GEOCHEMICAL ANALYSIS OF LOCKHART LIMESTONE FOR HYDROCARBON POTENTIAL IN KOTAL SECTION, KOHAT BASIN, KHYBER PAKHTUNKHWA, PAKISTAN

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A thesis submitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of MS in Geology

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DEDICATIONS

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my loving parents. I would like to thank my Brother Waqar Hussain as he supported me in all of my education carrier so much.

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ABSTRACT

The present research is based on source rock evaluation of Lockhart Limestone. Field was done to well exposed section in Kohat Ranges near Dara Adam Khel. Total of 13 samples were collected randomly and upon those samples geochemical analysis and petrographic analysis were done. Geochemical analysis includes TOC and rock eval pyrolysis, TOC of the samples were S1- 0.32, S2- 0.30, S3- 0.28, S4- 0.30, S5- 0.23, S6- 0.43, S7- 0.26, S8- 0.32, S9- 0.22, S10- 0.26, S11- 0.28, S12- 0.24, S13- 0.20 respectively. Only five samples were qualified (S1, S2, S4, S6 and S8) for rock eval pyrolysis having S1 values of 0.02, 0.02, 0.02, 0.04, 0.01 respectively. S2 values of 0.06, 0.04, 0.03, 0.12, and 0.03 accordingly. Similarly, the value of S3 is 0, 0, 0, 0.06, and 0. Whereas the values of Tmax (°c) are 474, 324, 483, 446, and 483. The kerogen type is type II & type III, and mostly of them lies in dry gas window having transitional between anoxic & terrestrial environment. In petrographic analysis 13 thin sections were studied and different diagenetic features and fossils were discovered, fossils includes lockhartia , lockhartia hemai, lockhartia conditi, rotalia , plano-rotalite, plano-rotalite pseudomorphs, bryozoans, algal filaments, small & large benthic forams, bivalves, gastropods, miscellinea miscella, miliolid, taxtularia , and broken bioclastic fragments in bioclastic wackestone, packstone, mudstone and wackestone-packstone facies. From the above results it concluded that Lockhart Limestone is a poor source rock.

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Abbreviations	Full Wording
TOC	Total organic carbon
MCT	Main Central Thrust
MBT	Main Boundary Thrust
HFF	Himalayan Frontal Fault
VR	Vitrinite Reflectance
Lc.Sp	Lockhartia Sp
B Frg	Broken fragments
Tst.Sp	Taxtularia Sp
Lc.H	Lockhartia Hemai
Misc	Miscellinea
Misc.Yv	Miscellinea Yvettae
Mic Sty	Microstyllolites
Lc.Con	Lockhartia Conditi
Rot. Sp	Rotalia Sp
Gstp	Gastropods
Plnk.Frm	Planktonic Foram
Sm.Bnt	Small benthic
Cal V	calcitic vein
Bnt	Benthic
Replm	replacement
Sm.Bnt	Small benthic foram

Ceb	Cebiside
Pln.Rot	Plano-Rotalite
Ostr	Ostracod
Plno-Rot Pseu	plano-rotalites pseudomorphs
Alg	Algal filaments
Bio.C Frg	bioclastic broken fragments
Biva	Bivalve
Bio.C	bioclasts
Dol	crystals of dolomitization
Bryo	Bryozoans
Mil	Miliolid
OGDCL	Oil and Gas Development Company Limited
PI	Production Index
Tmax	Maximum temperature
HI	Hydrogen Index
OI	Oxygen Index
GP	Genetic Potential

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Traditionally, in field of petroleum geology and geochemistry, certain types of rocks commonly give rise to hydrocarbon reservoirs. Additionally, certain carbonate rocks rich in organic matter that developed in low-energy settings have the potential to serve as source of hydrocarbon (Welte and Tissot 1984; Katz et al. 2000; Xia et al. 2019). Consequently, the majority of research has predominantly concentrated on examining reservoir properties of rocks, relatively than investigating their qualities as source rock in a broader sense. While carbonates are primarily recognized for their qualities as source rock, their fundamental geochemical properties and their subsequent hydrocarbon generation characteristics are not yet fully understood. This lack of understanding stems from the fact that carbonates often coexist with argillaceous source rocks, making it challenging to differentiate the hydrocarbon generation potential of each rock type. Consequently, these complexities pose significant challenges within the realm of petroleum geology and geochemistry (Xia et al., 2019).

