PETROPHYSICAL AND MICROFACIES ANALYSIS OF SAKESAR LIMESTONE, BALKASSAR AND FIMKASSAR OIL FIELDS, POTWAR SUB BASIN, PAKISTAN

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DEDICATION

This dissertation is dedicated to my wonderful parents, for their endless love, support and encouragement. They always helped and facilitated me in every sphere of my life with immense practical advice and fulfilled my wishes.

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ABSTRACT

The Potwar Basin, is the prolific hydrocarbon prospect zone due to a number of discoveries recorded in the Eocene carbonate succession which also include the Sakesar Limestone. The present study evaluated the Sakesar Limestone in terms of petrophysical properties with emphasis on microfacies analysis. An attempt was made to interpret Sakesar Formation using well logs data set and samples from exposed section of Sakesar Formation at Padhrar, Central Salt Range. The limestone of Sakesar Formation is planar to cherty and nodular in nature. Based on field and petrographic study, five microfacies have been identified 1) Nummulitic wackestone (PSL-1), (2) Benthic foraminiferal wackestone (PSL-2), (3) Lockhartia rich mud wackestone (PSL-3), (4) Bioclastic wacke-packstone (PSL-4), and (5) Miliolidal wackestone microfacies (PSL-5). Based on the allochems, orthochems and fossil assemblages, the identified microfacies of the Sakesar Limestone are interpreted to be deposited in the distal middle ramp to restricted inner ramp settings of homoclinal carbonate ramp environment. These microfacies include species of Nummulites, Lockhartia, Assilina, Alveolina and miliolids along with skeletal fauna of shallower fauna like echinoderms, Rotalia, algae and their bioclasts. Among the diagenetic fabrics, the dissolution and microfracturing enhance the reservoir efficacy and cause the formation of secondary (inter- and intragranular) porosities like moldic, channel and fenestral porosities. Petrophysical analysis of Sakesar Formation encountered at Fimkassar-02 and Balkassar OXY-01A wells shows acceptable ranges of permeability and effective porosity. In Fimkassar-02, a 26m thick zone of interest at the depth (~3008m to 3034m) represents hydrocarbon saturation of 61%, the average effective porosity of 0.049% and permeability of 1.353 mD indicating good reservoir potential. In Balkassar OXY-01A, a zone of interest of ~9m at the depth (~2496m to 2505m) indicates fair reservoir properties having 58 % of hydrocarbon saturation with average permeability 0.06% and 0.02 % effective porosity. The dissolution and microfracturing mainly reflect positive correlation with surface Fimkassar-02 and result in porosity generation in the Sakesar Limestone. In Balkassar Oxy-01A, the physical and chemical compactness negatively affect the reservoir aspect of the formation that could be resulted by cementation and overburden pressure.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

The Potwar Plateau is an important oil-producing province of Pakistan where the Khaur field was explored as a first prolific discovery from Sakesar Limestone in 1914 (Awais et al., 2020; Kadri, 1995). Eocene is the most significant epoch in the geological history of Pakistan as it represents the dominant hydrocarbon yield (Hussain et al., 2021). In the Potwar Plateau, Eocene and Paleocene strata have been the main focus of hydrocarbon exploration as they have proved conventionally productive reservoir intervals mainly producing from fractured limestone (Ishaq et al., 2019; Jadoon et al., 2005; Mujtaba and Abbas, 2001). In the Potwar Plateau, oil and gas generally are produced from the stacked successions of Cambrian to Eocene clastic and carbonates (Jadoon et al., 2015). The Paleocene to Eocene strata of carbonate in the Potwar Plateau are the main hydrocarbon source rocks (Awais et al., 2020) and among them, the carbonate strata (e.g. Sakesar & Chorgali) are the proven hydrocarbon reservoirs throughout Upper Indus Basin (Hussain et al., 2021; Khitab et al., 2020; Shah et al.,2021). In the Potwar Plateau, the carbonate reservoirs possess secondary porosity of around 3.5% in Eocene Chorgali or Sakesar Limestone (Awais et al., 2020; Jadoon et al., 2003). Similarly, for Eocene reservoirs, carbonaceous shale beds in Patala Formation have been reported as important source rocks, especially in Potwar Plateau (Fazeelat et al., 2010; Shah and Ahmed, 2020; Shah and Ahmed, 2021; Wandrey et al., 2004; Yasin et al., 2021). The early Eocene stratigraphic succession, in form of the Nammal Formation, Sakesar Limestone, Chorgali Formation, and Margalla Hill Limestone, were deposited in the Potwar Plateau at the prevailing open marine platform conditions (Shah et al., 2009).

The studies about the sedimentology of the Eocene rocks in different parts of Pakistan have been undertaken by various authors (e.g. Ahmad et al., 2013; Awais et al., 2020; Hanif et al., 2015; Hussain et al., 2021, Khitab et al., 2020; Swati et al., 2013, 2014). In the Potwar Plateau, the outstanding exposure of early Eocene succession is well preserved in area of Salt Range. The present study makes use of samples from Central Salt Range. The Sakesar Limestone has a wider exposure at all parts of the Salt Range, ranging from eastern, central and western. In this research Sakesar Limestone exposed at the Padhrar section of the Central Salt Range is investigated (fig 1.1). The present research work has taken into consideration the distribution of carbonate microfacies, their fossil assemblages and related reservoir characteristics based on field and petrographic studies of the early Eocene Sakesar Limestone.

1.1 Previous Studies

The Potwar Plateau has been the subject of geological studies and exploration with respect of hydrocarbon prospects and it is one of the oldest oil producing regions in Pakistan (Shah and Abdullah, 2017; Wandrey et al., 2004). Some of the notable studies undertaken regarding hydrocarbon prospects and reservoir investigation in the Potwar Plateau include (e.g. Craig et al., 2018; Jadoon et al., 2005; Khan et al., 1986; Khalid et al., 2015; Kadri, 1995; Khitab et al., 2020; Wandrey et al., 2004; Nazir et al., 2020). Salt Range makes the southernmost part of the Potwar Plateau and represents the southern boundary of Himalayan fold and thrust belt.

The earliest studies of the Sakesar Limestone have been carried out by Davies and Pinfold (1937) and Gee (1989) who investigated the marine Paleogene stratigraphy and documented the assemblage of larger benthonic foraminifera. Their investigations concluded about the lithology of the Sakesar Limestone; as light to dark gray and creamy in places, nodular, thin to thick-bedded limestone. A multitude of studies on the biostratigraphy and sedimentology of the Sakesar Limestone have been carried at different parts of the Salt Range (Afzal and Butt, 2000; Ahmad et al., 2013; Baitu et al., 2008; Boustani and Khwaja, 1997; Ghazi et al., 2010; Murteza and Azam, 1997; Nizami et al., 2010; Sameeni and Butt, 2004). The biostratigraphic conclusions of the above studies depicted that the Sakesar Limestone encompasses a number of pivotal genera of larger benthic foraminifera i.e. Assilina, Nummulites, Lockhartia, Operculina and Alveolina coupled with gastropods, brachiopods, pelecypods, bryozoa, and shallower fauna of echinoderms, corals, sponges, blue-green and Red Algae. The Sakesar Limestone majorly consists of massive to thick-bedded, cherty and nodular dark grey limestone beds, which are fossiliferous. The Sakesar Limestone marks the basal and top contacts with the

Nammal and Chorgali formations respectively in the rest of the Salt Range but in the study area the contact is not exposed with the Chorgali Formation.

Sajjad (2014) have studied the diagenesis, microfacies and reservoir aspects of Sakesar Limestone.

This research work involves a detailed investigation of the Sakesar Limestone in terms of microfacies analysis coupled with reservoir studies and their correlation. Very limited and few studies are available regarding microfacies, diagenesis and reservoir rock evaluation. In this study an integrated approach of these techniques have been used to investigate in depth. Therefore, this research work is necessitated to elucidate the significance and role of the Sakesar Limestone in the petroleum plays in terms of reservoir rock in any subsequent fields or blocks of the Potwar Plateau.

1.2 Location

The Sakesar Limestone is exposed near Chabb village in Padhrar section (fig 1.1). The area is located in district Khushab, Punjab province, Pakistan (Latitude 32°38'56.58"N and Longitude 72°29'14.44"E). The study area lies in the south of Capital Territory of Pakistan, Islamabad at a distance of 165km approximately. The outcrop, where sampling was carried out, lies on the Dheri road side while travelling to Chabb village from Kallar Kahar main road.

Two wells Balkassar OXY-01A and Fimkassar-02 were selected for well Log Analysis i.e. for reservoir characterization. Balkassar OXY-01A and Fimkassar-02 wells are about 58.4km and 80 km respectively to the north of Padhrar section (Fig. 1.1).

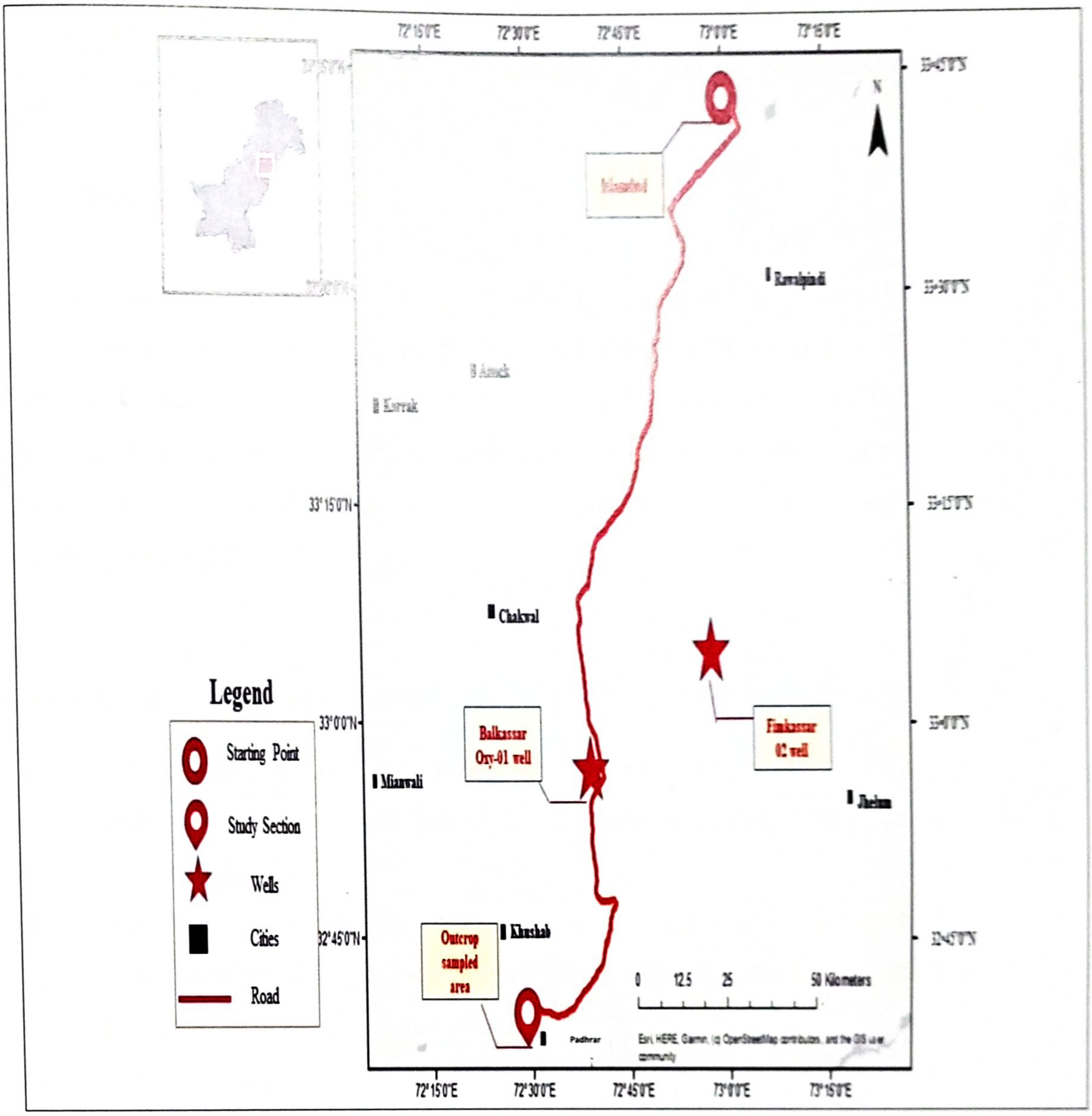


Figure 1.1 Location Map of Study Areas

1.3 Aims and Objectives

The current research study aims at evaluating the reservoir characteristics and carrying out the microfacies analysis of the Sakesar Limestone. The main aim of proposed study is to evaluate potentiality of Sakesar Formation in Potwar Basin subsurface. This aim is achieved by the petrophysical study of the Sakesar Limestone encountered in Balkassar Oxy-1A and Fimkassar-02 wells, through wireline logs and petrographic analysis by using field data.

In order to achieve the aforementioned aim, the given objectives are set to achieve;

i. To investigate microfacies of Sakesar Limestone comprehensively.
ii. To elucidate the diagenetic features and the aspects effecting the potentiality of the Sakesar Limestone.
iii. To evaluate hydrocarbon potential of Sakesar Formation as a reservoir rock.
iv. To correlate the petrographic interpretations with the petrophysical analysis of Balkassar Oxy-01A and Fimkassar-02 wells.

CHAPTER 2

GEOLOGY AND TECTONICS

2.1 Tectonic and Geological Settings of the Study Area

Potwar, which is a sub-basin of greater Indus Basin, has a thickness of about 5000 m sedimentary successions of Precambrian to Recent and the study area of the Salt Range lies within the Potwar Basin, and it preserves the great view of tectonics and paleo-environments of the basin (Ghazi et al., 2014; Shah et al., 2009). Balkassar and Fimkassar fields are a segment of Himalayan Fold and Thrust Belt of Pakistan (Farah et al., 1984; Kazmi and Jan, 1997). The study area is located within a compressional region and has many sub-categories based on structural tectonics like Kharsel Fault in the north, Joya Mair Thrust Fault in the east, Jhatia and Ghabbir Faults in the west and to south, Kalarkahar Fault and Salt Range Thrust Fault exist. The structures enclose the Eocene rocks (Sakesar and Chorgali Formation) towards the center and on their flanks, the Miocene rocks (Chingi Formation) lies.

The Potwar Basin is bounded by MBT towards north and the Salt Range marks the southern boundary. The strike slip faults of Jhelum and Kala Bagh mark the east and west peripheries of the basin respectively (Jadoon et al., 2003; Kadri, 1995). A deformed thrust sheet typifies the Potwar Basin that encompasses of Northern Potwar Deformed Zone (NPDZ) and Southern Potwar Platform Zone (SSPZ), which are segregated by the Soan syncline (Jaswal et al., 1997; Jadoon et al., 2003). The structural complexity towards the north (NPDZ) is more pronounced due to the prevailing complicated structural features like tight folds and complex faults in comparison to south where the isoclinal thrusts and folds persist. On the other hand, the pop up structural features exist in eastern part of the Potwar (Amir and Siddiqui, 2006; Jadoon et al., 2003). Majorly, the plain of detachments in a form of decollement prevails in the Salt Range Formation, yet geophysical analysis reflects wider structural variations from east to west of the basin (Amir and Siddiqui, 2006). The driven causes of the structural complications are due to varied mechanical aspects at the time of propagation and detachment between Jhelum and Kala Bagh strike slip faults along with the prevalence of salt. The structural trends are left stepping in eastern Potwar; on the other hand, they are right stepping in patterns of en-echelon towards the east of Kala Bagh Fault. By virtue of these structural effects, the basin tends to have direction of migration towards south; on the contrary, along HFT (Himalayan Frontal Thrust) it thrusts over Punjab Plain (Kazmi and Jan, 1997).

2.2 Potwar Plateau

Plateau is an area which is fairly elevated plain land as compared to the surrounding areas. Potwar Plateau is bounded by Kala-Chitta and Margalla hills in the north, in south, Salt Range Thrust Fault bounds it. Jhelum fault, Hazara Kashmir syntaxes and Indus River bound the Potwar Plateau in the east and the Kohat plateau bounds it to the west (Kazmi and Jan, 1997).

2.3 Major Structures in Potwar

Southern margin of Himalayan collisional zone along with the fold and thrust belt represents the Potwar zone. In northern Potwar plateau, stress is more active than the south due to northern movement of the Potwar Plateau moves nearer the collision zone where some tight folds, nappes zones develop which have been thrusted over the NPDZ. The notable structural features in form of faults and folds in the Potwar area are discussed.

2.3.1 Khair-I-Murat Fault (KMF)

Khair-I-Murat Fault (KMF) is a north-dipping main emergent thrust in the Potwar (fig 2.1). Eocene carbonates of high velocity are thrusted southward over the Molasses of low velocity. Jadoon (2008) explained that, it soles out in the basal decollement at a depth of about 9km. Jaswal (1997) observed that, faults that have steep dips at the surface containing high faulted beds of Murree Formation to its north was due to back rotation, where alluvium covered most of the area.

2.3.2 Dhurnal Back Thrust (DBT)

Recent research has proved that DBT (Dhurnal Back Fault) has been considered as the eastward extension of the Kant Fault, (KF). It joins the KF west of Dhurnal and diverts towards the Southwest, gradually dying out at the surface. Jadoon (2008) explained that, steep DBT becomes shallower to the south which dies out at a depth of 2 to 4km. It merges with a north-dipping blind thrust that propagates up as a ramp from a layer of Eo-Cambrian evaporates at a depth of about 8km and flat along a politic horizon in Molasses strata.

2.3.3 Kanet Fault (KF)

The emerging thrust in the western part of the Potwar is a north dipping KF, bound the Kanet syncline from the north.

2.3.4 Mianwali Fault (MF)

Intra formational thrust at the surface is MF. MF can be traced only in streams. On the basis of faulted Breccia and Shear zones, out crop is present only in streams. Steep dips are exposed in the area between MF and KMF representing the northern Siwalik in the rocks.

