COMPARATIVE ANALYSIS OF SEDIMENTOLOGICAL CHARACTERISTICS OF THE LOCKHART LIMESTONE IN UPPER INDUS BASIN AND HAZARA BASIN, PAKISTAN

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01-262202-014

Department of Earth and Environmental Sciences

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A thesis submitted in fulfillment of the requirements for the award of the degree of Masters of Science (Geology)

Department of Earth and Environmental Sciences

Bahria University, Islamabad

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DEDICATION

With all the love and admiration this work is unequivocally dedicated to my family, I desire to pay my sincerest thanks to my father**, Late. Muhammad Ibrahim Khan** and mother for their prodigious support. I would not be me without their endless concern.

Furthermore, my heart wishes to appreciate my siblings for their tenacious efforts during my research. My whole hearted appreciation for **Jazeb sohail** whose encouragement made me struggle for the optimal results throughout the study.

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ABSTRACT

The Late Paleocene (Thanetian) Lockhart Limestone, exposed in the Nammal Gorge, Salt Range and Harnoi section Abbottabad. It is composed of light to dark grey and thin to medium bedded limestone. In total 32 samples were taken from the Harnoi and Nammal Gorge section i-e 17 samples from Harnoi section and 15 samples from the Nammal Gorge. The samples were taken for the petroghraphy analysis.The Formation is rich in larger benthic foraminifera, four microfacies were established in the measured sections i.e. MLLN-1 Lockhartia Assilina Packstone Microfacies and MLLN-2 Foraminiferal Wackstone Microfacies representing microfacies of the Nammal Gorge and MLLH-1 Bioclastic Mud-Wackstone Microfacies and MLLH-2 Planktonic Mudstone Microfacies representing the microfacies of the Harnoi section. The depositional environment of both section microfacies were also different.The MLLN-1 Lockhartia Assilina Packstone Microfacies representing the inner ramp environmment, MLLN-2 Foraminiferal Wackstone Microfacies indicates the middle ramp environment of the Nammal Gorge and microfacies of the Harnoi section MLLH-1 Bioclastic Mud-Wackstone Microfacies represents the outer ramp environment and MLLH-2 Planktonic Mudstone microfacies representing open marine settings. The analysis further showed that various diagenetic modifications observed in the Lockhart Limestone include micritization, dissolution, compaction (chemical and mechanical), fractures and calcite veins. The micritization, dissolution and unfilled fractures in the studied rock unit enhance the porosity where as neomorphism and mechanical compaction lead to porosity occlusion and thus impacts on the reservoir potential.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE

	APPROVAL FOR EXAMINATION	**i**
	AUTHOR'S DECLARATION	**ii**
	PLAGIARISM UNDERTAKING	**iii**
	DEDICATION	**iv**
	ACKNOWLEDGEMENTS	**v**
	ABSTARCT	**vi**
	TABLE OF CONTENTS	**vii**
	LIST OF TABLES	**x**
	LIST OF FIGURES	**xi**
	LIST OF ABBREVIATIONS	**xiii**
1	**INTRODUCTION**	
1.1	General Introduction	1
1.2	Previous work	2
1.3	Objective	2
1.4	Methodology	3
1.4.1	Field Work	3
1.4.2	Laboratory Work	5
1.5	Location and Accessibility	5
1.6	Climate	6
1.7	Topography	7
2	**REGIONAL GEOLOGY AND TECTONICS**	
2.1	General Introduction	8
2.2	Tectonic Zone	9
2.2.1	Karakoram Block	9
2.2.2	Main Karakoram Thrust	9
2.2.3	Kohistan Magmatic Arc	10

2.2.4 Main Mantle Thrust (MMT) 10
2.2.5 Main Boundary Thrust (MBT) 10
2.2.6 Northern Deformed Fold and Thrust Belt 11
2.2.7 Southern Deformed Fold and Thrust Belt 11
2.3 Tectonics of the Hazara Basin 12
2.4 Tectonics Setting of Potwar Basin 13
2.4.1 Salt Range 13

3 STRATIGRAPHY

3.1 Generalized stratigraphy of the Hazara Basin 15
3.1.1 Precambrian Succession 15
3.1.2 Paleozoic Succession 15
3.1.3 Mesozoic Succession 16
3.1.4 Cenozoic Succession 16
3.1.4.1 Hangu Formation 17
3.1.4.2 Lockhart Limestone 17
3.1.4.3 Patala Formation 18
3.2 Generalized stratigraphy of Nammal Gorge 18

4 MICROFACIES ANALYSIS

4.1 Introduction to Microfacies analysis 21
4.2 Basis of Microfacies analysis 21
4.3 Methods of Microfacies analysis 22
4.3.1 Field work 22
4.3.2 Sampling 22
4.3.3 Laboratory Work 23
4.4 Microfacies of Lockhart Limestone of Nammal Gorge 23
4.4.1 MLLN-1 Lockhartia Assilina Packstone Microfacies 24
4.4.1.1 Interpretation 24
4.4.2 MLLN-2 Foraminiferal Wackstone Microfacies 24
4.4.2.1 Interpretation 24
4.5 Microfacies of the Lockhart Limestone of Harnoi Section 25

4.5.1 MLLH-1 Bioclastic Mud-Wackstone 25
4.5.1.1 Interpretation 25
4.5.2 MLLH-2 Planktonic Mudstone 25
4.5.2.1 Interpretation 26

5 DIAGENESIS

5.1 Overview 32
5.1.1 Biogenic Alteration 32
5.1.2 Compaction 33
5.1.3 Neomorphism 33
5.1.4 Dissolution 34
5.1.5 Fractures and Veins 34
5.1.6 Pyratization 34
5.1.7 Nodular Limestone 35
5.2 Diagenetic Environments 35

CONCLUSIONS 40
RECOMMENDATIONS 41
REFERENCES 42

LIST OF TABLES

TABLE NO.	TITLE	PAGE
1.1	Methodology Adopted	03
3.1	Composite Stratigraphic chart of the Hazara area and Nammal Gorge	20
4.1	Represents the Allochems and grain percentages of the Lockhart Limestone of Harnoi Section, Abbottabad	26
4.2	Represents the percentages of Allochems and matrix of the Lockhart Limestone of Nammal Gorge, Salt Range	27
5.1	Diagenetic sequence of the Lockhart Limestone (Compiled after (Flügel and Munnecke, 2010)	36
5.2	Represents the diagenetic fabric of the Lockhart Limestone of Nammal Gorge	37
5.3	Represents the diagenetic processes of the Lockhart Limestone of Harnoi section	38

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Outcrops of the Lockhart Limestone (A) Harnoi Section in Abbottabad (B) Nammal Gorge in Salt Range	4
1.2	Microfacies and diagenetic analysis under the polarizing microscope in NCE in Geology, University of Peshawar	5
1.3	Location map of the study area. As red rectangle indicate the Harnoi area and green rectangle indicate the Nammal Gorge.	6
2.1	Regional tectonic map of north Pakistan (compiled after Calkins et al. (1975) Baig (2006).	12
2.2	Part of tectonic map of North Pakistan (modified after Jaswal et al. (1997). Rectangle in the map shows location of the concerned area. In map NPDZ = Northern Potwar Deformed Zone;	14
4.1	Plate 4.1 (a) Missilina (Ms), Broken fragments (BF), Assilina (As) (PPL. Mag.×10), (b) Missilina (Ms), Broken Fragments (BF) (CPL. Mag.×10), (c) Lockhartia Spp. (LS), Bioclasts (BC), Broken Fragments (BF), Dasycladecean Algae (PPL. Mag.×10), (D) (d) Assilina (As), Foraminifera Bioclast (FB) (PPL. Mag.×10),	28
4.2	Plate 4.2 (a) Ranikothalia (RS), Broken Fragments (BF) (CPL. Mag.×5), (b) Miscillina (MS), Bioclast (BC), Lockhartia (LS), Gastropode (G), Echinoderm (E) Broken Fragment (BF) (CPL. Mag.×5) (c) Milliliod (MI), Bioclast (BC), Foraminifera Bioclast (FB) (PPL. Mag.×10) (d) Brachiopod (B), Brachiopod Shell (BS), Broken Fragment (BF) (PPL. Mag.×10)	29
4.3	Plate 4.3(a) Showing Planktons (PL) and Bioclasts (BC) (PPL. Mag.×5), (b) Bioclasts (BC) and Planktons (PL) with abundant matrix (PPL. Mag.×5)	29
4.4	Plate 4.4 (a) Mudstone having more Planktons (PL) as compared to Bioclasts (BC) with abundant matrix content (PPL. Mag.×10) (b) Planktons (PL) (PPL. Mag.×5)	30

4.5	Depositional model for the Lockhart Limestone of Harnoi section Abbottabad	30
4.6	Depositional Model for the Lockhart Limestone of Nammal Gorge, Salt Range	31
5.1	Plate 5.1. (A) Compaction (Mc) has distorted the shape of Assilina. Lockhartia is neomorphosed (Neo) (PPL. Mag.×10) (B) the edge of Assilina are dissolved (Dis) and also micritize (Mic) (PPL. Mag.×10) (C) Micritization (Mic) in the fossils and also Neomorphism (Neo) (PPL. Mag.×10) (D) Fossils are fractured (Fr) and also micritization (Mi) (PPL. Mag.×10) (E) Bioclasts are neomorphosed (Neo) and some microfossils are dissolved (Dis) and micritized (Mic) (PPL. Mag.×5) (F) Calcite veins (Ve) and microfossils are neomorphosed (PPL. Mag.×5) (G) Nodules formation in Lockhart Limestone of Nammal Gorge	39

LIST OF ABBREVIATIONS

MMT	Main Mantle Thrust
MBT	Main boundary Thrust
MCT	Main central Thrust
HFT	Himalayan frontal Thrust
SRT	Salt range Thrust
MKT	Main Karakoram Thrust
MFT	Main Frontal Thrust
MLLN	Microfacies Lockhart limestone Nammal
MLLH	Microfcaies Lockhart limestone Harnoi
NCE	National centre of excellence
Ma	Megaanam (Million year)
NPDZ	Northern Potwar deformed zone
TRIR	Trans Indus ranges Thrust
PP	Potowar Plateau
KIA	Kohistan Island Arc

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Davies used the term Lockhart Limestone for the first time (1930). For a Limestone in the Kohat area of Paleocene age and later on utilized by the Stratigraphic Commission of Pakistan that has same units in other areas of the Upper Indus Basin and Hazara region. In the Upper Indus Basin, Trans-Indus Ranges, Salt Range, KalaChitta Range, Islamabad and as well as in the parts of Hazara and Kashmir, Lockhart Limestone is well exposed (Shah, 2009). The presence of Lockhart Limestone in Hazara along Nathiagali Abbottabad road section is excellent. The Harnoi area is easily reachable from Islamabad through Abbottabad-Nathiagali- road that is 5 km from the Abbottabad city where Paleocene-Eocene rocks are well exposed. It is 110 km north of the capital Islamabad. The study area lies in the north western Himalayas and shows an area with a well- deformed structural features and stratigraphic successions.

For the comparative analysis the area of interest is the Western Salt Range in the Nammal Gorge. Nammal Gorge is located about 200 km south of Islamabad and 300 km north of Lahore. The Lockhart Limestone is well developed in Nammal Gorge and its thickness is about 70m and stratigraphically it consists of Cratecous-Eocene succession and follows down to the Murree Formation.

However, the present work is based upon, To determine and understand the Microfacies analysis and to know the diagenetic fabric, Depositional properties and to understand the sedimentological characteristics of the Lockhart Limestone in Upper Indus Basin and Hazara Basin.