More than 50% world's hydrocarbon reserves present in carbonate rocks and also host a remarkable volume of ore resources. The complex interaction among different parameters i.e. tectonic stresses, eustatic level, siliciclastic input, hydrodynamics, temperature, accommodation space, nature of producing ecologies, and ocean chemistry deeply affected both the deposition as well as production of carbonate rocks (Schlager, 2000). After deposition, major changes take place in the sediments or lithified rock fabric, composition, porosity and mechanical strength occur during burial through diagenetic processes, such as compaction, cementation, dissolution, microbial micritization, neomorphism, and finally mineral replacement (Lapponi et al., 2014).

Extensive and comprehensive sedimentological investigations have been conducted to thoroughly understand the significance of Paleocene carbonates as reservoir rocks for oil and gas, as well as for their future potential, within the Kohat-Potwar Sub-basins. The sedimentary basins in Pakistan encompass a wide range of oil and gas reservoir rocks, spanning from the Cambrian to Miocene periods, including both carbonate and siliciclastic formations. Among these formations, the Paleocene and Eocene carbonates are particularly favorable targets for exploration and have yielded productive oil and gas reservoirs.

The sedimentary basin of Pakistan is classified into the Indus Basin and Balochistan Basin, which have evolved through distinct sedimentological and geotectonic processes. Ongoing geological and tectonic activities have further subdivided the Indus Basin into the Upper Indus Basin and Lower Indus Basin. Illustrating the Indus Basin, its subdivisions, and the location of the study area. The Sargodha High acts as a dividing feature separating the Upper Indus Basin from the Lower Indus Basin. The Upper Indus Basin can be further divided into the Potwar and Kohat Sub-basins. The eastern part corresponds to the Potwar Sub-basin, while the western part represents the Kohat Sub-basin, with the Indus River acting as the boundary between the two. Both the Potwar and Kohat Sub-basins comprise substantial sedimentary successions ranging from the Pre-Cambrian to the Quaternary. These sedimentary sub-basins primarily consist of carbonates, siliciclastics, and clays, with unconformities occurring at various stratigraphic levels (Malik et al., 2014).

1.1.1 Previous Literature

The Lockhart Limestone is previously investigated by many authors in various aspects. As the reservoir compartments within the Lockhart Limestone are classified into three zones. Petrophysical interpretation indicates that zone-1 and zone-2 exhibit poor reservoir characteristics, while zone-3 shows potential as a moderate to good reservoir zone for hydrocarbons. Zone-1 and zone-2 demonstrate minimal hydrocarbon saturation, whereas zone-3 exhibits high hydrocarbon saturation within the formation. The petrophysical analysis further reveals that the Lockhart Limestone is highly compacted, resulting in low porosity and permeability throughout the formation, except for zone-3. This reduced the overall reservoir quality of the formation in the Shakardara Oil Field. Consequently, the Lockhart Limestone predominantly functions as a tight reservoir, with only sporadic instances of excellent reservoir potential for hydrocarbon exploration (Khan et al., 2020).

Source rock sedimentology for Potwar basin, host to most of Pakistan's major hydrocarbon fields, has been well-researched, but potential of the Lockhart formation, one of the sources in the basin, had not yet been fully established. To understand its source rock potential, petrological techniques and organic geochemical analysis of Lockhart samples measured the type of organic matter, quality of organic matter, and thermal maturity. Organic petrographic and organic geochemical analysis indicate that the formation has good oil-gas generative capacity and may act as a significant source in the basin (Shah, 2021).

Khan et al., 2022 examined the depositional facies, diagenetic processes, and sequence stratigraphy of the Samanasuk Formation, a shallow marine carbonate unit in the Kohat Basin. The main objective was to evaluate reservoir quality of studied formation. Samana Suk Formation is composed of diverse lithologies, including thin to thick-bedded, oolitic, bioclastic, dolomitic, and fractured limestone. By integrating data from outcrop observations, petrographic analysis, and biofacies studies, it is inferred that Samanasuk Formation was deposited in a peritidal setting, encompassing lagoonal areas and carbonate shoals, on a gentle homoclinal ramp. Analysis of microfacies variations, based on sea-level changes, has identified seven Transgressive Systems Tracts (TSTs) and six Regressive Systems Tracts (RSTs). The formation has undergone various diagenetic processes, such as mechanical and chemical compaction, cementation, micritization, dissolution, and dolomitization. Petrographic analysis reveals the evolution of porosity during different depositional and diagenetic phases. Fenestral porosity developed predominantly in peritidal carbonates during deposition, while burial dissolution and diagenetic dolomitization have significantly enhanced the reservoir potential of the rock unit. This is further supported by the analysis of plug porosity and permeability. The porosity and permeability values were found to be higher in shoal facies deposited during TSTs compared to lagoonal and peritidal facies, except for the dolomite in mudstone, which was deposited during RSTs. Consequently, the study suggests that the shoal facies exhibit good reservoir potential, while the lagoonal and peritidal facies display moderate and poor reservoir potential, respectively. Moreover Yaseen et al., 2021 studied structural distortion and hydrocarbon prospective of the southern peripheries of the Peshawar Basin, along with nearby Kohat-Kotal Range, which is influenced by hanging wall stratigraphy of Main Boundary Thrust. Through surface and subsurface analysis, mapped area demonstrates various types of distortions that occurred at different periods in geological history. Study area comprises three main geological areas: the Peshawar Basin in north, the Kotal Kohat Range in central region, and the Kohat Basin in south. Kohat-Kotal Range is characterized by highly deformed east-west trending anticlines separated by synclines, with faults delineating their boundaries. Towards the south of the study area, the first major fault encountered is the Main Boundary Thrust (MBT), which juxtaposes Jurassic Samana-Suk Formation over younger Miocene packages. Which suggests significant deformation in the area, with a maximum throw of approximately 3000 meters. MBT is believed to consist of several splays.