2.3.5 Riwat Fault (RF)

In the eastern Potwar Plateau, Hinterland-dipping Fault with passive roof thrust is RF in the south of Soan syncline. Along the southern flank of the Chak Beli Khan anticline, RF dies out. In Northeast RF dies out near the Soan syncline axis.

Besides Major faults, some of the other structures present in the area are as follows:

2.3.6 Soan Syncline:

Potwar Plateau is divided into northern and southern Potwar deformed zone by the Soan Syncline. Soan Syncline is wide, broad and asymmetrical syncline. Its axis is marked by the Soan River. Dhok Pathan Formation overlying the Nagri Formation crops out south of Dhurnal area ion the northern limb of Soan syncline. Here crustal shortening is due to the collisional tectonics.

2.3.7 Chak Naurang Anticline

Chak Naurang has two dipping limbs. These limbs are namely, southern limb which is dipping steeply while northern limb dipping moderately. Anticline is an example a fault propagated fold.

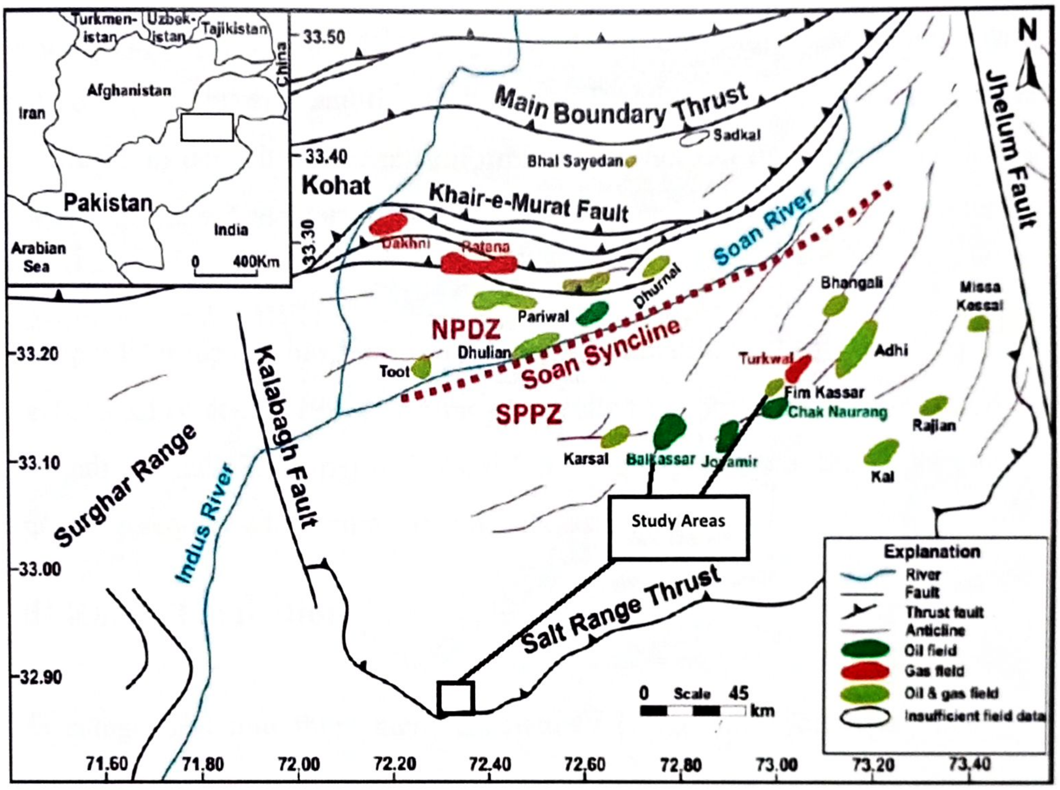


Figure 2.1 Geological map of the study areas in Potwar basin, (after Riaz et al.2019)

2.4 Stratigraphy of the Area

In the Potwar sub-basin, the sedimentary successions range from Infra-Cambrian to Pliocene representing the Salt Range Formation as an oldest and Nagri Formation as the youngest formation (Ahmed et al., 1993). These successions have the period of non-deposition in between which include Infra-Cambrian- Permian, Permian-Triassic and Eocene to Miocene majorly.

The exposed outcrops at the study area at Padhrar section are mainly of Sakesar and Nammal Formation and the Chorgali Formation is not exposed there. Subsurface investigations reveal that in Balkassar-Oxy-01A the sedimentary successions with Precambrian to Eo-Cambrian, Cambrian to Permian, Permian to Paleocene and Eocene to Miocene breaks in deposition i.e. unconformities prevail. On the other hand, in the Fimkassar-02 well, the sedimentary successions of Paleocene to Pliocene exposed with no any known unconformities.

Rawalpindi Group that has Murree and Kamlial formations reflects the Himalayan provenance (Chaudhry et al., 1998) and they deposited uncomformably upon middle Eocene Chorgali Formation. Chingi and Nagri Formations prevails at the upper part of Miocene molasses sequence in Fimkassar and Balkassar wells.

2.4.1 Salt Range Formation

It is categorized into three members namely Billianwala Salt Marl member, Sahiwal Marl member and Bandar Kas Gypsum member. Lithology of this formation consists of claystone having red color with intercalation of salt bodies. gypsum, salt beds and dolomite are present at the lower part of this formation. Upper contact of formation is with Khewra sandstone while the base of the formation is not exposed. The formation has maximum thickness of about 2100m (Kadri, 1995).

2.4.2 Khewra Sandstone

The name of Khewra Sandstone was given by (Fatmi et al., 1973). The Formation consists of purple to brown massive bedded sandstone with lower part consisting of red shale. Features constraining this formation includes mud cracks, Ripple marks and few trails of fossils. The lower contact of Khewra Sandstone is with Salt Range Formation (Shah et al., 1997) while the upper part is in contact with Kussak Formation and is disconformable. Khewra Formation is of Cambrian age with having thickness of 200m at Eastern Salt Range (Shah et al., 1997).

2.4.3 Kussak Formation

The type locality of the formation is nearer the Kussak Fort. The composition of the Kussak Formation comprises of greenish-grey glauconitic sandstone. Additionally, the Sandstone is micaceous and contains dolomitic siltstone interbeds. The lower contact of the Formation is disconformable and is with Khewra Sandstone whereas the upper contact is in contact with Jutana Formation. The thickness of Kussak Arrangement is around 70m (Shah et al., 1997).

2.4.4 Jutana Formation

Jutana village is the type locality of the Jutana Formation. It is composed of green, massively bedded sand dolomite, whereas the topmost part is encompassed of massive dolomite. The top and basal part of the formation is in contact with Baghan Wala Formation and Kussak Formation and it is conformable. Jutana Formation is of Cambrian age and its thickness is almost 75m (kazmi and Jan, 1997).

2.4.5 Baghan Wala Formation

The name Baghan Wala was assigned after its type locality nearby to Baghan Wala Village. The formation consists of sandstone along with reddish brown shale. The sandstone has a feature of ripple marks, mud cracks and salt pseudomorphs. The basal contact is confirmable with Jutana Formation while the upper part is conformably in contact with Tobra Formation. It has around thickness of 110m at its type locality and is of Cambrian age (Kazmi and Jan, 1997).

2.4.6 Tobra Formation

The Formation is oldest in Nilawahan group. Its type locality is near to Tobra village, Salt Range (Shah et al., 1997). This formation is composed of sandstone having cobles, glaciated pebbles and massive sub angular shaped lithics and shales. The formation has interbeds of conglomerate and boulders with matrix of sand. The conglomerates have pebbles and boulders of sedimentary, metamorphic and igneous rock fragments. Tobra Formation is of Permian age with a maximum thickness of 140m. The formation marks an unconformable contact with Bhaganwala Formation and upper conformable contact with Dandot Formation (Kazmi and Jan, 1997).

2.4.7 Dandot Formation

The Formation has dark green to grey shale, siltstone and sandstone. Dandot Formation is of Permian with a thickness of approximately 50m in Salt Range. The Formation has its lower and upper conformable contact with Tobra Formation and Warcha Sandstone respectively (Kazmi and Jan, 1997).

2.4.8 Warcha Sandstone

Warcha Nala is the type locality of the formation. The formation is composed of massively bedded, medium to coarse grained sandstone which is of reddish brown color and is cross bedded. One feature of Warcha Sandstone is that no fossil is recorded in it. The Formation is of Permian age and is of 165m in thickness. Warcha Sandstone is sandwiched between fossiliferous Dandot and Sardhai Formation of early Permian age (Kadri, 1995).

2.4.9 Sardhai Formation

Near Sardhai Gorge, the type locality of the formation exists and the formation consists of bluish to greyish clay with some sand part and some beds of siltstone. Clays of Sardhai Formation host the chalcopyrites. The thickness of the Formation is about 42m with its lower contact with Warcha Sandstone and upper contact with Zaluch Group.

Sardhai Formation is of Permian age with features such as fossils, plant leftovers and fish scales in Salt Range (Shah et al., 1997)

2.4.10 Hangu Formation

The Hangu Formation is of grey to brown reddish in color, whereas dark rusty brown in weathered surface. The grain size range between fine-coarser and upper part possesses intercalations coupled with thick-medium beds of shale. Hangu Formation is of Paleocene age with its upper contact conformable with Lockhart Limestone (Kadri, 1995).

2.4.11 Lockhart Limestone

Lockhart Limestone mostly consists of Limestone with medium to thick beds having weather surface and is yellow greyish in color, while fresh surface has grey to light grey color. The limestone in Lockhart Formation has 8-11cm diameter of nodularities while at some places these nodularities range from 14-16 cm. Lockhart Limestone is of Paleocene age, has conformable basal contact with Hangu Formation, while the upper contact is conformable with Patala Formation (Shah et al., 1997).

2.4.12 Patala Formation

The Formation is mainly composed of carbonaceous, calcareous shale and marl with limestone and interbeds of sandstone in Salt Range. Patala Formation represents the boundary and time span gap between Paleocene and Eocene. Patala Formation has also been considered as the main source rock in the Potwar Basin.

2.4.13 Nammal Formation

The type locality of the Nammal Formation section is exposed in Nammal gorge. The formation is majorly encompassed of beds of mainly limestone with some shale and marl and their intercalations. The shale is of green in color, while the limestone is grey. The color of the marl in Nammal Formation is bluish grey. It has basal conformable contact with Patala Formation and Sakesar Limestone makes the upper conformable contact with the Nammal Formation. Nammal Formation is of Eocene age (Shah et al., 1997).

Larger benthic foraminifera of Nammal Formation reported by (Cheema et al., 1997) include species of Assilina, Nummulites, Lockhartia, Discocyclina and Operculina and some smaller foraminifera. Nammal Formation is suggested to be of Early Eocene age (Kazmi and Abbasi, 2008).

2.4.14 Sakesar Limestone

The name of Sakesar Formation was assigned by (Gee et al., 1945). The thickness of the formation is variable. At Salt Ranges and Surghar Ranges it is about 70 to 150m and is extensively distributed in Salt Range, while at Chichali Pass the formation is about 220m. The upper conformable contact is with Chorgali Formation, while in the central and western Salt Range and Surghar Ranges of Pakistan, it has unconformable contact Rawalpindi Group. Its lower contact is conformable with Nammal Formation.

The Sakesar Limestone consists of thin to thickly bedded limestone beds, while at some parts Limestone of Sakesar Formation have shale beds and marl. It commonly shows variations in thicknesses in terms of nodularity while the upper part of the Formation consists of cherty nodules. Limestone in Sakesar Formation is of light to dark grey while in some parts the limestone shows creamy color. Bioturbation is common in Sakesar Limestone. Fossils found in Sakesar Limestone majorly are larger and smaller benthic foraminifera along with the other fossils such as gastropods, ostracods.

2.5 Borehole stratigraphy of Balkassar OXY-01A

The encountered formations in the Balkassar OXY-01A well range in age from Precambrian to Pliocene in which oldest formation is the Salt Range and youngest is Nagri Formation. Till the depth of 3129.2m the Balkassar well has been drilled and the Sakesar Limestone is encountered in the Balkassar OXY-01A well at the depth of 2467.2 m making a total thickness of around 135m. The detailed borehole stratigraphy of the Balkassar OXY-01A well is given in (Table 2.1).

2.6 Borehole stratigraphy of Fimkassar-02

Unlike the Balkassar Oxy-01 well, in the Fimkassar-02 well, the encountered formations are in age from Paleocene and Pliocene in which Patala Formation is the oldest and Nagri Formation is being the youngest respectively. This well has been drilled up to 3,067 m depth and the Sakesar Limestone is encountered at the depth of 2946 meters making a total thickness of 121 meters. The detailed borehole stratigraphy of the Fimkassar-02 well is given in (Table 2.2)

Table 2.1: Borehole stratigraphy of the Balkassar Oxy-01 well

Age	Formation	Depth (Meter)
Pliocene	Nagri	00.0
Miocene	Chinji	000478.8
Miocene	Kamlial	001408.1
Miocene	Murree	001514.8
Eocene	Chorgali	002421.5
Eocene	Sakesar Limestone	002467.2
Paleocene	Patala	002602.9
Paleocene	Lockhart Limestone	002624.2
Paleocene	Hangu	002659.3
Permian	Sardhai	002686.7
Permian	Warcha Sandstone	002796.4
Permian	Dandot	002938.1
Permian	Tobra	002999.1
Cambrian	Khewra Sandstone	003050.9
Precambrian	Salt Range	003129.2

Table 2.2: Borehole stratigraphy of the Fimkassar-02 well

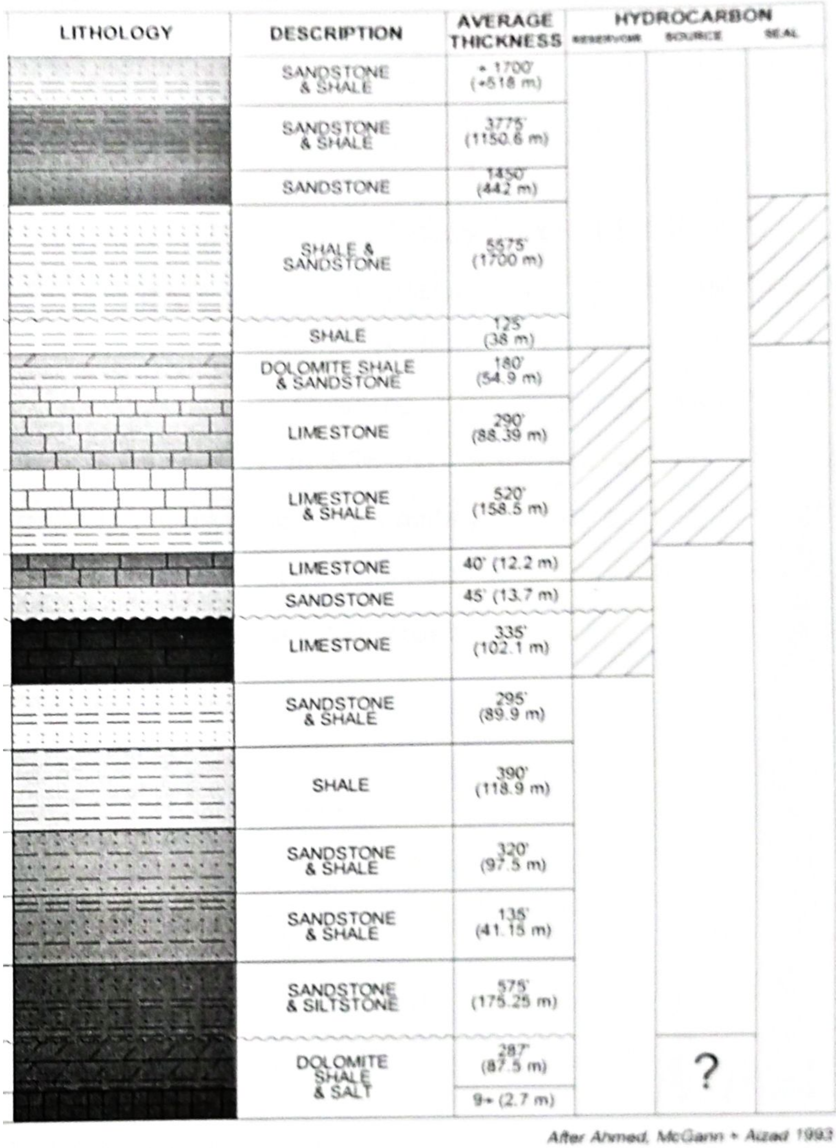
Age	Formation	Depth (Meter)
Pliocene	Nagri	00.0
Miocene	Chinji	595.00
Miocene	Kamlial	1,543.00
Miocene	Murree	1,703.00
Eocene	Chorgali	2,902.00
Eocene	Sakesar Limestone	2,946.00
Paleocene	Patala	3,067.00

2.7 Hydrocarbons Play of Study Area

The Potwar Plateau is an important oil-producing province of Pakistan where the first commercial discovery was made at Khaur Oil field from Sakesar Formation 1914 (Awais et al. 2020; Kadri et al., 1995). In the geological history of Pakistan, the most significant and famous reservoirs are Eocene reservoirs (Hussain et al. 2021).Oil and gas in Potwar Plateau are generally produced from the stacked successions of Cambrian to Eocene clastic and carbonates (Jadoon et al. 2015).

Various petroleum plays in terms of structural features include in the Potwar Basin are overturned and asymmetrical anticlines that are salt cored and faulted (Jadoon et al., 2003). The eastern segment of Potwar is typified by the pronounced fracturing in comparison to the western segment. The eastern segment of the basin has hosted many discoveries of hydrocarbons and the segment mainly contains elongated anticlines that trend north east to south along steeply dipping flanks owing to the salt pop-up (Jadoon et al., 2003). The hydrocarbon prospects exploited closer to NPDZ are majorly associated with east to west trending asymmetric anticlines, contrary to this, towards the west of Soan syncline, discoveries of hydrocarbons were made majorly from north east to east trending, symmetric decollement and Cenozoic anticlines (i.e. Dhakni and Dhuran fields; Jadoon et al., 2003). The hydrocarbons traps have been developed due to thin- skinned tectonics and were formed due to faulted anticlines, pop-up and positive flower structures

›reover, the lithologies in form of shales and clays of the Murree able horizontal and vertical seal to Eocene reservoirs wherever doon et al., 2003).



