Kohistan-Island Arc welded with Eurasia at Shyoke-Suture zone while India and Eurasia are sutured along the Indus-Tsangpo Suture zone which resulted the closure of Neo-tethyan ocean. The Kohiatan Island Arc and Erasian plate is marked by a boundary known as Main- Karakoram Thrust (MKT) while the Indus-Tsangpo Suture zone is called the Main-Mantle Thrust (MMT), characterized by Ophiolites (obducted oceanic lithosphere). The sediments deposited in different environmental conditions along the coastal regions of the Indian plate during its journey as an island.

2.2 Sedimentary basins

The sedimentary basin of Pakistan is divided into the following (shah, 2009):

A. Southern stratigraphic basin

I. Indus Basin
   a. Kohat-Potwar sub-basins
   b. Sulaiman-kirthar Province

II. Axial Belt

III. Baluchistan Basin

B. Northern tectano-stratigraphic basin

A. Himalayan tectono-stratigraphic Basin
   a. Higher Himalaya
   b. Lesser Himalaya
   c. Sub-Himalaya

C. Kohistan Island Arc

D. Karakoram-Hindukush stratigraphic basin

2.2.1 Indus Basin

The indus basin is the most studied and longest basin of Pakistan. This basin contains strata ranging from Pre-Cambrian to Tertiary with a regional unconformity of Ordovician, Silurian, Devonian, and Carboniferous ages. These deposits are missing either eroded or not deposited. The indus basin is bounded by Main Boundary Thrust (MBT) to north and Arabian Sea to south. Its western boundary is marked by West Pakistan fold and thrust belt. The entire Indus basin is divided into the following based on the stratigraphy, structural differences, and sedimentary rocks (Bender and Raza, 1995).

- Upper Indus Basin: It is bordered by Main Boundary Thrust (MBT) to the North and Sargodha Highs to the South.
- Central Indus Basin: central basin extends from Sargodha Highs to Jacobabad Highs
- Lower Indus Basin: it extends from Jacobabad Highs to off-shore Indus or Arabian sea.

2.2.2 Upper Indus Basin

Upper Indus Basin is separated from Lower Indus Basin by Sargodha Highs which is part of the Indian shield rocks. This part of the greater Indus basin contains rocks exposures from Pre-

Cambrian to recent. Upper indus basin is divided into two parts Kohat sub-basin and Potwar sub-basin based on deformation and structural differences. Geographically, Indus River divided the kohat and potwar sub-basins. In potwar region, Salt Tectonics played a key role in deformation in Potwar area because it comprises mobile beds that released the stresses applied from South during collision of Indian plate.

2.3 General Stratigraphy

The Sedimentary sequence in Potwar plateau include rocks from Pre-Cambrian to recent age are well exposed (Fatmi, 1973). The Pre-Cambrian evaporites (Salt Range Formation) is overlain by the Cambrian Jhelum Group sequence. These Cambrian rocks include shallow marine to non-marine sediments of dolomites, shales, and sandstone sediments. The Cambrian succession is unconformably by Permian clastic and carbonate strata (Nilawahan and Zaluch Group). As mentioned earlier, there is regional unconformity from Ordovician to Carboniferous (Kazmi and Jan,1997). The Cambrian rocks are followed by Mesozoic and Cenozoic sequences. The marine sedimentation ended with the closure of Tethyan ocean during Eocene age, therefore, the Eocene strata is overlain by molasse sediments of terrestrial origin from the Himalayan orogeny.

2.3.1 Precambrian

The Precambrian age is represented by **Salt Range Formation** named by Asrarullah (1967). Salt Range Formation is composed of Marls, Gypsum, Salt, and Oil shale. It is divided into three members, *a) Sahiwal Marl Member b) Bhandarkas gypsum Member* and *c) Bilianwala Salt Member*. This Formation is characterized by igneous body known as ‘Khewrites’ or ‘Khewra Trap’. The marls are consisting of clay, dolomite, and gypsum while the Salt is thick-bedded with laminations and pink colored bands. Lower contact of the Formation rest on Pre-Cambrian Indian Shield rocks as indicated in oil wells. Its upper contact is conformable with Khewra Sandstone.

2.3.2 Cambrian (Jhelum Group)

Stratigraphic Committee of Pakistan introduced the name ‘**Khewra Sandstone**’ (Fatmi,1973). Khewra Sandstone is predominantly composed of purple-brown and yellowish to brown colored, fine-grained, thick bedded to massive sandstone with red color shale at the basal part. This formation contains sedimentary structures including, laminations, mud-cracks, ripple marks, cross laminations etc. The lower contact of Khewra sandstone with the Salt Range Formation is subject of dispute. The upper contact of the formation is conformable with middle Cambrian Kussak Formation. Schindewolf and Seilacher (1955) reported trails of trilobites.

The Khewra Sandstone is overlain by **Kussak Formation'.** Stratigraphic Committee of Pakistan given the name 'Kussak Formation' (Fatmi, 1973). This formation is predominantly composed of greenish glauconitic sandstone with greenish-grey siltstone interbedded with dolomites. This formation is fossiliferous and produced. Its lower contact is conformable with Khewra Sandstone while the upper contact is conformable with Jutana Dolomites. The age of Kussak Formation is Early to Middle Cambrian.

Kussak Formation is followed by **Jutana Formation**. Stratigraphic Committee of Pakistan given the name 'Jutana Formation' which was earlier named by Noetling (1894) as 'Magnesian Sandstone'. Lower part of the formation composed of massive, light green sandy dolomite while the upper part consists of brecciated dolomites. Teichert (1964) reported some fossil species. Its lower contact is conformable with Kussak Formation while upper contact is conformable with Baghanwala Formation.

Jutana Formation is overlain by **Baghanwala Formation** of late Cambrian age. This formation consists of clay, red color shales with flaggy sandstone. The sandstone exhibits many colors like pink, green, grey, and blue. The diagnostic feature of this formation is the presence of pseudomorphs of salt crystals. This formation is non-fossiliferous and having common sedimentary structures i.e ripple marks, mud cracks. The upper contact is unconformable with Permian age Tobra Formation.

Ordovician-Carboniferous Unconformity

The Ordovician and Silurian sedimentary rocks are only present in Peshawar Basin and Chitral District of Khyber Pakhtunkhwa, Pakistan (Shah, 2009). The Baluchistan and Indus Basins are devoid of rocks of these ages. There is a regional unconformity (hiatus) between the Cambrian and Permian age rocks in the Salt range.

2.3.3 Permian

The Permian rocks of Salt Range is divided into two groups named as *a)* ***Nilawahan Group*** and *b)* ***Zaluch Group***.

Nilawahan Group

The first member of Nilawahan Group is **Tobra Formation** which is the oldest formation of this group previously known as 'Salt Range boulder Bed'. According to Teichert (1967), this formation is composed of three different types of facies including: A) Tillite facie consists of granitic boulders, quartz fragments, feldspar, magnetite, shale, garnet, and sandstone B) Fresh water facie composed of siltstone and shale C) Mixed facie of sandstone, boulders and diamictite. Lower contact is disconformable with Cambrian rocks while the upper contact is conformable with Dandot Formation.

Tobra Formation is followed by **Dandot Formation**. The name 'Dandot Formation' is assigned to the rock unit previously named by Noetling (1901) and Waagen (1879) as 'Dandot Group' and 'Spackled Sandstone' respectively. This formation is predominantly composed of yellowish olive-green sandstone with occasional thin beds of pebbles and interbedded splintery shales. The age of the formation is interpreted from fossil contents and its stratigraphic position as Early Permian.

Dandot Formation is overlain by **Warcha Sandstone**. It was previously known as 'Spackled Sandstone' (Gee, 1945). This formation is consisting of medium to coarse-grained Arkosic sandstone which is conglomeritic at places with shale interbeds. In western salt range, at Burikhel, Warcha Sandstone contains carbonaceous shale with coal seams. This is the only Permian coal reported in Pakistan, but its production is low and poor quality.

The name **Sardhai Formation** was introduced by Gee and approved by the Stratigraphic committee of Pakistan. This formation consists of greenish grey and bluish clay, with siltstone and minor sands as well as carbonaceous shale. The clay shows lavender color having some copper minerals (chalcopyrite). In Khisore Ranges the Sardhai Formation changes facies from lavender clays in Salt Ranges to black shale and argillaceous limestone. Lower contact is transitional with Warcha Sandstone and the upper contact is conformable with Amb Formation.

Zaluch Group

The first member of this group is **Amb Formation** which is named by Teichert (1966). This formation is composed of sandstone, limestone, and shale. Lower part of the formation consists of medium-thick bedded, medium grained calcareous sandstone. Upper part is composed of brownish-grey medium bedded, richly fossiliferous with productus sandy limestone with dark grey shale. Balme (1970) reported abundant pollen and spores. This formation contains important index fossil Monodiexodina kattaensis of Artinskian age (Dunbar, 1933).

Amb Formation is overlain by **Wargal Limestone** which was introduced by Teichert (1966) and accepted by Stratigraphic Committee of Pakistan. From base to top, the formation consists of Sandy limestone, sandstone, brachiopods rich limestone followed by finely crystalline massive dolomites, limestone with chert nodules and highly fossiliferous thin to medium bedded argillaceous limestone. The Wargal Limestone is richly fossiliferous and Teichert and Kummel (1970) reported pollen and spores from the formation.

Dunbar (1933) introduced the the name **'Chhidru Formation'**. Kummel and Teichert (1970) studied the biostratigraphy in details and they presented the evidence of the Para-conformity at the P-T boundary (Permian-Triassic boundary). The formation is composed of yellowish to dark grey color shale having rare phosphatic nodules. This unit is followed by sandstone and sandy limestone. The topmost part of the formation is composed of white sandstone bed containing ripple marks Chhidru Formation is highly fossiliferous. Based on ammonoids, its age is interpreted as Late Permian.

2.3.4 Triassic (Mosakhel Group)

The first member of this group is **Mianwali Formation** which is consists of olive green and grey color calcareous shale with flaggy brown limestone, dolomites, sandstone, and siltstone. Mianwali Formation is divided into three members. The lower *Khatwai Member* is composed of dolomite and limestone. The middle *Mittiwali Member* consists of limestone followed upward followed by shales and subordinate sandstone. The Mittiwali Member is followed by *Narmia Member* which is composed of highly fossiliferous limestone. This formation was deposited in shallow marine environment (Gee, 1989).

The name **Tredian Formation** was assigned to substitute his previous name 'Kingriali Sandstone' (Kummel, 1966). This formation is divided into two members: *a) Landa Member* and *b) Khatkiara Member. The* Landa member is composed of micaceous, pinkish, redish grey to greenish grey, thin to thick bedded sandstone with slump and ripple marks structures. The Khatkiara member consists of thick-bedded, massive white sandstone with some dolomite insertions. The microfossil in this formation is reported by Balme (1970).

Tredian Formation is overlain by **Kingriali Formation,** introduced by Gee (1945). This formation into two members, *a) Doya Member* which is mainly composed of soft, micaceous, and thick bedded sandstone, dolomite, limestone and minor shale. *b) Vanjari Member* consists of brown, purple, coarse-grained, hard, brecciated, jointed, fractured and massive dolomites. The upper contact is disconformable with Jurrassic Datta Formation. From its contacts with Datta Formation and Tredian Formation and its stratigraphic position, its age is doubtfully interpreted as Late Triassic.

2.4.5 Jurrassic (Surghar Group)

The name of **Datta Formation** (first member of Surghar group) was introduced by Danilchik (1967). Datta Formation is of terrestrial origin and composed of variegated, green, red, maroon, grey, white sandstone, siltstone, mudstone, shale and carbonaceous, dolomitic, ferruginous glass sand and fireclay horizons (Fatmi, 1977). The formation disconformably overlies Kingriali Formation and the upper contact is gradational with Shinawri Formation.

Stratigraphic Committee of Pakistan coined the name '**Shinawri Formation'** to replace the names 'Maira Formation' of Davies and Gardezi (1965) and 'Wazirwal member of Datta Formation' of Fatmi and Cheema (1972). The formation is composed of fine to coarse-grained, well bedded limestone of brownish color, nodular marl, calcareous and non-calcareous shale and quartzose, ferruginous, calcareous sandstone. Sedimentary structures like ripple marks and current beddings are also present in this formation. Both lower and upper contacts are transitional with underlying Datta Formation and overlying Samana suk Formation.

This name **Samanasuk Formation** is coined to replace the 'Sikhar Limestone' of Latif (1970a). The formation at the type locality consists of dark grey, medium-thick bedded, oolitic limestone with shale intercalations and subordinate marl. Lower contact with Shinawri Formation is transitional and the upper contact is disconformable with Chichali Formation. The formation yielded, brachiopods, ammonoids, bivalves, gastropods, and crinoids.

2.4.6 Cretaceous (Baroch Group)

The name **Chichali Formation** was introduced for the rock unit which was previously known as the 'Belemnite Beds'. it is composed of green to greenish grey glauconitic sandstone with dark to bluish grey, sandy, silty, and glauconitic shale. The lower unit consists of glauconitic, dark green sandstone. Middle unit consists of fine-medium grained calcareous sandstone. The upper member is glauconitic, generally non-fossiliferous. Based on the fossil contents, the age of the formation is described as Oxfordian to Valanginian. The formation yielded abundant fossils including Belemnites, ammonoids and other.

Samanasuk Formation is overlain by **Lumshiwal Formation** which is formalized after 'Lumshiwal Sandstone' of Gee (1945). In the type locality, Lumshiwal Nala, it consists of thick bedded to massive and current bedded sandstone with silty, glauconitic sandy shale at the base. Abundant molds of brachiopods, ammonoids, belemnites and echnoids are reported from Samana Range section. Lower contact is gradational with Chichali Formation and the upper contact with Kawagarh Formation is disconformable.

The third member of Baroch group, **Kawagarh Limestone** name was approved by Stratigraphic Committee of Pakistan to replace the name 'Darasmand Limestone'. The formation consists of marls and shale with nodular limestone in Kohat region. It is divided into two members in kohat area, upper 1) *Tsukhel Tsuk Limestone* and lower 2) *Chalor silli Member*. From Darasmand area collignoceratid ammonoids are reported.

2.4.7 Paleocene (Makarwal Group)

Hangu Formation name is coined by Stratigraphic Committee of Pakistan. This formation in Kohat area, is composed of sandstone with shale intercalations in top. The sandstone is white, redish brown, fine to coarse grained, medium to thick bedded. In Salt Range, Hangu Formation consists of variegated sandstone, carbonaceous shale, shale, and argillaceous nodular limestone. It also has ferruginous sand bed at the base. its age is Early Paleocene.

Davies (1930) introduced the name **'Lokhart Limestone'**. This formation is mainly composed of grey color, medium to thick bedded, brecciated limestone in the Kohat area. In salt Range, it is characterized by light grey, medium bedded, nodular limestone with presence of minor marls and calcareous bluish color shale in the lower portion. Lokhart Limestone is richly fossiliferous. Various workers reported abundant foraminifera species. Based on the presence of fossils species its age is Early to Middle Paleocene.

The name **'Patala Formation'** which is the third member of Makarwal group, is formalized by SCP after the 'Patala Shale' of Davies and Pinfold (1937). In salt range, the formation is mainly composed of marls and shale with subordinate sandstone and limestone. The shale is calcareous, greenish-grey, carbonaceous, and having marcasite nodules in places. The subordinate sandstone is found in the upper part of the formation. The Patala Formation bear coal seams in Dandot area of Eastern Salt Range. Smout and Haque (1956) recorded larger foraminifera. Based on fossils, its age is Late Paleocene.