Another vital thrust fault observed in region is the Akhurwal-Back-Thrust (ABT), which has a northwest-west orientation which steeply-gently south-dipping. Along its surface trace, the ABT acts as a back thrust fault, placing Mesozoic strata of Kotal/Kohat Ranges in its hanging wall over the Miocene Murree Formation of southern Peshawar Basin. Split line A-B, oriented SSW-NNE, and intersects both the MBT and linked ABT. Cross section suggests that Patala Formation in footwall has been displaced southwards by MBT, although the extent of displacement along the MBT is not clearly discernible due to the absence of cutoffs observable in segment. It postulated that hanging wall strata have moved approximately 70-80 kms from northward. Basal decollement, smoothly dipping northwards at depths of around 10,000 to 11,000 meters, serves as primary detachment level, with several faults originating from it. Presence of a dense cover of Eocene rocks to south of MBT resulted in abundant hydrocarbon reserves due to the presence of excellent seals and traps. Structural rebuilding of distorted section A-B, without the MBT, indicates an overall limitation of approximately 45.701%, implying long-term tectonic stresses since the Mesozoic era. Presence of Main Boundary Thrust and Akhurwal-Back-Thrust clearly indicates that tectonic forces played crucial role in inducing structural changes in the area.

Siyar et al., 2021 studied Chichali Formation, encountered in the Chanda 01 well situated in Shakardara Kohat, Khyber Pakhtunkhwa, Pakistan, has been extensively investigated a potential hydrocarbon source. 9 drill cuttings from formation were subjected to geochemical analyses and organic petrography to assess quality, quantity, maturity, and depositional environment of organic matter. Several screening techniques, including total organic carbon (TOC) analysis using a Leco-CS analyzer, Rock Eval pyrolysis, and organic petrography, were employed. Suggest that Chichali Formation is an effective source rock in the process of generating hydrocarbons and falls within the oil window. Geochemical parameters such as the hydrogen index (HI), oxygen index (OI), and Tmax, along with organic petrography analysis (maceral), were utilized to evaluate the type of kerogen. The modified Van Krevlen diagram, incorporating HI vs OI from Rock Eval pyrolysis and maceral analyses, indicates a kerogen type II/III and a transition from anoxic to oxic depositional environments for the studied Chichali Formation. Overall, the findings suggest that Chichali Formation holds significant potential as a source rock for hydrocarbons, with favorable geochemical properties, maturity levels, and kerogen type.

The present work focuses on the hydrocarbon geochemistry of the Paleocene Lockhart Limestone in the Kohat Ranges Kotal section Kohat which is not previously investigated.

1.2 Study Area

The study area is situated at 71º28'23"E longitude and 33º38'15.49"N latitude. It conveniently accessible as it is located along the Kohat-Peshawar road (Figure 1.1).