›d stratigrahy of Potwar sub basin, Upper Indus Basin,

›ks

›ificant sedimentary successions of source rock potential which are Basin. According to Ahmed (1993), the carbonaceous shales of the ›nsidered as the main and prolific source of the Potwar fields. Other ›, Pre-Cambrian Salt Range Formation also encompasses oil shale ›lepict the source rock potential (Wandrey et al.,2004). The Khewra t shales and encompasses coaly to different amorphous (along vital woody herbaceous) kerogen, have the generating potential of paraffinic to normal crude gas. Based on the correlation of oil to source correlation, it was revealed that the major and prolific production of oil has been sourced through the Patala Formation in Potwar Basin (Wandrey et al., 2004).

2.7.2 Reservoir Rocks

Sedimentary succession from Paleozoic to Tertiary is exposed in the Salt Range which make the petroleum systems in Potwar. The Sakesar and Chorgali formations are considered as the carbonate strata for generating repositories in Balkassar and Fimkassar (Ahmed et al., 1993). The sandstone of Cambrian Khewra are the main potential reservoirs of hydrocarbons. The upper and middle units of the Khewra Sandstone have the moderate range of porosity porous mainly representing primary porosity in range of 10 to 12%. The uniform distribution of grain size with moderate sorting makes it an excellent reservoir nature of the Khewra Sandstone (Kadri, 1995).

CHAPTER 3

METHODS AND MATERIALS

This chapter will highlight the techniques and materials used in this research work. For the current research work, the employed methods include laboratory and field studies as follow;

a. Open-hole wire line logs of Balkassar OXY-01A and Fimkassar-02 wells were required for the petrophysical analysis and for the reservoir characterization. Well log data was acquired from the DGPC and LMKR.
b. Outcrop samples collection for microfacies analysis and for the diagenetic studies of the Sakesar Limestone.

The methodology employed for the current research work is given at (fig 3.7).

3.1 Field work

A detailed fieldwork was carried out to collect samples from the studied section of Padhrar Central Salt Range. Based on the outcrop features and rock physical appearance, detailed observations and field features were recorded. The outcrop features include lithological texture, color, sedimentary features, fossils identification and diagenetic features. During the fieldwork, twenty representative samples were collected systematically and randomly based on the variations of color and outcrop features from the fresh and un-weathered beds of Sakesar Limestone and these samples were collected at significant lithological changes from upper, middle and lower part of the section (fig 3.1). The measured thickness of the Sakesar Limestone was about 26.5 meters. Five representative outcrop samples were also used for the plug analysis for the permeability and porosity measurements. A Global Positioning System (GPS) device was used for the coordinates and a measuring tape was used for measuring the stratigraphic thickness of section.

Field observations include the color and texture of the formation which are greyish to creamy white, whereas fresh color is whitish to light brown color and the formation is characterized with nodular fabric, cherty composition and fossil assemblages of some larger benthic foraminifera (fig 3.3 & 3.4). The upper contact of the Sakesar Limestone with the Chorgali Formation was not visible clearly however the lower contact is conformably with Nammal Formation that is covered with vegetation and debris at the study section.

Figure 3.1: Field photograph of the exposed outcrop of the Sakesar Limestone in the study area

Figure 3.2: An outcrop picture showing cherts of the Sakesar Limestone

Figure 3.3: An outcrop picture showing the larger benthic foraminifera of the Sakesar Limestone at the study section

Figure 3.4: Stylolitic (Sty) and microfracturing (Mf) diagenetic fabrics of the Sakesar Limestone

3.2 Laboratory studies

The laboratory studies consist of:

1. Petrographic and
2. Petrophysical analyses

3.2.1 Petrographic analysis

For the petrography, the collected outcrop samples of the Sakesar Limestone were thin-sectioned at the Department of Geology, University of Peshawar. Thin-sections were used for the microfacies analysis and for other microscopic observation like digenetic fabrics and they were studied under the polarized microscope.

3.2.2 Petro physical analysis

The main purpose of Petro physical analysis is to provide a valid model that can estimate the properties of the formation like clay volume, effective porosity and water saturation in Balkassar OXY-01A and Fimkassar-02 by using open-hole log data. In Balkassar OXY-01A and Fimkassar-02; Chorgali, Sakesar, Patala and Nammal formations were encountered, out of which petrophysical analysis was done on Sakesar Limestone.

The petro physical analysis involves systematic steps which are taken in the sequential order (fig 3.5) and the sequence is;

a. Collection of data that is processed and analyzed for the errors and purification.
b. Zones of interest are marked in the wells of Balkassar OXY-01A and Fimkassar-02
c. **Volume of Clay**: Volume of clay was calculated by using gamma ray log. Calculating gamma ray index is the first and the major step in determining the clay volume and it is calculated through the formula of Schlumberger (1974).

$$IGR=\frac{GR\ log-GR\ min}{GR\ max-GR\ min}$$

Where;

GR log = the gamma ray reading at the zone of interest

GR min = lowest/minimum gamma ray reading (Usually the mean minimum through clean sandstone or carbonate formation)

GR max = highest/maximum gamma ray reading (Usually the mean maximum through a shale or clay formation).

d. **Porosity**: Porosity calculation is followed after calculating the volume of clay and porosity is calculated by the help of neutron and density Logs.
   i. **Density Porosity**: The density porosity can be calculated using density log. For this calculation two separate values are to be used; bulk density and the matrix density. Bulk density is the density of overall formation/ area of interest, whereas matrix density refers to mass/ volume of rock solid framework.

Density Porosity has been calculated by applying the formula (Hilchie, 1978)

$$\Phi D = \frac{\rho ma - \rho b}{\rho ma - \rho f}$$

Where, ΦD = Density Porosity, ρma = Matrix density ($2.71 g/cm^3$) ρb = Formation bulk density (1)

ρf =Log response in the zone of interest/ Fluid density (usually 1 for fresh water and 1.1 for saline water)

ii. **Neutron Porosity**: The Neutron porosity of the formation is calculated by Neutron log. The calculation of Neutron porosity is estimated with the help of values taken directly from neutron log. It provides us exact estimated value of the porosity in particular zone of interest.

iii. **Sonic Porosity**: Sonic Log porosity can by calculated by the help of transit time(DT) taken by the elastic waves.

$$\Phi sonic = \frac{(DT[Log] - DTma)}{(DTfld - DTma)}$$ (Pairaudeau,1989)

Where, $\Phi sonic$ = Sonic Porosity,

$DT[Log]$= Interval transit time of the formation

$DTma$ = travel transit time of the matrix material, $DTfld$ = Interval transit time of the fluid within the well bore

iv. **Total Porosity:** Afterwards, total porosity is calculated by taking the average of density and neutron porosity. Total porosity was calculated using Rider methods (Rider, 2002) through applying the following formula.

$$\Phi T = \frac{(\Phi D - \Phi N)}{2}$$ Where, ΦT = total porosity

v. Effective Porosity:

$$PHIE[\,] = PHIT[Log] * (1 - Vshl[Log])$$

Where,

$PHIT$ = Total porosity

$PHIE$ = Effective porosity

$Vshl$ = Volume of shale

If volume of shale will be high, the effective porosity will be low and vice versa, as effective porosity has an inverse relation with volume of shale.

e. Resistivity of water (Rw) Estimation

To calculate Rw several methods can be applied out of which some methods involve using the standard Schlumberger plots, while there are the other methods in which standard equations are used.

$Rw = \Phi^2 * Rt$ (Archie Equation, 1942)

f. Estimation of Water Saturation (Sw)

Water Saturation is calculated using Indonesian method

$$Sw=\left\{\frac{\sqrt{\frac{1}{RT}}}{\left(\frac{Vshl^{(1-0.5Vshl)}}{\sqrt{Rshl}}\right)+\sqrt{\frac{\phi e^{m}}{a.Rw}}}\right\}^{\left(\frac{2}{n}\right)}$$ (Poupon and Leveaux, 1971)

Where;

Sw= Saturation of water, n=saturation exponent, a= Lithological coefficient, m=cementation factor,

Rw= formation water resistivity,

Rt=observed bulk resistivity

We assume the values of "m", "n" and "a" as constant that are as follow;

m=2, n=2, a=1

g. Bulk Volume water (BVW)

It is mainly the product of water saturation (Sw) of formation and its porosity (Morris and Biggs, 1974).

$$BVW = \Phi E * Sw$$

h. Saturation of Hydrocarbon (Shc)

Hydrocarbon's saturation is calculated by employing the formula of schlumberger (1974).

$$Shc = 1 - Sw$$

I. Permeability

It is calculated by using Wyllie equation;

$$K = \frac{Kw * PHIE}{SWI}$$

Where;

PHIE= Effective porosity

SWI=Irreducible water Saturation

Whereas "Kw", "e" and "d" are core calibrated constant values

Kw=20

e=2

d=2

j. Net Pay

The thickness of Net pay is evaluated through applying cut-off values to the clay volume, effective porosity and water saturation. The cut-off values are as follow;

k. Fimkassar-02 and Balkassar Oxy 01A Cutt-off applied

In order for the reservoir to be a producing and a prolific one cutt off is applied. For Fimkassar-02 the porosity, water saturation and clay volume cutt-off applied is 0.02, 0.6, 0.2 respectively.

Whereas for Balkassar OXY-01A, 0.005, 0.6 and 0.25 cutt-off for the porosity, water saturation and clay volume are applied respectively.

l. Lithology Determination

Multiple cross plots are prepared for the determination of lithology in each zone of interest. In Fimkassar-02 well, for lithology identification Neutron-Density and Neutron-Sonic cross plots were used. In Density-Neutron cross plot the overlay lines are used of Schlumberger Density/Neutron Corr. Rhof 1.0 where as in Neutron-Sonic cross plot the overlay lines are used of Schlumberger Neutron/Sonic Wyllie Dtf 189. Both Neutron-Density and Neutron-Sonic cross plots indicate that the lithology majorly consists of limestone.

3.2.3 Plug porosity and permeability analysis

The first and foremost step for this analysis includes the core plug preparation. For handling samples, preparation of plugs, cleaning and drying standard procedures were followed based on the procedures outlined in API RP40 (The Recommended Practice for Core Analysis Procedure, 2005). The procedure of the core plug preparation is as follow;

Firstly, the Plug sample is prepared and the core plugs of samples of diameter 1″ with variable lengths (according to sample size) were prepared using Core Drill Press (Delta, USA).

Secondly, cutting and trimming of the plugged samples are carried out to make both ends parallel so that it can be used properly.

Thirdly, cleaning of the sample is done and in this all those fluids which are filled within the core sample available pore space due to formation fluids and drilling mud are removed. This cleaning process involves flushing, flowing, or contacting with toluene to remove hydrocarbons, water and brine within the sample. But the famous method is distillation extraction (Recommended Practices for Core Analysis, 2005).

Fourthly, drying of the core samples in the conventional oven along with vacuum method has been carried out. Benchtop vacuum oven (Hot pack) was used for the purpose of drying core plugs. The weight of each sample becomes constant when dried. Drying time varies, but most of the time it takes four hours to complete (Recommended Practices for Core Analysis, 2005). Precautionary measures should be taken while drying sample for routine core analysis. Following techniques are mentioned in detail in table for drying conventional core samples.

Table 3.1: Techniques employed for drying conventional core samples (Colin McPhee, 2015)

Rock Type	**Method**	**Temperature °C**
Sandstone (low clay content)	Conventional oven Vacuum oven	116 90
Sandstone (high clay content)	Humidity oven, 40% relative humidity	63
Carbonate	Conventional oven Vacuum oven	116 90
Gypsum-bearing	Humidity oven, 40% relative humidity	60
Shale or other high clay rock	Humidity oven, 40% relative humidity Conventional vacuum	60

Lastly, the samples are preserved and preservation of sample depends upon the time duration in the laboratory that is required between the tests and type of tests to be completed. While adopting any storage or preservation method it has been made sure that integrity of sample is preserved and unwanted drying, evaporation and oxidation are avoided (Recommended Practices for Core Analysis, 2005).

After the preservation of the samples, porosity and permeability of the samples are analyzed. The details of the porosity and permeability are as follows;

The detailed method of the determination of the porosity is given;

i. Firstly, the pressure transducer is calibrated through its simple, quick, and highly accurate shunt calibration feature.

ii. Then up to five reference volumes are measured to establish current values for these sections of the plumbing system.

iii. Core sample is placed in the sample cup, the volumetric disks are removed, and the sample cup is pressurized to 100 psi (Helium).

iv. Operating the sample chamber valve results in a second, low pressure from which Boyle's Law gives the grain volume of the sample, subtracting grain volume from bulk volumes gives the pore volume or porosity of the core Sample.

v. After determining bulk volume by callipering the length and diameter of core sample, grain volume can be determined by using Boyle's Law helium porosimeter. The Temco Helium Porosimeter is employed for the effective porosity measurements in core samples.

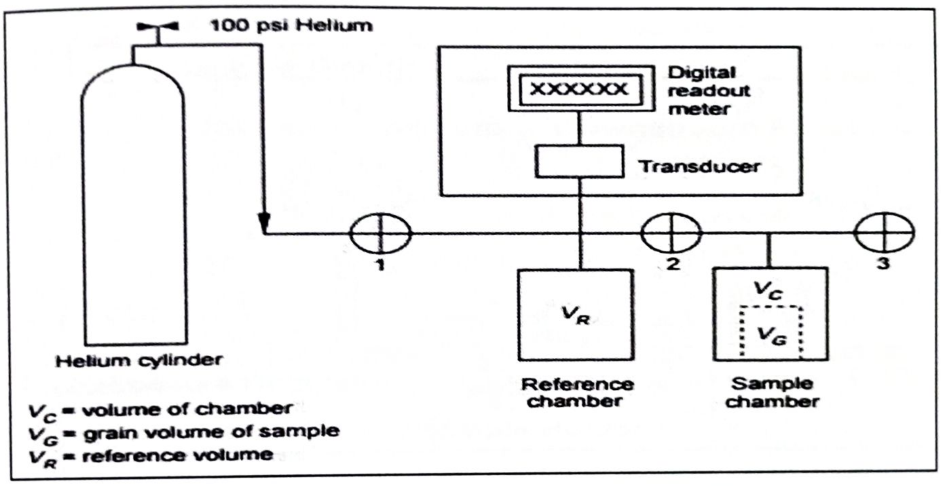


Figure 3.5 Double-Cell Boyle's Law Porosimeter (Colin McPhee, 2015)

Principle of the method is based on Boyle's Law. For calculation of porosity, method given in the instruction manual (M-HP-I01) issued by Temco, P.O, Box 582550, Tulsa, Oklahoma, USA was adopted.

The instrument, Ultra-PermTM" 200 (Core Labs, USA) is used for determination of permeability, based on Darcy's Law. The method given in Ultra-Perm 200, Operations Manual version 2.10, issued by Core Labs, USA, was adopted

The detailed method of the determination of the permeability is given;

i. Dry gas has been selected as the standard fluid for use in permeability determinations because it minimizes fluid-rock reaction and is easy to use. In the laboratory, air is caused to flow through a clean and dry sample of measured length and diameter (Recommended Practices for Core Analysis, 2005).

ii. The pressure differential and flow rates are measured and the permeability is calculated from the Darcy equation.

iii. A clean, dry sample is placed in a holder; it must fit tightly and allow no air to bypass along the sides of the sample.

iv. Upstream and downstream pressures are measured to determine the pressure differential across the core.

v. As the given shows, the calibrated orifice allows the flow rate in cm^3/s to be measured at atmospheric pressure. (D.L & D.C, 1983).

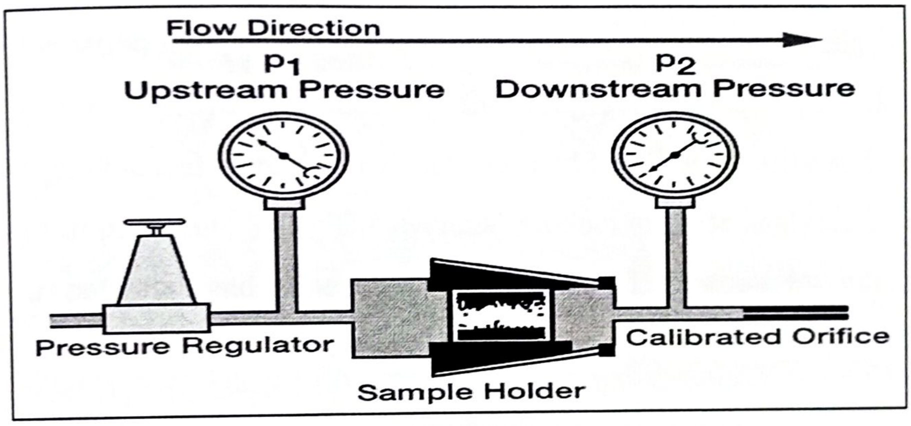


Figure 3.6 Schematic Flow Diagram of Permeameter (Colin McPhee, 2015)

The Darcy's equation to determine the gas permeability is employed. It requires the measurement of the core cross-sectional area, core length, pressure drop across the core, and the gas flow rate at that pressure drop. Measuring ambient pressure and flowing gas temperature, and including their values in the calculation, improve accuracy. Ambient pressure is in the equation, and temperature affects the viscosity of flowing gas.

Basic Darcy's Equation for isothermal steady-state gas flow;

$$Ka = \frac{2\mu QbPbL}{A\,(P12-P22)} \qquad \text{Eq. 3.2}$$

Where;

Ka = air or gas permeability, Darcy's

μ = viscosity, centipoises, of gas at its average flowing temperature and pressure in core

Qb = volumetric flow rate referenced to Pb, cubic centimeters per second

Pb = standard reference pressure for mass flow meters = 1.00 atmospheric

P1 = Upstream pressure, atmospheres

P2 = downstream pressure, atmosphere

L = length of core (centimeters)

A = An area of crossectional core perpendicular to lines of flow, square centimeters.