1.2 Previous Work

Microfacies analyses and diagenetic fabric of the Lockhart Limestone–along the Nathiagali-Murree Road in the District Abbottabad, Pakistan, were investigated by Hanif et al. (2014). This unit represents Middlemiss (1896) "Nummulitic Series," Wynne (1873) and Cotter (1933) "Hill Limestone," Gee (1934) "Khairabad Limestone," Eames (1952) "Tarkhobi Limestone," and Latif (1970) "Marl Limestone".

Sameeni et al. (2009), have conducted study on the foraminiferal microfacies and biostratigraphic investigation of Paleocene Lockhart Limestone from the Jabri Area in Hazara, North Pakistan. The stratigraphy of the District Abbottabad in Pakistan is described by Waagen and Wynne (1872). (Imraz et al., 2013) did essential study on the microfossil assemblage, biostratigraphy, and depositional settings of the Paleocene Lockhart Limestone Western Salt Range. (Middlemiss, 1896); (Waagen and Wynne, 1872); (Gardezi and Ghazanfar, 1965); (Latif, 1973). Research work was carried out on the Lockhart Limestone including microfacies analysis, paleontological, diagenetic fabric, lithofacies features and sequence stratigraphy.

1.3 Objectives

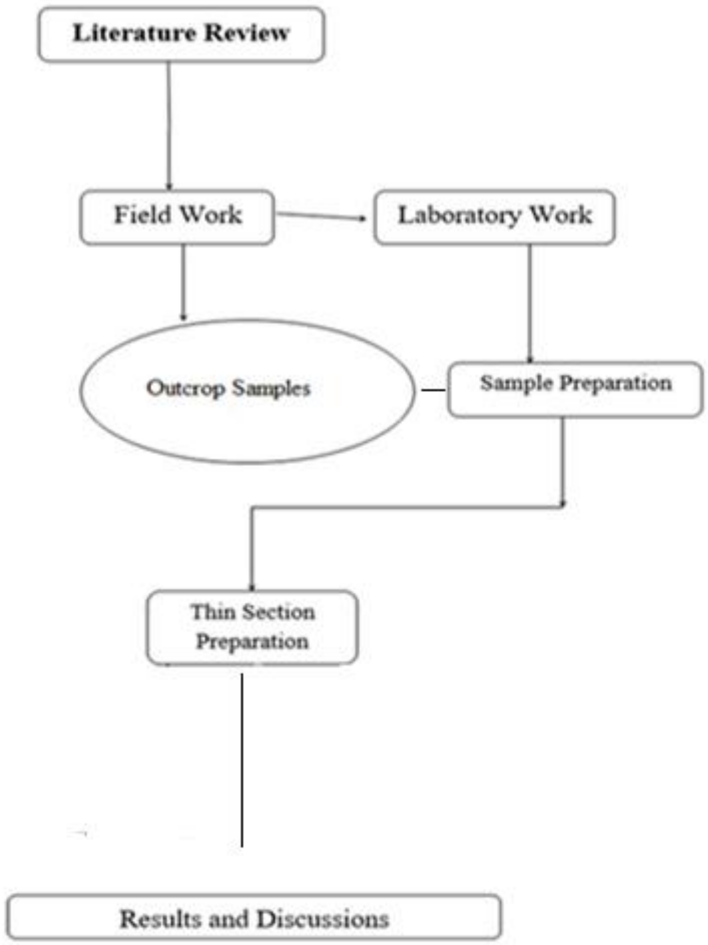
Since late 19th century many Geologists have been attracted by the geology of this area. The present work is focusing on the sedimentological particulars of Lockhart Limestone in stratigraphic sections of the study areas. The objectives of this study are as follows;

1. To perform petrography for creating carbonates microfacies.
2. To construct a schematic model of deposition for concerned formation.
3. To reconstruct diagenetic history of the formation.

1.4 Methodology

The methodology includes field work and laboratory analysis.

Table1.1 Methodology Adopted



1.4.1 Field Work

Detail field work is carried out in order to collect the samples from Harnoi and Nammal Gorge section. Field work comprised of section measurement, collection of samples, field observations and photography. By keeping in mind the sampling that is done in the field is based upon the systematic sampling. We did stratified sampling of Lockhart Limestone 32 samples were collected from Harnoi and Nammal Gorge section.

Fig 1.1 Outcrops of the Lockhart Limestone **(A)** Harnoi Section in Abbottabad **(B)** Nammal Gorge in Salt Range.

1.4.2 Laboratory Work

Thin sections were prepared from the collected samples at Bacha Khan University, Charsadda. After preparation of thin sections the petrographic study and analysis was carried out in sedimentological lab, NCE in Geology, University of Peshawar in order to determine the textural variations, fossils identification and to observe the diagenetic features to identify the fossil assemblage and microfacies analysis of the Lockhart Limestone. For microfacies identification and demarkation of the depositional environment Dunham (1962), Flügel (2004) and Wilson (1974) classifications were used Photomicrographs were taken for the observations made in petrographic study.

Fig 1.2 Microfacies and diagenetic analysis under the polarizing microscope in NCE in Geology, University of Peshawar

1.5 Location and Accessibility

The Harnoi section where Lockhart Limestone is well exposed along Nathiagali-road Abbottabad is 5 km from the Abbottabad city, located between lat. 34°,16 " N and long. 73°.31 " E. It is 110 km north of the capital Islamabad as shown in Fig 1.3.

The Nammal Gorge is located in the District Mianwali of Punjab. The Nammal Gorge is situated in the South of Islamabad at a distance of about 200 km approximately. The coordinates for Nammal Gorge are 32° 39’ 54’’ North and 71°. 48’ 07’’ East as represent in Fig 1.3.

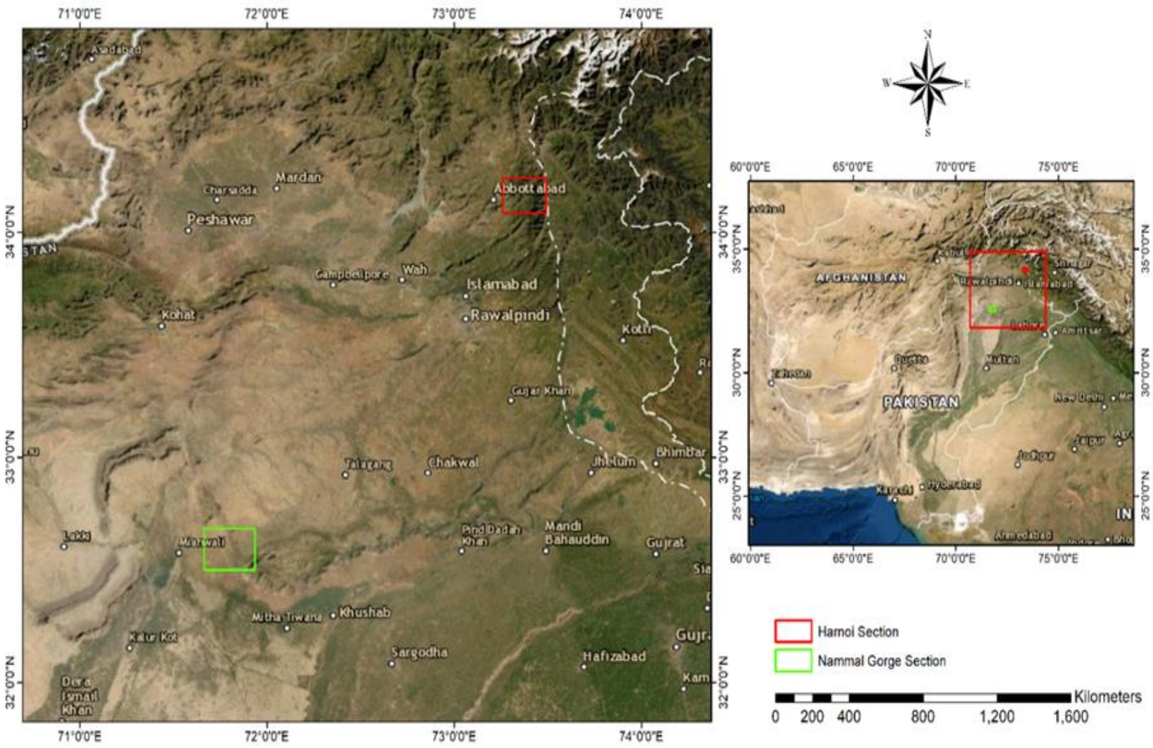


Fig 1.3 Location map of the study area. As red rectangle indicate the Harnoi area and green rectangle indicatethe Nammal Gorge.

1.6 Climate

The Harnoi area has a humid climate and the temperature can rise as 38 °C during the months of mid-summer and drop down to -5 °C (23 F) in the extreme cold condition and occasionally snowfall occurs during the months of the December and January, while substantial rainfall observed in the rainy season from July to September months.

The climate condition in the Nammal Gorge is usually hot and dry. The average rainfall occurs in the area is about 70 to 80 mm per year while the maximum precipitation occurs in the monsoon months of July and August. In the months of winter December, January and February there is minimum precipitation which makes it possible to visit the Nammal Gorge.

1.7 Topography

As the topography of Abbottabad is surrounded by hills and mountains. The mountains present in the Abbottabad are the part of the lesser Himalayas. One in all its levels flanks the proper bank of Kunhar and Jhelum River and enters Abbottabad District from the North. From these levels many spurs task on both aspects. The spurs enter toward the west are longer with valleys lying in between. The height of the land present in the West ranges from 600 to 1,500 meters. (Population Census Abbottabad, 1998).

The Nammal Gorge is present in the western Salt Ranges and it is dominated by mountains and hills and the area in the Nammal Gorge is rocky, bushy and rickety and is along the water channel which comes from the fall of the Nammal Dam.

CHAPTER 2

REGIONAL GEOLOGY AND TECTONICS

2.1 General Introduction

The Himalayas and Indian Ocean are the two major global structures in Pakistan's immediate vicinity, and both share a same origin (Kazmi and Jan, 1997). In the Middle to Late Eocene, the Himalayas were created by the collision of Eurasian and Indian plates (Molnar and Tapponnier, 1975). The Tethyan, Laurasian and Gondwanian domains can be found north to south in the Eurasian Plate. In the Late Paleozoic, all of these domains was single continent named Pangaea, which was encompassed by the Panthalassa Ocean (Kazmi and Jan, 1997). In the Late Triassic, this supercontinent was split into Laurasia and Gondwanaland, with the Tethys Ocean separating both from each other.

Continental drifting and sea floor spreading resulted in the formation of the Indian Ocean and the Himalayas. Around 130 Ma, Gondwanaland began to divide, and the Indo-Pak subcontinent glided away, result~~s~~ing in depletion of Neo-Tethys and opening of the Indian Ocean behind it. The Indian Plate then migrated over 5000 km before colliding with the Eurasian Plate. The Himalayas were formed as a consequence of this collision, and closure of the Neo Tethys Ocean and intra-cratonic subduction made succession of volcanic arcs, including the Nuristan, Kandahar and Kohistan–Ladakh arcs. The Main Mantle Thrust (MMT) separates the Kohistan Island Arc from Indian plate, and Main Karakorum Thrust divides the Eurasian plate from Kohistan island arc (MKT). Since 55 Ma ago, the Indian plate has been rotating counterclockwise, causing convergence at Balochistan, resulting in pile-up of some crustal blocks creating the Balochistan fold and thrust belt, as well as the closure of certain minor basins (Kazmi and Jan, 1997). When the Indian and Eurasian plates collided, a broad ophiolitic belt formed along the Zhob valley and Lasbella area. After the deposition of Early Eocene Nummilitic limestone, compressional tectonics began.