2.4.8 Eocene (Chherat Group)

Nammal Formation

The name 'Nammal Formation' is accepted by SCP which was earlier known as 'Nammal marl' of Danilchik and Shah (1967). The section exposed in Nammal Gorge Salt Range is designated its type locality. Throughout its extent, the formation is composed of shale, marl, and limestone. The shale is olive-green to grey in color and the limestone and marls are bluish grey to light grey. The formation is about 100m thick in the type locality (Nammal Gorge). Its lower and upper contacts with Patala and Sakessar Limestone are transitional. Nammal Formation is highly fossiliferous and yielded molluscs and foraminifers. The larger foraminifera include *Nummulite atacicus, Lockhartia tipperi, L. hunti, L. conditi, Operculina nummulitoides, Discocyclina ranikotensis, and Fasciolites oblonga* and smaller foraminifera include *Textularia crookshanki, Quinqueloculina gapperi, Alabamina wilcoxensis, Loxostomum applinae, etc.* Early Eocene age is assigned to Nammal Formation based on fauna.

Sakessar Limestone

The name 'Sakessar Limestone' was presented by Gee for the Eocene rock unit in the Trans-Indus Ranges and Salt Range. The Sakessar Peak (highest peak in Salt range) is selected as the type section for the Sakessar Limestone but it is a prohibited area due to military camp. Therefore, other reference sections for the field purposes and sampling are Bhadrar village section Central Salt Range, as proposed by Fatmi (1973). The formation is dominantly composed of light grey to cream white nodular limestone with marls. The limestone is cream to light grey in color, massive, with chert in the upper part. The marl forms a persistent horizon of light grey color at the upper part of the formation.

Sakessar Limestone has widespread occurrence in the Salt Range and Surghar Range. In some areas like Bhadrar, Dandot, Nilawahan, Nammal and Majuchh etc, the Sakessar Limestone may be called Dolomitic Limestone because here it consists of (10-50%) yellowish orange to pink color dolomite (Boustani, 2000). The lithology of Margalla Hill Limestone and Sakessar Limestone are almost similar, so the Nammal Formation and Sakessar Limestone in Salt Range and southern Potwar plateau are lateral equivalent of Margalla Hill Limestone. The quantity of chert increases toward the top of the formation as observed by different scientists. According to various workers, the chert nodules in Margalla Hill Limestone are larger and the increase in amount of chert toward the top is the differentiating characteristic between Margalla Hill and the Sakessar Limestone. But in the Sakessar Limestone large size up to 50cm chert nodules are also found, so this criterion cannot be used for distinguishing these two formations.

The Sakessar Limestone is highly fossiliferous and produced various fossils including foraminifers, echnoids and molluscs. Among the foraminifers, *Fasciolites oblonga, Assilina leymeriei, Fasciolites globosa, Lokhartia conditi, Opercula nummulotoids, L. hunti, Orbitolite camplanatus* and *Sakesaria cotteri* are common. Boustani (2000) for the first time reported green algae from this formation. The Algae reported belong to the genera Uteria, Neomeris, Cymopolia, Trinocladus Ctvpeina, Acicularia orioporela Ovulites and Furcoporella. According to the stratigraphic distribution, these types of algae have been reported from the Eocene rocks. Based on these fossils' assemblages, its age is Early Eocene (Ypresian).

Its thickness varies between 70m to 150m in the Salt Range. In Chichali Pass it thickness is about 220m while about 300m in other parts of the Salt Range. According to Fatmi (1977) and Shah (1980), the Upper contact of the Sakesar Limestone is conformable with Chorgali Formation in Central Salt Range while disconformable in the western Salt Range. The lower contact is conformable with Nammal Formation.

Chorgali Formation

The name 'Chorgali Formation' is formalized by the stratigraphic committee of Pakistan which was previously named by Latif (1970) as 'Lora Formation'. It is divisible into two parts in the salt range where the lower part is composed of limestone and shale and the upper part is composed of limestone. The limestone is argillaceous and light grey in color while the shale is greenish grey and calcareous. In the salt range, it the formation rests conformably on the Sakesar Limestone and is unconformably overlain by Murree Formation. According to Shah (2009), the formation is richly fossiliferous and foraminifers, molluscs and ostracods has been reported by Davies and Pinfold (1937), Eames (1952),

2.4.9 Miocene (Rawalpindi Group)

After collision of Indian plate with Eurasian plate in Eocene age, the Tethyan ocean closed, the marine sedimentation stopped and terrestrial setting prevailed. The name Rawalpindi Group is given to the rock units which comprise the **Murree** and **Kamlial** Formations. The Murree Formation is composed of purple and red clay, greenish grey sandstone and intraformational conglomerate. The lower part is composed of calcareous sandstone and conglomerate with abundant derived larger foraminifera of Eocene age. The formation is dominated by sandstone which is medium to coarse grained in the Kohat area. This formation throughout its extent, unconformably overlies various formations of Eocene age (Figure 2.1).

The '**Kamlial Formation'** is dominantly composed of purple-grey to red sandstone with interbeds of hard shale and intraformational conglomerate. This formation is differentiated from the underlying Murree Formation by its spheroidal weathering and heavy mineral content. It is widely distributed in Kohat and Potwar areas. Several fossil mammals have been recorded from the formation.

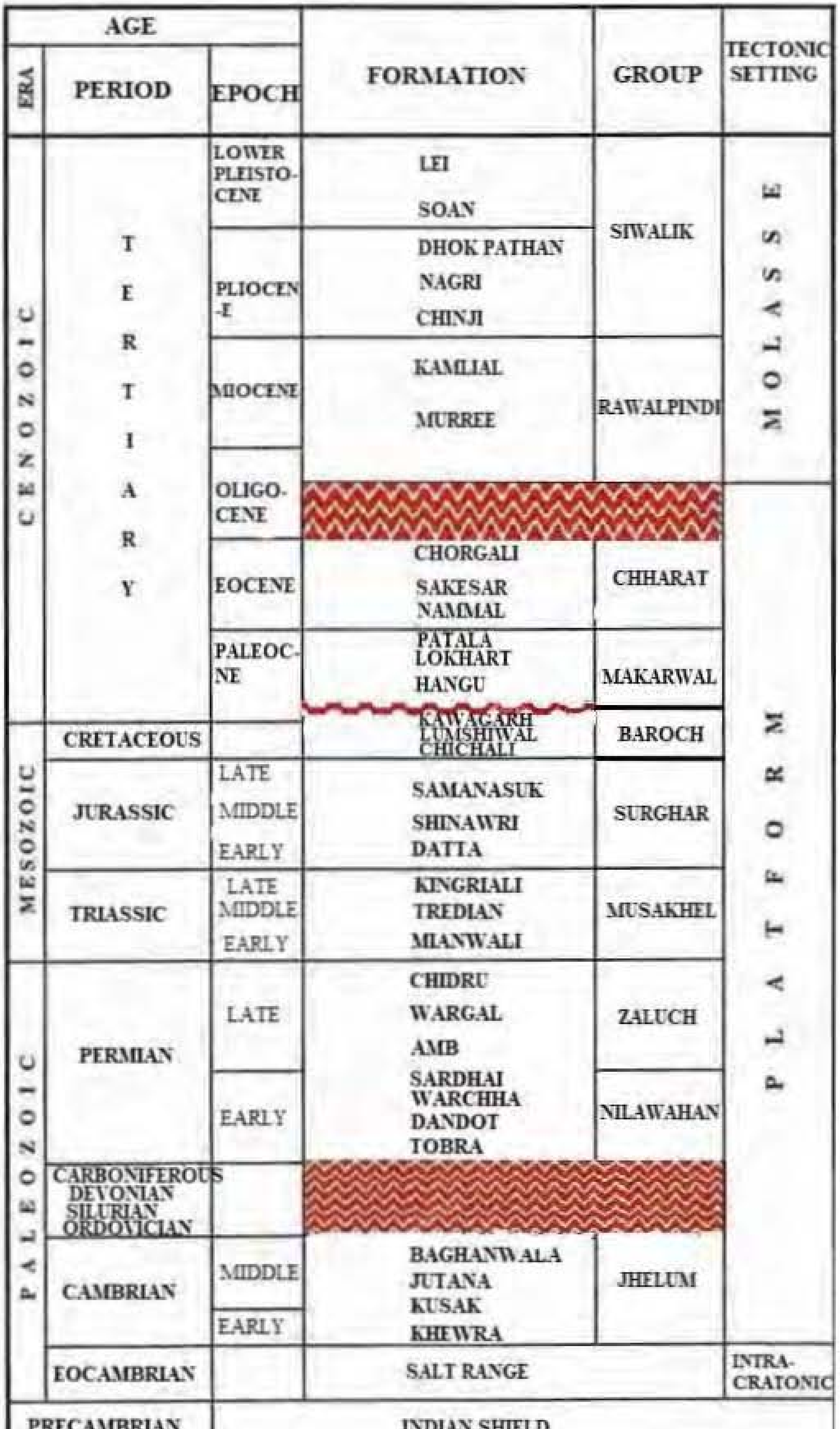

Figure 2.1. Generalized Stratigraphy of the Salt Range (modified after Robert D. Lawrence, 2015).

Chapter-03 Outcrop Observations

3.1 Introduction

For convenience in field, a reconnaissance field was conducted to eastern and central Salt Range to mark the sections and find accessibility to the outcrop exposure of the Sakesar Limestone at various sections. The samples were collected based on variation in lithofacies and different features were also observed at outcrop scale. In reconnaissance field, we marked 3 sections for sampling i.e Ratucha Village section (32°41´14.93´ N, 72°58´51.85´´ E), Dandot village Section (32°40´12.43´´ N, 72°57´26.60´´ E) in the eastern salt range and Sardhai village section (32°41´0.60´´ N, 72°43´1.54´´ E) in the central salt range. During the field work for sample collection, all the field features of the formation observed and studied as well as the rock unit exposed were sampled in a systematic way.

3.2 Eastern Salt Range

3.2.1 Ratucha Village Section

The Sakesar Limestone is mined by Frontier Works Organization (FWO) near Ratucha village, Choa Saidan Shah and the limestone unit is well exposed in this quarry. Here the thickness of Sakesar Limestone is about 35m having massive limestone at the bottom followed by medium to thin beds on the top (Figure 3.4). In this section, the formation can be differentiated into two parts based on color variations and limestone behavior (Figure 3.1).

A) Lower Massive Limestone unit

The lower unit of the formation is yellowish grey to light grey nodular limestone. This unit is characterized by marls which are present around the limestone nodules. The limestone nodules range in size from 15cm to 20cm, but it has larger than 20cm in places. The limestone is fractured in this lower part in this section. From the bottom, the limestone is composed of about 7m massive, yellowish, grey-dark grey, (light color on fresh surface) nodular limestone. This is overlain by about 8m thick yellowish to grey limestone with shale intercalations (Figure 3.1). According to Ghazi et.al (2014) these nodules are regarded to be of diagenetic origin and it is the characteristic feature of the Sakesar Limestone.

B) Upper well bedded Limestone unit

The lower limestone unit is followed by approximately 11m thick, massive, light grey nodular limestone with shale intercalations and marl matrix. In the middle part of the formation, a 1.5m thick, hard, white color limestone bed is observed. This bed is different from above and below units of the limestone because it shows no nodularity and it is hard. This unit is overlain by medium bedded, creamy-white color limestone with shale intercalations and this interval is about 5m thick. It is overlain by a light grey to yellowish color, massive limestone bed which is about 3.5 to 4m thick. This thick unit is overlain by white to cream color medium to thick-bedded limestone units and it is about 4m thick. In this section, the lower contact of the Sakesar Limestone is not exposed while the upper contact with the Chorgali Formation is wavy, sharp, and conformable.

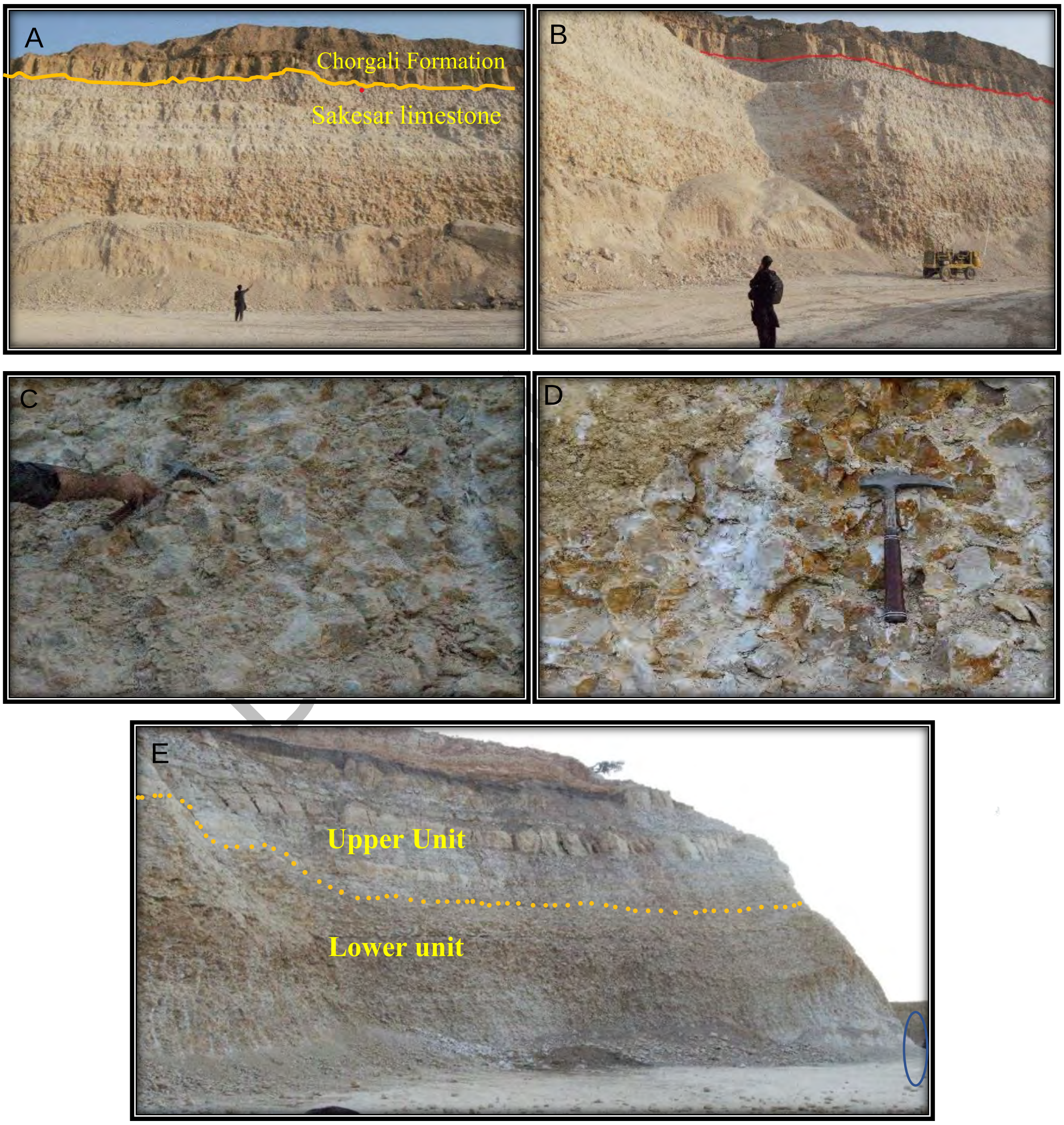

Figure 3.1. Photographs Showing Field features of Sakesar Limestone Eastern Salt Range. (A, B) contact with Chorgali Formation. (C, D) Nodular Limestone with marls. E) Upper and lower Units.