To sum it up, the methodology begins with the literature review to find the scientific gap based on which the specified area is selected for the research work. The flow of the methodology after the literature review categorizes into a two-fold studies i.e. the surface studies of the study area like field work and the under surface investigation or data of the formation like petrophysical analysis in the encountered wells. The detailed flow chart of the employed methodology that ranges from the fieldwork, laboratory studies, petrographic and petrophysical analyses and the plug porosity and permeability analysis is given in (Figure 3.7). The eventual product of these analyses is to elucidate the reservoir potential and aspects of the Sakesar Limestone by integrating and interpreting surface and sub-surface data and results.

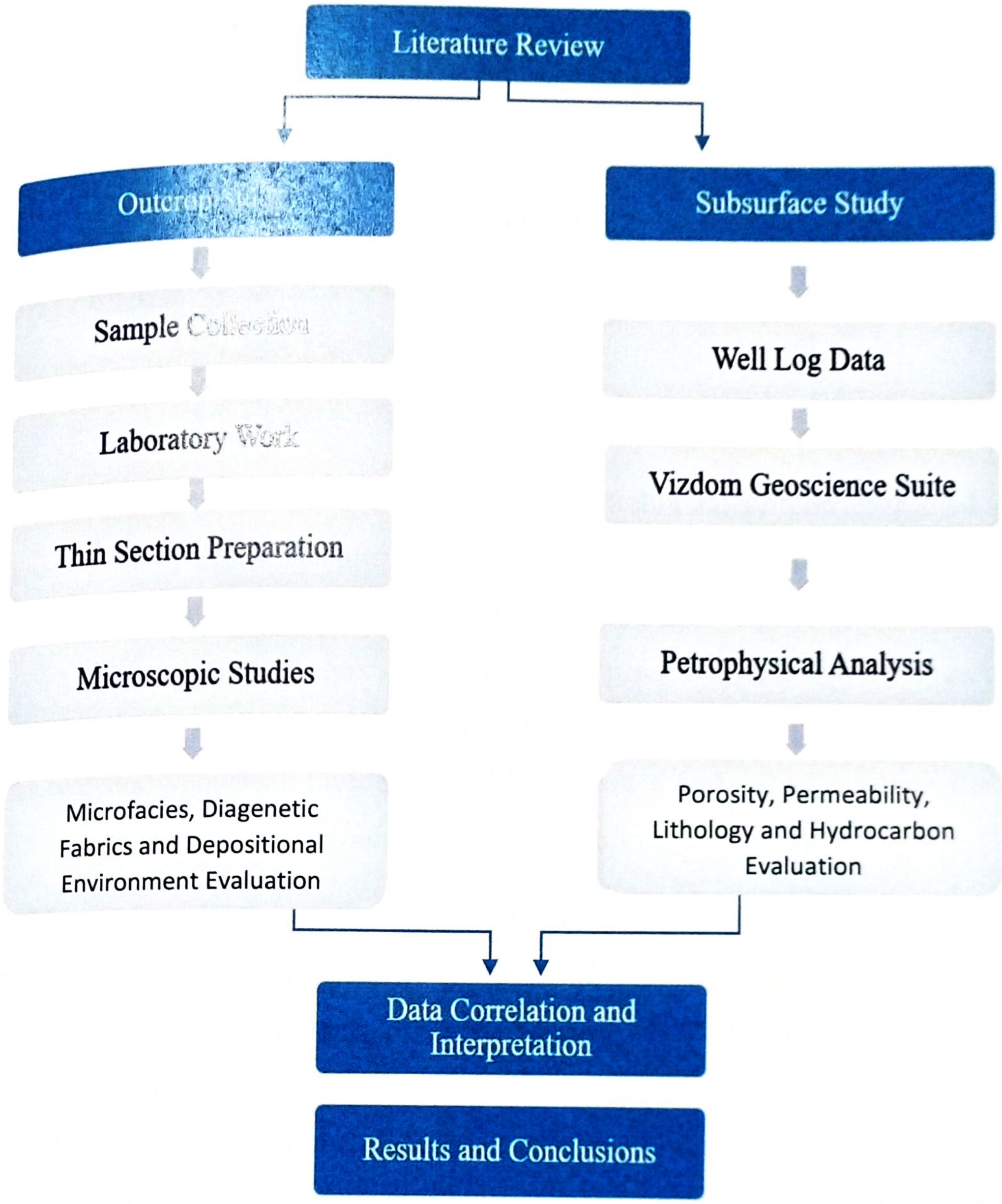


Figure 3.7: The employed Methodology for the current Research Work

CHAPTER 4

MICROFACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENT

Microfacies is the petrographic and paleontological criteria examined in thin sections (Cuvillier, 1952). According to (Flugel, 2004), the term microfacies is defined as the total of all paleontological and sedimentological criteria, which can be classified using thin sections. In carbonates, the dominant processes that form the carbonates sediments are biological and biochemical processes (Tucker, 2001). In the microfacies analysis, we study physical, biological and biochemical features to decipher the site of deposition or depositional environment of the formation within a basin.

Many classification schemes are employed for classification of carbonates, among them the most popular classifications used for limestone are two that are Folk (1959, 1962) and Dunham (1962). Folk's classification uses relative percentage of grains and matrix while Dunham's classification uses mud versus grain supported fabric. In this research, Dunham's (1962) classification is employed to categorize different microfacies of the Sakesar Limestone. For detailed microfacies analysis, the Sakesar Limestone is investigated at Padhrar section of Eastern Salt Range. Detailed sedimentological investigations on the basis of outcrop features and petrography are carried out in the study area for delineating the microfacies of Sakesar Limestone.

Lithologically, the Sakesar Limestone is comprised of light-medium grey to dark light grey, massive, nodular limestone and petrographically, it mainly comprises of wackestone depositional texture. Details of the identified microfacies in the study area of the Padhrar section are as follow.

4.1 Microfacies of the Sakesar Limestone

In the study area, the formation is encompassed of light to medium and dark grey to brown, cherty, fractured and at intervals nodular limestone that has the lower contact with Nammal Formation (fig2.1) and upwards, nodularity and fractures enhance while at the middle part some parts of the formation are devoid of nodularity. The in-depth microfacies analysis results in formation of five microfacies of the Sakesar Limestone in younging up sequence and details of the identified microfacies are given below.

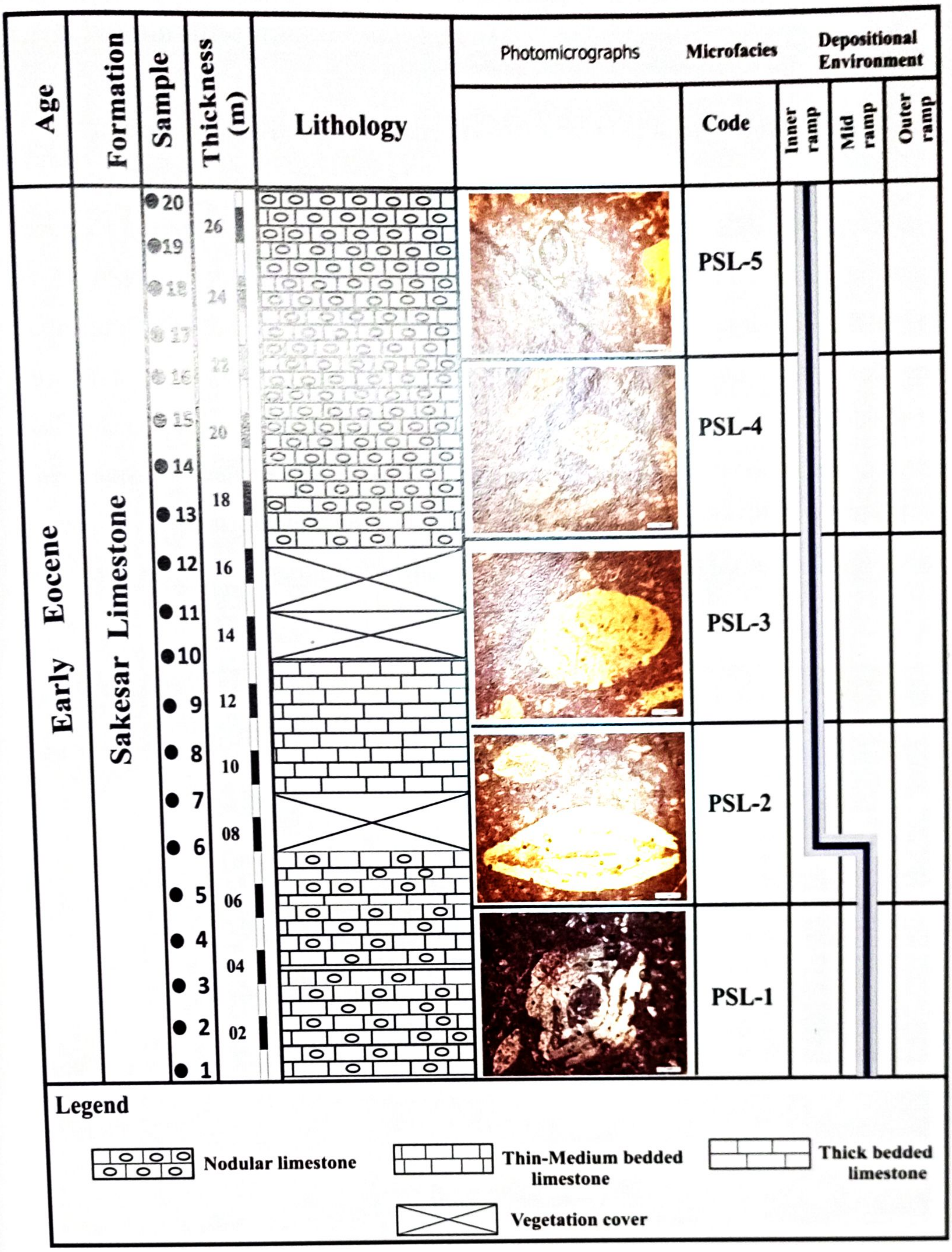


Figure 4.1: A litholog of the Sakesar Limestone at the study area

4.1.1 Nummulitic wackestone (PSL-1)

This microfacies in the study area is encompassed of light grey to pale brownish grey, nodular, fractured, thick bedded limestone constituting the basal part of the formation having lower contact with the Nammal Formation. The PSL-1 is represented by the ESP-1, ESP-2, ESP-3 and ESP-4 samples from bottom part of the formation. Petrographically, this microfacies is dominated by the *Nummulites sp.* (6-9%) followed by *Assilina sp.*, *Lockhartia sp.* larger benthic foraminifera (LBF) with minor Rotalia and echinoids coupled with bioclasts (5-7%) of LBF, ostracods and echinoids (Table 4.1). The diagenetic features observed in this microfacies include micritization, micritic envelope formation, neomorphism, microfractures and dissolutions (Plate 1). Based on allochems and matrix, it constitutes the wackestone depositional texture making up the ratio of about 1:3.

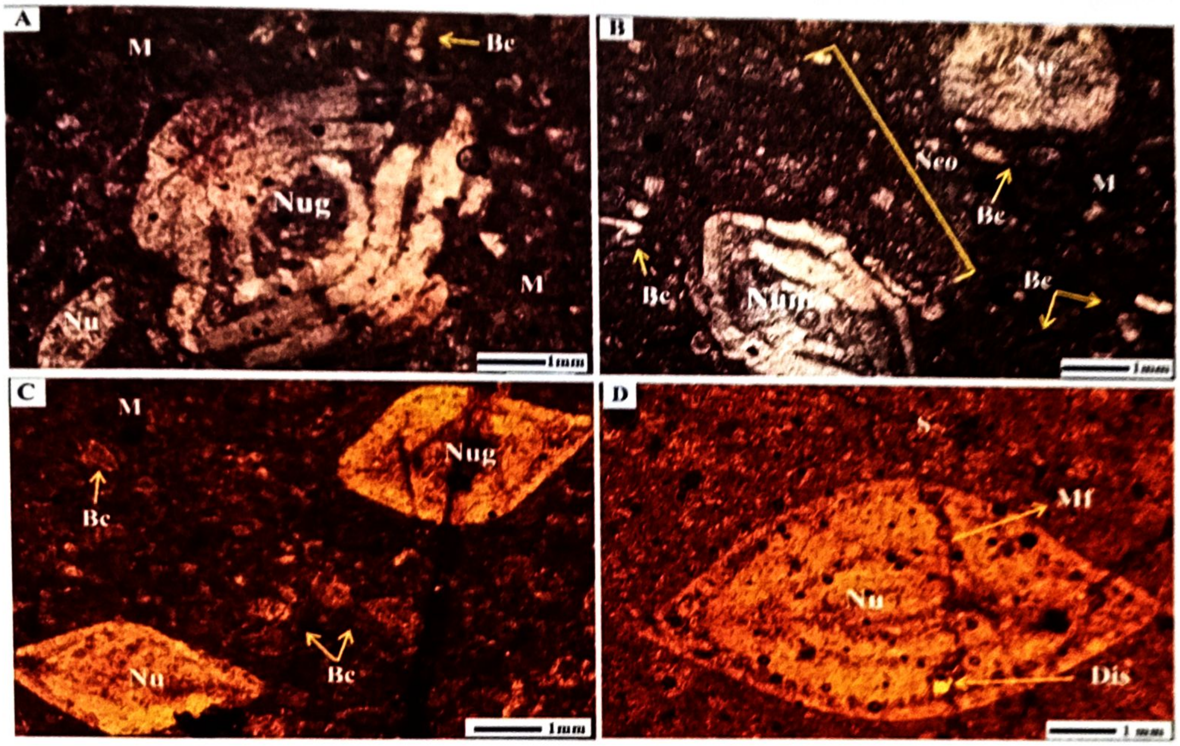


Plate 1: Micrographs showing Nummulitic wackestone microfacies of the Sakesar Limestone in the study area. Plate 1 represents microphotographs (A- D, 1 mm scale, plain polarized, 4X magnification) of the Nummulitic wackestone microfacies (PSL-1). A: *Nummulites globolus* as (Nug), *Nummulites sp.* as (Nu), micrite matrix as (M) and bioclast as (Bc) B: *Nummulites mamilatus* as (Num), *Nummulites sp.* as (Nu), biolcasts as (Bc), micrite matrix as (M) and neomorphism as (Neo). C: *Nummulites globolus* as (Nug), *Nummulites sp.* as (Nu), micrite matrix as (M) and bioclast as (Bc) D: *Nummulites sp.* as (Nu), microfracture as (Mf), dissolution as (Dis) and sparite as (S)

4.1.1.1 Depositional environment (PSL-1)

The dominance of larger benthic foraminifera dispersed in micritic matrix relatively show calm and low energy conditions. According to (Flugel et al., 2010; Hussain et al., 2021), the micritic coverage of the skeletal grains depicts deposition in the photic zone and depth of lower than 100 - 200 m. The foraminiferal diversity in the PSL-1 microfacies and presence of micritic matrix points towards deposition in low energy proximal open marine middle ramp setting below the FWWB (Fig 4.2).

4.1.2 Benthic foraminiferal wackestone (PSL-2)

This microfacies is consisted of light to pale grey nodular, highly fractured, and medium to thick bedded limestone and it is represented by the outcrop samples of ESP-5, ESP-6, ESP-7 and ESP-8. The PSL-2 microfacies is characterized mainly by the allochems of benthic foraminifera dominantly of *Nummulites sp.* (3-5%), followed by *Lockhartia* (2-3%), *Assilina*, *Alveolina* and *Rotalia* species of larger benthic foraminifera with some echinoids (3%) and non-existent smaller benthic foraminifera. The allochems of this microfacies also include bioclasts of some larger and smaller benthic foraminifera with echinoderm and other poorly preserved skeletal biodebris (Table 4.1). The observed diagenetic features of this microfacies are micritization, stylolitization, dissolutions and microfractures (Plate 2). Based on allochems to matrix ratio that is about 1:4, it constitutes the wackestone depositional texture.