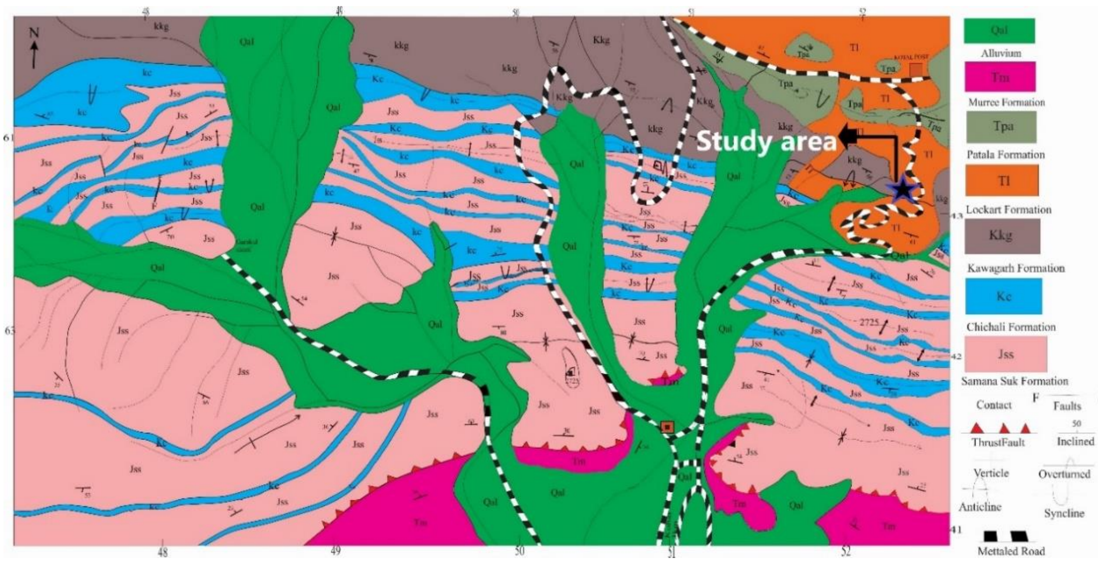

Figure 1.1. The field map of Kotal section Kohat Ranges Kohat basin (Yaseen et al., 2021).

1.3 Objectives

The study is aimed to achieve following objectives.

i. To study thin sections for petrographic analysis.
ii. To estimate TOC values from outcrop samples.
iii. To perform geochemical analysis on Lockhart Limestone to investigate their thermal maturity, organic richness, type of kerogen.

CHAPTER 2

GEOLOGY AND TECTONICS

2.1 Tectonic Settings

Eurasia, a vast landmass, can be divided into three major geological divisions: the Laurasian, Tethyan, and Gondwanian domains. These divisions have their origins in the Late Paleozoic era when the continents merged to form the supercontinent Pangaea, which stayed together for approximately 100 million years. Pangaea was surrounded by the Panthalassa, global ocean, with Tethys Sea wedged among southern and northern parts of Pangaea. Eventually, Pangaea divided into 2 super-continents: Laurasia in north and Gondwanaland in south, parted by Tethys seaway (Kazmi & Jan, 1997).

Eurasia comprises multiple crustal blocks of different ranges that have been closed alongside ophiolite belts. Many of those masses were added to Laurasian landmass since Carboniferous age. These blocks are remnants of Gondwanaland that broke away from main landmass, drifted northward, and struck with Laurasian area. The current Eurasian landmass consists of original Laurasian landform (the Laurasian Domain) and the combine fragments of Gondwanaland, which are referred to as the Tethyan Domain. Southward from the Tethyan Domain, there are Arabian and Indian peninsular shields, they also originated from Gondwanaland and were last to be added to Eurasia. However, these peninsular shields are distinct from other Gondwanian blocks because they contain extensive outcrops of Archean and Proterozoic metamorphic and igneous rocks. They are referred to as the Gondwanian Area. Pakistan lies at intersection of Gondwanian and Tethyan domains (Kazmi & Jan, 1997).

2.1.1 Gondwanian Domain

The domain known as the Arabian and Indian shields is characterized via continental crust, crystalline basement that formed during Precambrian period. It exhibits platform-kind development during Paleozoic era. In Asia, this domain primarily represented by Arabian and Indian shields. Indian shield forms Indo-Pakistan subcontinent, and its north boundary consists of the crystalline thrust sheets of Himalayan orogenic belt. The Himalayan orogenic belt extends eastside and westward, forming sequence of deformed, oroclinal, marginal fold belts in various regions such as Arakans, Sub-Himalayan Siwalik Range, Potwar Plateau, Salt Range, and Sulaiman-Kirthar Ranges. Indo-Pakistan subcontinent is traditionally distributed into three main physiographic and geological dissections: Peninsular Region, Himalayan Fore Deep, and Himalayas (Kazmi & Jan, 1997).

Peninsular area is composed of succession of metamorphosed plutonic, volcanic, and sedimentary rocks having age from the Archean to Late Proterozoic. These Precambrian rocks are exposed as Archean cratons bounded by several Proterozoic mobile belts. Along the north margin of Peninsular Section, wide raged plains of Indus and Ganges rivers, covered by Cenozoic to Mesozoic sedimentary deposits, conceal Indian Peninsular Shield. More north, Himalayas and its lower ranges have formed due to subduction of Indo-Pakistan crustal plate. Overall, Arabian, Indian shields, including Indo-Pakistan subcontinent and the Himalayan orogenic belt, exhibit a complex geological history with a combination of ancient Precambrian rocks, mobile belts, and ongoing tectonic activity (Kazmi et al., 1997).