3.2.2 Dandot Village Section

The Sakesar Limestone in Dandot village section is exposed and here the thickness of the formation is about 22m. Lower contact is not exposed and the Chorgali formation is also missing in Dandot village section. From the base, the formation is composed of thin to thick bedded, light to cream color, fossiliferous limestone beds with shale intercalations. These beds are overlain by about 4m thick massive limestone unit of same color. These limestone beds are highly fractured having vertical and horizontal fractures (Figure 3.2) and some fractures are filled by cementing materials. These limestone units are followed by medium bedded limestone and massive limestone which continues to the top. The upper massive beds are yellowish to white, fossiliferous, and nodular limestone that have chert nodules of different sizes as shown in the Figure 3.2. The formation has a greenish color shale bed and marls in the upper part.

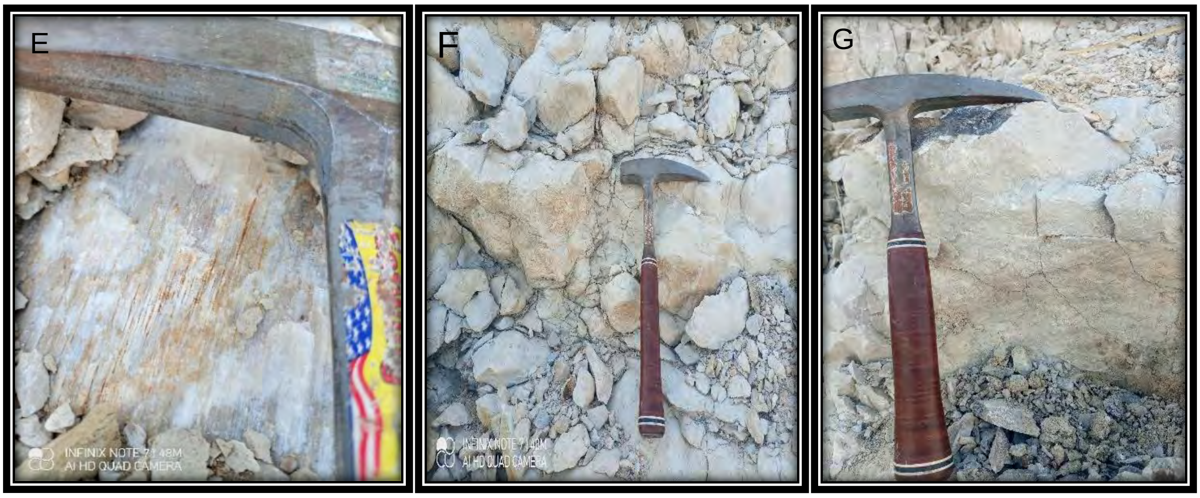

Figure 3.2. Photographs showing Field features of Sakesar Limestone, Dandot village section. (A, D) lower part with medium to thick bedded, fractured (arrows) limestone. (B) upper massive nodular limestone. (C, F, G) shale intercalations in limestone beds. (E) quartz cementation in some fractures.

3.3 Central Salt Range

3.3.1 Sardhai Village Section

The Sakessar Limestone in the central salt range makes well exposures in peaks and both the upper and lower contacts are exposed. In Sardhai village section the limestone has conformable contact with the underlying Nammal Formation and a wavy sharp contact with the overlying Chorgali Formation. Here the formation is composed of yellowish to light color, fossiliferous, fractured, and nodular limestone with chert nodules in the upper portion (Figure 3.3). The chert nodules are of different sizes and increases from middle to top of the strata. The limestone is medium to thick bedded and massive as we move from base to top. The thickness measured in this section is about 30m. There are shale intercalations in the middle, marls in the upper part of the formation.

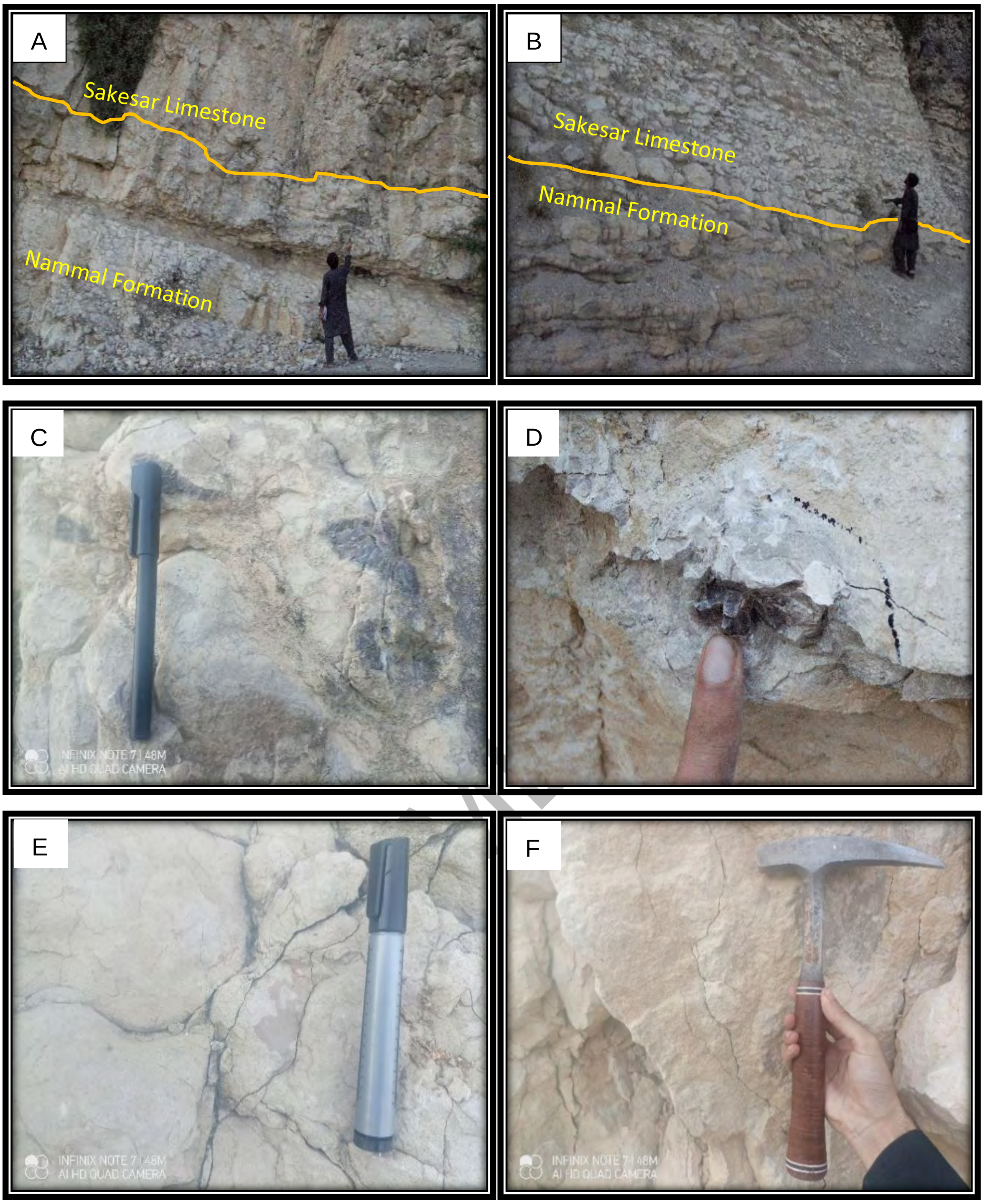

Figure 3.3. Photographs showing, (A, B) Contacts between sakesar limestone and Nammal Formation central salt range. (C, D) Chert nodules. (E, F) horizontal and vertical fractures in the Sakesar Limestone.

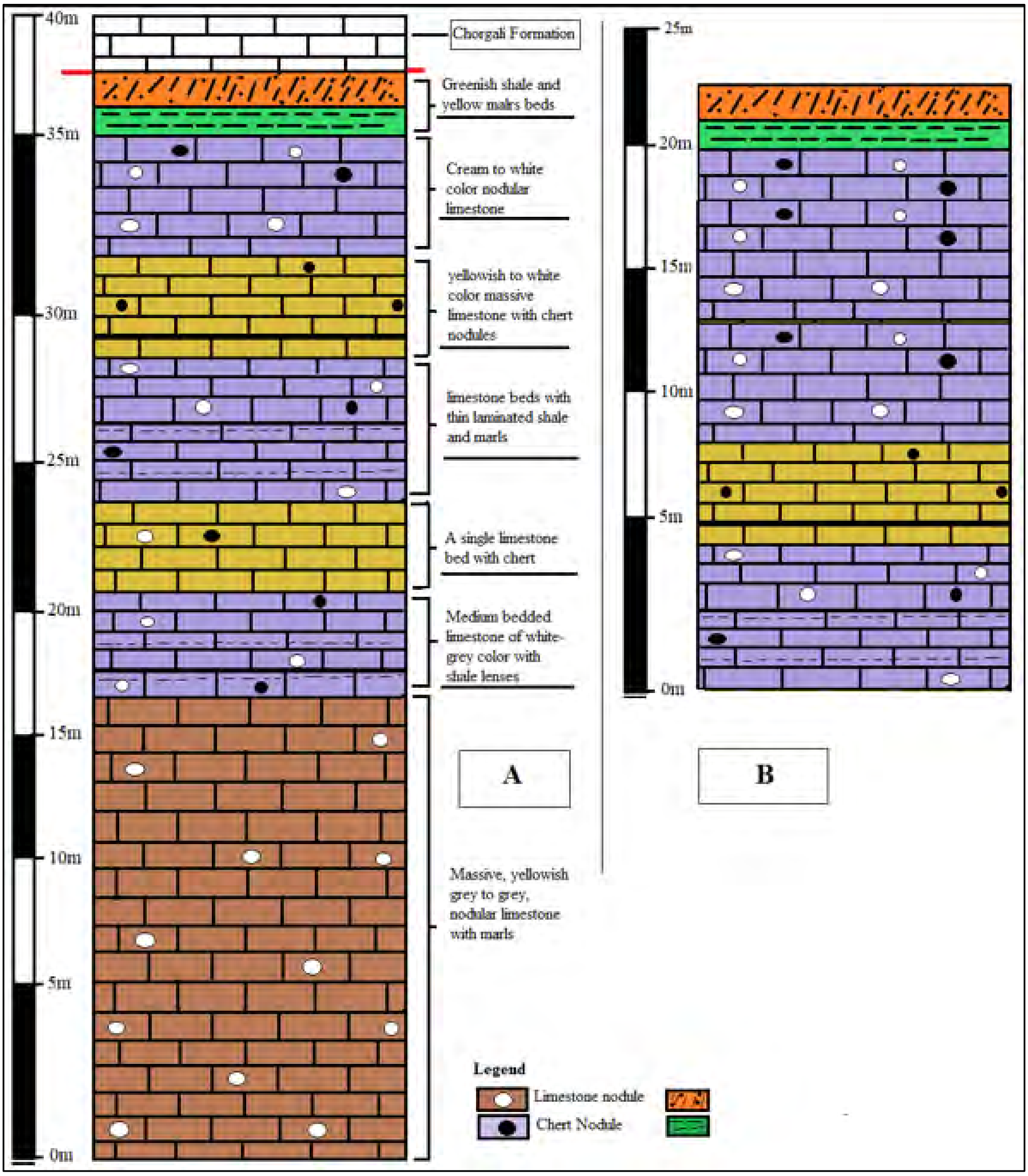

Figure 3.4. Litho-log of Sakesar Limestone in the (A) Ratucha Village section and (B) Dandot village section, eastern Salt Range.

Chapter-04 Core Studies

4.1 Introduction

In the present studies the core cuttings of Sakesar Limestone studied is from Balkassar oil field well number 7. The Balkassar Oil Field is located in Block Balkassar, eastern flank of Soan Syncline, Potwar sub-basin, onshore Pakistan and it is operated by Pakistan Oil Fields. It is a conventional oilfield which recovered about 91% of its recoverable hydrocarbon's reserves. The Balkassar Oil Field production reached its peak production in 2010 which was about 0.43 thousand bpd of condensate and crude oil (Global Data fields database, April 2022). According to the information provided in Global Data fields database, the production from Balkassar oil field will continue till 2036 when it will reach its economic limit.

4.2 Core features of Sakesar Limestone

Core of Sakesar Limestone were studied from top to bottom from Balkassar Oil Field well number 7 and the features observed are discussed as follows.

The total length of the core was about 8.25m (from 8032 ft to 8064 ft interval). From top to bottom, the core consists of light brown to dark, fossiliferous, and fractured limestone. The Limestone samples are hard which have medium to fine grain texture with different fossil assemblages. The top part of limestone is characterized by chert nodules having very fine grain texture. The dark color of the limestone may be due to high TOC contents. Lower portion of limestone have an interval which is less fossiliferous as compared to above and below samples and the density of fractures is also low in this part. The limestone is characterized by bedding parallel and vertical, low and some high amplitude stylolites, mostly horizontal and some vertical factures and some of these fractures are filled with cementing materials as shown in the Figure 4.1. These fractures and stylolites in some places merge into one another. The Limestone shows no observable primary depositional structures in hand specimens. the cements composed of fine silica and some fractures contains calcite cements. The microfossils present in the core samples cannot be identified without microscope but some species are identified in hand specimens including Alveolina and Assilina species with the help of a hand lens. The lower part of the Sakesar Limestone in the present studied core also has chert nodules. Overall, from top to bottom, the limestone is brown to dark, fossiliferous, fractured and having chert nodules. The features of Sakesar Limestone in hand specimens studied in the present study is displyed in Figure 4.2.