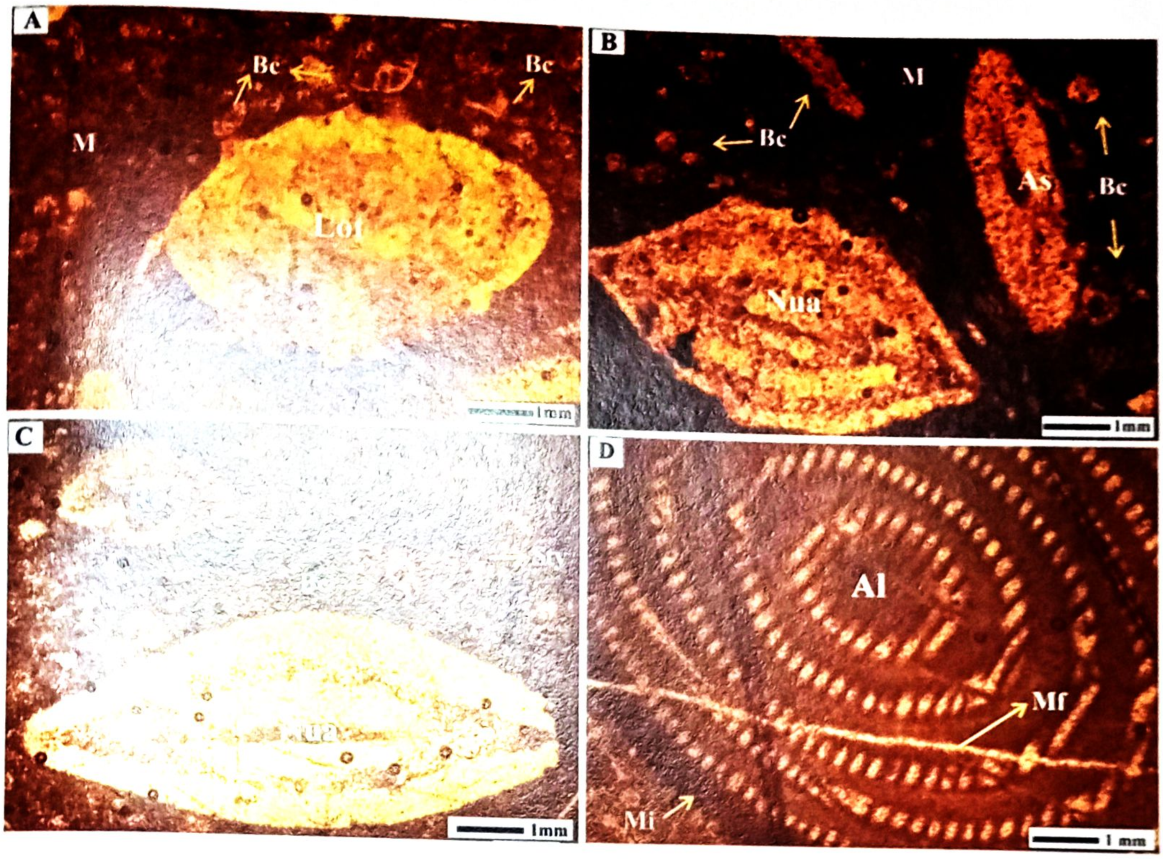


Plate 2: Micrographs of Benthic foraminiferal wackestone microfacies of the Sakesar Limestone in the study area. Plate 2 represents microphotographs (A- D, 1 mm scale, plain polarized, 4X magnification) of the Benthic foraminiferal wackestone microfacies (PSL-2) A: *Lockhartia tipperi* as (Lot), micrite matrix as (M) and bioclasts as (Bc) B: *Nummulites atacicus* as (Nua), *Assilina sp.* as (As), bioclast as (Bc) and micrite matrix as (M) C: *Nummulites atacicus* as (Nua), *Rotalia sp.* as (Ro), bioclast as (Bc) and micrite matrix as (M) and stylolite (Sty). D: *Alveolina sp.* as (Al), microfracture as (Mf) and micritization as (Mi)

4.1.2.1Depositional environment (PSL-2)

The dominant allochems of this microfacies is larger benthic foraminifera followed by echinoids and very rare smaller benthic foraminifera with orthochem of micrite matrix mainly. The Larger benthic foraminifera have been the dominant constituents of shallow marine shelf carbonates formed in warm waters since the late Paleozoic time (Flügel, 2004). Moreover, Thin-walled *Assilina* and *Nummulites* are suggested to representative of the outer carbonate ramp depositional environments with water depth ranging between 80 to 120 m (Hottinger, 1997) and the close association of *Nummulites* and *Assilina* depict that deposition took place below the FWWB (Racey, 1994). However, the presence of *Lockhartia sp* and *Alveolina sp.* and most importantly presence of Alveolina sp. indicates shallow warm water conditions with a depth range 5-

80 m (Buxton and Pedley, 1989; Hohenegger, 1999). Therefore, the PSL-2 microfacies is consistent with distal inner to proximal middle ramp settings above the fair weather wave base (FWWB) (Fig 4.2).

4.1.3 Lockhartia rich mud wackestone (PSL-3)

It is comprised of pale to dark grey nodular, cherty, fractured, and thick bedded limestone and this microfacies is represented by the outcrop samples of ESP-9, ESP-10, ESP-11 and ESP-12. The PSL-3 microfacies is typified mainly by the allochems of benthic foraminifera dominantly of *Lockhartia sp.* (4-6%), followed by *Nummulites*, *Alveolina* and *Rotalia* species of larger benthic foraminifera (Plate 3) with echinoids and. bioclasts of some larger benthic foraminifera and shallower fauna (Table 4.1). The observed diagenetic features of this microfacies are micritization, dissolutions and microfractures. In this microfacies allochems to matrix ratio is roughly 1:9, making up the mud-wackestone depositional texture.

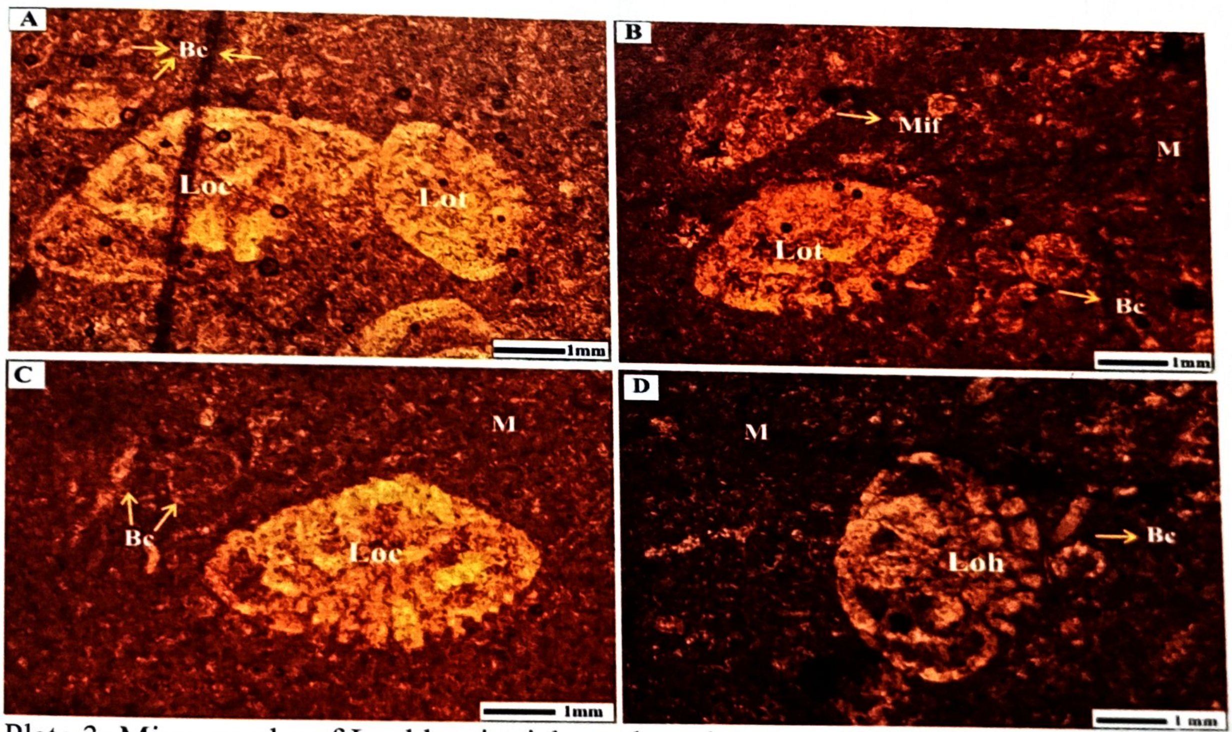


Plate 3: Micrographs of Lockhartia rich mud wackestone microfacies of the Sakesar Limestone in the study area. Plate 3 represents microphotographs (A- D, 1 mm scale, plain polarized, 4X magnification) of the Lockhartia rich mud wackestone microfacies (PSL-3) A: *Lockhartia tipperi* as (Lot), *Lockhartia conditi* as *(Loc)*, and bioclasts as (Bc) B: *Lockhartia tipperi* as (Lot). Micritized foraminifera (Mif), bioclast as (Bc) and micrite matrix as (M) C: *Lockhartia conditi* as *(Loc)*, bioclast as (Bc) and micrite matrix as (M) D: *Lockhartia haimei* as *(Loh)*, bioclast as (Bc) and micrite matrix as (M)

4.1.3.1 Depositional environment (PSL-3)

The characterizing allochems of this microfacies are mainly Lockhartia species followed by Assilina sp. with bioclasts of echinoids, Rotaliida with larger benthic foraminifera, whereas the orthochem of the microfacies is micrite matrix mainly. According to (Racey, 1994), Lockhartia sp. manifests inner to middle ramp settings and Assilina sp. are suggested to occupy a mid-ramp environment (Ghose, 1977). The orthochem micrite matrix shows calm and low energy conditions (Hussain et al., 2021). The dominance of Lockhartia and Assilina species coupled with micrite matrix in (PSL-3) microfacies corresponds to the open ramp to distal inner ramp settings (Fig 4.2).

4.1.4 Bioclastic wacke-packstone (PSL-4)

It is comprised of light to dark grey, highly nodular, fractured, and thick-bedded limestone and this microfacies is represented by the outcrop samples of ESP-13, ESP-14, ESP-15 and ESP-16. The PSL-4 microfacies is characterized mainly by the allochems of bioclasts (15-17%), of echinoids, algae, larger benthic foraminifera like *Lockhartia*, miliolids and other shallower fauna (Table 4.1). The observed diagenetic features of this microfacies are microsparitization, micritization, recrystallization, dissolutions and microfractures. Allochems to matrix ratio in this microfacies is roughly 3:7, forming the wacke-packstone depositional texture.

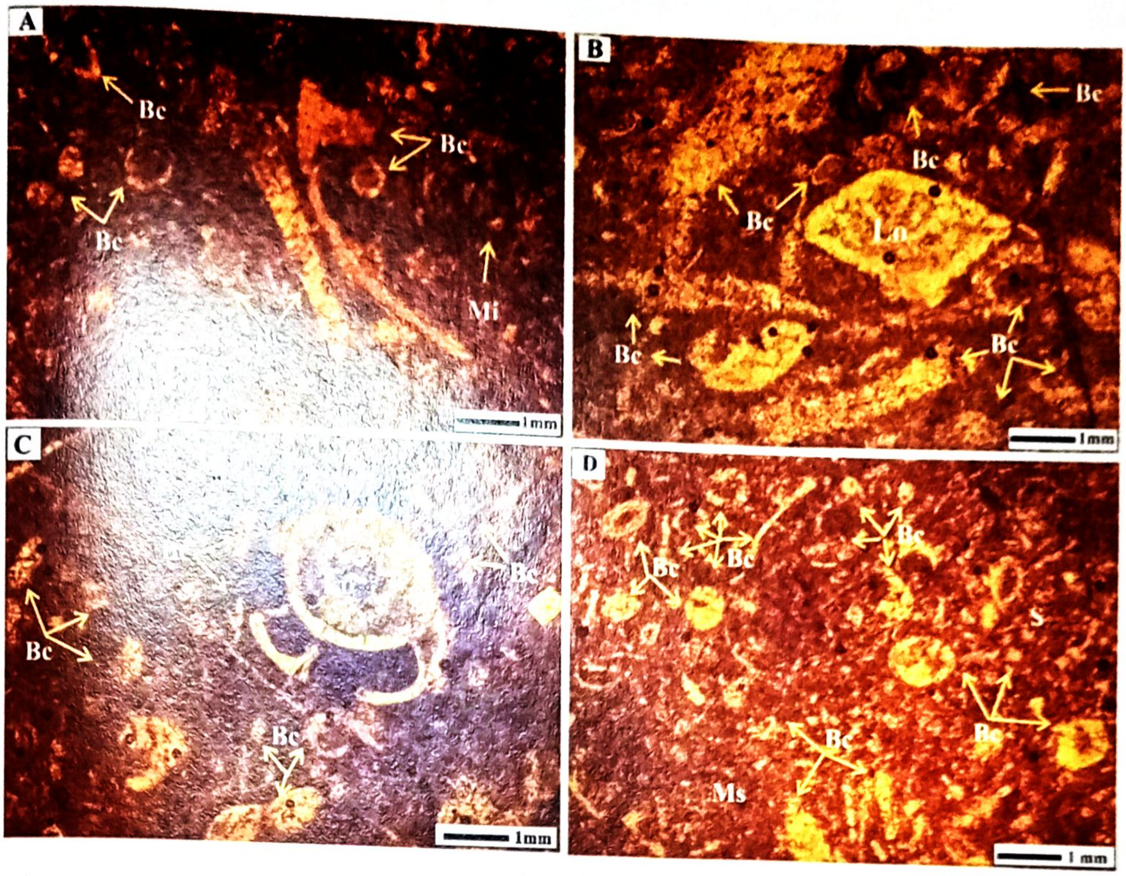


Plate 4: Micrographs of Bioclastic wacke-packstone microfacies of the Sakesar Limestone in the study area. Plate 4 represents microphotographs (A- D, 1 mm scale, plain polarized, 4X magnification) of the Bioclastic wacke-packstone microfacies (PSL-4) A: Miliolid as (Mi) and bioclasts as (Bc) B: *Lockhartia sp.* as (Lo). Micritized foraminifera (Mif), bioclast as (Bc) and micrite matrix as (M) C: *Lockhartia sp.* as (Lo), bioclast as (Bc) and micrite matrix as (M) D: Bioclasts as (Bc) and microsparite or microspar matrix as (Ms)

4.1.4.1 Depositional environment (PSL-4)

The dominant allochems of this microfacies are the biolcasts of diverse fauna of echinoids, *Lockhartia* and algae dispersed in micritic and microsparite matrix. The *Lockhartia sp* with miliolids along with green algae dasycladales points toward inner turbulence conditions in inner ramp setting (Beavington-Penney, 2006; Racey, 1994). Based on the faunal assemblage and depositional texture of wacke-packstone, this microfacies is consistent with open ramp of inner ramp depositional setting (Fig 4.2).

4.1.5 Miliolidal wackestone microfacies (PSL-5)

This microfacies is comprised of pale grey nodular, fractured, and medium to thick bedded limestone and it is represented by the outcrop samples of ESP-17, ESP-18, ESP-19 and ESP-20. The PSL-5 microfacies is characterized mainly by the allochems of Miliolids dominantly followed echinoids, algae and biolcasts of shallow fauna with rare Lockhartia, Alveolina and Lockhartia species of larger benthic foraminifera (Table 4.1). Allochems to matrix ratio in this microfacies is about 1:6, constituting the wackestone depositional texture.

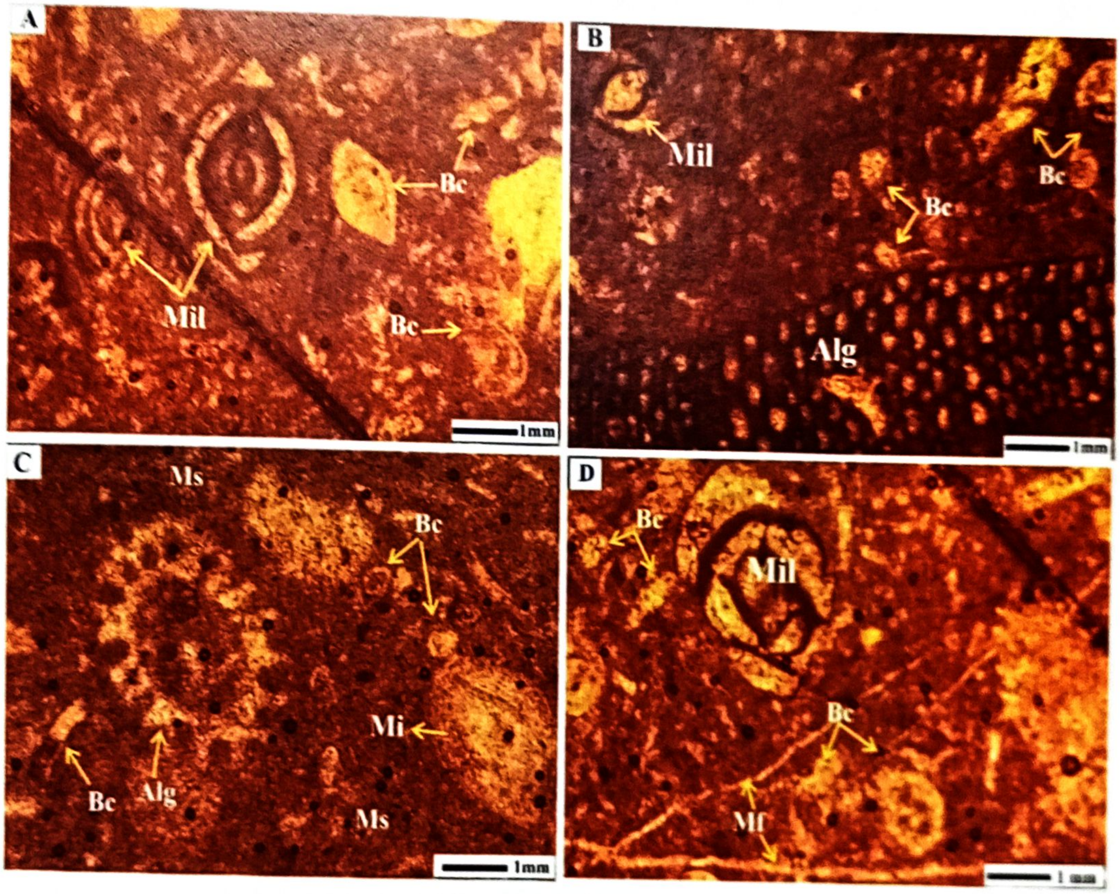


Plate 5: Micrographs of Miliolidal wackestone microfacies (PSL-5) of the Sakesar Limestone in the study area. Plate 5 represents microphotographs (A- D, 1 mm scale, plain polarized, 4X magnification) of the Miliolidal wackestone microfacies (PSL-5). A: Miliolid as (Mi) and bioclasts as (Bc) B: Miliolid as (Mi), algae is dasycladales as (Alg) and bioclasts as (Bc). C: Miliolid as (Mi), algae is as (Alg) bioclasts as (Bc) and microspar matrix as (Ms) D: Miliolid as (Mi), bioclasts as (Bc) and microfractures as (Mf) and some ghosts of foraminifera are present

4.1.5.1 Depositional environment (PSL-5)

This microfacies is typified by the presence of Miliolids followed by dasyclads (algae) and bio debris of shallow fauna dispersed in micritic and microsparite matrix. The presence of miliolids represents shallow warm water conditions of inner ramp setting (Beavington- Penney and Racey, 2004). The presence of green algae further underscores inner ramp environment (Zhicheng, 1997) Based on the abundance of miliolids, the deposition of this microfacies is consistent with shallower deposition of restricted lagoon to open ramp setting of proximal inner ramp environment (Fig.4.2).