2.1.2 Peninsular Region

The region mainly comprises foundations of Indian Shield, which is categorized by the following features:

i. Granite-greenstone terrains: These include the Kama-taka, Jeypore Bastar, and Singh-bhum regions. They consist of Archean to Proterozoic magmatic rocks known as Peninsular Gneisses, along regions of older supra-crustal rocks such as the Gorur and Sargur Group. Archean Banded Gneiss and granites are also present in the Bundelkhand region.

ii. Late Archean reactivated basement rocks: The Dharwar Super group represents Late Archean rocks that have undergone reactivation and now surround by more aged gneisses.

iii. Proterozoic mobile belts: These include the Eastern Ghat, Satpura, and Aravalli-Delhi belts have been tectonically covered around earlier Archean and Proterozoic rocks. Middle to Late Proterozoic granites invades above mentioned belts.

iv. Middle Proterozoic rifting: This geological process resulted in the formation of extensive grabens covered with sediments. Late Proterozoic (Cuddapah) and Paleozoic to Mesozoic (Gondwana) sediments are found in these grabens.

v. Late Proterozoic shallow-marine to deltaic deposits: The Vindhyan Supergroup represents a thick and extensive sequence of sedimentary deposits. These deposits consist of coarse clastics (such as sandstones) and carbonates, interspersed with volcanic rocks. They were formed in a shallow-marine to deltaic environment.

The Late Cretaceous flood basalts, commonly known as the Deccan Traps, represent a significant geological feature in the region. These flood basalts cover a vast area of approximately 500,000 square kilometers on western flank of Peninsular Shield. The Deccan Traps are composed of extensive layers of basaltic lava flows that were erupted during a period of intense volcanic activity in the Late Cretaceous. The dominant rock type in the Deccan Traps is a greyish-green, vesicular (containing voids or gas bubbles), augite basalt. Augite is a common mineral found in basaltic rocks. However, variations in color, texture, and composition can be observed at different locations within the Deccan Traps. These variations may be attributed to differences in the composition of the magma source, eruption style, or post-eruption alteration processes. (Kazmi & Jan, 1997).

2.1.3 Himalayan Fore Deep

The foredeep region in this area is located on a gently sloping continental platform and is characterized by a basement consist of Archean and Proterozoic metamorphic, plutonic rocks. This region exhibits a sequence of upward, intervening depressions, as well as horst and graben structures, they are delineated through geophysical surveys. Westward part of the foredeep is protected by Indus sedimentary basin. This basin consists dense prism of sediments that slope west oriented and range in age from Precambrian to Holocene. Towards the east, the sediments thin out and the bedrock becomes exposed or occurs at shallow depths in areas such as the Shahpur-Delhi buried ridge, Jacobabad-Khairpur high, and Khandkot-Mari high (Kazmi et al., 1997).

To the south and west, sedimentary cover condenses more than 5,000 meters. In the northern part of the foredeep, the Gangetic Plain is present. This area is characterized by a thick alluvial cover, reaching up to 1,700 meters in thickness, it is underlain by Siwalik molasse. In East Punjab, Siwalik molasse unconformably overlies Eocene-Early Miocene rocks, which in turn covers basement rocks. Cenozoic sequence in this region can reach a thickness of about 5,000 meters, and Proterozoic Vindhyan sequence come across at depths 4,400 meters. Moving eastward, Ganga Basin is generally composed of a thick pile of Siwalik molasse, ranging from 900 to 4,000 meters in thickness. This molasse unconformably overlies Pre-Tertiary sequences, predominantly the Gondwana or the Vindhyan rocks. Overall, the foredeep region in this area exhibits a complex geological history with varied sedimentary sequences, including alluvium, molasse, and older rock formations, reflecting the tectonic and depositional processes that have occurred over time. (Kazmi & Jan, 1997).

2.1.4 Himalayas

Himalayas, nearby Indus-Ganga Basins, constitute prominent mountain range that stretches for approximately 2,500 kilometers in length and varies in width from 160 to 400 kilometers. It is characterized by chain of echelon mountain ranges with broad intervening valleys. Near its eastern and western ends, Himalayas exhibit sharp oroclinal loops or syntaxial bends, while its offshoots form north-south trending mountain ranges that are less elevated and less visually striking. Himalayas are formed along the north margin of Indo-Pakistan crustal plate. This region is filled with almost complete Phanerozoic sedimentary sequence extending up to Eocene. The impact between Indian and Eurasian tectonic plates gave rise to vast mountain ranges, resulting in accumulation of extremely deformed Phanerozoic sediments, interleaved with fragmented, thrust blocks of Proterozoic basement rocks. The region has also experienced multiple episodes of magmatic activity and undergone various metamorphic events, adding to the geological complexity of the Himalayas. (Kazmi & Jan, 1997).