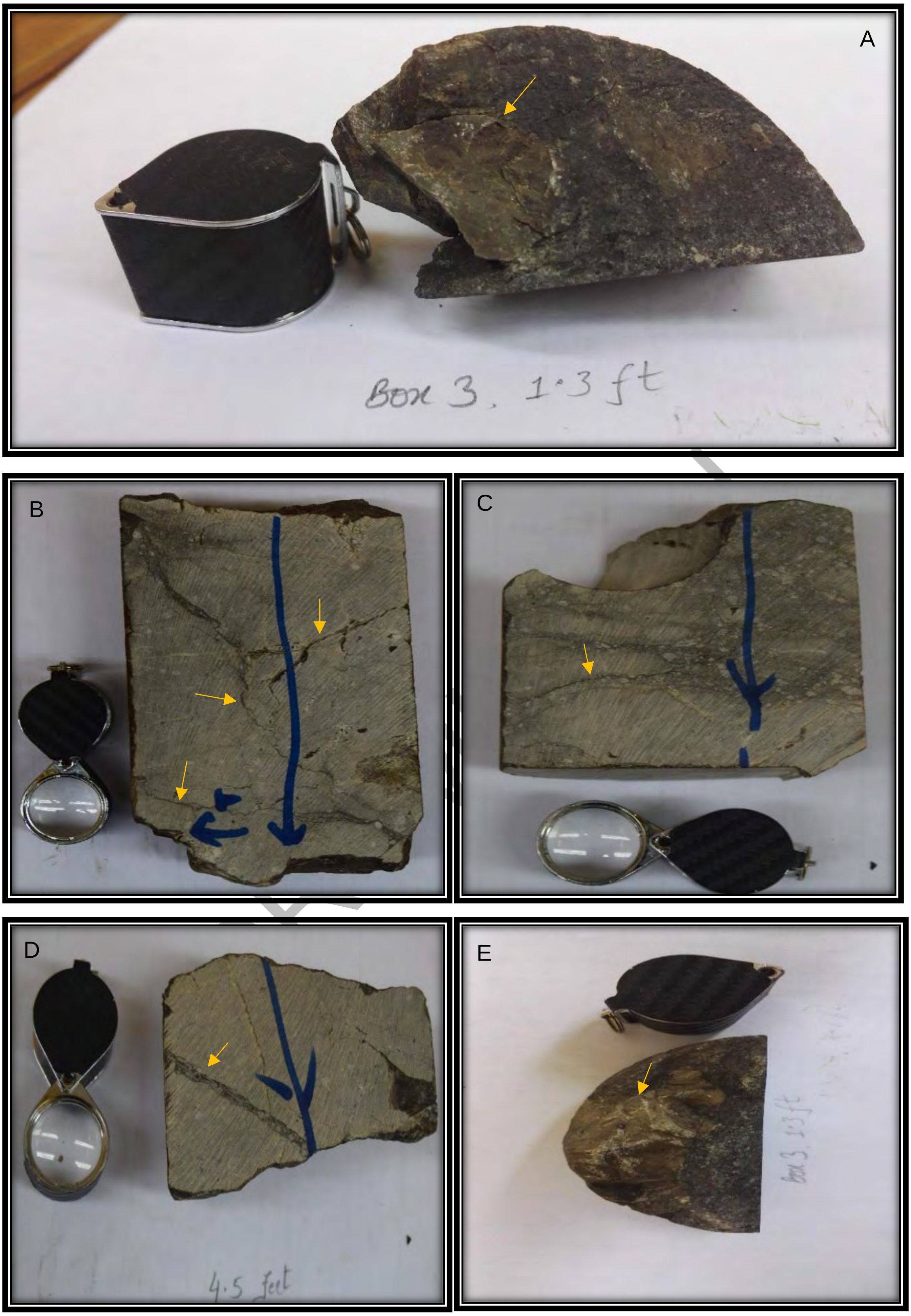

Figure 4.1. Photographs showing core features of Sakesar Limestone from the Balkassar-7 well. A, E) Chert nodules (arrows). B, C, D) horizontal and vertical fractures and stylolites (arrows point towards fractures). Some fractures are filled with cement (c).

4.3 Well-tops of Balkassar-7

The well-tops of Balkassar-7 well are given in the Table 1.

Table 1. Showing Well-tops of Balkassar-7 well, Potwar Basin.

Formation	Depth in feet	Depth in meters	Thickness (m)
Nagri	0	0	455
Chinji	1492.8	455	935.4
Kamlial	4561.9	1390.4	106.7
Murree	4911.9	1497.7	901.6
Chorgali	7870.13	2398.7	49.4
Sakesar	8032.2	2448	119.2
Patala	8423.3	2567	

4.4 Plugs selection

The location of core plugs for porosity and permeability assessment were selected based on the features like fractured zones, relatively low fractured zone, or unfractured limestone and fossil contents at various depths as shown in Figure 4.2.

Chapter-05 Results and Discussion

5.1 Introduction

To convey and communicate the information about rocks, they are classified into various types. The limestone classification is modified and updated with time which enabled us to understand the origin and depositional environments of the carbonate rocks (Peter, 2011). According to Flugel (1982), the limestone microfacies and rock type should be classified in such manner which are related to some environmental conditions in which the deposition of the corresponding sediments occurred. The microfacies developed based on sedimentological and fossil contents thus shows certain sedimentary environmental conditions (Flugel, 1982, Wilson 1975).

The most widely used classifications of carbonate rocks are those of Dunham (1962) and Folk (1959, 1962) and both classify limestone primarily based on amount of matrix and major component grains. Folk classified a rock as allochemical rock if it contains more than 10% allochems (carbonate grains). Based on percentage of matrix, the rock maybe further divided into two groups; sparry allochemical limestone which contains coarse sparry calcite and microcrystalline allochemical limestone which contains microcrystalline calcite, micrite, mud. Further division is based on the ratios of allochems. If Dunham and Folk's classifications schemes are compared, a rock rich in carbonate mud are called micrite by Folk and a wackestone or mudstone by Dunham. Similarly, if a rock having small amount of matrix is called sparite by Folk and packestone or grainstone by Dunham.

5.2 Dunham's classification of Limestone (1962)

Dunham classification scheme is shown in Figure 5.1. This classification is based on the fabric of particles and the type of particle which are binding during deposition. Dunham used names that combine the names of type of fabric and name of grain types present in a sample/thin-section. For example, if the grains in the limestone touching each other and it contains no or negligible mud contents, then it is called a grainstone. If there is a small amount of mud and the carbonate is grain supported, the limestone is called packestone. If the sediment is mud supported and possess more than 10% grains or allochems, then it is known as a wackestone. If it is mud supported and contains less than 10% grains then it is called a mudstone. In case of the reef limestone, this classification is modified by Embry and Klovan (1971) and they introduced the terms floatstone (grains larger than 2mm in size) and rudstone. These terms bafflestone, bindstone and framestone are used for the fabric of organically bound and other biogenic rocks.

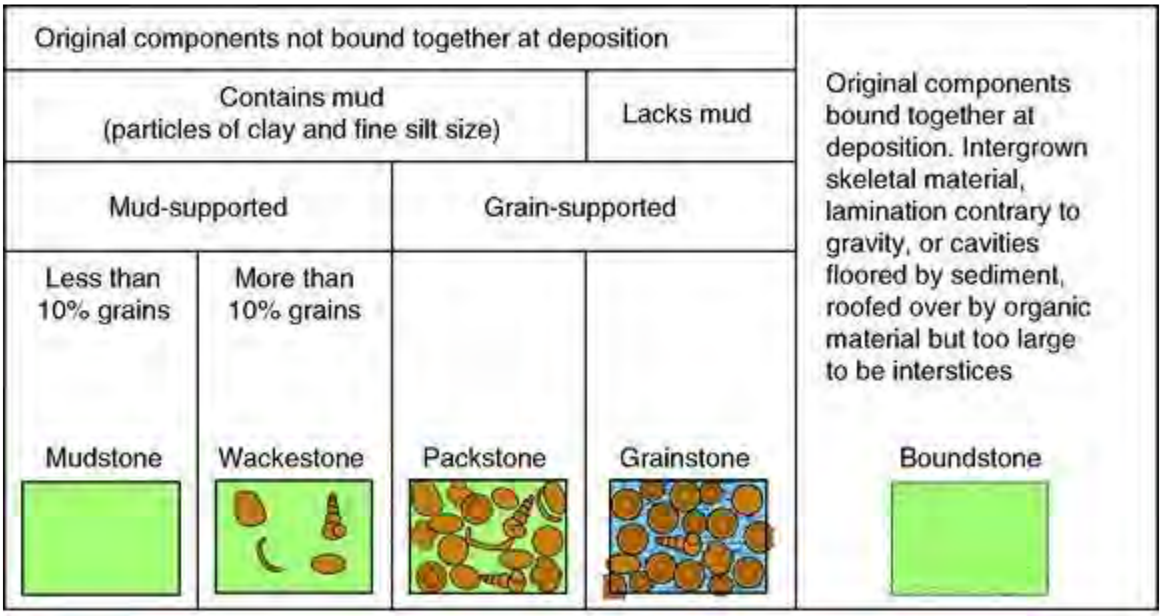

Figure 5.1. Dunham classification of limestone (Kendal, 2005).

5.3 Petrography

In the present study, the petrographic analysis was carried out to explain the characteristics of Sakesar Limestone like the amount of matrix, allochems, cement, and other constituents. The petrographic data is then used to identify the microfacies. In turn, the microfacies characteristics is then helpful in interpretation of the depositional environment of the Sakesar Limestone. The main constituents recognized in the Sakesar Limestone includes skeletal allochems or bioclasts, micrite and sparite. The bioclasts are present in a micrite matrix and most samples also contains sparite. The skeletal grains present are mostly composed of larger benthic foraminifera, green algae, some planktonic foraminifera, Gastropods and Echnoids as well as broken parts of organisms. Micritization is observed in various thin sections which shows the early diagenetic alterations of Sakesar Limestone. The Skeletal grains are composed of whole tests of organisms and broken parts. Some skeletal grains are replaced by equant calcite cement. In thin-section SLR-11 from Ratucha village section contains coarse to medium grained sparite which replaced the micrite almost completely. Those samples which have fractures and stylolites shows that Sakesar Limestone experienced tectonic forces because of which these fractures formed and later filled with diagenetic cements. Sparry calcite precipitation within the void spaces become coarse from margin toward the center of the void space (Flugel, 1982). The Sakesar Limestone in the studied sections are petrographically classified as micritic limestone.

5.4 Microfacies

After thin-sections studies, the paleontological and sedimentological data i.e the percent amount of matrix and micrite or matrix and allochemical grains or bioclasts of Sakesar Limestone is used and the microfacies are recognized in the studied sections. Following the Dunham (1962) classification scheme of limestone, from bottom to top, the major microfacies recognized in the Sakesar limestone are wackestone and packestone. These microfacies possess allochems and matrix in variable amount and these two are the main microfacies identified in this study. The following five different microfacies are recognized within the wackestone and packestone microfacies from bottom to top in the studied thin-sections from eastern and central Salt Range.

5.4.1 Calcareous Algal-Miliolidal wackestone microfacie (MF-1)

This microfacie is represented by the samples SLR-1A-C, SLR-2, SLR-3, and SLR-10, from eastern salt range and SLC-3, SLC-4, SLC-6 from central salt range. This microfacie is dominantly consist of *Algae* with *Miliolid* as skeletal grains and micrite as matrix. The micritic content range from about 48% to 55% and the skeletal grains range from about 35% to 40% with an average of 37%. Calcite spar present 5% to 8%. The dominant skeletal grains in this microfacie are green algae *Dasycladaceae*. The internal cavities and in some cases the outer parts are replaced by micrite and the other body parts by calcite. The Dasycladaceae include *Acicularia specie, jodotella veslensis, Neomeris plagnensis, Cymopolia cf. Mayaense, Halimeda sp,* (Figure 5.2). Other skeletal grains include Miliolids and broken fragments of foraminifera. This microfacie is characterized by high pyritization and some dissolution is also observed. Neomorphism and micritization is present around the bioclasts. Microfractures are also present in some thin-sections of this microfacie which are filled by equant calcite cement.

Depositional Environment

The green algae *Dasycladaceae* mostly favors the shallow warm-water settings of euphotic zone and this is low energy marine lagoonal condition of the inner ramp (Beavington-Penney et al. 2006; Granier 2012). Similarly, *Miliolids* are also present in this microfacie which can be found in calm shallow lagoonal-water conditions of the inner-ramp (Adabi et al. 2008; Swei and Tucker 2012). This suggests that this microfacie of green algae associated with Miliolids foraminifera and the extent of micrite matrix, was deposited in the shallow water lagoonal environment of the inner-ramp.

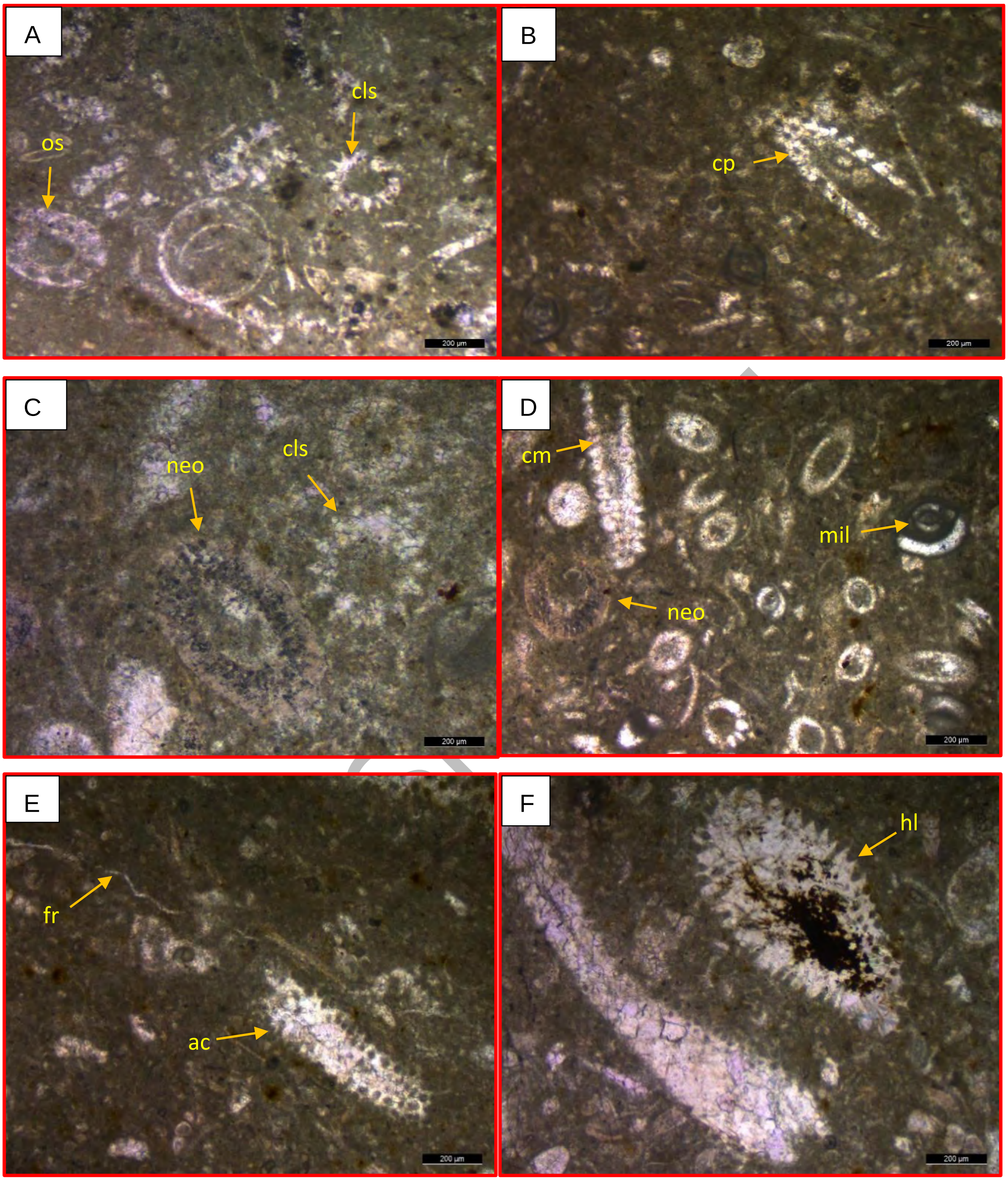

Figure 5.2. Photomicrographs showing Calcareous Algal-Miliolidal wackestone (MF-1). A) Otternstella lemmensis (os), Clypeina sp. (cls), (sample SLR-1B). B) Cymopolia cf. (cp) (Sample SLR-1B). C) Clypeina sp. (cls), Neomeris plagnensis (neo) (sample SLR-1C). D) Cymopolia cf. Mayaense (cm), Miliolid sp. (mil) (sample SLR-10). E) Acicularia sp. (ac), filled fracture (fr) (sample SLR-2). F) Halimeda? Sp. (hl) (sample SLR-2).