Table 4.1: The visually estimated allochems and orthochems ratio of microfacies

Microfacies # Of the Sakesar Limestone	Bioclasts %	Nummulites %	Assilina %	Lockhartia %	Rotalia %	Alveolina %	Echinoids %	Miliolids %	Algae %	Allochems %	Matrix%	Grain: Matrix	Classification of Dunham (1962)
PSL-1	5-7	6-9	4	3	2	-	2	-	-	24	74	1:3	**Wackestone**
PSL-2	4-6	3-5	2	2-3	2	2	3	-	-	21	79	1:4	**Wackestone**
PSL-3	2-4	2	-	4-6	1	-	1	-	-	12	88	1:9	**Mud-wackestone**
PSL-4	15-17	1	-	3	1	1	4	1	2	29	71	3:7	**Wacke-packstone**
PSL-5	2-4	-	-	1	-	1	2	4-6	3	15	85	1:6	**Wackestone**

4.2 Depositional environment of the Sakesar Limestone

Based on the biogenic components, carbonate texture and depositional fabric, five microfacies have been erected: PSL-1 (Nummulitic wackestone microfacies), PSL-2 (Benthic foraminiferal wackestone microfacies), PSL-3 (Lockhartia rich mud wackestone microfacies), PSL-4 (Bioclastic wacke-packstone microfacies) and PSL-5 (Miliolidal wackestone microfacies). These microfacies have mainly larger benthic foraminifera of species *Nummulites*, *Lockhartia*, *Assilina* and *Alveolina* with other faunal assemblage of miliolids, rotalia, echinoids, algae and their biolcasts. The species of the Nummulites in the identified microfacies are of *Nummulites atacicus*, *Nummulites globolus* and *Nummulites mamilatus*, the species *Lockhartia* include *Lockhartia conditi*, *Lockhartia haimei* and *Lockhartia tipperi* with species of *Alveolina*, *Assilina* and *Miliolids*. In these microfacies, micrite is in abundance having no any reefal or grainstone facies with no any evidence of re-sedimentation in form of turbidities that overall characterize low-energy setting on a low-gradient slope of a ramp setting rather than a shelf (Adabi et al., 2008). On the basis of the fossil assemblages, allochems and orthochems, the environment of deposition is suggested to be homoclinal ramp-like carbonate system with gentle slope without any obvious break in slope (Fig 4.2).

Nummulites predominantly reflect middle ramp environment and when they are associated with Assilina sp. they depict a relatively deeper environment (Anketell and Mriheel, 2000; Racey, 1994; Racey, 2001). These Nummulites and Assilina species are the representative of distal middle to proximal middle ramp settings. Shallow deposition of inner ramp settings of the Sakesar Limestone is typified by the presence of algae, *Alveolina* and miliolids as the *Alveolina sp*. and miliolids represent shallow warm water conditions of inner ramp setting (Beavington- Penney and Racey, 2004; Gilham and Bristow, 1998; Racey, 2001). The abundance of biolcasts of various shallower fauna further underscores upwards shallower condition during the deposition of the Sakesar Limestone as the presence of recognizable bioclasts is indicative of increased relative energy and thus, shallower water (Mehrabi et al., 2014). As evidence by the depositional proxies of the larger benthic foraminifera identified and allochems and orthochems presence, the erected five microfacies of the Sakesar Limestone depict the deposition of the Sakesar Limestone in the distal middle ramp to restricted inner ramp settings of the homoclinal carbonate ramp environment (Fig 4.2).

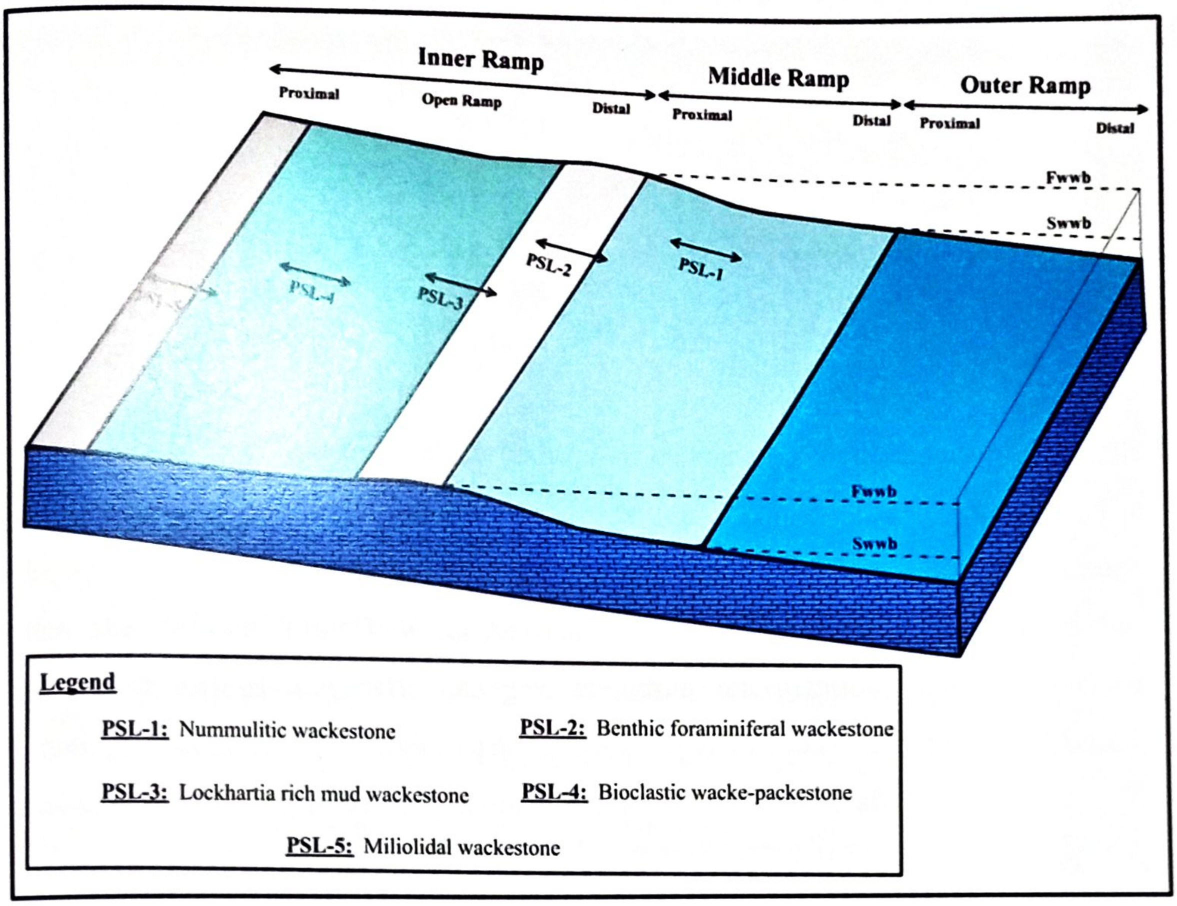


Figure 4.2: A proposed depositional model of the Sakesar Limestone in the study area

CHAPTER 5

DIAGENETIC FABRICS OF THE SAKESAR LIMESTONE

The diagenetic fabrics are the features or changes the sedimentary rock entails once it is undergone through the process of deposition, lithification and compaction. The Sakesar Limestone has been investigated for the diagenetic imprints or changes through which the Sakesar Limestone underwent through. The Sakesar Limestone has encountered various diagenetic changes; including micritization, micritic envelope formation, neomorphism (microsparitization, sparitization) or recrystallization, dissolution, cementation and compaction (chemical and mechanical).

5.1 Micritization

Micritization is the conversion of some allochems into dense micrite by the action of endolithic algae and is the first diagenetic phase in the formation of carbonate rocks (Adabi et al., 2009; Jafarian et al., 2018). In the Sakesar Limestone, the observed micritization varies from partial to intense (Fig 5.1 B; D). Micritization has effected the skeletal grains of mostly wackestone microfacies. The micritization process developed black micritic envelope around the skeletal grains margins (Fig 5.1 B).

5.2 Neomorphism

In the Sakesar Limestone, the neomorphism has majorly affected almost all microfacies and neomorphism is marked by mainly aggrading neomorphism (Fig 5.2 C; D). In this process, recrystallization occurs in which size changes from micrite or lime mud to microspar or microsparite followed by pseudo-sparite.

5.3 Cementation

Cementation is the diagenetic process of precipitation of cements or mineral contents. The Sakesar Limestone has been affected by the different cementation including acicular cement, blocky, drusy and granular cements (Fig 5.3). The Sakesar Limestone is mostly cemented by calcite and rare iron minerals. The iron minerals are also seen around the stylolites and microfractures.

5.4 Dissolution

In the Sakesar Limestone, dissolution has resulted in the formation of void spaces in the shells of foraminifera, mollusks and through the matrix (Fig 5.1 C; E) and sometimes caused the refilling of the void spaces. The dissolution has been the mostly found diagenetic fabric in the identified microfacies that resulted in creation of moldic, channel and vuggy porosities (Fig 5.1 C; E). Intense twinning in calcite is caused by usually by dissolution and dislocation of crystals and this is mainly due to burial loading or tectonic deformation (Scholle and Ulmer-Scholle, 2003).

5.5 Compaction

In the Sakesar Limestone, there are two types of compactions observed; chemical and mechanical.

5.5.1 Chemical compaction

The chemical compaction in the Sakesar Limestone is represented by the stylolitization that occurs in the form of irregular to high amplitude types of stylolites (Fig 5.1 B; E). The stylolitization occurs in the formation in rare and mostly are sutured in nature.

5.5.2 Mechanical compaction

The Mechanical compaction involves grain breakage, plastic grain deformation, and grain re-orientation (Meyers, 1980). The Mechanical compaction is evident by shell discontinuities like broken allochems and fossil distortions which are very rare in the Sakesar Limestone (Fig. 5.1 D; E). One of the manifestations of the mechanical compaction is the microfracturing, caused by burial and or tectonic activity that are present in which some are filled, while others are vacant (Fig. 5.1 C; D; E). These fractures can be formed by mechanical compaction.

5.6 Impacts of diagenetic fabrics on reservoir aspect of the Sakesar Limestone

Diagenetic fabrics or imprints play crucial rule to access the reservoir properties of the formation. The diagenetic processes in carbonates imparts pivotal role in the assessment of reservoir quality and heterogeneity and causes the reservoir properties for hydrocarbon accumulation (Ali et al., 2018, Jafarian et al., 2017). The diagenetic processes within the Sakesar Limestone resulted in the two fold impacts of the reservoir quality of the Sakesar Limestone. The first one involves the processes that enhance the potentiality of the reservoir and the second one entails the processes that decrease or partially decrease the efficacy of the reservoir. Among the diagenetic changes of the Sakesar Limestone, the secondary porosity resulted from mainly microfracturing, fracturing and dissolution are the ones that enhance the reservoir efficacy (Hussain et al., 2021). On the other hand, diagenetic events of micritization and cementation and compaction reduce the reservoir quality of the Sakesar Limestone.

Among the diagenetic fabrics of the Sakesar Limestone dissolution and microfracturing are the main factors enhancing the reservoir potential and they have often resulted in formation of intergranular and intragranular porosities and secondary porosities like moldic, channel and fenestral porosities. The dissolution fabric throughout the identified microfacies increases the reservoir aspects of the Sakesar Limestone due to its role in evolution of various porosity which result in enlargement of pore spaces (Fig 5.3).

The secondary porosity resulted from dissolution and microfracturing is predominantly present in the formation and it has caused the formation of primary porosity at places. Moldic pores observed in the Sakesar Limestone generated during dissolution, have improved the reservoir quality of the Sakesar Limestone (Fig 5.1 E). The dissolution results in the removal of the central portion or marginal allochems mainly biolcasts (Fig 5.1). At outcrop, cavities are observed in the Sakesar Limestone and they are resulted from the pressure solution. Cavities and pressure solution are also responsible for generation of secondary porosities in the Sakesar Limestone. Other than the microscopic microfractures, the mesoscopic fractures are also recorded in the outcrop section that facilitate fracture porosity. The microfractures coupled with mesoscopic fractures of the Sakesar Limestone both enhance the storage capacity and permeability for the flow of hydrocarbon fluids (Ferket, 2003).

Among the diagenetic fabrics of the Sakesar Limestone, micritization, cementation, neomorphism and both chemical and mechanical compactions decrease the reservoir quality (Fig 5.3). The micritization is the major diagenetic process that is present as micritic envelopes around the grains and in form of partial or complete skeletal micritization (Fig. 5.1 B; D). Micritzation can reduce the permeability by due to filled pore throat (Hussain et al., 2021; Taghavi et al., 2006). The cementation reduces porosity or permeability as the fractures that are closed make hindrances to fluid movement due to chemical precipitation or in-filling of minerals (Hussain et al., 2021). The neomorphism observed in the formation also decreases the porosity (Hussain et al., 2021). The mechanical compaction results in compaction of the bulk volume of the rock owing to the overburden pressure. Due to the compaction, the intergranular and intragranular porosities coupled with permeability are either completely reduced and/or pore throats reduce in size (Ishaq et al., 2019). The chemical compaction or stylolitization completely or partially destroys porosity and eliminates permeability as a result of pressure dissolution where pores are either developed as primary or during earlier diagenetic history (Ferket, 2003).

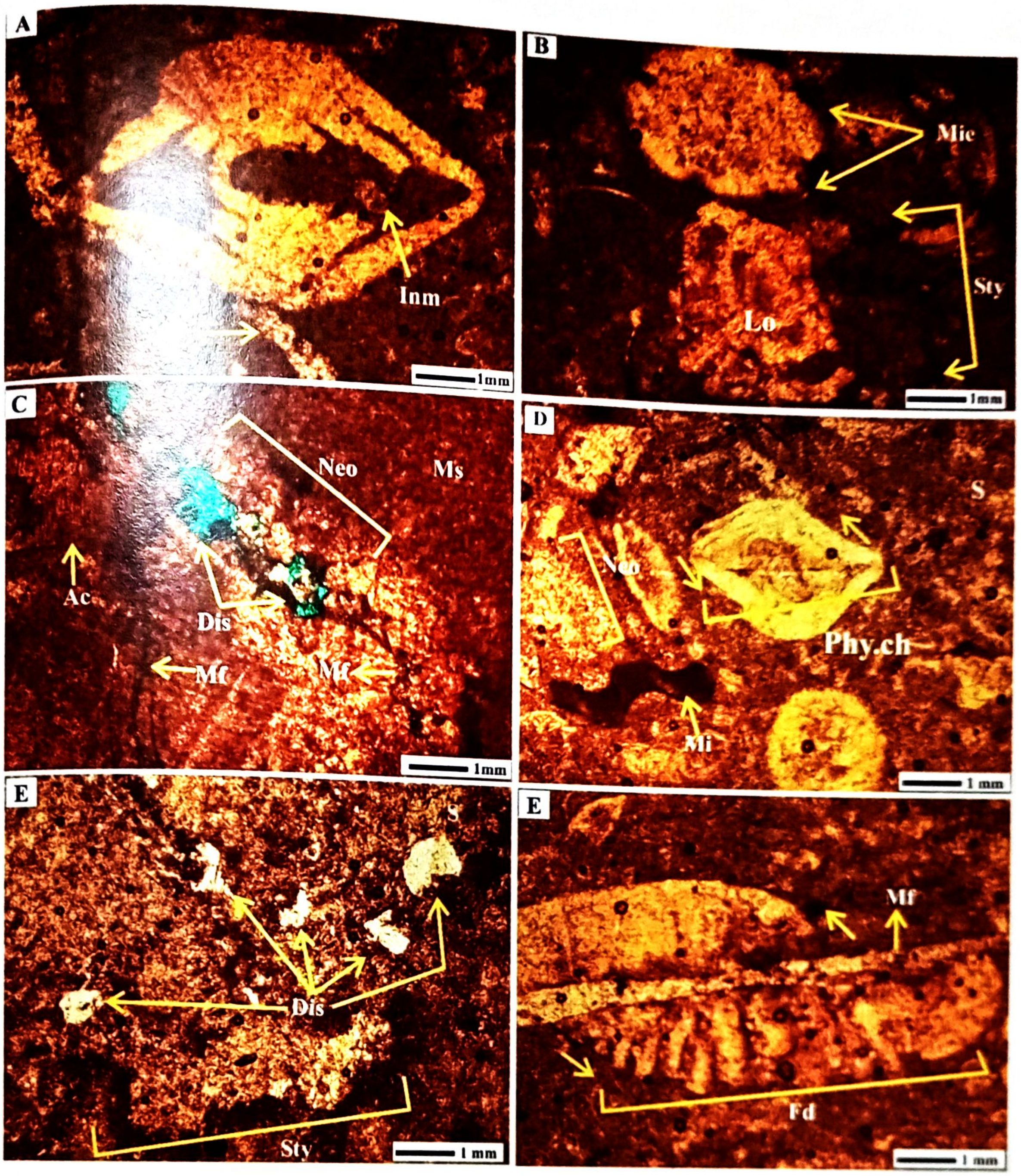


Figure 5.1: Micrographs depict the diagenetic fabrics of the Sakesar Limestone in the study area. (A) internal micritization (Inm) and microfractures (Mf) filled by sparite. (B) micritic envelope (Mie) and stylolitization (Sty). (C) microfractures (Mf), dissolution (Dis) that constitutes channel porosity, neomorphism (Neo), microsparite (Ms), acicular cement (Ac). (D) physical compaction (Phy.ch), neomorphism (Neo), micritization (Mi) and sparitization (S). (E) dissolution (Dis) in form of moldic porosity and chemical compaction or stylolitization (Sty). (E) denotes physical compaction with dislocated fossil fragment (Fd) shown by yellow arrows and microfracture (Mf)