2.2 Tectonic Zones

Pakistan has been divided into tectonic zones based on orogenic history, geological environment and tectonic features: Kohistan-Ladakh magmatic arc, Indus platform, Himalayan fold and thrust belt, Kakar-Khorasan Flysch Basin, Chagai magmatic arc, Karakoram block and foredeep and Makran accretionary zone, Pakistan off shore and Baluchistan fold and thrust belt. Based on stratigraphy and physiography, the Himalayas are separated into numerous tectonic domains. The Kohistan Island Arc, Karakoram block, the northern deformed fold and thrust belt, Punjab foredeep and the southern deformed fold and thrust belt are domains in question. Main Karakoram Thrust (MKT), Main Boundary Thrust (MBT), Main Mantle Thrust (MMT) and Salt Ranges and Trans Indus Ranges Thrust split, areas from north to south (Kadri, 1995).

2.2.1 Karakoram Block

The Karakoram block is a structural zone that is 70 to 120 km wide and 1400 km long. The Sarobi fault runs through it on the west, and the Karakoram fault runs through it on the east. It's a complicated assemblage of deformed meta-sedimentary, sedimentary, and igneous rocks from the Eurasian plate's south side. Its southern border meets the Main Karakorum Thrust (MKT), which divides its Paleozoic meta-sediments from the Cretaceous-Tertiary sediments of the Kohistan-Ladakh arc (Tahirkheli, 1982) (Kazmi and Jan, 1997).

2.2.2 Main Karakoram Thrust

The northern suture zone or Shyok suture zone is another name for the Main Karakoram Thrust (Pudsey et al., 1985). It arise from the collision of the Karakoram plate towards north and KIA towards south.(Tahirkheli and Jan, 1978, Tahirkheli, 1982). The thrusting of meta-sedimentary rocks over the Kohistan-Ladakh Arc was induced by this fault. It's on the meta-sedimentary band south of the Karakorarn batholiths. Grey to greenish grey slates were interbedded with clastic deposits and clasts of greenstone, red shale, limestone and minor ultra-mafics in the suture zone's stratigraphy (Pudsey et al., 1985).

2.2.3 Kohistan Magmatic Arc

The Kohistan-Ladakh region was formed in consequence of the Neo-Tethys Ocean subduction beneath the Eurasian plate due to the Indian plate moving northward during the Jurassic and Cretaceous periods. It is an E-W directed arc limited in the east and west by Karakoram block and the Indo-Pakistan crustal plate, respectively, and in the north-south direction by the Main Mantle Thrust (MMT) and Main Karakorum Thrust (MKT). The Nanga Parbat Haramosh Massif which is a North-South trending, divides it into Kohistan and Ladakh arcs. It consists of a variety of Late Cretaceous and Paleocene volcanic and plutonic rocks, as well as their subordinate sedimentary strata with varied degrees of deformation and metamorphism. According to gravity studies, the Kohistan arc terrain is 8 to 10 km thick(Kazmi and Jan, 1997).

2.2.4 Main Mantle Thrust (MMT)

The MMT originated in the Eocene when the Indian plate crashed with the Kohistan island arc on its southern border (Gansser, 1980). The Indus Suture is made up of a series of mélanges made up of ophiolites. The closing of the Neo-Tethys Ocean pushed all of the sediments onto the Kohistan Magmatic Arc, resulting in a sequence that includes blue schists, meta-volcanics, meta-sediments and green schist's, in a matrix of shear sediments and serpentines (Kazmi and Rana, 1982). The MMT is centered on a prominent structural feature known as Nanga Parbat Syantaxis. In India, the MMT could be related to the Indus suture. During the Late Cretaceous to Early Tertiary period, the thrusting of MMT proceeded southward (Wells, 1984).

2.2.5 Main Boundary Thrust (MBT)

The Murree Formation is terminated in the east, west, and north by a sequence of faults. A parallel thrust fault runs west and north of this fault zone, thrusting Precambrian sequence over Mesozoic and Paleozoic strata (Kazmi and Jan, 1997). Wadia (1931), has given these two faults the names: Murree and Panjal thrusts. In the foreland zone, the MBT runs 1500 km from Kashmir in the west to Assam in the east. The fault dip is 50 to 70m east in the North -West of Muzaffarabad, 70m in the south, and vertical locally (Kazmi and Jan, 1997). The MBT fault is made up of parallel thrust faults that divide the N-W Himalayan sequence into a deformed and metarnorphosed hinterland and a southern deformed zone known as foreland. The continental shortening along the Main Central Thrust and Main Mantle Thrust was transferred along the MBT detachment (Le Fort, 1975).

2.2.6 Northern Deformed Fold and Thrust Belt

In the Himalayan foreland, tectonic features were continously developing in the Salt Range and Potwar Plateau (PP) as wedge of sediments were contracted and thrusted in the south direction along decollment.NPDZ can be divided into two parts .Western NPDZ is an emergent fold and thrust front while the eastern NPDZ is of buried origin (Jaswal et al., 1997). These deformed zones were divided by soan syncline.

2.2.7 Southern Deformed Fold and Thrust Belt

This fold and thrust belt zone is bounded on the north by the MBT and on the south by the SRT and TIRT (Trans Indus Range Thrust) which separates it from the Indo-Gangetic Foredeep. The fold and thrust belt is concerned with E-W and is underlain by a thick pile of river deposits (Coward, 1985).

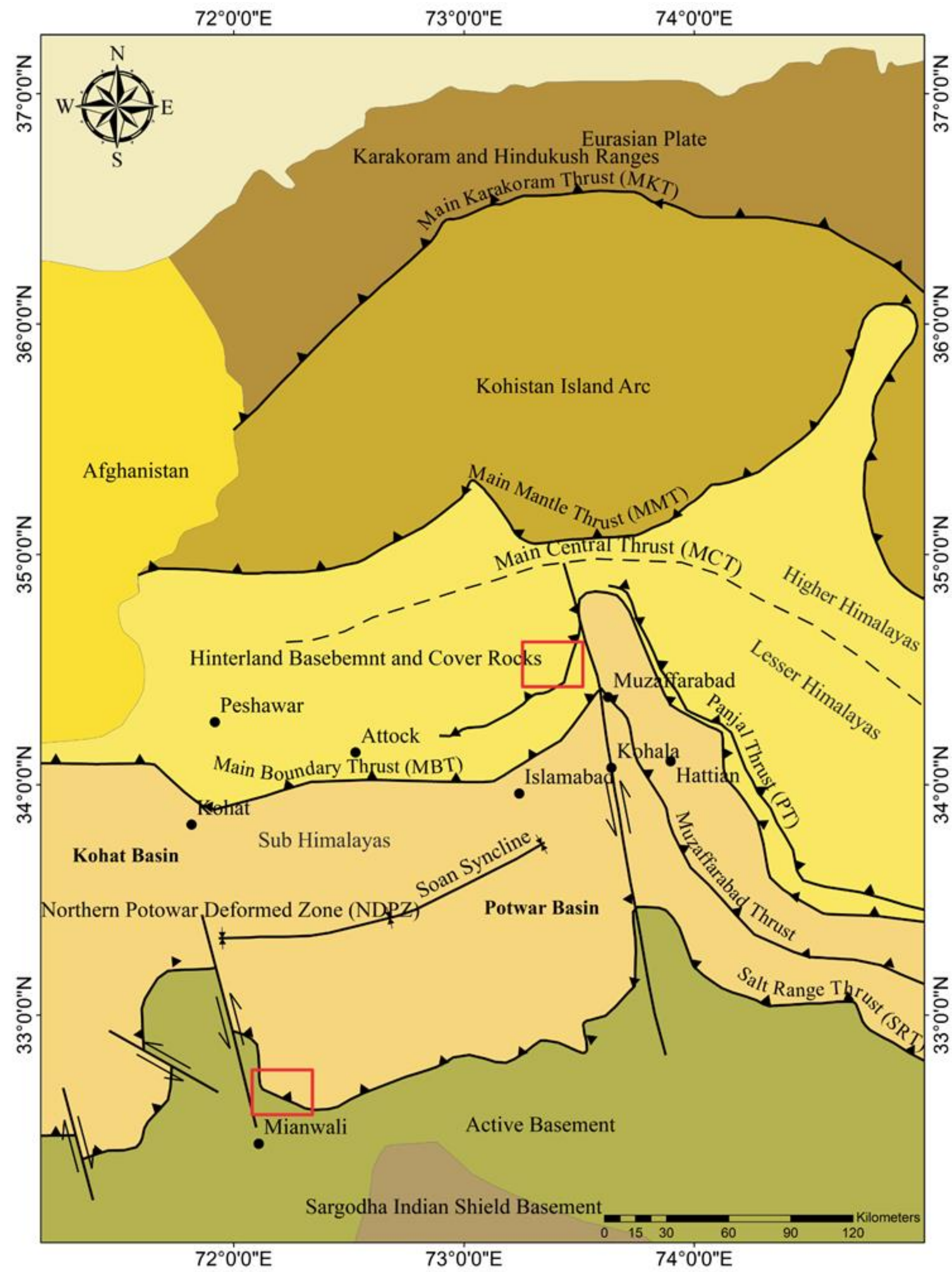


Fig 2.1 Regional tectonic map of north Pakistan (compiled after Calkins et al. (1975), Baig (2006).

2.3 Tectonics of the Hazara Basin

The North-Western Himalayan Fold, Suleiman Belt and Thrust Belt divide the Active faults and thrust belts along the North western edge of the Indo-Pakistan plate into two portions. The former is thought to represent a zone of transpiration, whereas the latter is linked to the major Himalayan convergence zone (Jadoon and Baig, 1991). The continuous collision of the Eurasian and Indo Pakistan plates, which happened from the Late Eocene to the Early Oligocene, is thought to be causing compressional pressures in the North-Western Himalayan Fold and Thrust Belt. The Indian plate is continuing advancing northwards at a rate of 2mm/year in relation to the Eurasian plate (Patriat and Achache, 1984). Gansser (1980) ,categorized Himalayas from south to north as follows:

1. Sub Himalayas, from MFT to MBT.

2. Lesser Himalayas, from MBT to MCB.

3. As higher Himalayas, MCT became MMT.

Due to its proximity to MBT (to the north of MBT), the South East Hazara has seen significant deformation. This deformation is characterized by South East trending thrust faults and North-East Trending Anticlines in the research region. The principal structures' North-East orientation implies that the area has been subjected to North-West South-East oriented forces (Latif, 1970).

Most of the folds in the studied region have North East-South West trending hinge lines, indicating that the area is subjected to North-West South-East compressive pressures (Latif, 1970).

The Western side of the Hazara Kashmir Syntaxes changes from the Eastern side in terms of style and distortion (Latif, 1970).

2.4 Tectonics Setting of Potwar Basin

In the western Salt Range, the research area is located. The Western Salt Range and the Indus River pass through the research region, which is characterized by a large strike slip fault. The Kalabagh Fault is an active dextral fault that runs southward and has a number of documented earthquake epicenters. The faults' southerly expansion also displaces the SRT and creates new sub-parallel faults (Kazmi and Jan, 1997).

2.4.1 Salt Range

The Salt Range is made up mostly of a succession of intricate anticlines and salt diapers, with the best coverage of Pre-Cambrian to Paleozoic rocks found in various parts. It stretches between Jhelum and Indus rivers with southern edge of the

Salt Range; the zone of thrust is mostly covered with conglomerate and alluvium, but it also exposes Jhelum plain Quaternary deposits in certain parts (Kazmi and Jan, 1997).