5.4.2 Alveolina-Miliolidal Packestone (MF-2)

This facie is represented by samples SKD-1, SKD-2, SKD-3, SKD-4, SLR-8, SLR-12, SLR-13 from the eastern salt range and SLC-5, SLC-7 and SLC-12 and 13 from central salt range. This microfacie is characterized by about 50% to 71% allochemical grains and about 29% to 45% micrite matrix (Table 2). The interlocking blocky calcite crystals observed is about 4% to 7%. The well preserved bioclastic grains are dominantly composed of *Alveolina* and *Miliolids* species along with planktonic foraminifera in small amount (Figure 5.3). The bioclasts internal parts are partially recrystallized with calcite. The microfacie also contains smaller benthic foraminifera. All the studied samples except SKD-2 are characterized by excessive diagenetic pyrite. Open and filled micro-fractures and microstylolites are commonly present. The fractures are filled with calcite. Dissolution and micritization is also observed around the grains.

Depositional Environment

The Alveolina specie and Miliolid both favor calm and shallow water environmental conditions (Beavington-Penney and Racey 2004, Hohenegger et al. 1999). From fossil constituents and micritic contents, this microfacie was deposited in inner ramp, low energy depositional conditions.

5.4.3 Assilina-Nummulitic Wackestone microfacie (MF-3)

This microfacie is observed in samples SLR-5, SLR, 9, SKD-6, SKD-9, from the eastern salt range and SLC-8,10, SLC-11 and SLC-17 and 18 from central salt range. This microfacie is composed of about 32% to 42% bioclasts and 55% to 60% carbonate mud or micrite. About 5% to 8% sparry calcite is also present. The bioclastic content is well preserved and dominated by *Assilina* and *Nummulite* larger benthic foraminiferal assemblage. The Assilina species include *Assilina spinosa, Assilina subspinosa,* while the Nummulite species include *Nummulite globolus* and other *Nummulite sp.* (Figure 5.4). This microfacie also contain *Alveolina* specie. Broken shells of ostracods, broken unidentified bioclasts and some ghosts are also present. Some bioclasts are replaced by cements and their Molds are present in some samples which are filled with cements. Sample SLR-6 possess little pyritization but the remaining samples have high diagenetic pyrite content. Sample SKD-6 have vertical burrows. All samples contain unfilled fractures but some are partially filled with calcite. Micritization is common in all thin-sections and they occure around the margins of bioclasts. The filled fractures observed are filled with interlocking crystals of blocky calcite. The sample SKD-9 contain green algae.

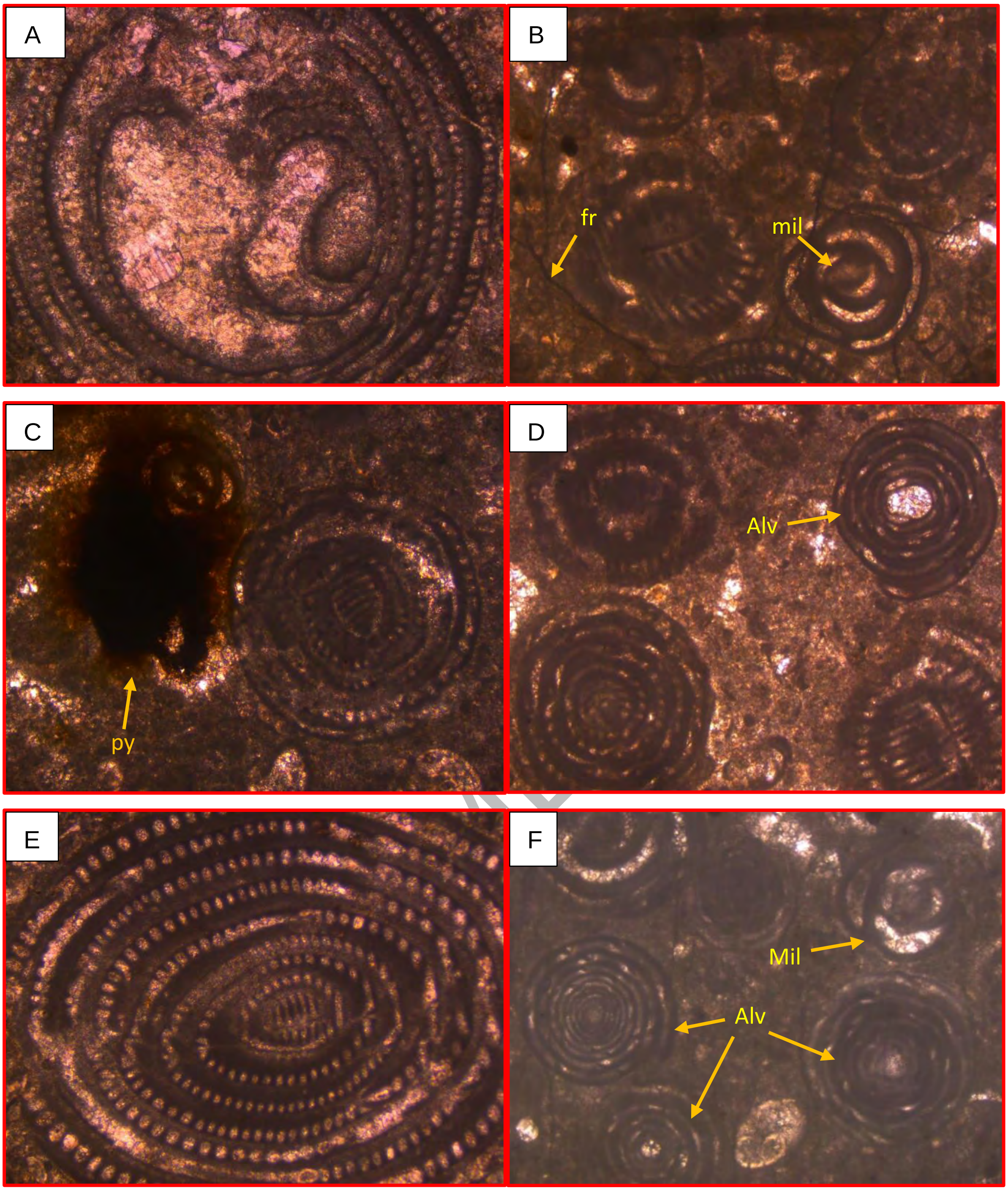

Figure 5.3. Photomicrographs showing Alveolina-Miliolidal Packestone (MF-2). A) Alveolina nuttalli (Sample SKD-4). B) Alveolina and Miliolids species (mil), fracture (fr) (sample SKD-2). C) pyritization (py) and Alveolina sp. (sample SKD-1). D) Alveolina aff. Varians (sample SKD-1). E) Alveolina cf. levantina (sample SKD-4). F) Alveolina (alv) and Miliolids sp. (mil) (sample SKD-1).

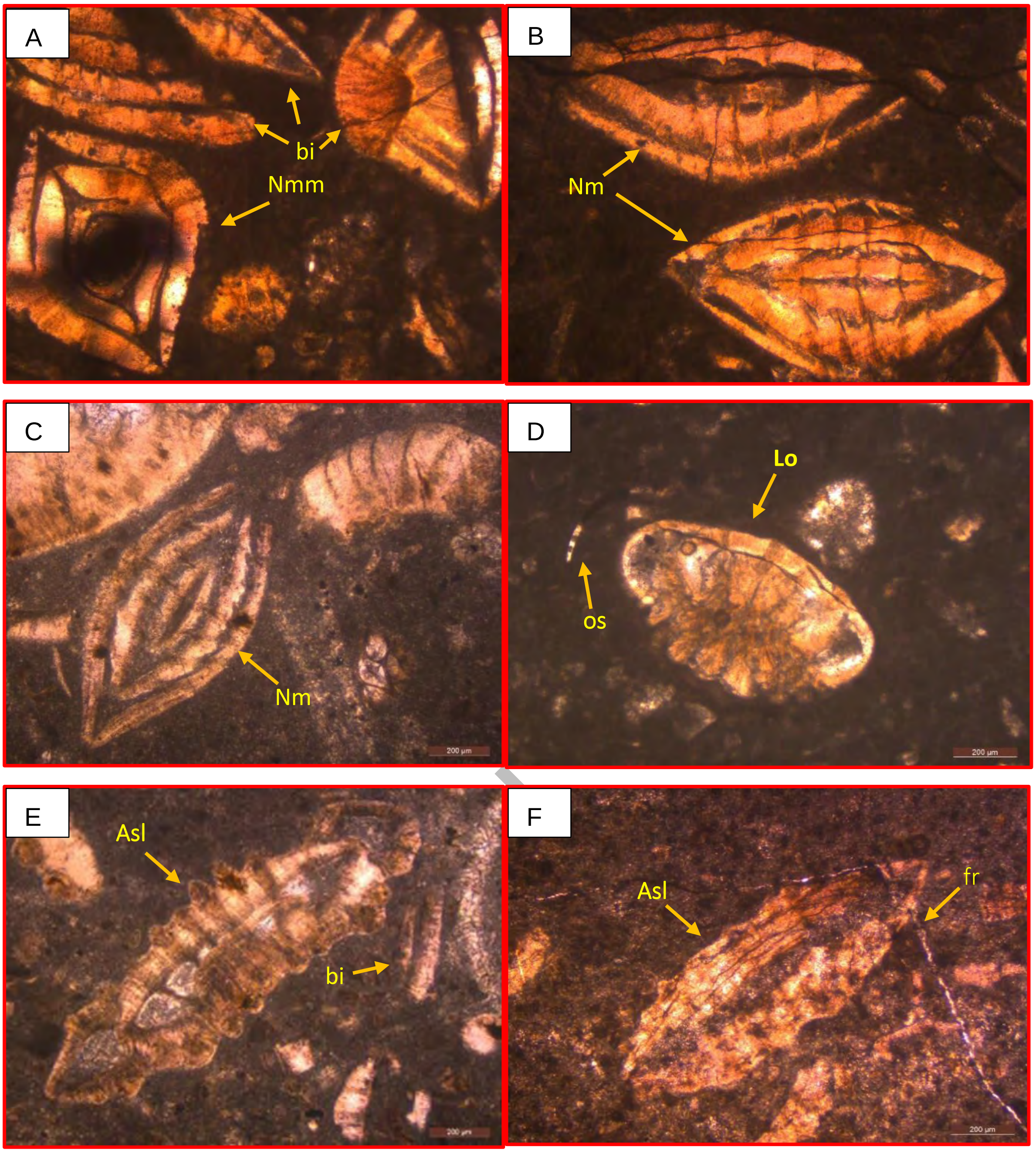

Figure 5.4. Photomicrographs showing Assilina-Nummulitic wackestone (MF-3). (A) *Nummulites mamillatus* (Nmm) and bioclasts (bi), sample SKD-10. (B, C) *Nummulites sp.* (Nm), Sample SKD-10 and SLR-9. (D) *Lokhartia sp.* (Lo) and broken shells of Ostracods (os), sample SKD-9. (E) *Assilina spinosa* (Asl) and bioclasts, Sample SLR-9. (F) *Assilina sub-soinosa* (Asl) with fracture (fr), Sample SLR-9.

Depositional Environment

The Nummulites reported from various parts of the world are commonly found in the middle ramp environment but if they are associated with Assilina, then it represents a little deeper environmental condition (Vaziri-Moghaddam et al. 2006, Mriheel 2000, Mehr and Adabi 2014, Racey 2001). As this microfacie (MF-3) have Alveolina and according to Hohenegger (1999) the Alveolina shows warm water environmental conditions. So, MF-3 is dominated by Nummulite and Assilina along with Alveolina, its deposition occurred in middle ramp with low energy conditions.

5.4.4 Lokhartia rich, Foraminiferal wackestone (MF-4)

This microfacie is represented by SLR-4 and SLR-7 from eastern salt range and SLC-2, SLC-1, 2 and SLC-9 from the central salt range. This facie is predominantly composed of *Lokhartia* specie as allochems and micrite matrix (Figure 5.5). The matrix content in sample SLR-4 is relatively higher as compared to the SLR-7. The allochemical content range from 34% to 40% and micrite from 56% to 65%. Other larger benthic foraminifera present in this microfacie include, *miliolids*, and *gastropods*. Molds and broken shells of ostracods are also observed which are filled with medium grained calcite cement. Small benthic foraminifera are also present. The dissolved portion of limestone is filled with blocky interlocking calcite. Micritization and diagenetic pyrite is also present. In sample SLR-7, stylolites and filled fractures are observed.

Depositional Environment

According to Racey (1994), the *Lokhartia sp.* represent inner-middle ramp environment. Lokhartia in association with miliolids shows inner-ramp restricted conditions with low water turbulence environmental conditions (Adabi et.al 2008, Beavington-penny, 2006). Therefore, the MF-4 microfacie was deposited in outer lagoonal of inner-ramp to middle ramp depositional environment.

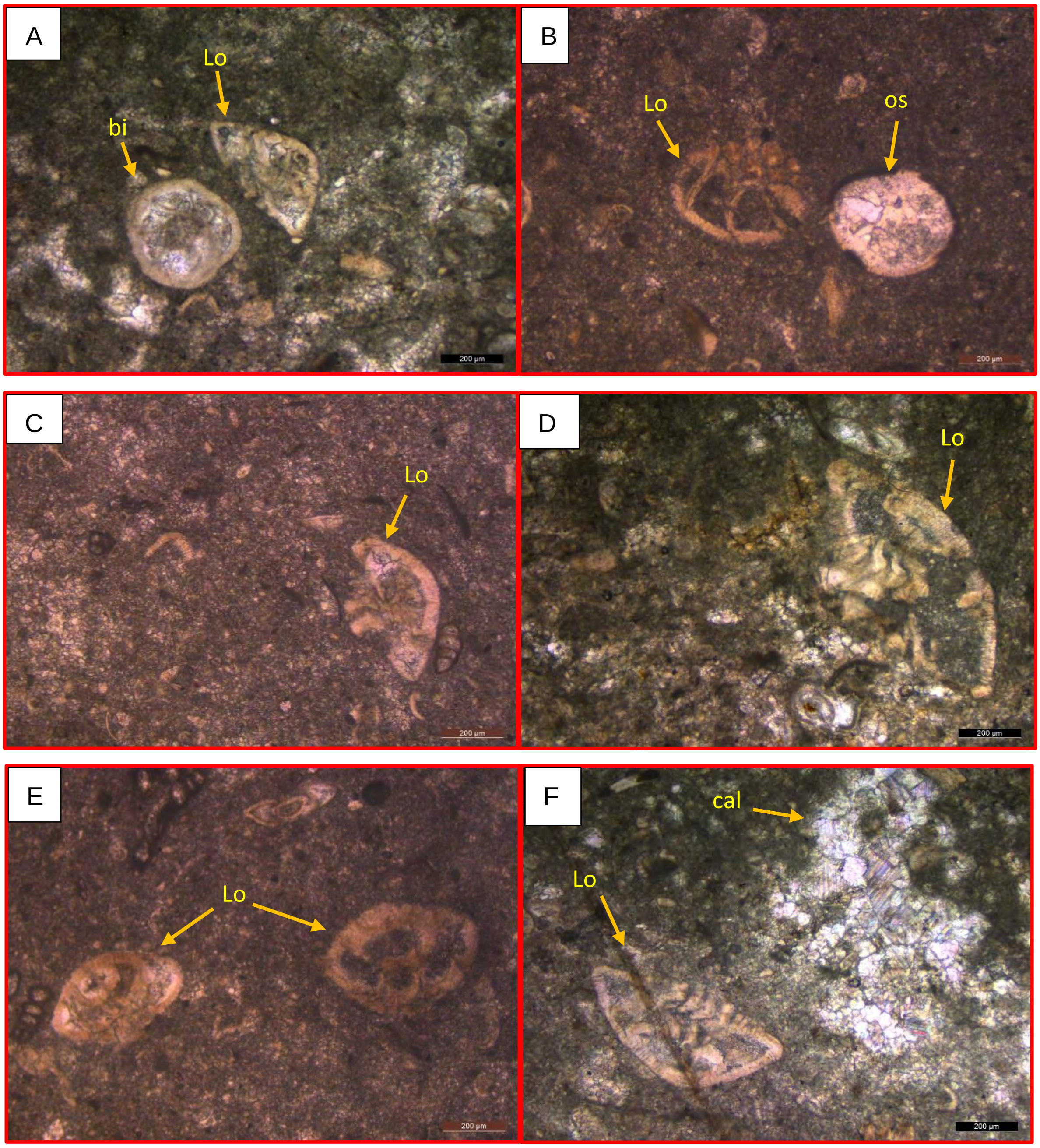

Figure 5.5. Photomicrographs showing Lokhartia Rich-Foraminiferal wackestone (MF-4). (A, C, D, E) *Lokhartia sp.* (Lo) with bioclasts (bi). (B) *Lokhartia sp.* and mold of *Ostracod* (osm). (F) coarse calcite cement (cal) with *Lokhartia sp.* samples SLR-4, SLR-7.