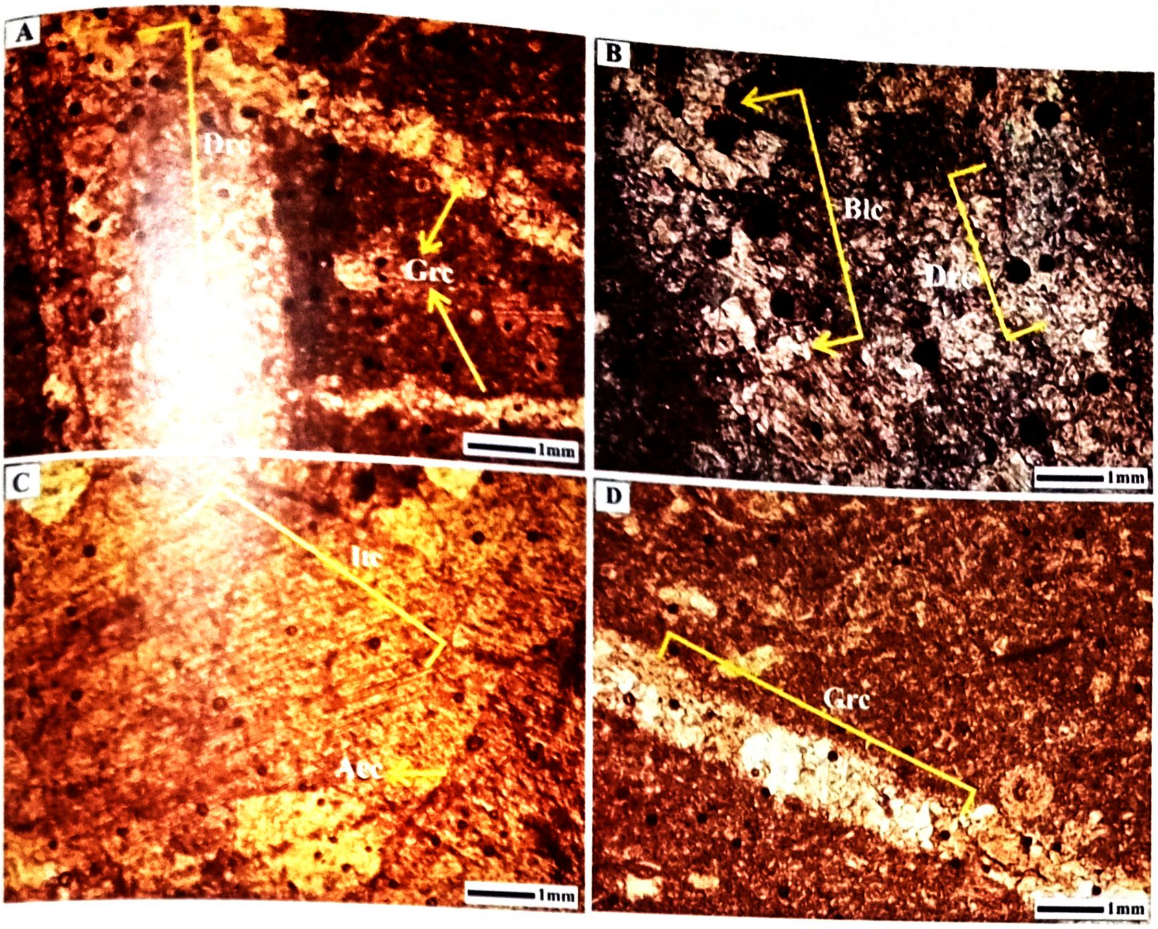


Figure 5.2: Micrographs depict the diagenetic cements of the Sakesar Limestone in the study area. (A) shows drusy cement (Drc) and granular cement (Grc), (B) depicts blocky cement (Blc) and drusy cement (Drc). (C) denotes intensive calcite twinning (Itc) and acicular cement (Acc), (D) granular cement (Grc)

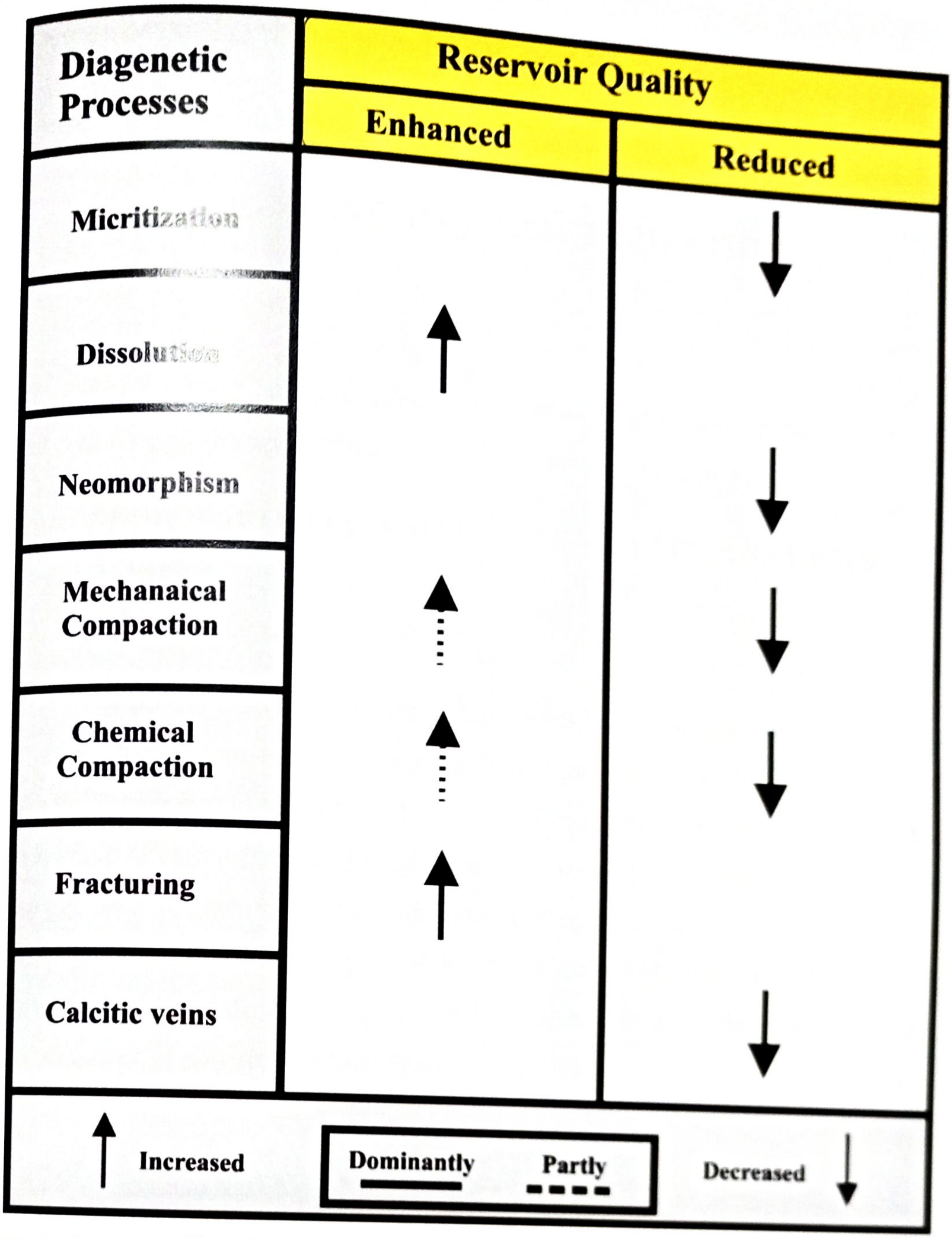


Figure 5.3: Depositional fabrics and their impacts of reservoir of the Sakesar Limestone in the study area

CHAPTER 6

RESERVOIR CHARACTERIZATION

For reservoir characterization five outcrop rocks samples were collected and analyzed for porosity and permeability using standard techniques.

6.1 PLUG POROSITY AND PERMEABILITY ANALYSIS

6.1.1 Porosity

Porosity is basically the measure of space in a rock that is not occupied by the solid structure or framework of the rock. It is explained as the fraction of the total bulk volume of rock that is not occupied by solids. Total porosity is the total void spaces in a rock while effective porosity includes only the pore spaces, which are interconnected. The geometry of packing of grains and sorting play a vital role in controlling the size and number of voids in different type of sedimentary material (Saxena and Gupta, 2017). The porosity ranges of different rocks and lithologies are given in (Table 6.1). For the measurement of porosity, Helium Porosimeter PHI-220 (Temco, USA) was used.

Table 6.1: Approximate ranges of porosities for some common lithology (Glover, 2012)

Lithology	Porosity Range (%)
Unconsolidated sands	35-45
"Reservoir" Sandstones	15-35
Compact Sandstones	5-15
Shales	0-45
Clays	0-45
Massive Limestones	5-10
Vuggy Limestones	10-40
Dolomite	10-30
Chalk	5-40
Granite	<1
Basalt	<0.5
Gneiss	<2
Conglomerate	1-15

6.1.2 Permeability

Permeability is the measure of the ability of a rock under a potential gradient, to transmit fluids. This "measure" represents the avenues or communication lines between pore spaces. Permeability depends upon the pore dimensions and configuration Permeability like porosity also depends on rock properties such as cement texture, grain shape, grain and size distribution. Permeability is second important reservoir characteristic property (Saxena and Gupta, 2017). Given below are the Hydraulic conductivity/ Permeability of different lithologies.

Table 6.1: Typical ranges in hydraulic conductivity of common rock types (Anderson, S.R. & B.D Lewis, 1989)

Lithology	**Hydraulic conductivity (md)**
Clay	5×10^{-7} to 10^{-3}
Loess	10^{-2} to 1
Silt	10^{-3} to 10^{-1}
Sand	10^{-1} to 5×10^{2}
Gravel	5×10^{1} to 5×10^{4}
Sand and gravel	5 to 10^{2}
Till	10^{-7} to 5×10^{-1}
Halite	5×10^{-6} to 5×10^{-3}
Limestone, dolomite	5×10^{-6} to 10^{0}
Karstic limestone	10^{-1} to 10^{3}
Chalk	Up to 5
Sandstone	5 x 10-5 to 2 x 101
Shale	5 x 10-8 to 10-4
Lignite	10-1 to 10
Friable tuff	2 x 10-2 to 2
Welded tuff, ignimbrite	5 x 10-5 to 2 x 10-1
Dense basalt	10-6 to 10-3
Fractured basalt	10-4 to 1
Vesicular lava	10-4 to 10-3
Lava	Less than 5 x 10-9 to 103
Slate	5 x 10-9 to 5 x 10-6
Schist	10-7 to 10-4
Dense crystalline rock	5 x 10 –8 to 10-5
Fractured crystalline rock	10-3 to 10

6.2 Core Plug Analysis

Core plug analysis test is conducted on the samples in order to identify the reservoir capabilities of the Sakesar Formation. The final report of the test on five samples of the Sakesar Formation is given below in the table

Table 6.2: Plug porosity and permeability analysis results

S.No	Sample No.	Plug Length (cm)	Plug Diameter (cm)	Dry Weight (gram)	Grain Density (g/cc)	Porosity (%)	Permeability (mD)
1	P1	6.038	2.535	82.02	2.699	0.285	0.00
2	P2	4.458	2.536	60.39	2.700	0.684	0.00
3	P3	5.416	2.535	72.89	2.713	1.722	0.00
4	P4	3.505	2.537	47.05	2.718	2.313	0.00
5	P5	4.746	2.537	62.53	2.694	3.237	0.0264

6.3 PETROPHYSICAL ANALYSIS

The main purpose of petrophysical analysis is to provide a valid model that can estimate the properties of formation like clay volume, effective porosity and water saturation in Balkassar OXY-01A and Fimkassar-02 by using open-hole log data. In Balkassar OXY-01A and Fimkassar-02 Choragali, Sakesar, Patala and Nammal formations are encountered among which petrophysical analysis is carried out on Sakesar Limestone.

6.3.1 Lithology Determination

Multiple cross plots are prepared for the determination of lithology in each zone of interest. In Fimkassar-02 well, for lithology identification Neutron-Density and Neutron-Sonic cross plots were used. In Density-Neutron cross plot the overlay lines are used of Schlumberger Density/Neutron Corr. Rhof 1.0 (Fig 6.1) where as in Neutron-Sonic cross plot the overlay lines are used of Schlumberger Neutron/Sonic Wyllie Dtf 189 (Fig 6.2). Both Neutron-Density and Neutron-Sonic cross plots indicate that the lithology majorly consists of limestone.

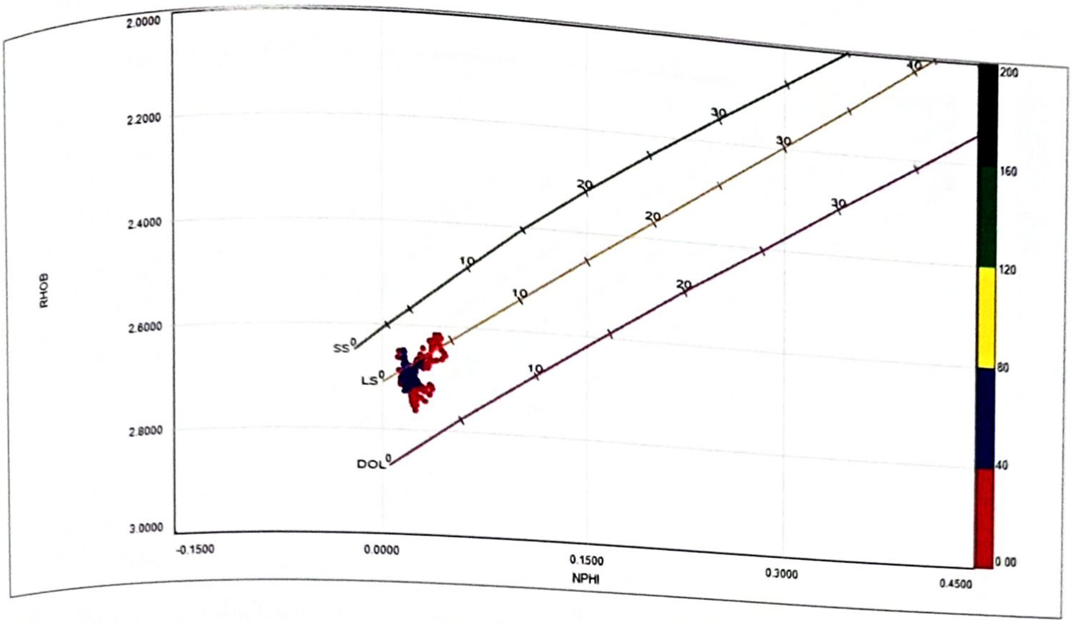


Figure 6.1: Neutron-Density cross plot of Sakesar Formation showing majorly limestone consisting lithology in Fimkassar-02

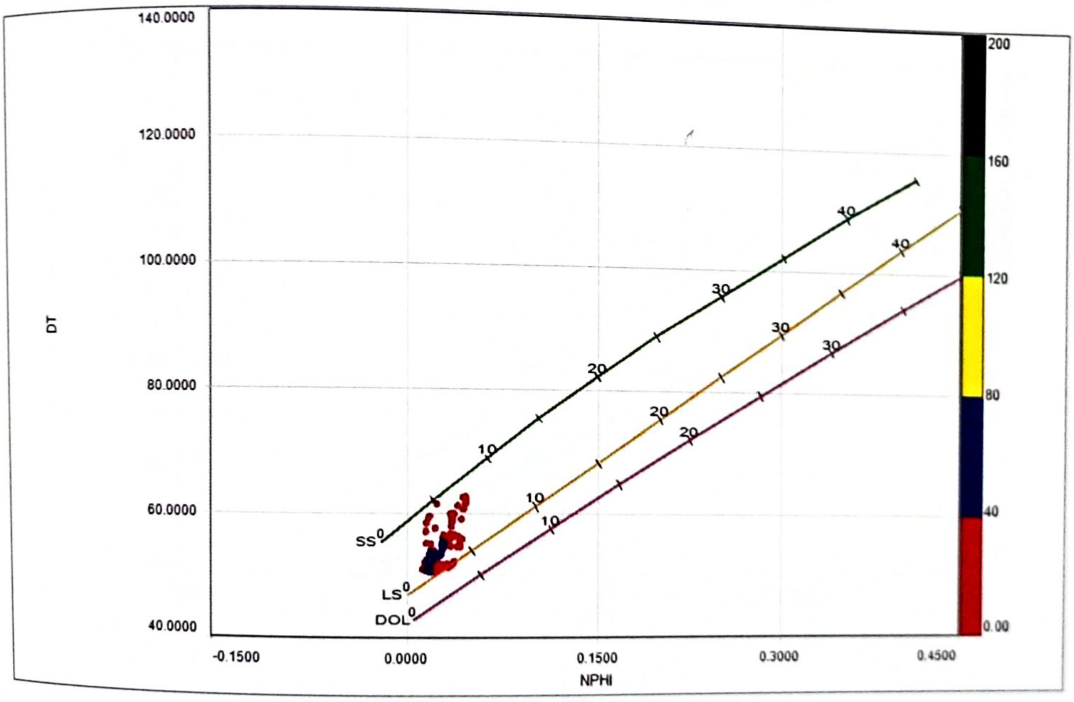


Figure 6.2 Neutron-Sonic cross plot of Sakesar Formation showing majorly limestone consisting lithology in Fimkassar-02

In Balkassar OXY-01A well, for lithology identification Neutron-Density and Neutron-Sonic cross plots were used. In Density-Neutron cross plot the overlay lines are used of Schlumberger Density/Neutron Corr. Rhof 1.0 (Fig 6.3) where as in Neutron-Sonic cross plot the overlay lines are used of Schlumberger Neutron/Sonic Wyllie Dtf 189 (Fig 6.4). Both Neutron-Density and Neutron-Sonic cross plots indicate that the lithology majorly consists of limestone.