To the north, the Himalayan topography ends along Indus-Tsangpo Suture Zone. Geophysical data proposes that continental crust is in this area, encompassing the high Himalayas and Tibetan Plateau, exceptionally thick, ranging from 50-80 kilometers, having approximately double the normal thickness of continental crust. Thickening is attributed to ongoing process of India's underthrusting and underplating beneath the Asian plate (Kazmi et al., 1997). Overall, the geology of the Himalayas is intricate, reflecting the complex tectonic and geological processes involved in the collision and ongoing interaction between the Indian and Eurasian plates. (Kazmi & Jan, 1997).

Powell et al. (1973) documented that sub-ducted mass of Indian Shield can be divided in two blocks. Frontal block, also known as Tethyan Himalayas, has strucked with Asian plate along Indus-Tsangpo Suture. On other hand, rear block of Indian plate remains to be subducted and formed an underthrust below frontal block and Asian plate. The impact of these blocks resulted in obduction (upward movement) of widespread masses of mélanges (a mixture of different rock types), exotic blocks, and ophiolites (sections of oceanic crust and upper mantle). This obduction has taken place in the suture zone, where the two blocks have come together. Additionally, the collision has caused the formation of southward verging folds and thrust belts in Phanerozoic sediments (sediments from last 540 million years) and volcanic rocks overlying basement rocks of frontal block (Tethyan Himalayas).

The ongoing under-thrusting of rear block resulted in the scraping off of Phanerozoic sediments and volcanoclastic (volcaniclastic sedimentary rocks) from sea floor. Some of basement rocks have also involved in this process. These materials have been pushed southward as highly tectonized (deformed by tectonic forces) and metamorphosed (altered by high pressure and temperature) masses, forming nappes (large sheets of rock) and thrust slices. In summary, the collision between Indian and Asian plates has led to formation of distinct blocks and associated tectonic features, such as folds, thrust belts, mélanges, and obducted masses, along Indus-Tsangpo Suture. Ongoing underthrusting of the rear block continues to shape the geological characteristics of the region (Kazmi et al., 1997). The lesser Himalayas, also known as the imbricated metasediments, form a distinct morpho-tectonostratigraphic belt in the region. These metasediments have been intensely buried and subjected to friction, resulting in their reactivation and remobilization. The region of the high Himalayas is often stated to as Central Crystalline Axis, where crust has experienced significant burial and deformation. (Kazmi & Jan, 1997).

Moving southward, crystalline rocks of Central Crystalline Axis are extensively thrust. Main Central Thrust (MCT) is primary thrust along which Cenozoic gneisses and schists have settled, following a deep crustal fracture. In certain divisions south of MCT, crystalline rocks of the Central Crystalline Axis have formed large nappes, and their offcuts observed as klippes within lesser Himalayas. Rocks of lesser Himalayas have undergone southward thrusting are now overlying Neogene Siwalik molasse. This thrust region is known as Main Boundary Thrust (MBT), which passes alongside foothills of Himalayas. Further south, a new fault called Himalayan Frontal Fault

(HFF) is present, where folded Siwaliks have been faulted less deformed Siwalik sequence of Ganga Basin. In the geological setting of the surrounding regions, Pakistan holds a unique position as it is situated at the intersection of Gondwanian and Tethyan Areas. South-east part of Pakistan belongs to Gondwanian Area is supported by Indo-Pakistan crustal plate. This geographic location contributes to the diverse geological features observed in Pakistan (Figure 2.1).