The Pre Cambrian evaporites sequence is an effective zone that enabled the thrust to extend and the Salt Range,Potwar Plateau to shift southward across the Jhelum plain. In the Central Salt Range, the Precambrian time is pushed southward by at least 29 km from the overlying Paleozoic-Cenozoic sequence. The Salt Range is bisected in the east by the Diljabba and Chambal-Jogi Tilla ridges, which run north-east. The Kalabagh fault separates the Salt Range from the Trans Indus Ranges in the west, while the Salt Range Thrust marks the Salt Range's southern end.

Potwar Plateau is along Indus River in the west and Jehlum River in the east direction.Salt range is in south and Kalachitta-Margilla ranges to the south. The Nothern Potwar Deformed Zone is located in the northwestern half of the region and is characterized by strongly deformed east-west tight and complicated folds (Kazmi and Jan, 1997).

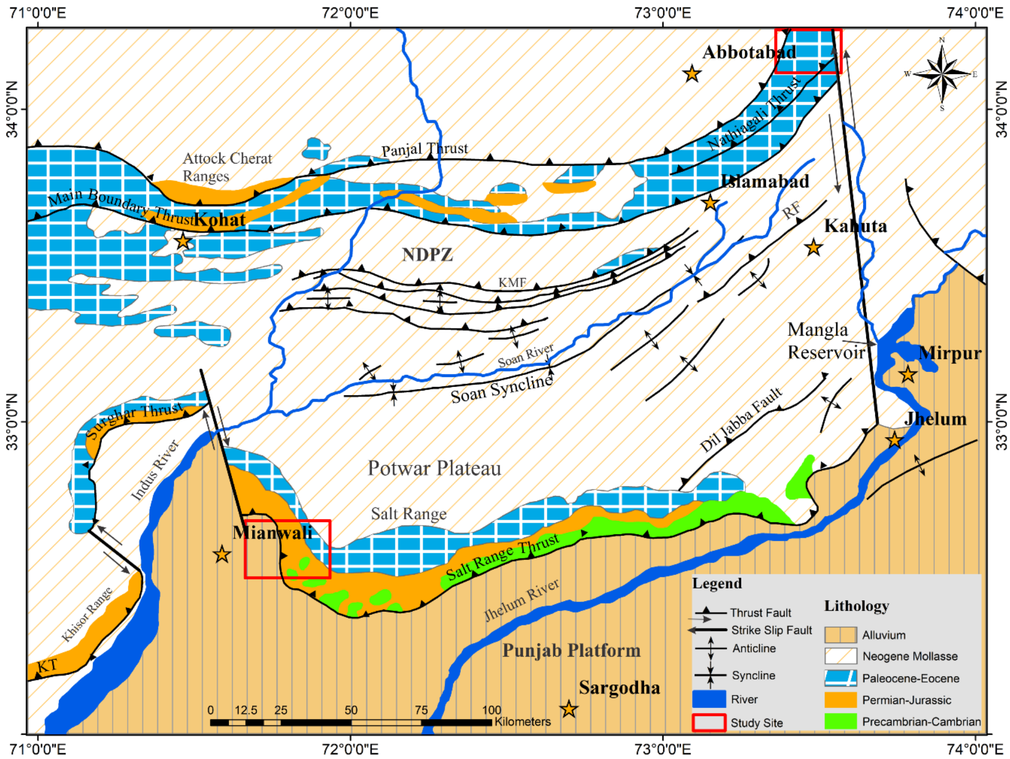


Fig 2.2 Part of tectonic map of North Pakistan (Jaswal et al. (1997). Rectangle in the map shows location of the concerned area. In map NPDZ = Northern Potwar Deformed Zone;

CHAPTER 3

STRATIGRAPHY

3.1 Generalized stratigraphy of the Hazara Basin

The rock stratum in proposed study area varies in age from Precambrian to Miocene. These formations were broadly circulated in Hazara area and could be known easily by their numerous features. Since the Lockhart Limestone, according to Shah (2009) belongs to Cenozoic era, so the Paleocene age stratigraphy would be conferred in more detail. The stratigraphy of the Harnoi area in Hazara basin is as following;

3.1.1 Precambrian Succession

Precambrian rocks cover a significant region in Hazara Fold and Thrust Belt during the Himalayan orogeny. It is Pakistan's greatest collection of Precambrian rocks (Shah, 2009). Sedimentary and metamorphic units predominate, with acidic and basic igneous rocks intruding often. Slates, shales and phyllites with little limestone make up the Hazara Formation, whereas phyllites and quartzites make up the Tanawal Formation. In the Hazara area Tanawal Formation which is made up of schist, marble and gneiss with a little proportion of carbonaceous material.

3.1.2 Paleozoic Succession

Lydekker (1878), Middlemiss (1910) and (Latif, 1969) have all altered the Paleozoic stratigraphy in north Pakistan. It is, however, still ineffectively dated, and stratigraphic correlation in numerous regions is difficult to achieve with existing understanding. In northern parts, the upper Tanawal Formation has the earliest record of Paleozoic sedimentary strata. From the Late Precambrian to the Cambrian, it displays composite lithologies of metamorphic and metasedimentary rocks. The Tanawal Formation is spread over the surface by fossiliferous Paleozoic rocks mostly argilites, marbles, and dolomite.

3.1.3 Mesozoic Succession

The Mesozoic sedimentary rocks are major components of the Himalayan Thrust and Fold belt's geological sequences. In most portions of the Indus Platform, they make a thick, submerged cover sequence above basement rocks (Kazmi and Abbasi, 2008). These deposits in the upper Indus Basin were characterized by significant breaks at the base of the Triassic, among the Jurassic and Triassic, between the Jurassic and the Cretaceous, and at the top of Cretaceous (Shah, 2009). Shallow marine waters (Shinawari and Samana Suk Formation) dominate the exposed sediments, with small river dominated transitional environments (Datta Formation).

The Triassic succession is lacking in Hazara, and Jurassic rocks disconformably overlie Paleozoic and Precambrian rocks (Shah, 2009). Chichali, Lumshiwal, and Kawagarh formations are Cretaceous rocks found in the Hazara region.

3.1.4 Cenozoic Succession

The Cenozoic era has an exceedingly detailed record of the geodynamic events that led to the Tethys Ocean's demise throughout that time period (Tahirkheli and Jan, 1978, Bard, 1983). The Himalayas, the world's greatest mountain ranges, were also developed during this time period. Paleogene layers are hidden by Neogene successions of terrestrial origin under the Cenozoic sedimentary cover of the Indus Basin. The thickness of this Cenozoic sequence is over 1500m (Shah, 2009). The K-T boundary, which is a disconformable contact between the Late Crataceous Kawagarh Formation and the Early Paleocene Hangu Formation, marks the end of the Mesozoic Era (Kazmi and Rana, 1982).

Due to collision in the north, the Paleogene layers were dumped in a broad, wide sea that gradually retreated to the south. Varied parts of this stratum have different thicknesses and lithologies. The Paleocene and Eocene sediments are mostly made up of oceanic limestones and marls. Hangu, Lockhart, and Patala formations are among them. Marghala Hill limestone, Chorgali, and Kuldana strata include substantial Eocene deposits such as local red beds of continental origin, anhydrite seams and gypsum. The Rawalpindi and Siwalik Groups were characterized by conglomeratic sandstones, mudrocks and siltstones of river origin in Neogene layers.

The Quaternary sediments are characterized by coarse clastics dominated by conglomerates (Shah, 2009). The following is a list of Paleocene formations.

3.1.4.1 Hangu Formation

The Stratigraphic Commission of Pakistan (Fatmi, 1973) named the "Hangu Shale” of Davies (1930) from the Kohat region as Hangu Formation, the term is stretched to encompass Davies' "Dhak Pass beds.

In the subsoil, the Hangu Formation is abundantly visible in Hazara territories. Mandeha Banni in Hazara has a height of 35 metres. It is uniformly covered by the Lockhart Limestone is a kind of limestone found in Lockhart, Texas. Hangu Formation have brownish to blackish layers covering two metres of Marls that were formed in a shallow ramp or shallow platform environmrnt. . (Sameeni et al., 2009).

3.1.4.2 Lockhart Limestone

Davies (1930) used the name "Lockhart Limestone" to describe a Paleocene limestone in the Kohat area, and the Stratigraphic Committee of Pakistan has expanded this usage to include comparable units in further portions of the Hazara and Kohat-Potwar areas. The "Nummulitic Scries" of Middlemiss (1896) is represented by this unit. The "Khairabad Limestone" is a portion of Wynne (1873) and Cotter (1933) "Hill Limestone."Gee (1934) "Tarkhobi Limestone", Eames (1952) "Tarkhobi Limestone", and (Latif, 1970) "Marl Limestone".

The limestone in the Hazara region is black and dark grey in colour, with marl and shale intercalations. On a new surface, the limestone is typically bituminous and emits a foetid odour. In the Hazara region, the elevation ranges from 90 to 242 metres. The Hangu Formation and Patala Formation, respectively, are conformably and transitionally overlain and underlain by the formation. Foraminifers, corals, mollusks, echinoids, and algae abound in the Lockhart Limestone. Operculinapatalensis and Miscellanea miscella are essential. A number of foraminifers, including Lockhartia conditi, have been stated from the Hazara region by Latif (1970). Lockhart Limestone have two-meter thickness of brownish to blackish Marls which have shallow ramp or shallow platform type of environment of deposition. (Sameeni et al., 2009).

3.1.4.3 Patala Formation

The Stratigraphic Commission of Pakistan provides the title Patala Formation to describe the "Patala Shale" of Pinfold (1937), and it was afterwards used to Hazara regions. "Wynne (1879), part of the Middlemiss (1896) "Nummulitic Series" and Latif (1970) "Kuzagali shale".

In the Hazara region, the elevation ranges from 60 to 182 m . The Margala Hill Limestone conformably and transitionally overlies the Patala Formation in Hazara. The formation is rich in fossils, with foraminifcrs, mollusks, and ostracodes aplenty. Globoratalia was among the smallest foraminifera identified by Latif (1970) from Hazara. Patala formation extract shows open marine environment of deposition where terrestrial input to some extent were available too. (Kadri, 1995).

Glohigerina primitiva, Triloculina trigonula, Rotalia, Elongata Miscellanea prehaimei and Trochidoformis. Raza's fetfgest foraminifera discovery Assilina dandotica, Assilina granulosa, Assilina spinosa, Assilina Lockhartia conditi, L. hunti, Operculina danieli, D. khatiyahi, D. langhami, Daviesina danieli, Daviesina Sakesariaomata canalifera, O. patalensis, Rotalia dukhaniaid (Kadri, 1995).

3.2 Generalized stratigraphy of Nammal Gorge

Nammal Gorge is a great site for researching the geology of Salt Range sequence. It is visible in the Western Salt Range. Apart from the strata exposed in Salt Range, this region contains a highly fossiliferous record of the ocean sediments straddling the Paleozoic-Mesozoic transition, making it a major location for PT-biostratigraphy and the study of end Permian mass extinction. Nammal Gorge is located in Mianwali, Pakistan, 3 miles northeast of Musakhel. The stream, which now flows into Nammal Lake, carved a deep gorge through the anticlinal formation. The Gorge is faulted and uneven heavily. The rocks at Nammal Gorge come from the upper Permian and Triassic periods. Jurassic, Eocene and Paleocene epochs. Nammal Gorge contains a diverse lithology with the greatest exposures of Upper Permian, Mesozoic, and Cenozoic rocks. The Nammal Gorge in Pakistan's Salt Range maintains a record of Triassic open-marine carbonate sedimentation, cyclic siliciclastics progradation, and changing relative sea level. The Permian Zaluch Group is represented by the earliest rocks in Nammal Gorge. The Permian Zaluch Group is overlain by the Triassic Musakhel Group. The Late Permian Zaluch Group is mostly limestone with a lot of brachiopod fossils. The renowned Permo-Triassic Boundary divides the Zaluch Group's Chiddru Formation from the Mianwali Formation. Paraconformity grades the lower interaction of Triassic series, i.e. the contact among the Chhidru and Mianwali Formations (Shah, 2009).