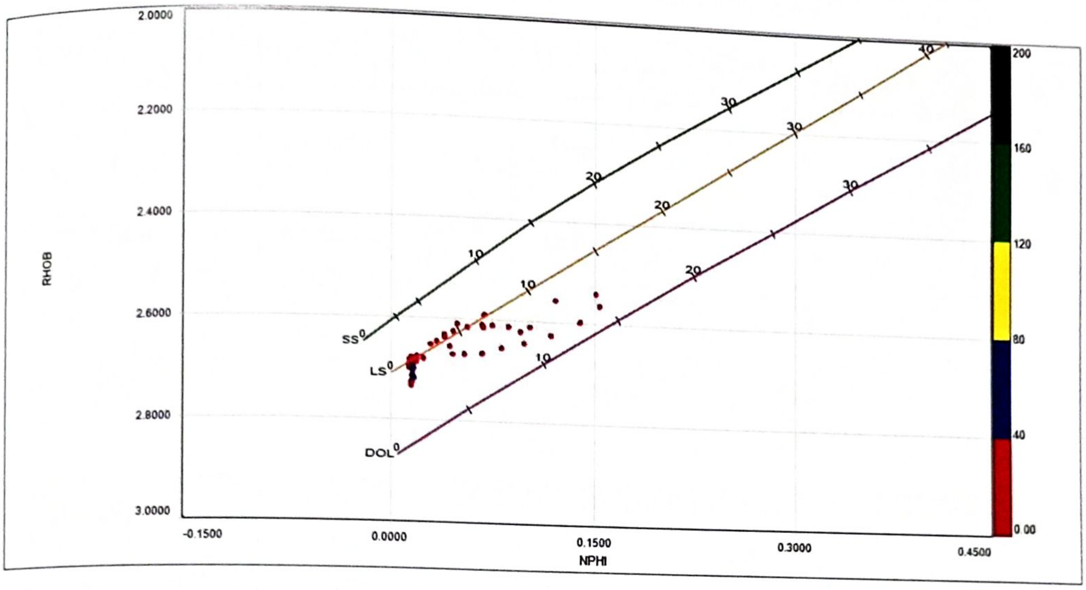


Figure 6.3: Neutron-Density cross plot of Sakesar Formation showing majorly limestone consisting lithology in Balkassar OXY-01A

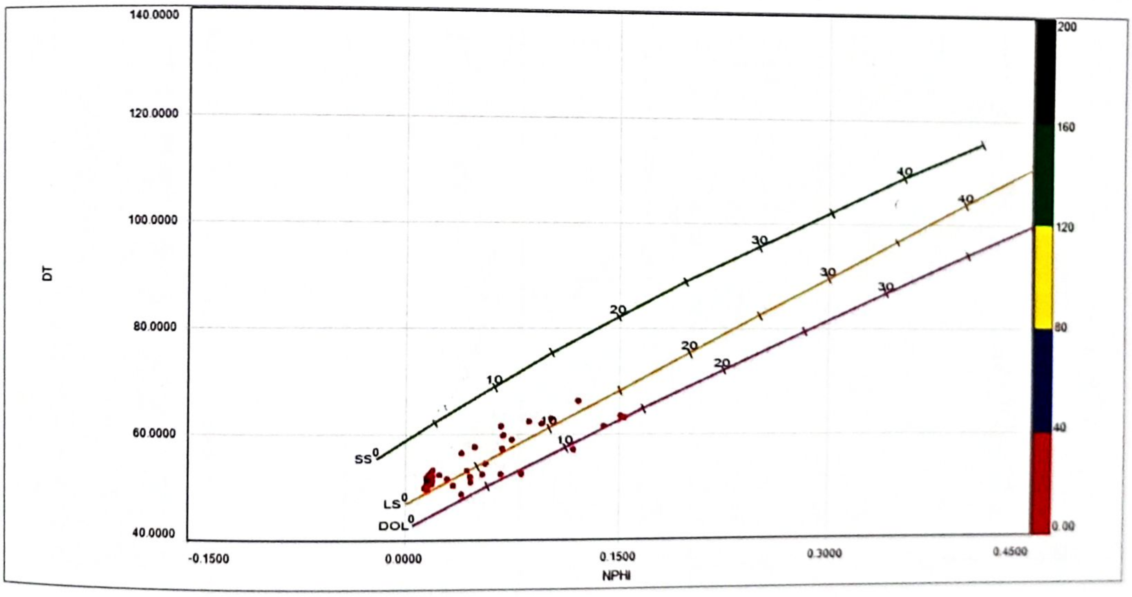


Figure 6.4 Neutron-Sonic cross plot of Sakesar Formation showing majorly limestone consisting lithology in Balkassar OXY-01A

6.3.2 Zone of Interest

In this study the targeted formation is Sakesar Formation of Eocene age

Table 6.3: Zone of interest in Balkassar OXY- 01A and Fimkassar-02 wells

Well	Formation	Top (m)	Bottom (m)	Thickness (m)
Balkassar OXY- 01A	Sakesar	2496	2505	9
Fimkassar-02	Sakesar	3008	3034	26

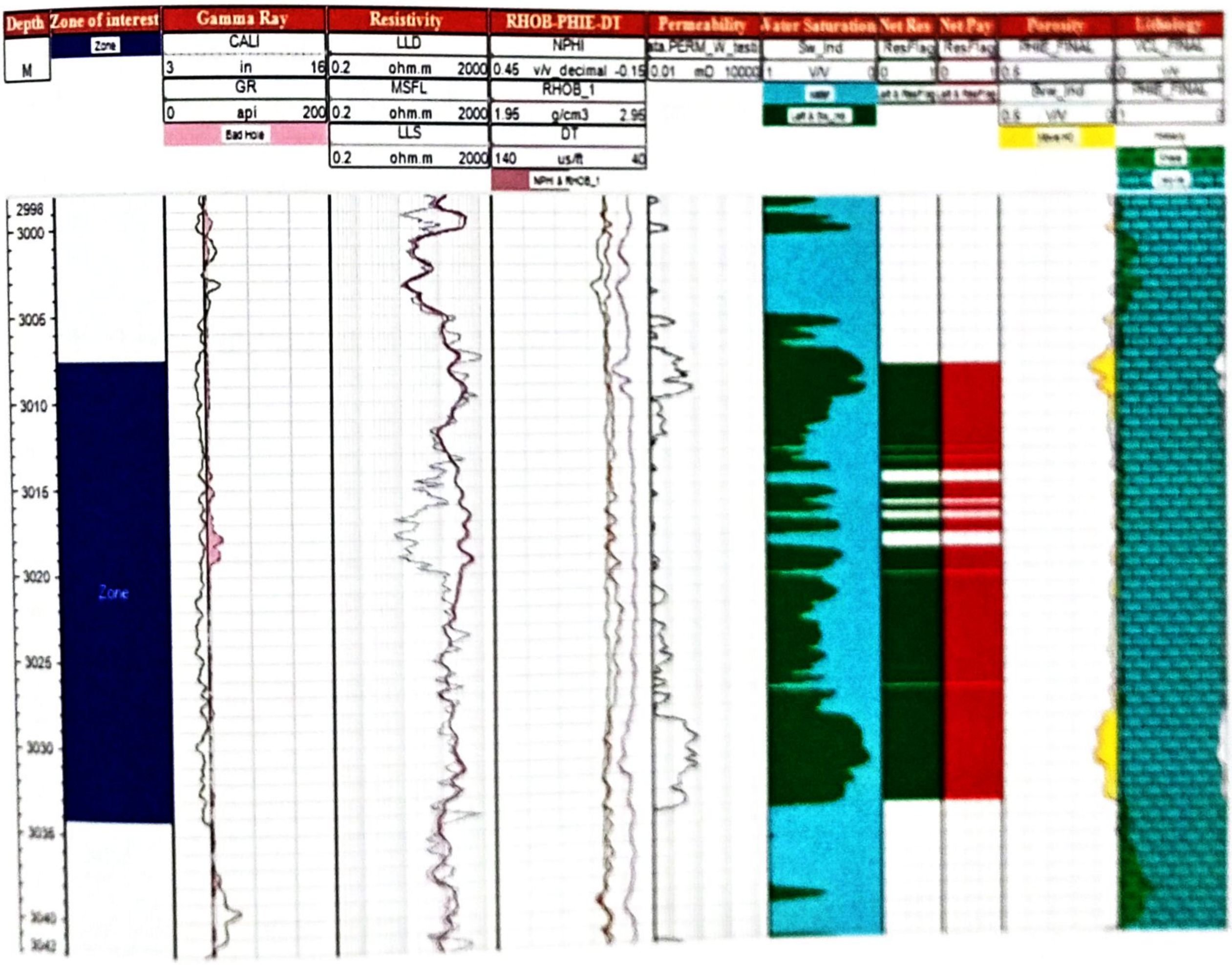


Figure 6.5: A composite log plot view of the Fimkassar-02 well

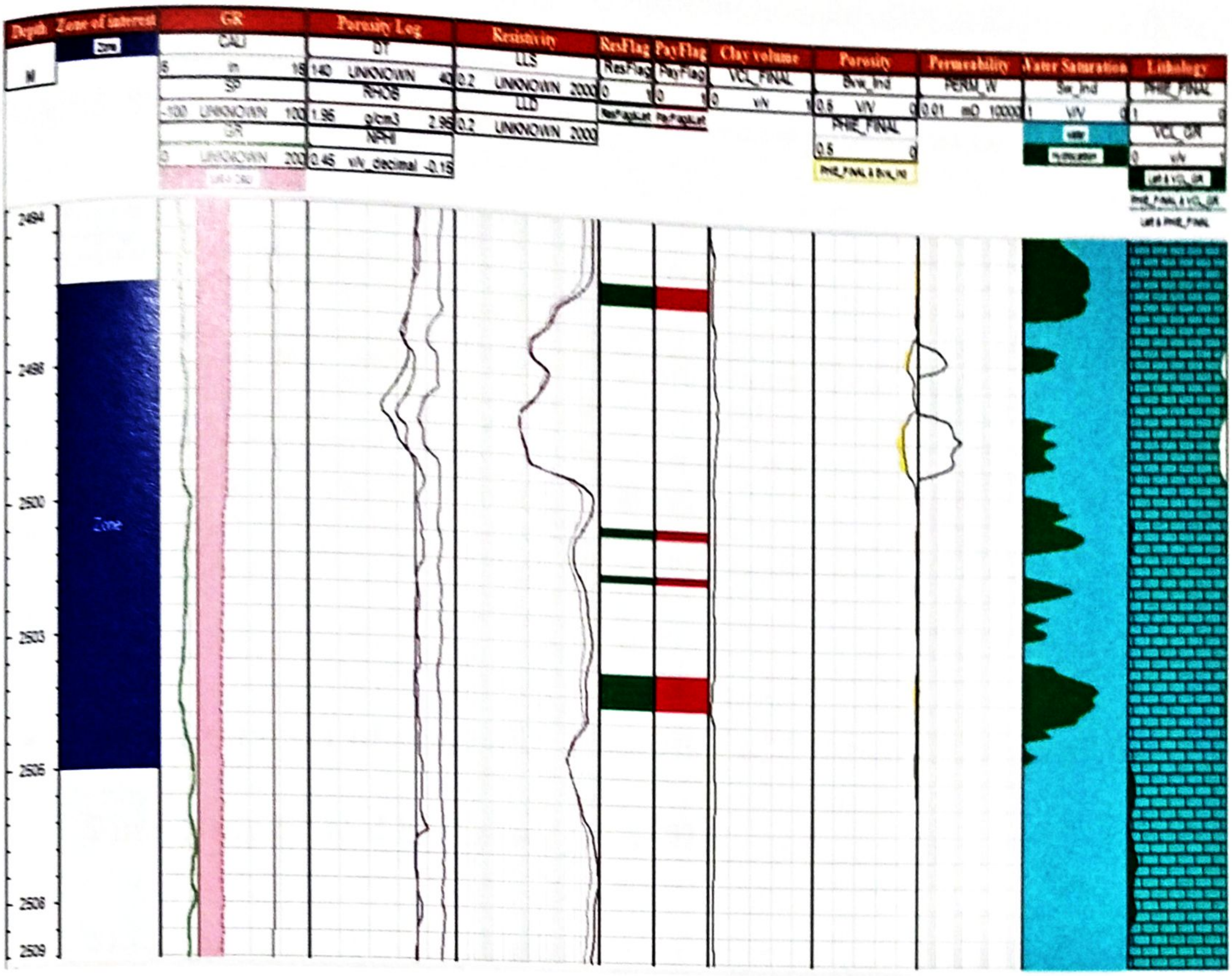


Figure 6.6: A composite log plot view of Balkassar OXY-01A well

6.3.3 Reservoir Summation Reports

Fimkassar-02

Table 6.4: Showing average values for the Sakesar Formation in Fimkassar-02 well

Cut off applied: Vclay=0.2, Phi cut=0.02, Sw cut=0.6				Average Values			
Zone Name	Top m	Bottom M	Thickness m	Volume of clay Vcl	Effective Phi %	Permeability mD	Saturation of hydrocarbons
Sakesar	3008m	3034m	26m	0.0039	0.0497	1.353	69%

Balkassar OXY-01A

Table 6.5: Showing average values for the Sakesar Limestone in Balkassar OXY-01A well

	Cut off applied: Vclay=0.25, Phi cut=0.005, Sw cut=0.6			Average Values			
Zone Name	Top m	Bottom M	Thickness	Volume Of clay Vcl	Effective Phi %	Permeability mD	Saturation of hydrocarbon
Sakesar	2496m	2505m	9m	0.0426	0.021	0.06	58%

6.4 Interpretation of reservoir properties of Sakesar Limestone in Fimkassar-02 and Balkassar OXY-01A

The interpretation of Sakesar Limestone reservoir properties of Fimkassar-02 and Balkassar OXY-01A.

During log analysis of Fimkassar-02, it is observed that the Sakesar Limestone in Fimkassar-02 well is comprised of mostly limestone because as it shows low GR values. At 3044 to 3045m borehole shows rugosity. Overlying resistivity curves such as LLS and LLD on higher side of the resistivity scale indicates compactness of the zone of interest. (Fig 6.1). A zone of interest at the depth ranging from 3008m to 3034m making up the thickness of 26 m is marked in the Fimkassar-02 well.

Interpretation of Fimkassar-02 shows the average volume of clay in the zone of interest is 0.0039 which is calculated by Gamma ray. For cross relation, the neutron log was also used for the estimation of volume of shale, but the curves of both Gamma ray and Neutron Log were cross relating each other. After calculating volume of shale different porosities are calculated. The average water saturation in Fimkassar-02 well and at the zone of interest is 0.031 or 31 %, which in turn makes saturation of hydrocarbon of 69%. In this well, the average effective porosity is 0.049%, which is a good indication for the Sakesar Limestone to bear a good reservoir aspect. This is also attested by the average permeability of 1.353 mD percent making the Sakesar Limestone as a good reservoir in the Fimkassar-02 well.

While log analysis of Balkassar OXY-01A, it is observed that the Sakesar Limestone in Balkassar OXY-01A well is comprised of mostly limestone because as it shows low GR values and shown by the MN plots too. Overriding resistivity curves such as LLS and LLD on higher side of the resistivity scale indicates compactness of the zone of interest (Fig 6.2). Interpretation of Balkassar OXY-01A shows that at the depth of 2496m to 2505m a thickness of 9 m makes up a zone of interest in which the average volume of clay is 0.0426 that is calculated by Gamma ray. For cross checking, the neutron log was also used for the volume of shale, but the curves of both Gamma ray and Neutron Log were cross relating each other. After calculating volume of shale different porosities are calculated. The average water saturation at the zone of interest in this well is 0.4219 which makes around 58 % of hydrocarbon saturation with the average calculated values of permeability and effective porosity 0.06mD and 0.021 % respectively overall indicate fair to acceptable reservoir aspects of the Sakesar Limestone as a reservoir. The low permeability and porosity in this well can be attributed towards the factor of diagenesis like compaction and cementation.

CONCLUSIONS

The present research deals with outcrop based microfacies analysis, depositional environment, and reservoir evaluation of the Sakesar Limestone in Padhrar area along with petrophysical analysis of Sakesar Limestone in Fimkassar-02 and Balkassar OXY-01A wells. In this study following conclusions are drawn;

i. Based on the fossil assemblages, carbonate texture and depositional fabric, five microfacies are identified which include: (1) Nummulitic wackestone (PSL-1), (2) Benthic foraminiferal wackestone (PSL-2), (3) Lockhartia rich mud wackestone (PSL-3), (4) Bioclastic wacke-packstone (PSL-4), (5) Miliolidal wackestone microfacies (PSL-5)

ii. These microfacies mainly have larger benthic foraminifera include species of Nummulites, Lockhartia, Assilina and Alveolina, miliolids along with skeletal fauna of echinoderms, Rotalia, algae and their bioclasts.

iii. Based on the allochems, orthochems and erected microfacies, the Sakesar Limestone is consistent with deposition in the distal middle ramp to restricted inner ramp settings of homoclinal carbonate ramp environment.

iv. Among the diagenetic fabrics, the diagenetic processes of dissolution and microfracturing play imperative role that enhance the reservoir efficacy and caused the formation of primary (intergranular and intragranular) porosities and secondary porosities like moldic, channel and fenestral porosities. The dissolution fabric throughout the identified microfacies enhances the porosity of the Sakesar Limestone as it has played a major role in evolution of various porosity that lead to the enlargement of pore spaces. However, among the diagenetic fabrics of the Sakesar Limestone, micritization, cementation, neomorphism and both chemical and mechanical compactions decrease the reservoir quality.

v. Petrophysical analysis reveals that effective porosity and permeability data show the Sakesar Limestone is fair to acceptable reservoir. In Fimkassar-02 there is acceptable reservoir characteristics at the 26m zone of interest marked at the depth between 3008m to 3034m. That is based on hydrocarbon saturation of 69%, the average effective porosity of 0.049% and permeability of 1.353 mD thus making the Sakesar Limestone a good reservoir. In Balkassar OXY-01A, a zone of interest of 9m at the depth of 2496m to 2505m is characterized by 58 % of hydrocarbon saturation with the average calculated values of permeability and effective porosity 0.06mD and 0.021% respectively overall indicating fair to acceptable reservoir character for the Sakesar Limestone.

vi. Based on the petrographic analysis, the diagenetic processes of dissolution and microfracturing enhance the reservoir porosity of the Sakesar Limestone, which is correlatable with the subsurface in Fimkassar-02 well. In Balkassar-Oxy-01A, the compactness is observed through reduced reservoir character that could be due to compactness and cementation.

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