5.4.5 Nummulitic-Heterostegina packestone microfacie (MF-5)

The MF-5 microfacie is identified in sample SLR-11 from eastern salt range and SLC-14 and 15 from the Sardhai village section. This microfacie is represented by bioclasts including *Nummulites* and *Heterostegina* foraminifera along with *Ranikothalia*. The nummulite species in this microfacie includes *Nummulite globolus* and *Ranikothalia.* Other bioclasts include *Lokhartia,* small forams and broken fragments (Figure 5.6). The groundmass is about 55% to 72% which is dominantly composed of calcite crystals of medium grained size and micrite is in small amount up to about less than 30%. This microfacie contain unfilled fractures. Some bioclasts are replaced by coarse equant calcite cement. The filled fractures are filled with blocky interlocking calcite crystals. Some pyritization is also found but in very small extent.

Depositional environment

The *Nummulites* represent middle-ramp environmental conditions. The *Heterostegina sp.* represent proximal middle ramp environment (Hossein Ghanbarloo et al, 2020). Therefore, the MF-5 microfacie of the Sakesar Limestone was deposited in middle ramp environment.

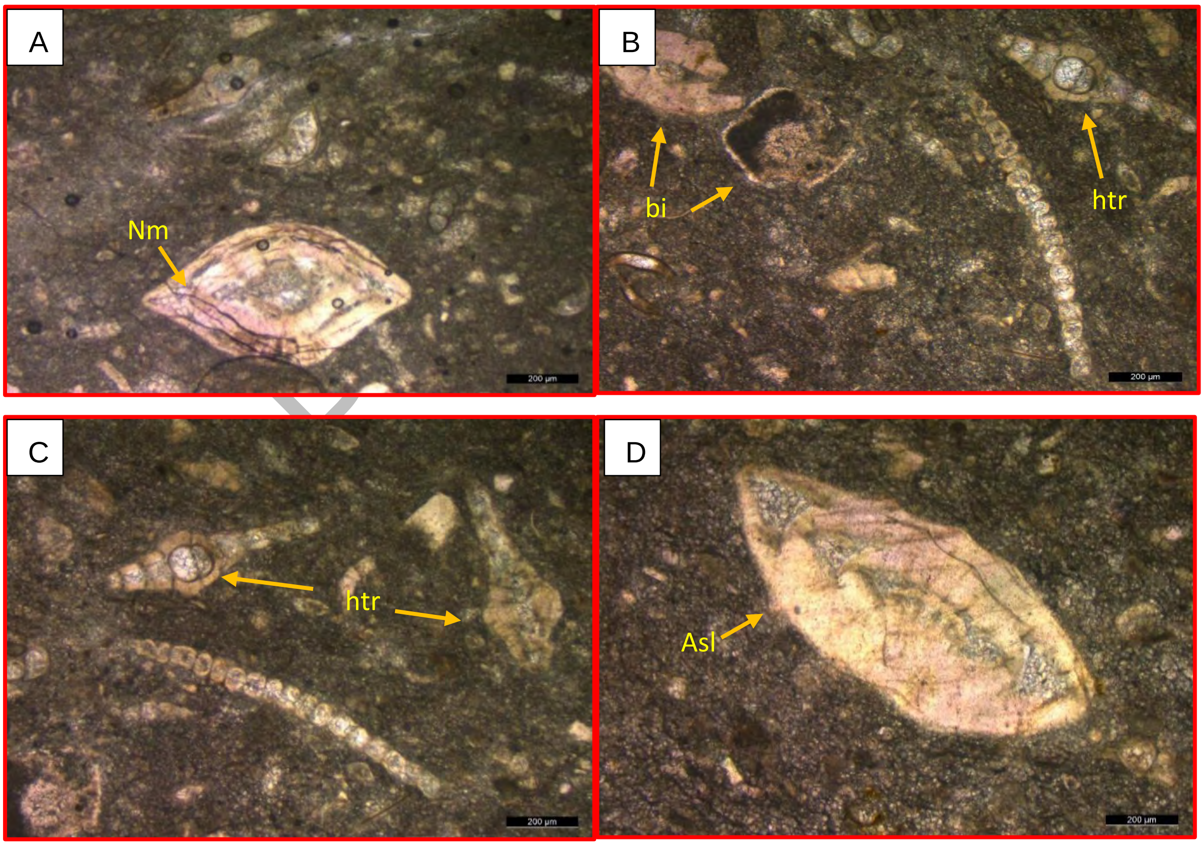

Figure 5.6. Photomicrographs showing Nummulitic-Heterostegina packestone microfacie (MF-5). (A) *Nummulite sp.* (Nm). (B, C) *Heterostegina sp.* (ht) with bioclasts (bi). (D) *Assilina sp.* (Asl).

Table 2: Percentage of skeletal grains, porosity (visual) and matrix in microfacies of Sakesar Limestone.

Microfacie	Skeletal grains (%)	Matrix (%)	Sparite (%)	Porosity (visual) (%)
MF-1	35-40	48-55	6-9	0.71
MF-2	50-71	29-45	4-7	2.1
MF-3	32-42	55-60	5-8	1.3
MF-4	33-40	56-65	6-8	2.9
MF-5	40-44	25-35	12-15	1.5

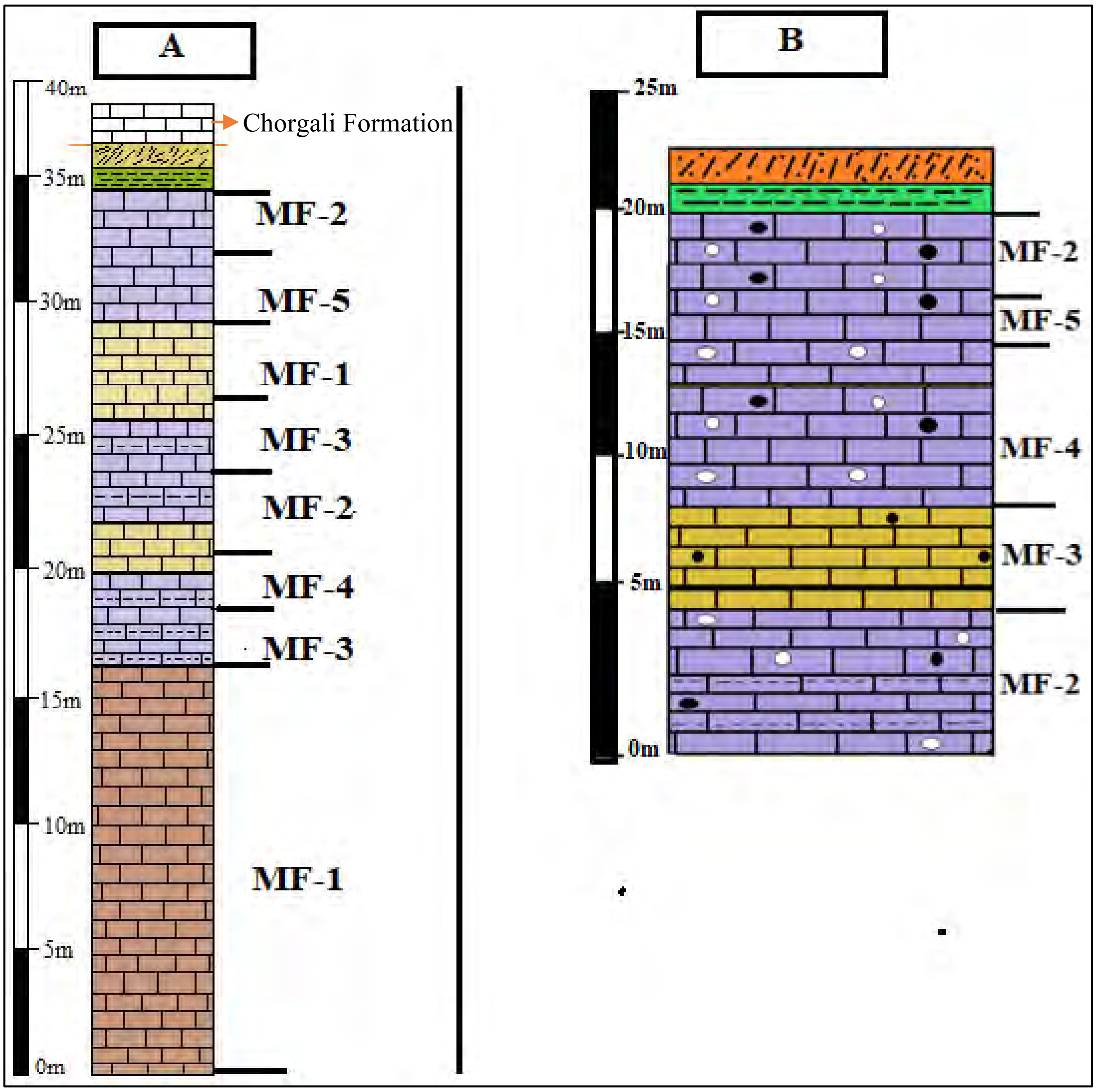

Figure 5.7. Distribution of the microfacies in the (A) Ratucha village section and (B) Dandot village section, Salt Range.

5.5 Reservoir Characterization

5.5.1 Introduction

Porosity and permeability are the two most vital and important parameters that enable a reservoir rock to hold and permit the fluids to flow through its pore network. Porosity and permeability of a rock depends on many factors such as depositional environment, lithofacies, diagenesis, fracturing etc. Permeability is an important parameter which show flow rates in a porous media. Porosity and permeability dependence and its results of the present research work are discussed as follows.

5.5.2 Porosity

Porosity is the void spaces in a rock that can be filled with oil, gas, water, or mixture of these all fluids. Porosity of sedimentary rocks depends on the grain shape, packing, orientation, size, and sorting of the sediments. The cubic packing of sediments has the highest porosity of 48% (Fraser and Graton). The porosity of carbonate rocks is strongly affected by many factors which may increase or decrease it. When the sediment is deposited, it has initial porosity called primary porosity. This primary porosity is altered by diagenetic processes like bioturbation, compaction, cementation, dissolution or leaching with geological time. Bioturbation in limestone sediments mixes the sediments and fine grains are precipitated. Cementation of sediments leads to destruction of primary porosity. The dissolution of sediments creates void spaces which increase the porosity. The porosity generated after the deposition of the rock is called the secondary porosity. Similarly, the clay coatings completely fill the void spaces by growing on the surface of grains over geological time (Schutjens, 1991).

The ratio of volume of void spaces in a rock to the total volume of the rock expressed as percentage and denoted by Φ.

$$\Phi = \frac{\text{Pore Volume}}{\text{Pore volume + volume of rock}} \times 100$$

There are two main types of porosity which are **Total porosity** and **Effective porosity**. Total porosity Φ_T, is the ratio of total volume of voids to the total volume of rock including the voids. Effective porosity Φ_e is the ratio of interconnected pores to the total bulk volume of the rock. It is the effective porosity which play a key role in the reservoir characterization and connect the pore spaces thorough pore throats for the flow of fluids.

5.5.3 Permeability

Permeability of a rock is the ease measurement with which a fluid can flow in the pore spaces. The flow of fluid is proportional to the pressure gradient. Permeability of a rock is dependent on pore spaces, pore throats, cements type between the sediments and size of pore space. There are three types of permeabilities are used in petroleum industries. The **absolute permeability** refers to the permeability of a rock when it is completely saturated with fluid. Permeability is **effective** to a particular fluid when that fluid occupies less than 100 % of the pore space. The ratio of effective permeability to the absolute permeability is called **Relative permeability**.

The formula used for finding permeability is given by:

$$K = Q\,\mu / A\,(\Delta P/L)$$

where k is the permeability

The unit of permeability is Darcey but the commonly used unit is millidarcy (md). Permeability determines the productive capacity of a reservoir rock. The permeability of a rock can be measured horizontally as well as vertically.

5.6 Visually Estimated Porosity

Different types of porosities were observed in the Sakesar Limestone. Reservoir analysis, both qualitative and quantitative from outcrop and well-cuttings were carried out with the help of petrographic analysis. Microscopic studies and mesoscopic scale analysis is used to identify different porosity types. For quantitative measurement of porosity and permeability, the core plug data were utilized from outcrop as well as well-cuttings.

A) Mesoscopic porosity

The mesoscopic scale porosity or outcrop scale porosity of the sakesar limestone is found by the existence of large and small fractures and small caverns in the study area. Both vertical and horizontal fractures are identified. The vertical fractures are more dominant at Dandot village section which are throughgoing (extensional fractures) from the base to the top (Figure 5.8). These fractures range in size from 1cm to 2cm and even larger which can play a key role in the flow of fluids (hydrocarbons) of Sakesar limestone because these fractures are mostly not filled. These fractures are associated with tectonic activity (folding) before faulting (Jadoon et. al 2005). Some caverns are also present which increase the porosity of the formation and can store large volume of hydrocarbons. They are formed due to the dissolution processes of the limestone.

Similarly, the well cuttings observed have fractures and stylolites that contribute to the high porosity and permeability values. Stylolites are irregular surfaces that form because of deep burial and vertical movements (Sadd JL. 2000). Both bedding parallel and vertical fractures are present some of which are filled with cementing materials but overall, most of the fractures are unfilled which has positive impact on the reservoir quality.