The Tredian Formation sits over the Mianwali Formation that is in turn atop the Kingriali Formation. The Tredian Formation is made up mostly of sandstone, whilst the Kingriali Formation is mostly made up of Dolomitized limestone. An unconformity a conglomeratic bed marks the upper contact of the Kingriali Formation with the Datta Formation. On top of the Triassic series, there is a thick Jurassic (Surghar Group) Datta Formation that is varied, and it underlies the Shinawari Formation, which is limestone, above which is the Samana Suk Formation. Hangu, Lockhart, and Patala Formations (Makarwal Group) are Paleocene rocks found in the Nammal Gorge. The Hangu sandstone sits beneath the Lockhart Formation. Patala Shales are found atop Nammal Formation and Sakesar Limestone (Chherat Group).

Nammal Gorge is highly significant economically. The Gorge is used to harvest large amounts of limestone, sandstone, and silica sand. The limestone quarries in this area serve the demands of cement plants as well as construction projects. Our research region is part of the Makarwal group, which includes the Nammal Gorge’s Lockhart Limestone.

Table 3.1 Composite Stratigraphic chart of the Hazara area and Nammal Gorge

Composite stratigraphic chart of Hazara area and Nammal Gorge

AGE	FORMATIONS		LITHOLOGY	DESCRIPTION
	HAZARA AREA	NAMMAL GORGE		
MIOCENE	MURREE			Cyclic deposits of sandstone,siltstone and shales
EOCENE	KULDANNA			Shale with interbedded gypsum and sandstone
	CHORGALI	SAKESAR		Limestone with interlayer of marl and shales
	MARGALLA	NAMMAL		Limestone with shale interbeds
PALEOCENE	PATALA	PATALA		Marly shale with few limestone beds
	LOCKHART	LOCKHART		Nodular limestone with shale layers
	HANGU	HANGU		Sandstone with shales intercalations
CRETACEOUS	KAWAGARH			Limestone with shales in lower part
	LUMSHIWAL			Sandstone, siltstone and shales
	CHICHALI			Sandstone with sandy, silty glauconitic shales
JURASSIC	SAMANASUK	SAMANASUK		Grey, medium to thick bedded limestone and dolomite
	DATTA	DATTA		Calcerous sandstone, conglomerates and fireclay
TRIASSIC		KINGRIALI		Sandstone, dolomite and dolomitic limestone
		TREDIAN		Micaceous shales, sandstone and dolomite
		MIANWALI		Marl, limestone, sandstone, dolomite and shales
PERMIAN		CHIDRU		Sandstone with ripple marks and limestone
		WARGAL		Shales, limestone and dolomite
CAMBRIAN	HAZIRA			Calcareous shales, marl and siltstone
	ABBOTTABAD			Sandstone with dolomite shales and conglomerates
PRE CAMBRIAN	HAZARA			Slates, phylites and shale with minor limestone

CHAPTER 4

MICROFACIES ANALYSIS

4.1 Introduction to Microfacies analysis

Brown (1943) and Cuvillier (1952) first defined the term microfacies as "microfacies referring only to paleontological and petrographic standards examined in thin-sections." Nowadays, microfacies is defined as "all paleontological and sedimentological data which could be classified and described by thin sections, polished slabs, peels, or rock samples" (Flügel and Munnecke, 2010), while Middleton (1973) states facies as "structural, lithological and organic characteristics can be detected in rocks of field."

4.2 Basis of Microfacies analysis

Thin sections were used to split facies into units with comparable compositional aspects, which represent particular depositional settings and regulators (Flügel and Munnecke, 2010). By investigating the paleontological and sedimentological properties of rocks, microfacies research seeks to identify overarching patterns which briefs about the history of the rocks.

Rock composition, depositional texture, and fossil distribution of individual samples can all be used to identify different microfacies (Tucker and Wright, 2009, Flügel and Munnecke, 2010). Facies were distinguished in general by what aspect of the rock or sediment is being studied, or it depends on the facies type, which can be lithofacies, which is characterized by sedimentary qualities such as sedimentary structures, grain size, bedding and color, or petrological characters such as mineralogy, etc. Facies types can also include biofacies, which are defined by fossil content such as flora and fauna, ichnofacies, which are defined by an assemblage of trace fossils, and seismic facies, which are defined by seismic reflection technique and interpreted in standings of large-scale lithological characteristics. Facies associations are made up of genetically related facies and several facies that occur together and typically represent one depositional environment, whereas facies succession is made up of a progressive change in certain facies properties such as sedimentary structures, grain size, thickness, and so on in a specific direction, such as vertically or laterally. The facies model, established by Walker as "the generic description of depositional system," can be used to explain facies assemblages and succession (walker 1992). So a model of facies is a broad overview of a depositional system that includes numerous specific examples derived from recent sediments and older rocks. Paleoecological and palecoenvironmental interpretations rely on the size and form of grain constituents, bioclasts, lithology, and richness of fauna.

The current investigation of the Lockhart Limestone in the Harnoi section Abbottabad and Nammal Gorge is based on field work and petrographic criteria to interpret paleoenvironments using microfacies concepts.

4.3 Methods of Microfacies analysis

Microfacies study involves describing field observations of outcrops and the lithological differences, bedding properties, faunal distribution, and petrographic behaviours of the rocks under a microscope**.**

4.3.1 Field work

The first and most important step in microfacies study is to go on a field trip to the designated location and take notes and other essential descriptions of outcrops, lithologies, variations, and other stratigraphic factors. Texture, lithology, rock colour, bedding, sedimentary structures, diagenetic characteristics and biogenic structures fossils are some of the criteria which could be evaluated in outcrop for facies analysis (Flügel and Munnecke, 2010).

4.3.2 Sampling

After creating thin sections out of the samples, sampling is used to determine the composition and characteristics of the rock under a microscope, and it becomes the basis of microfacies analysis and petrographic investigations. Outcrop conditions, such as sampling units defined by types and thickness of bedding and outcrop exposure, influence the amount and types of samples taken**.**

Sampling for Microfacies should result in (1) lithologic samples with structures, textures and fossils at hand specimen scale, (2) laboratory samples, and (3) paleontological samples (Flugel, 2010).

As a result, appropriate samples should be selected, as well as their size and number, to represent the outcrop facies and to determine their relevant composition, characteristics, and depositional context based on petrographic and paleontological investigations of the samples obtained.

4.3.3 Laboratory Work

The laboratory work includes, the preparation of thin sections of acquired samples in laboratory is the first step. Thin section, polished slabs, and peels are among the typical laboratory procedures employed in the microfacies examination. Thin sections of more than 30 microns are normally preferable for regular microfacies study because such "thick sections" frequently permit the limestone texture and structure to be identified more simply. Ultra-thin sections (0.5 to 5.0 microns) can be created when fine details are required.

Micro-facies investigations require good polarizing microscopes and binocular microscopes, and microscopic analysis of thin sections of carbonate rocks offers the simple micro-facies data (Flügel and Munnecke, 2010). Following the preparation of thin sections, peels, or polished slabs, these are thoroughly examined and analyzed in order to identify facies of various compositions, characteristics, and diagenetic features, as well as to construct depositional settings or paleo-environment interpretations of the facies studied using petrographic and paleontological evidence.

4.4 Microfacies of Lockhart Limestone of Nammal Gorge

The detailed studies of the Lockhart Limestone of Nammal Gorge sections, two microfacies were identified based on the matrix and Allochems. These two microfacies were labelled as MLLN (Microfacies of Lockhart Limestone Nammal).

4.4.1 MLLN-1 Lockhartia Assilina Packstone Microfacies

The limestone is grey to dark grey, thin to medium bedded and highly fossiliferous with thickness of about 35 m. This microfacies have high Allochems content as compared to matrix. The average grain to matrix ratio is about 3:1. There is about 40%-60% of Allochems content consisting of the fossils fauna of Larger Benthic Foraminifera such as Assilina, Lockhartia, Discocyclina, Alveolina, Missilina, Ranikothalia, and Milliods with algae, planktons and broken Bioclasts of different fossils groups. The microfacies is represented by samples NL-1, NL-3, NL-4, NL-5, NL-6, NL-9, NL-10 and NL-11 (Plate 4.1, a-d).

4.4.1.1 Interpretation

MLLN-1 Lockhartia Assilina Packstone microfacies have variety of fossil fauna. The presence of Larger Benthic Foraminifera together with Dasycladecean algae and Alveolina represents depths between 12-15 meters of restricted circulations. Similarly, the presence of shallow environment fossils Bioclasts also points towards not much deeper settings. So on the basis of the above fossils fauna, it is concluded that the microfacies is deposited in the inner ramp environment (Fahad et al., 2021, Swati et al., 2013).

4.4.2 MLLN-2 Foraminiferal Wackstone Microfacies

This microfacies are represented by NL-2, NL-7, NL-8, NL-12, NL-13, NL-14 and NL-15. The average grain to matrix ratio of this microfacies is 1:4. The microfacies consist of about 20%-40% Allochems contents that is embedded in the matrix. The fossil fauna that have identified are Lockhartia, Assilina, Discocyclina, Ranikothalia, Milliod, Missilina, Planktons with bioclastic fragments (Plate 2, a-d).

4.4.2.1 Interpretation

The limestones of this microfacies have more matrix content so it is termed as wackstone microfacies. The microfacies have less diverse fossils with more matrix contents. The Lockhartia and Assilina together with planktons represent slightly deeper settings. So the environment of deposition of this microfacies is middle ramp settings (Fahad et al., 2021, Swati et al., 2013).

4.5 Microfacies of the Lockhart Limestone of Harnoi Section

In Harnoi Section, Abbottabad, two microfacies were also discovered and is represented by MLLH (Microfacies of the Lockhart Limestone of Harnoi).

4.5.1 MLLH-1 Bioclastic Mud-Wackstone

The samples of the Harnoi section such as HL-1, HL-2, HL-3, HL-6, HL-7, HL-10, HL-12, HL-13, HL-17 and HL-24 represents this microfacies.The matrix content is high i.e. the average grain to matrix ratio is about 1:4. The limestone of the microfacies is grey to dark and finely crystalline. The Allochems contents are mostly planktons and bioclastic fragments (Plate 3, a-b).

4.5.1.1 Interpretation

Mostly the microfacies are finely crystalline with high matrix content. The microfacies is less fossiliferous contains mostly Bioclasts with Planktons, due to which it shows the deeper settings. An outer ramp environment is suggested to this microfacies (Heldt et al., 2008, Rehman et al., 2021).

4.5.2 MLLH-2 Planktonic Mudstone

The samples of the Harnoi section HL-19, HL-26, HL-31, HL-33 and HL-38 represent such microfacies with 10 m thickness. The lithology of the microfacies is grey, thin bedded and fine grain limestone. The grain to matrix ratio is about 1:9 i.e. high matrix contents. The Allochems contents is less than 10% and mostly consist of planktons with less amount of different fossils Bioclasts Plate 4, a-b).

4.5.2.1 Interpretation

The microfacies have more matrix than fossils content, due to which it is interpreted as mudstone. Planktons are free swimmers and cosmopolitan (globally present). So its presence with Bioclasts represents an outer ramp environment to open marine environment (Heldt et al., 2008).