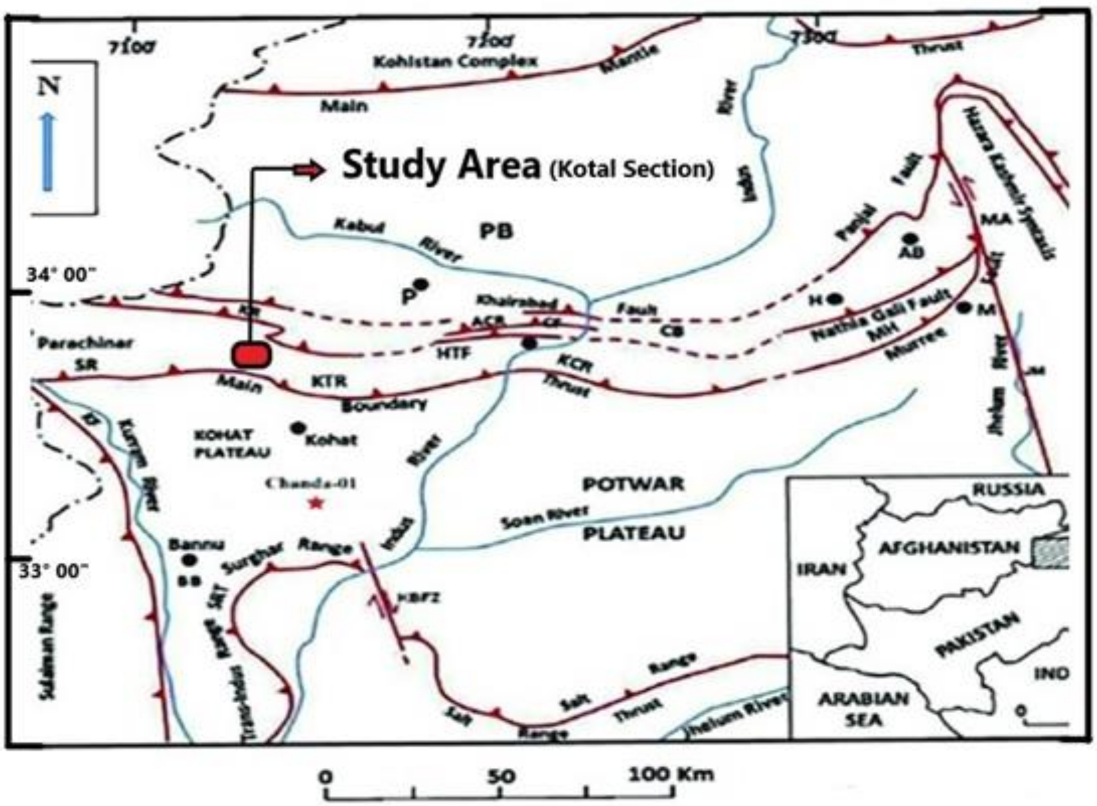

Figure 2.1. Tectonic map of Kohat/Potwar Plateau in North Pakistan where the red box shows the study area (Sercombe et al., 1998).

2.2 Local Geology

The Study area consists of rocks ranging in age from Jurassic to Miocene succession which are as follows (Figure 2.2).

2.2.1 Samana-Suk Formation

Samana-Suk Formation, comprised of limestone, fractured dolomitic-limestone. Limestone varies in thickness from thin to thick beds and is typically light to medium grey in color, while weathered rocks tend to be yellowish brown. Important feature of the limestone is the abundance of ooids, which are small spherical grains formed from concentric layers of calcium carbonate, Interbedded with the limestone, there are gray-brown dolomitic limestones along gray-colored limestone. Thickness of formation in type locality is about 350m. The lower contact of the Samanasuk Formation visible, but it is known to be unconformably overlain by the Chichali Formation (Kazmi &Jan, 1997).

2.2.2 Chichali Formation

Chichali Formation with a thickness of around 50 meters is comprised of glauconitic sandstone, sandy shale. It contains large numbers of belemnites, which are fossilized. Upper contact of the Formation conformable, indicating a relatively consistent deposition process. On the other hand, the lower contact with the underlying Kawagarh Formation is disconformable, suggesting a time gap or erosional event between the two units. Based on the existing of fossils, formation aged as late to early Cretaceous age (Kazmi &Jan, 1997).

2.2.3 Lumshiwal Formation

Lumshiwal Formation primarily consists of sandstone with minor clay content. Sandstone characterized by a light yellow color, and grain size ranges from fine-coarse. On weathered surfaces, it appears rusty gray to brown color, while fresh surfaces exhibit a brick red coloration. In the type locality, the Formation has been observed to have a thickness of approximately 150 meters. The lower contact of the Lumshiwal Formation with the underlying Chichali Formation is sharply defined, indicating a distinct boundary between the two units. However, upper contact with Kawagarh Formation is dis-conformable, suggesting a potential time gap or erosion between the two formations (Kazmi &Jan, 1997).

2.2.4 Kawagarh Formation

Kawagarh Formation is composed of limestone, with thin to medium-sized beds that are horizontally layered. The sandy limestone component exhibits a pale yellow color when weathered, while it appears dark to brown on fresh surfaces. Within formation, there are intercalations of shales. Lower and upper portions of formation are characterized by thin-medium sized beds. The typical limestone found in formation is light grey, occasional occurrences of secondary marl and shale. Thickness of formation can vary because of significant folding at type locality; but, generally ranges from 90 to 100 meters. The formation displays a disconformable contact with the underlying unit, indicating a break or erosion in deposition between the two formations. Conversely, its contact with the overlaying Lockhart Limestone is conformable, suggesting a continuous sedimentary sequence (Kazmi &Jan, 1997).