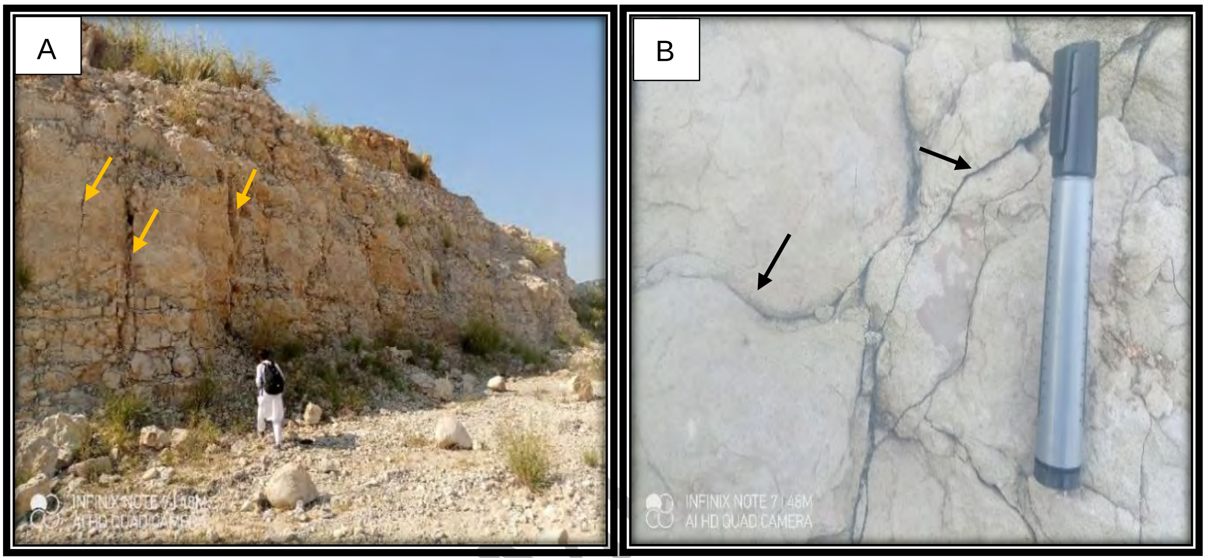

Figure 5.8. Photographs showing mesoscopic fractures in Sakesar Limestone. A) vertical fractures eastern salt range. B) vertical and horizontal fractures, central salt range.

B) Microscopic Porosities

The microscopic porosities are recognized using imageJ software from the samples all the studied sections. The most common porosity in the Sakesar limestone is the microfracture and stylolitic porosity, which are present in almost all the studied thin-sections. These fractures are overlapping each other as observed in some thin-sections. The intraparticle porosity is present in the identified microfacie and most of these are filled by cements or micrite (Figure 5.9). The interparticle porosity is present in MF-2, MF-3, and MF-4 microfacies. The solution porosity is present in MF-1 which can be regarded as the fluid solution which is undersaturated with respect to calcium-carbonate and dissolving the cements forming biomoldic and intracrystalline porosity. Overall, the visually estimated porosity values of Sakesar Limestone for all samples range from 0.7% to 2.9%. The dominant recognized microscopic porosity is of secondary origin with exception of some intraparticle porosity which can be regarded as depositional primary porosity. Fracture porosity is most common secondary porosity in the Sakesar Limestone which contribute and play a vital role in in increasing the reservoir rank and fluid storage development.

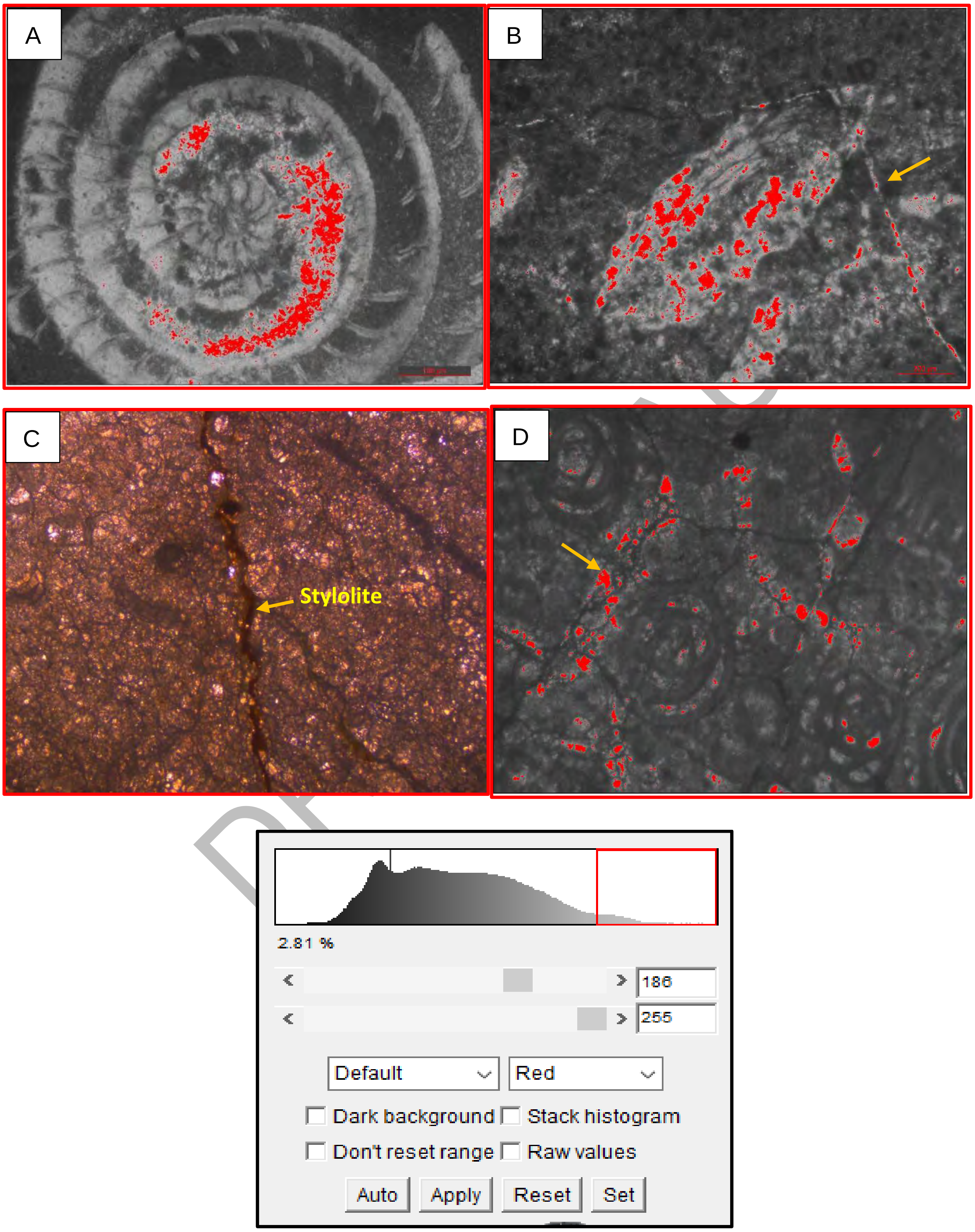

Figure 5.9. Photomicrographs showing microporosity types in various samples/thin sections. (A) intraparticle porosity (sample SLR-5). (B, D) microfracture (samples SKD-3 and SLR-9). (C) Stylolite (sample SKD-2).

5.7 Plug Porosity and Permeability

The visual measurement of porosity and permeability from microscopic examination give exaggerated values, therefore for the quantitative measurement, porosity and permeability is measured from the plugs of well-cuttings and outcrop samples. The plug porosity and permeability of the selected 12 samples including 5 outcrop samples (SKD-9, SKD-11 from Dandot village section, SLR-1, SLR-3, SLR-7 from Ratucha village section) and 7 well-cuttings from Balkassar-7 well (BK-1, BK-2, BK-3, BK-4, BK-5, BK-6, BK-7) at different depths was analyzed.

5.7.1 Porosity and permeability of outcrop samples

The measured plug porosity, permeability, grain density and other parameters values of the Sakesar Limestone from outcrop samples are summarized in Table 3. The samples SLR-1 and SLR-3 is representing the MF-1 microfacie (calcareous Algal-Miliolidal wackestone) while the Sample SLR-7 is belonging to the MF-4 microfacie (Lokhartia rich Foraminiferal wackestone). Sample SKD-9 represent MF-3 microfacie (Assilina-Nummulitic wackestone) and SLR-11 represent the MF-5 microfacie. All the values of porosity lie in the range from 0.66% to 2.98% with an average of 1.58%. Highest porosity value is 2.98% belonging to the MF-4 and lowest 0.66% for the MF-3. Similarly, the plug permeability varies from 0.05Md (millidarcy) to 0.09md (MF-1). The lowest value of permeability is for sample SLR-1 and highest permeability value is 0.09md exhibited by the sample SLR-3 from the Ratucha village section.

Table 3. Porosity, permeability, and grain density values of outcrop samples of Sakesar Limestone.

Sample ID	Sample Length (cm)	Sample Diameter (cm)	Dry Weight (grams)	Grain Density (g/cm^3)	Porosity %BV	Permeability (Md)
SLR-1	4.76	2.54	64.13	2.69	1.45	0.05
SLR-3	5.71	2.54	76.9	2.69	1.42	0.09
SLR-7	5.39	2.54	71.29	2.69	2.98	0.06
SKD-9	3.49	2.54	47.35	2.69	0.66	0.06
SLR-11	5.39	2.56	73.54	2.70	1.39	0.06

5.7.2 Porosity and Permeability of well-cuttings

Total of seven (7) plugs of Sakesar Limestone were selected from the Balkassar-07 well at various depths and analyzed for porosity and permeability values. The results of plug tests of porosity and permeability are summarized in Table 4. The highest value of porosity is for sample BK-7 which is 2.60% at depth of 8063ft and lowest for sample BK-1, 0.79% at a depth of 8032.9ft. and the average porosity is 1.37% for Sakesar Limestone. Similarly, the permeability lies in range between 0.06md and 0.44md.

Table 4. Showing Porosity and permeability values at various depths from the Balkassar-07 well.

Sample ID	Depth (ft)	Sample Length (cm)	Sample Diameter (cm)	Dry Weight (grams)	Grain Density (g/cm^3)	Porosity %BV	Permeability (md)
BK-1	8032.9	3.61	2.55	49.01	2.68	0.79	0.10
BK-2	8038.5	3.53	2.55	47.47	2.66	0.81	0.06
BK-3	8047.1	3.40	2.56	46.17	2.68	1.69	0.09
BK-4	8049.4	3.17	2.56	43.36	2.69	0.81	0.10
BK-5	8052.7	3.56	2.55	48.53	2.70	0.97	0.13
BK-6	8058	3.43	2.55	46.14	2.68	1.98	0.44
BK-7	8063	3.20	2.55	43.22	2.71	2.60	0.17

5.8 Discussion

5.8.1 Microfacies and Depositional Environment

The vertical distribution of microfacies and their depositional environments interpreted, association of different fossils within the recognized microfacies, amount of skeletal allochems and other bioclasts, and matrix amount shows that the Sakesar Limestone deposition occurred in semi-restricted lagoonal shallow marine conditions of the inner-middle ramp (Figure 4.12). As stated earlier that during the Eocene time, there was abundant larger benthic foraminifera including *Nummulites, Miliolids, Assilina, Alveolina* (Adabi et al, 2014). The Nummulites sp. are found in a wide range of marine conditions of inner-middle ramp and sometime in outer-ramp (Racey, 2001). The smaller lenticular shape Nummulite sp. often in association with Miliolids, green algae and Alveolina sp. are found in inner-ramp environmental conditions and the flat shaped Nummulite along with Assilina sp. shows a little deeper condition of middle-outer ramp (Beavington-Penney and Racey 2004; Barattolo et al. 2007). Racey (1994) suggested the distribution of fossil associations along the carbonate ramp during the Eocene times which shows that Dasycladale algae and miliolids occure in the shallowest part of the ramp and Assilina, Nummulite and Alveolina species occure in the deep part of the middle-ramp. So, the larger benthic forams are used for facie interpretations and they are the best indicators of paleoenvironments and predicting reservoir properties which are deposited in shallow water marine conditions (Geel, 2000). The presence of larger benthonic foraminifera in the Sakesar Limestone shows that this formation deposition occurred in the photic zone.

5.8.2 Reservoir Quality

Reservoir quality refers to the storage capacity and deliverability of fluids of a given reservoir. The porosity values of Sakesar limestone at outcrop level and at depth lies in range between 0.66% and 2.98%. Similarly, the permeability values range from 0.05md to 0.44md. The 2.98% (MF-4) value show that it has relatively higher storage capacity compared to other samples. Similarly, the well-cuttings highest porosity value is 2.60% for the sample BK-7 as shown in Table 5. The relatively low permeability values shows that the pore system in the Sakesar Limestone is not interconnected which results in low values. Amaeful et al. (1993) introduced the terms RQI (Reservoir Quality Index), FZI (Flow Zone Indicator) and RPI (Reservoir Potentiality Index) to qualify the character of flow in a reservoir and it is successfully applied by many authors to explain the quality of reservoirs (Nabawy et al. 2018). The Reservoir Quality Index is calculated for the given values of porosity and permeability of Sakesar

Limestone using the formula given below (a) and summarized in Table 5. The resulted values are then compared with standard values to find rank and reservoir quality of Sakesar Limestone.

RQI = 0.0314 × √ (k / Ø) ……………..(a)

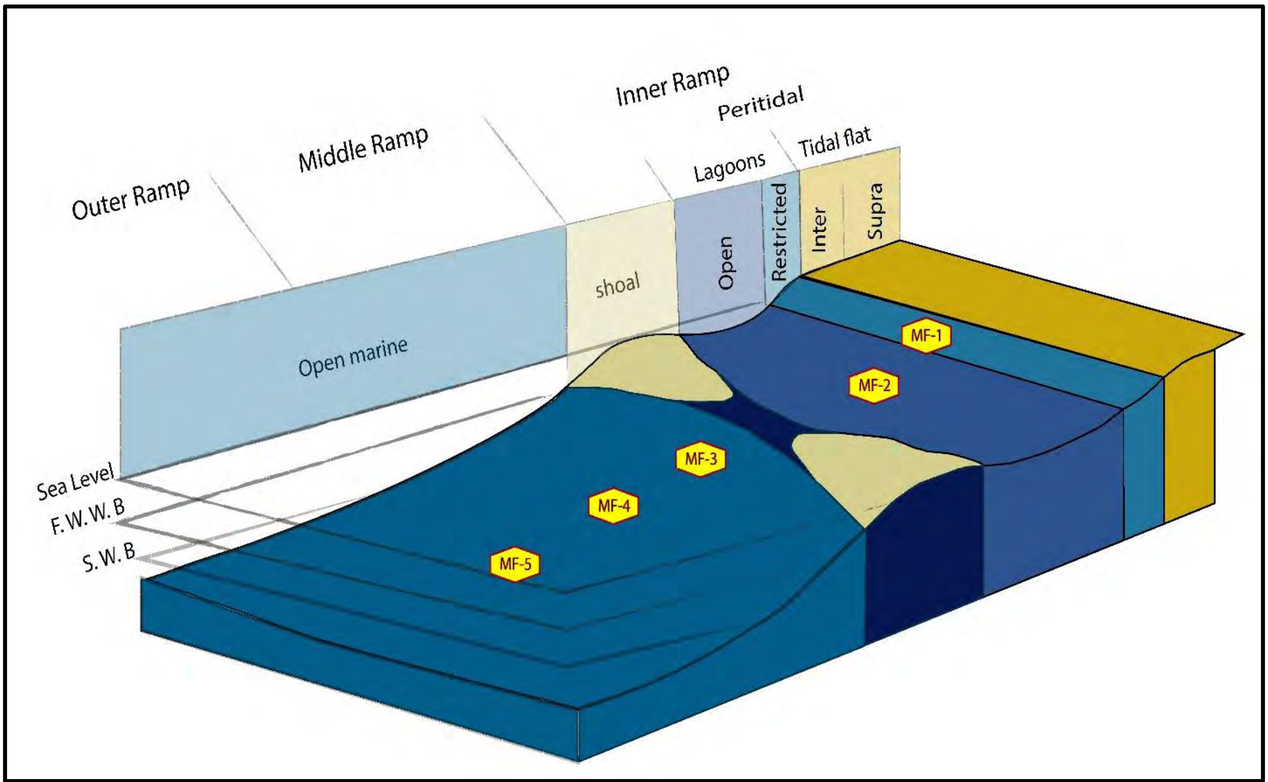

Figure 5.10. Depositional environment and distribution of microfacies of Sakesar Limestone.