Table 4.1 Represents the Allochems and grain percentages of the Lockhart Limestone of Harnoi Section, Abbottabad

S.no	**Sample Name**	**Allochems (%)**		**Matrix (%)**	**Grain: matrix**
		Planktonic Foraminifera	Bioclasts		
1	HL-1	15	35	50	1:1
2	HL-2	15	5	80	1:4
3	HL-3	18	7	75	1:3
4	HL-6	8	12	80	1:4
5	HL-7	22	3	75	1:3
6	HL-10	5	10	85	1:4
7	HL-12	15	25	60	2:3
8	HL-13	10	20	70	3:7
9	HL-17	10	25	65	7:13
10	HL-19	-	5	95	1:19
11	HL-24	9	16	75	1:3
12	HL-26	5	5	90	1:9
13	HL-31	3	2	95	1:19
14	HL-33	6	2	92	1:10
15	HL-36	8	-	92	1:10
16	HL-38	5	1	94	1:16
17	HL-39	7	3	90	1:9

Table 4.2 Represents the percentages of Allochems and matrix of the Lockhart Limestone of Nammal Gorge, Salt Range.

S.No.	**Sample Name**	**Allochems (%)**										**Ma**	**Gr**
		Assilina	Lockhartia	Discocyclina	Missilina	Ranikothalia	Alveolina	Milliolid	Algea	Planktons	Bioclasts		
1	NL-1	15	10	5	-	-	1	-	9	5	10	45	11:9
2	NL-2	7	15	2	-	1	-	-	1	1	3	**70**	3:7
3	NL-3	20	4	15	1	3	-	5	1	-	1	50	1:1
4	NL-4	35	15	4	-	-	1	-	1	1	3	40	3:2
5	NL-5	30	10	8	2	7	-	3	-	-	5	35	13:7
6	NL-6	25	15	6	-	-	2	2	1	-	4	45	11:9
7	NL-7	10	20	5	-	-	-	4	1	2	3	55	9:11
8	NL-8	15	5	5	1	5		5	1	4	4	55	9:11
9	NL-9	10	15	5	4	3	10	2	-	1	5	50	1:1
10	NL-10	10	25	5	2	5	-	-	-	3	5	40	3:2
11	NL-11	10	20	3	3	6	4	5	-	-	4	45	11:9
12	NL-12	10	10	5	-	3	-	5	-	2	5	**60**	2:3
13	NL-13	5	10	5	-	5	2	3	-	-	5	**65**	7:13
14	NL-14	5	10	5	-	2	-	3	-	-	5	**70**	3:7
15	NL-15	5	10	-	1	3	-	3	2	-	3	**75**	1:3

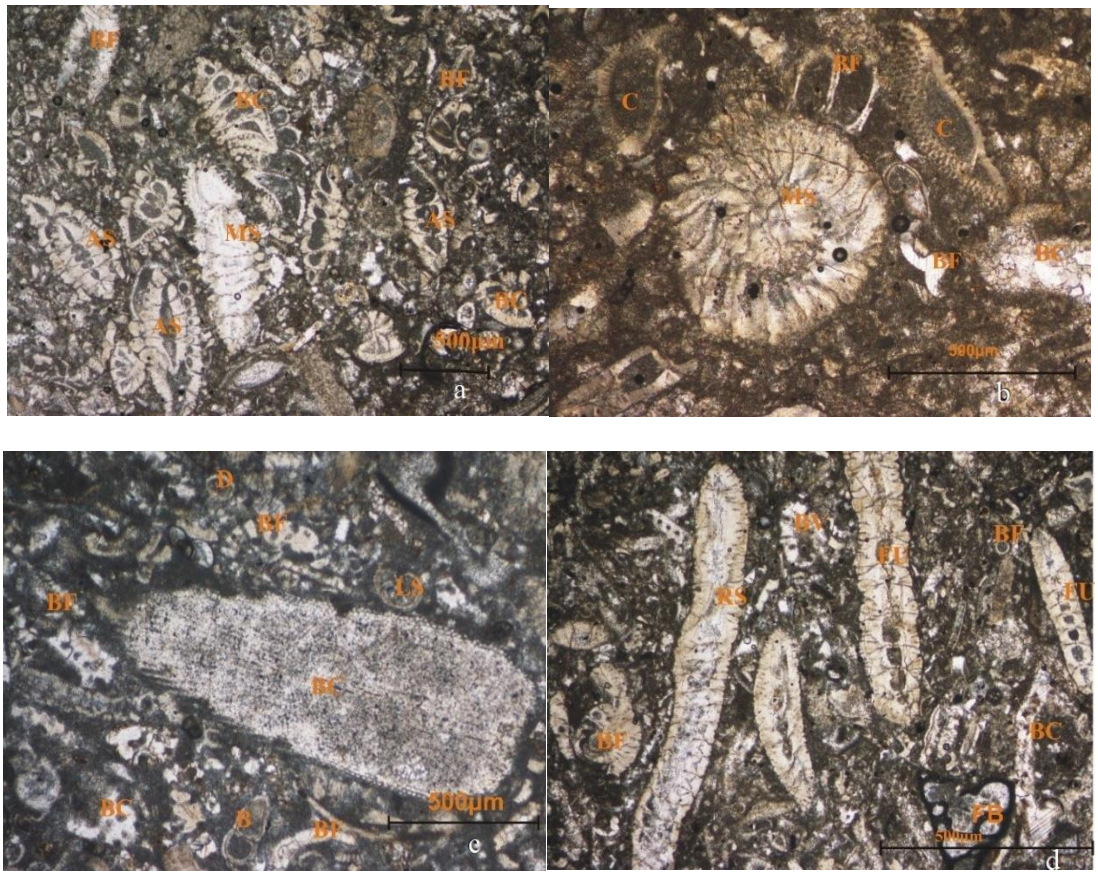


Fig 4.1 Plate 4.1 (a) Missilina (Ms), Broken fragments (BF), Assilina (As) (PPL. Mag. ×10) (b) Missilina (Ms), Broken Fragments (BF)) (CPL. Mag. ×10) (c) Lockhartia Spp. (LS), Bioclasts (BC), Broken Fragments (BF), Dasycladecean Algae (D) (PPL. Mag. ×10) (d) Assilina (As), Foraminifera Bioclast (FB) (PPL. Mag. ×10)

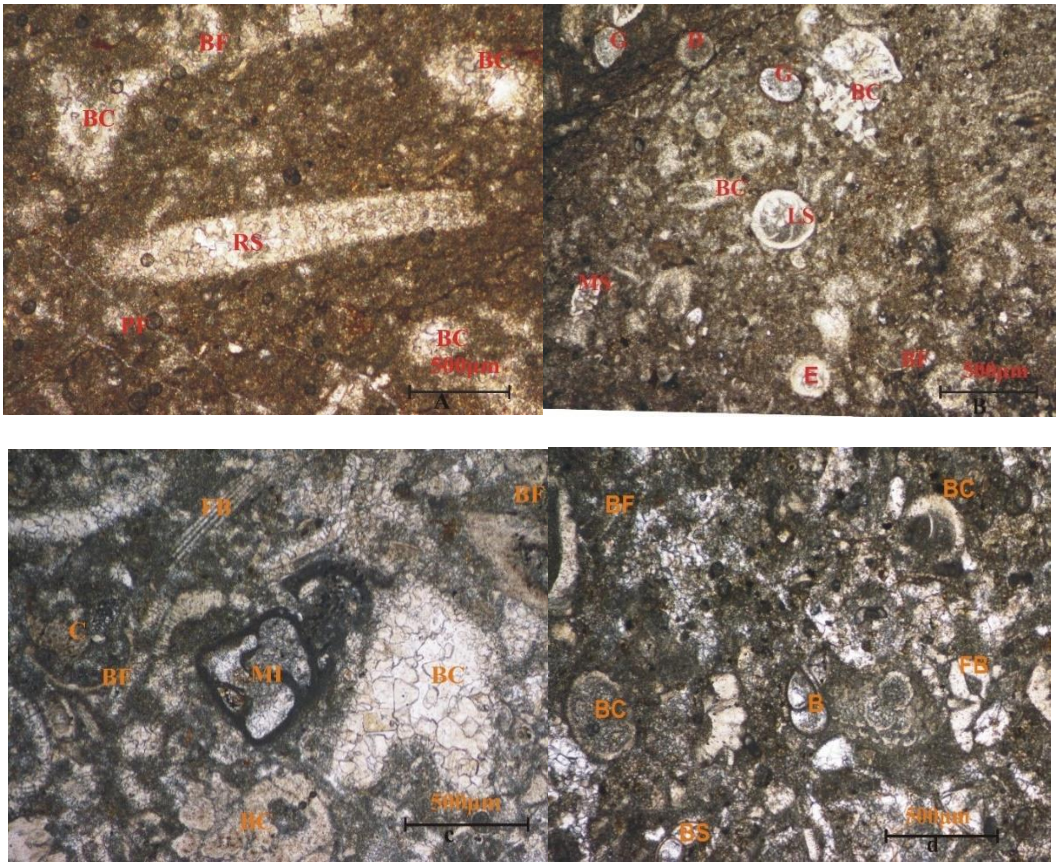


Fig 4.2 Plate 4.2 (a) Ranikothalia (RS), Broken Fragments (BF) (CPL. Mag. ×5) (b) Miscillina (MS), Bioclast (BC), Lockhartia (LS), Gastropode (G), Echinoderm (E), Broken Fragment (BF) (CPL. Mag. ×5) (c) Milliliod (MI), Bioclast (BC), Foraminifera Bioclast (FB) (PPL. Mag. ×10) (d) Brachiopod (B), Brachiopod Shell (BS), Broken Fragment (BF) (PPL. Mag. ×10)

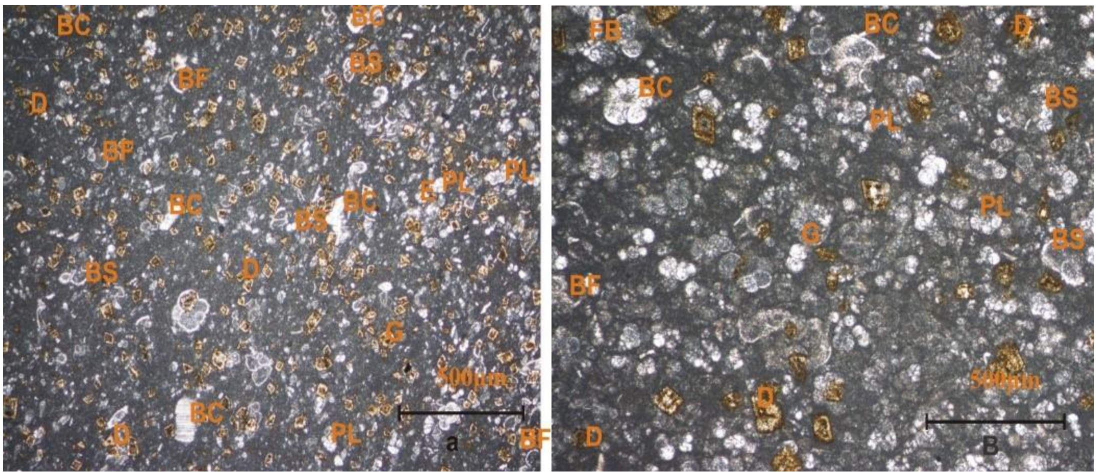


Fig 4.3 Plate 4.3(a) Represnts Planktons (PL) and Bioclasts (BC) (PPL. Mag. ×5) (b) Bioclasts (BC) and Planktons (PL) with abundant matrix) (PPL. Mag. ×5)