Table 5. Classification of Reservoir quality of Sakesar Limestone based on Porosity, permeability, and reservoir quality index.

Porosity (%)	Permeability (mD)	RQI (μm)
0.79	0.10	0.111
0.81	0.06	0.085
1.69	0.09	0.0724
0.81	0.10	0.11
0.97	0.13	0.114
1.98	0.44	0.148
2.60	0.17	0.0802

Table 6. Standard values of reservoir quality (Nabawy et al. 2018).

Porosity (%)	Permeability (md)	RQI (µm)	Rank
25 < Ø	1000 < k	5.00 < RQI	Excellent
20 < Ø ≤ 25	100 < k ≤ 1000	2.00 < RQI ≤ 5.00	Very good
15 < Ø ≤ 20	10 < k ≤ 100	1.00 < RQI ≤ 2.00	Good
10 < Ø ≤ 15	1.0 < K ≤ 10	0.50 < RQI ≤ 1.00	Fair
5 < Ø ≤ 10	0.1 < k ≤ 1.0	0.25 < RQI ≤ 0.50	Poor
0 < Ø ≤ 5	0 < k ≤ 0.1	0.00 < RQI ≤ 0.25	Tight

The resulted values of Reservoir Quality Index from Porosity and permeability data of Sakesar Limestone can be compared with standard values which shows that the reservoir quality and rank of Sakesar Limestone lies in range of Tight Reservoirs (Table 6).

The plug porosity and permeability are plotted on a semi-log graph to find a relationship between porosity and permeability of Sakesar Limestone. The porosity values show a positive correlation coefficient with the permeability (Figure 5.13). To fit a regression line to the set points of porosity and permeability values, the linear regression equation of $y=0.956x+0.0239$ has been calculated for the plug porosity and permeability values.

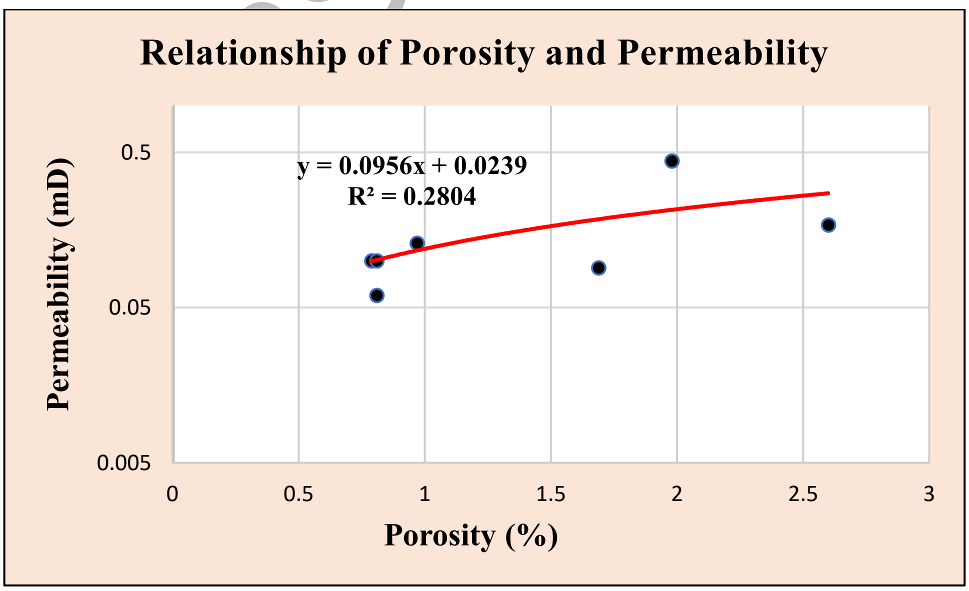

Figure 5.11. Showing Relationship between porosity and permeability of Sakesar Limestone.

According Nabawy et al. (2018) those rocks having porosity from 0 % to 5%, permeability from 0.1md to 1md, Reservoir Quality Index (RQI) from 0μm to 0.25μm are classified and ranked as 'tight reservoirs' (Table 6). Following this classification in the presence of plug porosity and permeability values of Sakesar Limestone, it can be concluded that it is a 'tight reservoir'. Because all the values of porosity, permeability and reservoir quality index falls in the above-mentioned range.

The carbonate reservoirs potentiality and storage capability are mainly controlled by the diagenetic modifications which can play a dual destructive or constructive role on a carbonate reservoir (Abuseda et al. 2015). This makes the carbonate reservoirs a very heterogenous body that changes its properties with time and environment. Micritization in the early history of Sakesar Limestone around the grains caused the filling of intraparticle pore spaces along with decreasing the pore throat size which in turn reduces the permeability. Cementation within the pore spaces during the early stages of diagenesis in Sakesar Limestone also reduced the reservoir quality. Cementation is one of the major processes that destroy the reservoir potentiality and quality by reducing pore spaces and pore throats (Rahimpour-Bonab 2009). Those facies having more than 10% calcite cement have low permeability values as compared to those facies which have less calcite cements (Cantrell and Hagerty 2003). Similarly, the precipitation of blocky calcite cement in later stages also reduced the pore spaces specifically the fractures, and as a result the reservoir quality of Sakesar Limestone is further reduced. The conversion of aragonite or micrite into micro-sparite in Sakesar Limestone by the process of neomorphism also reduced the porosity. The bulk volume is increased by 8% when aragonite converts to calcite which results in reduction of porosity by 8% (Selly 2000). Therefore, the early diagenetic modifications in Sakesar Limestone have impact on reservoir quality and it reduced its porosity by micritization and cementation.

On the other hand, the development of fractures in Sakesar Limestone which are observed on microscopic in almost all the samples and mesoscopic scale have positive impact on the reservoir quality. Because fractures increase the porosity as well as permeability. The stylolites formed in Sakesar Limestone during burial and its reopening and development of channels for fluid flow during tectonic uplift. Therefore, the stylolite development also has positive impact on reservoir quality by increasing total porosity of the Sakesar Limestone.

Conclusions

- The Early Eocene Sakesar Limestone having good exposures in eastern and central salt range are composed of grey to creamy white color nodular limestone with marls. The limestone contains chert nodules of various sizes and it increases from middle to top of the formation. The Sakesar Limestone is fractured and have vertical and horizontal fractures range in size from millimeter to centimeter and even larger.
- The core-cuttings of Sakesar Limestone from Balkassar-07 well are composed of light-dark brown limestone having fractures, stylolites, and chert nodules.
- The thin section studies shows that the Sakesar Limestone is composed of mainly wackestone, packestone and wackestone-packestone microfacies.
- From thin-section studies, five types of microfacies are identified namely Calcareous Algal-Miliolidal wackestone (MF-1), Alveolina-Miliolidal packestone (MF-2), Assilina-Nummulitic wackestone (MF-3), Lokhartia Rich-Foraminiferal wackestone (MF-4), and Nummulitic-Heterostegina packestone (MF-5).
- The association of fossil contents (Nummulites, Assilina, Algae, Miliolids, Lokhartia, Alveolina, small benthic foraminifera and planktonic fossils) matrix and other bioclasts it can be concluded that the Sakesar Limestone was deposited in Shallow-marine, Semi-restricted lagoonal conditions of inner-middle ramp depositional environment.
- The porosity values from outcrop samples on microscopic scale range from 0.7% to 2.9% which is dominated by fracture porosity.
- The plug porosity values range from minimum 0.66% to maximum of 2.98% and permeability from 0.05mD to 0.09mD for the outcrop samples. Plug porosity and permeability values of core-cuttings range from 0.79% to 2.60% and 0.06mD to 0.44mD respectively.
- The relationship between plug porosity and permeability of Sakesar Limestone on a semi-log plot shows a positive correlation coefficient.
- The porosity identified in thin sections include intraparticle and moldic porosities but the dominant type of porosity is the fracture porosity and these fractures have positive impact on the reservoir quality.

- The primary porosity of Sakesar Limestone is affected by diagenetic processes for example cementation, micritization, and compaction which mostly reduced the primary porosity and reservoir quality.

- The fractures developed in later stage due to tectonic processes and dissolution by undersaturated water or solution in Sakesar Limestone generally increased the reservoir potential because these fractures provide pathways for fluid flow and increase the storage capacity of the rock by creating and developing the pore spaces.

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MICROFACIES ANALYSIS AND RESERVOIR CHARACTERIZATION OF EARLY EOCENE (YPRESIAN) SAKESAR LIMESTONE

2**IN THE EASTERN AND CENTRAL SALT RANGE**

, UPPER INDUS BASIN, PAKISTAN By Arshad Jan M. Phil Geology

1**DEPARTMENT OF EARTH SCIENCES QUAID-I-AZAM UNIVERSITY ISLAMABAD, PAKISTAN**

2021-2023 Chapter-01 Introduction 1.1 Introduction In hydrocarbon industries, the standard indicators of reservoir quality are porosity and permeability. Both porosity and permeability are necessary for a reservoir rock to hold and yield hydrocarbons in commercial amount. The distribution of porosity and permeability in carbonate rocks are mainly controlled by factors like depositional facies, diagenetic modifications, and deformational processes. Approximately 50% of the fossil fuel in the world are extracted from carbonate reservoir rocks (Mazzallo, 2004). Hence, the study of reservoir properties of limestone is of great importance for the new discovery as well as for improving the existing production. The current reserves of oil and gas are on a very steep decline, so, to enhance the production from current conventional reservoirs, we need to know the reservoir properties in detail. The Eocene Sakesar Limestone is a potential and in some oil fields a proven reservoir in Upper Indus basin (Potwar and Kohat sub-basins) which produce hydrocarbons in various oil fields. In the early part of exploration history of Pakistan, approximately 50% of hydrocarbons reserves were added from the Eocene Reservoirs (Athar Jamil 2012). Porosity is the fundamental property of a reservoir rock and the reservoir is considered as good when it has porosity as well as permeability in the range which produce hydrocarbons in commercial amount. These two properties are the geometric properties of a rock, not genetic (F.K North) and production of hydrocarbons cannot be achieved without these fundamental properties. The distribution of porosity in a rock is dependent on depositional texture, distribution of depositional facies, rock fabric and diagenetic modifications. A rock may have high porosity and permeability when it is initially deposited but it may increase further or decrease with time because of the diagenetic changes, especially in case of carbonate rocks. 1.2 Previous work Many research work is published by various researchers on Sakesar Limestone which mainly focused on biostratigraphy, diagenesis, and depositional environment of the formation. According to Ghazi et. al, (2010), Davies, and pinfold (1937) worked out foraminiferal studies on Eocene successions of salt ranges. They described the lithology and reported larger benthic foraminiferal assemblages from Sakesar limestone. Later, paleontological studies were carried out by Gill (1953) and reported various fossil species. The exploration of hydrocarbons in Potwar area, is mainly from shallow lying Eocene and Paleocene rocks and they are mainly producing from the fractures (Jadoon et.al 2005, Abbas, 2001). According to Ibrahim Shah (2009), Sakesar limestone, Sheikhan Formation and upper part of the Margalla Hill Limestone are equivalent in Kohat, Kala-chitta and Hazara areas. Various researchers have contributed to sedimentological and biostratigraphic work on Sakesar Limestone in different parts of the Salt Range. According to Rahman (2017), Boustani (2000), Boustani and Khwaja (1997), Afzal and Butt (2000), Sameeni and Butt (2004), Ghazi et.al (2006,2010), Nizami et.al (2010) and Ahmed (2013) worked on the biostratigraphy and sedimentology of Sakesar Limestone. These different workers have reported that the Sakesar Limestone is composed of mainly two microfacies i.e wackestone and packestone. They also reported various fossils which includes larger benthic foraminifera. The common larger benthic foraminifera include Alveolina, Assilina, Lokhartia, operculina, Nummulites and brachiopods. These workers also reported some species of green Algae, Echnoids, Mollusks, and sponges. The diagenetic processes reported include cementation, dissolution, neomorphism, micritization, fracturing, filled veins, and open fractures. 1.3 Aim and Objectives This present work is an attempt to study and evaluate microfacies and reservoir properties including porosity and permeability from plugs of different depositional facies of outcrop samples of Sakesar Limestone collected at three stratigraphic sections in the eastern and central Salt Range along with core-cuttings from the Balkassar-7 well in the Potwar Plateau. Understanding the properties of reservoir rocks is an important task for geologists and reservoir engineers because without the proper evaluation of its properties, oil and gas production cannot be attained. This present research work is an integrated approach to: ? Evaluate porosity and permeability of the Sakesar Limestone ? Understand reservoir properties from outcrop samples and core-cuttings ? Identify microfacies from petrographic analysis to unravel the depositional environment of Sakesar Limestone ? Describe and understand the outcrop features of Sakesar Limestone 1.4 Location and accessibility to the study area The Sakesar Limestone samples were collected from eastern and central Salt Range Potwar Sub-Basin. Ratucha village section, Dandot village sections in the eastern salt range and Sardhai village section in central salt range. The Ratucha village section is located at 32°41´14.93´ N, 72°58 ´51.85´´ E and Dandot village section is located at 32°40´12.43´´ N, 72°57´26.60´´ E in the eastern salt range, District Chakwal, Punjab. Sardhai village section is located at 32°41´0.60´´ N, 72°43´1.54´´ E in the central salt range, Punjab, Pakistan. Sardhai village is situated about 90km South of the capital territory. The Ratucha and Dandot villages are about 160km and 166km from the capital area, Islamabad, respectively. The location of study area is shown on the map in Figure 1.1. Similarly, the Balkassar-7 well is located in Balkassar village at 32°55' 00” N and 72°39' 00”E, Chakwal, Potwar sub-basin onshore Pakistan as shown in the figure 1.2. 1.5 Methodology The methodology followed in this research work is comprised of field work and laboratory analyses for detail assessment of porosity, permeability and microfacies analysis of the Ypresian Sakessar Limestone at eastern and central Salt Range Potwar sub-basin, Pakistan. As mentioned earlier, the Sakessar limestone is well exposed in the Salt Range in different 4 areas including eastern, central, and western Salt Range. Detailed and informative Geological field were conducted to eastern and central Salt Range for data collection, sampling and observing the field features of Sakesar Limestone. The details of methodology are given in the flowchart (Figure 1.3). 1.5.1 Field Instruments The instruments used