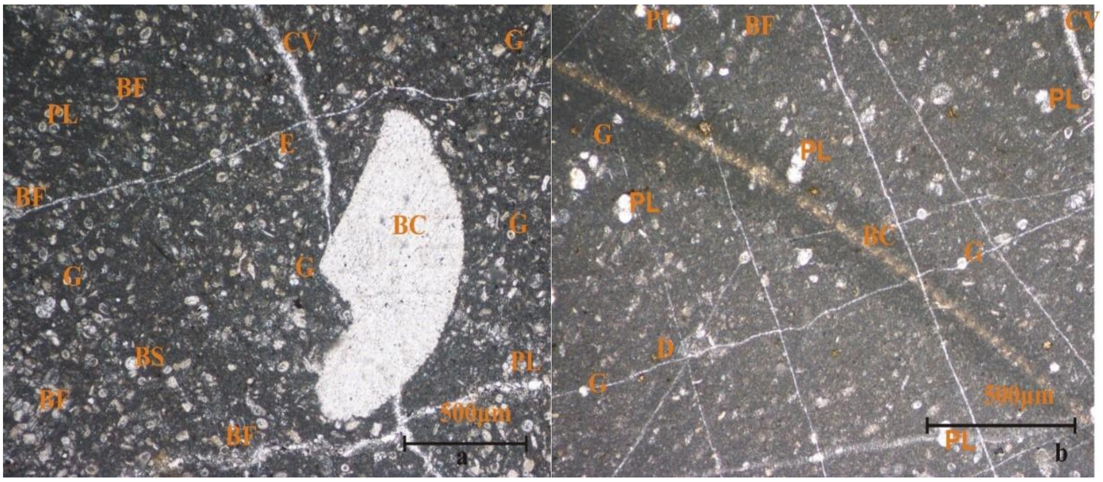


Fig 4.4 Plate 4.4 (a) Planktons (PL), Broken fragment (BF), Braciopode shell (BS), Calcite Vein(CV), Gastropode (G), Recrystalization of bioclast (BC),Mudstone having more Planktons (PL) as compared to Bioclasts (BC) with abundant matrix content) (PPL. Mag. ×10) (b) Planktons (PL), Broken fragment (BF), Braciopode shell (BS), Calcite Vein(CV), Gastropode (G), (PPL. Mag. ×5)

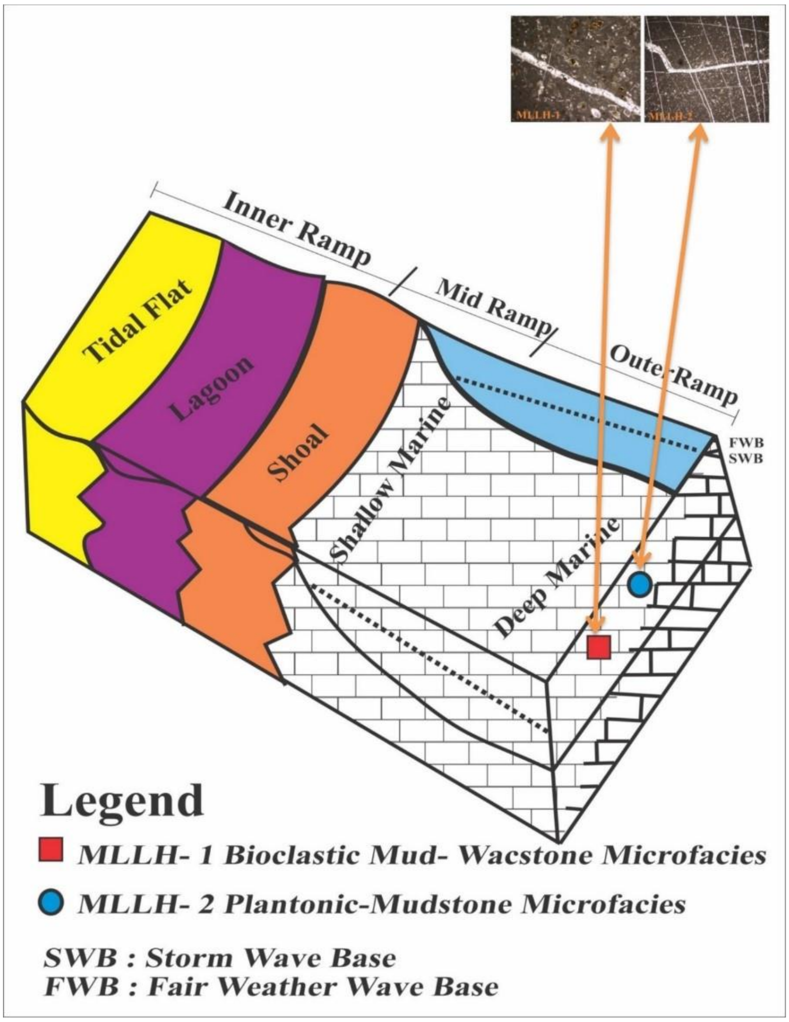


Fig 4.5 Depositional model for the Lockhart Limestone of Harnoi section Abbottabad

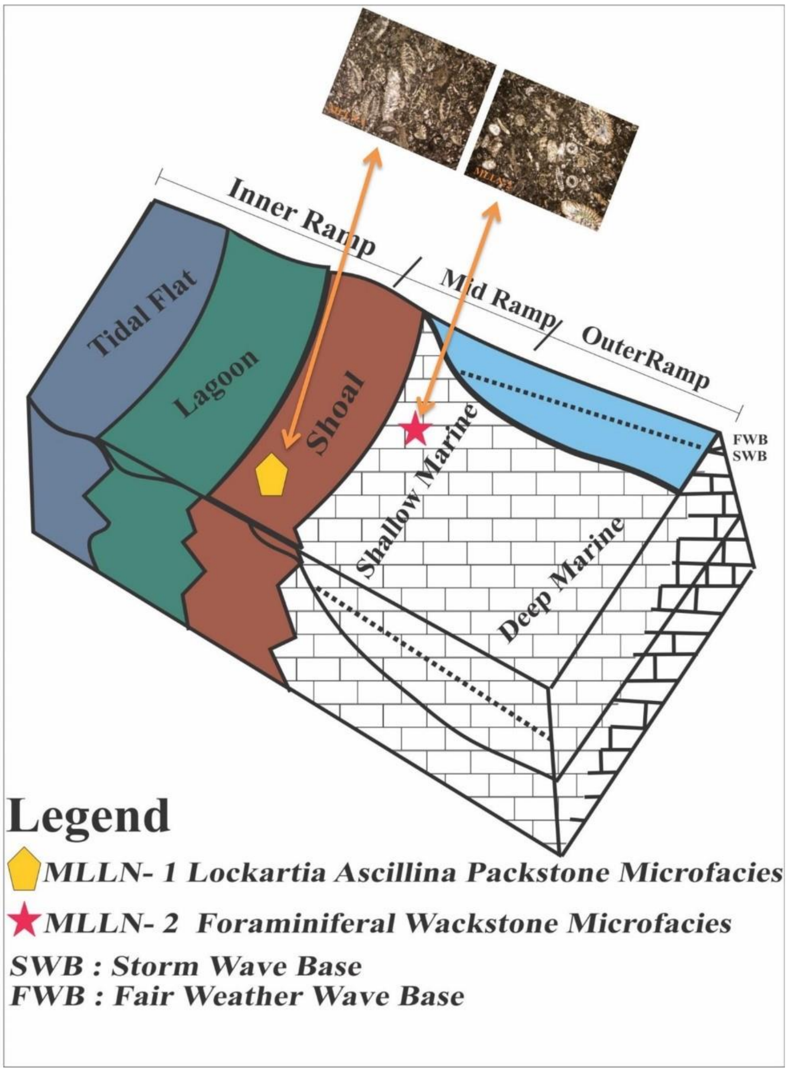


Fig 4.6 Depositional Model for the Lockhart Limestone of Nammal Gorge, Salt Range

CHAPTER 5

DIAGENESIS

5.1 Overview

Diagenesis refers to pre-metamorphic processes which have impact on sediments after they have been deposited. These reactions have the overall effect of cementing or dissolving the rock. Once grains are still washed away through the seas or are suppressed deep in subsurface, these alterations could be effective on sea floor. The mineralogy and composition of the sediments, the natural character of climate, pore fluids and burial/uplift/sea level fluctuations all influence diagenetic processes (Tucker and Wright, 2009). Within a single Limestone unit, this results in diagenetic differences on the lateral and vertical planes. Aragonite and High-Mg calcite are widespread in recent carbonate sediments, while these two minerals are rare in ancient carbonates, which are typified by Low-Mg calcite (Flügel and Munnecke, 2010).

The porosity of carbonate sediments can be increased or decreased as a consequence of digenetic processes. As a result of compaction and cementation, porosity and permeability often decrease with depth.

Higher porosities can be caused by water and fracture. As a result, Tucker and Wright (2009) found that understanding diagenetic processes is helpful in determining the petrophysical character of carbonate reservoirs. The marine, near-surface meteoric, and burying settings are the most common places where carbonate diagenesis occurs. Specific types of cement fabrics and other textural variations distinguish these environments. In both lateral and vertical dimensions, these environments eventually shift one into the other (Tucker and Wright, 2009). Different processes are involved in carbonate diagenesis such as.

5.1.1 Biogenic Alteration

Organisms are prone to altering carbonate rocks through burrowing, digging, and micritization. These processes destroy the rock's fundamental structures (Boggs, 2012). Endoolitic algae, fungus, and bacteria at or fair under the sea floor, most commonly in marine waters, change carbonate grains, particularly those of skeletal origin, through a process known as micritization. Microbes bore on the grain edges, which are then filled with micrite to form micritic envelops surrounding the grains in partial micritization. Micritization intensifies, resulting in the breakdown of the grain microfabric, which is then converted to micritized bahamitr peloids (Tucker and Wright, 2009).

Micritization was present in Nammal Gorge and Harnoi section of the Lockhart Limestone. The bioclast were also micritized.

5.1.2 Compaction

The growing overburden load on sediments causes dense packing of the grains, resulting in a significant loss of porosity. Simultaneously, burrier-induced fracture often improves porosity. Mechanical compaction refers to the tight packing of sediments (Tucker and Wright, 2009). As the load increases, the filled grains start to dissolve at contact points, resulting in sutured contacts and the formation of stylolites. Chemical compaction is a type of compaction in which dissolving is involved (Tucker and Wright, 2009). Microcrystalline stylolites can be found between two grains, or macrocrystalline stylolites can be found between several grains or between beds (Selley, 2000).

The Lockhart Limestone of the Harnoi section was more compact as compared to Nammal Gorge. Bioclasts were distorted due to mechanical compaction.

5.1.3 Neomorphism

The carbonate material is recrystallized and replaced throughout this procedure. In this process, the mineralogy may or may not be altered (Folk, 1959). Simply the crystal size vagaries with no change in mineralogy in recrystallization, however in spare, the innovative material is exchanged with a external substance that doesn't match the original component in chemistry (Tucker and Wright, 2009). Dolomite, quartz, anhydrite, pyrite, and hematite are some of the most common calcite substitutes (Boggs, 2012). In most diagenetic environments, these neomorphic processes are dominant.

The inversion processes (the alteration of aragonite to calcite) takings place in a dehydrated solid state. However, it could also happen in wet settings by dissolving and re-precipitating as calcite, a process known as calcitization (Boggs, 2012). In meteoric and burial diagenetic contexts, neomorphism is more widespread. During the petrographic investigation, several neomorphic processes were discovered. Recrystallization and arognite to calcite transformation are the most common.

In Lockhart Limestone the neomorphism is more obvious in bioclasts while less degree of neomorphism has been observed in the micrite. Neomorphism was common throughout the Lockhart Limestone.

5.1.4 Dissolution

The limestone's react to minor variations in chemistry of the fluids. They are simply precipitated in water that is calcite and aragonite saturated. They could be melted in undersaturated fluids that have been altered with carbon dioxide, whereas they cannot be dissolved in unsaturated waters that have been changed with carbon dioxide (Tucker and Wright, 2009). In nearby-surface meteoric waters, when aragonite and peak magnesium calcite dissolve, dissolution is common.

5.1.5 Fractures and Veins

Fractures are naturally occurring, microscopic or mesoscopic planar discontinuity which may be the result of tectonics or diagenesis (Passchier and Trouw, 2005). Fractures were observed in the Lockhart Limestone at outcrop scale and on microscopic scale (Fig 5.1) in the studied rock unit. Mostly fractures were filled with calcite.

5.1.6 Pyritization

It is the replacement of the original material by pyrite. Pyritization in the studied rock Unit is common both in the outcrop and under the microscope. The fractures and Stylolites at places are filled with pyrite (Figure 4.2, B). The pyrite also occurs in the form of discrete grains (Figure 4.3, E).

5.1.7 Nodular Limestone

The origin of the nodular fabric has been explained to be of diagenetic, sedimentary or tectonic in origin (Flügel, 2004). Diagenetic processes include solution processes as well as cementation and nodule growth within the sediment. Sedimentary origin underlines the role of transport and redeposition. Tectonic origin encourages the formation of nodules shear processes affecting limestone and marl. The limestone of the Lockhart Limestone has characteristic nodular fabric and can be attributed to compaction of the interlayered hard and compact limestone.

5.2 Diagenetic Environments

The diagenetic environments of the Lockhart Limestone in the Nammal Gorge and Harnoi Section are exposed to marine, shallow burial, deep burial and meteoric environments (Fig 5.1).

The dominant diagenetic processes in the Lockhart Limestone are micritization, dissolution, calcite filled veins, pyritization, unfilled fractures and neomorphism. Micrite is developed inside allochems. Mostly the allochems were dissolved and fractures were calcite filled forming veins. Pyrite grains were formed and are deposited in some of the fractures. Fractures and vein were abundant in the Harnoi section.

Table 5.1 Diagenetic sequence of the Lockhart Limestone (Compiled after (Flügel and Munnecke, 2010)

Time →	Early — Relative Timing → Late			
Diagenetic Environments →			Burial	
Diagenetic Process ↓	Marine	Meteoric	Shallow	Deep
Micritization	******			
Dissolution			....	******
Neomorphism	....	********	******	******
Nodular Fabric	....	********	******	
Compaction: Mechanical		....	******	******
Compaction: Chemical			******	******
Fracture			....	******
Calcite Veins				******

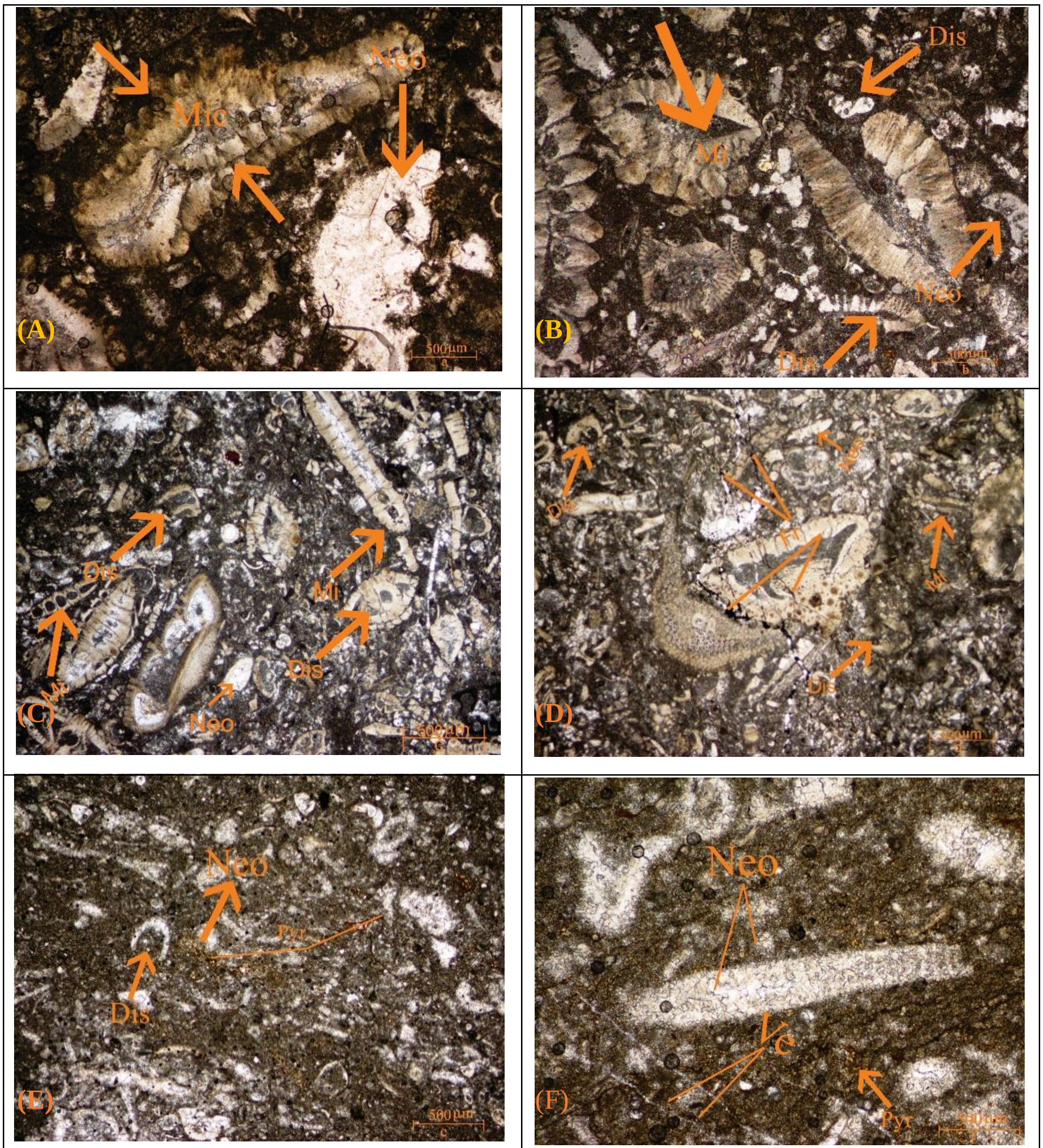
***** Dominantly ..... Partly

Table 5.2 Represents the diagenetic fabric of the Lockhart Limestone of Nammal Gorge.

Thin Section Name	Diagenetic Fabric						Remarks
	Micritization	Dissolution	Compaction	Neomorphism	Fractures/Veins	Pyritization	
NL-1	1	1	1	1	1	1	
NL-2	1	1	0	1	1	1	
NL-3	1	1	0	1	0	1	
NL-4	1	1	0	1	1	0	Packed
NL-5	1	1	1	1	1	1	
NL-6	1	1	1	1	1	1	
NL-7	1	1	1	1	0	1	
NL-8	1	1	0	•	1	0	highly neomorphosed
NL-9	1	1	0	•	0	1	
NL-10	1	1	1	1	1	1	
NL-11	1	1	1	•	1	1	
NL-12	1	1	0	1	1	1	
NL-13	1	1	0	1	1	1	
NL-14	1	1	1	1	1	1	
NL-15	1	1	0	1	1	1	
LEGENDS							
•= shows abundance 1=shows presence 0=shows absence							

Table 5.3 Represents diagenetic processes of the Lockhart Limestone of Harnoi section.

Thin Section Name	Diagenetic Fabric						Remarks
	Micritization	Dissolution	Compaction	Neomorphism	Fractures/Veins	Pyritization	
HL-1	1	1	0	1	1	1	Pyritized
HL-2	1	1	1	1	1	1	Pyritized
HL-3	1	1	1	1	0	1	
HL-6	1	1	0	1	1	0	
HL-7	1	1	1	1	1	1	
HL-10	1	1	1	1	•	1	Sheared
HL-12	1	0	0	1	1	1	
HL-13	1	0	0	•	1	0	
HL-17	1	0	0	•	1	1	
HL-19	1	0	1	1	•	1	Sheared
HL-24	1	1	1	•	1	1	
HL-26	1	1	0	1	1	1	
HL-31	1	0	1	1	•	1	Sheared
HL-33	1	0	1	1	•	0	Sheared
HL-36	1	0	1	1	•	0	Sheared
HL-38	1	1	1	1	•	0	Sheared
HL-39	1	1	1	1	•	1	Sheared
LEGENDS							
•= shows abundance 1=shows presence 0=shows absence							



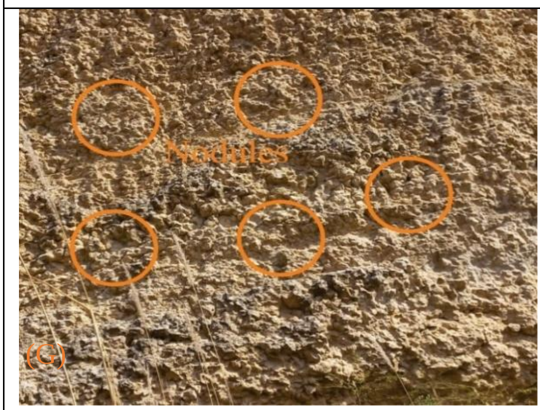


Fig 5.1 Plate 5.1. (A) Compaction (Mc) has distorted the shape of Assilina. Lockhartia is neomorphosed (Neo) (PPL. Mag. ×10) (B) the edge of Assilina are dissolved (Dis) and also micritize (Mic) (PPL. Mag. ×10 (C) Micritization (Mic) in the fossils and also Neomorphism (Neo) (PPL. Mag. ×10) (D) Fossils are fractured (Fr) and also micritization (Mi) (PPL. Mag. ×10) (E) Bioclasts are neomorphosed (Neo) and some microfossils are dissolved (Dis) and micritized (Mic) (PPL. Mag. ×5)(F) Calcite veins (Ve) and microfossils are neomorphosed (PPL. Mag. ×5) (G) Nodules formation in Lockhart Limestone of Nammal Gorge

CONCLUSIONS

This research work deals with microfacies analysis, diagenetic and depositional features of the Lockhart Limestone in Nammal Gorge, Salt Range and Harnoi Section, Abbottabad and the following conclusions are drawn.

1. The Lockhart Limestone in the Nammal Gorge is comprised of more nodular as compared to the Harnoi section Limestone with marl/shale interbeds.
2. Lockhart Limestone faunal assemblage is mostly dominated by large benthic foraminifera and dasycladaceam with small foraminifera, echinoderms, gastropode and bivalves.The foraminifera includes Lockhartia, Ranikothalia, Milliods and Miscellanea.
3. The Upper Paleocene (Thanetian) Lockhart Limestone is light to dark grey in color. A total thickness of 75 m from Nammal Gorge and 35 m from Harnoi section was measured, from which 32 samples were collected for laboratory analysis.
4. Four microfacies were identified i.e. MMLN-1 Lockhartia Assilina Packstone Microfacies, MMLN-2 Foraminiferal Wackstone Microfacies, MMLH-1 Bioclastic Mud-Wackstone Microfacies and MMLH-2 Planktonic Mudstone Microfacies representing inner ramp, middle ramp, outer ramp and open marine depositional environment respectively.
5. Main diagenetic processes in the Lockhart Limestone of Nammal Gorge and Harnoi section are micritization, neomorphism, dissolution, compaction (mechanical and chemical), fractures and veins representing dominantly shallow to deep burial diagenetic environments.

RECOMMENDATIONS

The resarch work can be improved through.

- Comparative analysis of microfacies interpretation, diagenetic depositional features with reservoir characterization of Lockhart Limestone in Upper Indus Basin.

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