2.2.5 Hangu Formation

Davies (1930a) initially referred to the Hangu Formation as Hangu shale and Hangu sandstone, naming it after the section located at southern side of Fort Lockhart in Samana Range of the Kohat area. Later, Cheema et al. (1977) made amendments to the Hangu Formation. This formation primarily consists of sandstone, accompanied by grey shale and coal deposits. Its age is believed to be the latest Cretaceous, deduced from correlations made with the Vitakri formation in the Sulaiman Basin. Due to the lateral extension and similar lithology and horizon, the Patala Formation is often considered synonymous with the Hangu Formation. Age of Hangu Formation is Early Paleocene.

2.2.6 Lockhart Limestone

Lockhart Limestone is characterized by series of gray limestone ranging from light to dark in color. On weathered surfaces, it appears yellowish brown to black. It predominantly forms ridges in the landscape. The limestone beds within the formation are relatively thin to medium in thickness and display a hard and massive composition at base. Upper section, however, is remarkably fractured and fragmented, forming breccias. Lower part exhibits prominent nodularity with nodules of varying sizes. Lockhart Limestone is separated from the underlying Kawagarh Formation by a disconformity, while it is conformably overlain by the Patala Formation. The Lockhart Limestone is highly abundant in fossils, particularly foraminifera, which provide evidence of its mid-Paleocene age (Kazmi &Jan, 1997).

2.2.7 Patala Formation

Patala Formation is composed of alternating layers of thin bedded shale and limestone. Upper section consists of fine grained shale, which in certain areas appears oxidized, ranging in color from brown to black. This shale is fissile and exhibits a dense texture. At the type locality, the Formation has a thickness of approximately 30-50 meters. The limestone portion of the Patala Formation displays nodularity and appears light yellow when weathered and gray when freshly exposed. Formation is found to be in conformable contact with the upper Lockhart Limestone. Age of Patala Formation is Late Paleocene age (Kazmi &Jan, 1997).

2.2.8 Murree Formation

Murree Formation, observed at where it is well exposed, has an approximate thickness of 40-50 meters. It is composed of greenish gray and occasionally purple gray, medium, coarse grained sandstone, along with purple to reddish brown siltstone and shale. Additionally, there are occasional layers of conglomerate within the formation. The Murree Formation is juxtaposed with molasse sediments settled in the foreland basin of the Kohat and Potwar area by MBT (Main Boundary Thrust). This tectonic fault carries Mesozoic-Cenozoic shelf sediments from Hills Ranges over molasse sediments. Specifically, at contact, Murree Formation shows a tectonic relationship with limestone found in the Samana-Suk Formation (Kazmi &Jan, 1997).

2.2.9 Panoba Formation

The Formation in question is situated on the northwestern branch of Tanda Dam syncline, near village of Ambad Band. At outcrop level, there is a clear distinction in lithology within this Formation, although it's weathered surface light yellow in color. Not any fossils were discovered during field investigations. Early researchers have attributed an early Eocene age to this Formation (Kazmi &Jan, 1997).

2.2.10 Kuldana Formation

Kuldana Formation primarily comprises purple, brown, and pale yellow shale, occasional layers of sandstone and gypsum beds. Formation has a thickness of many meters and does not contain any fossils. Lower contact of formation was not observable, but upper contact is in conformable alignment with Kohat Formation. Kuldana Formation is assumed to have been deposited in shallow marine environment.

Early researchers gave it an early to middle Eocene age to Kuldana Formation (Kazmi &Jan, 1997).

2.2.11 Kohat Formation

The Kohat Formation is characterized by thick-medium bedded limestone, interspersed with sections of dirty calcareous clays. In certain areas, formation shows significant weathering and brecciation. Upper contact of the Kohat Formation is disconformable, indicating a distinct boundary with the overlying Murree Formation. On the other hand, lower contact is conformable with Kuldana Formation. Kohat Formation having abundance of fossils, and based on these fossil groupings, it is assigned a Middle Eocene age (Kazmi &Jan, 1997).

2.2.12 Murree Formation

Murree Formation primarily consists of dark purple red-grey clays, occasional sandstone layers exhibiting gray-greenish coloring at surface. Within formation, there are also secondary intraformational conglomerate deposits. The age of Murree Formation is assigned as Early-Miocene (Kazmi &Jan, 1997).

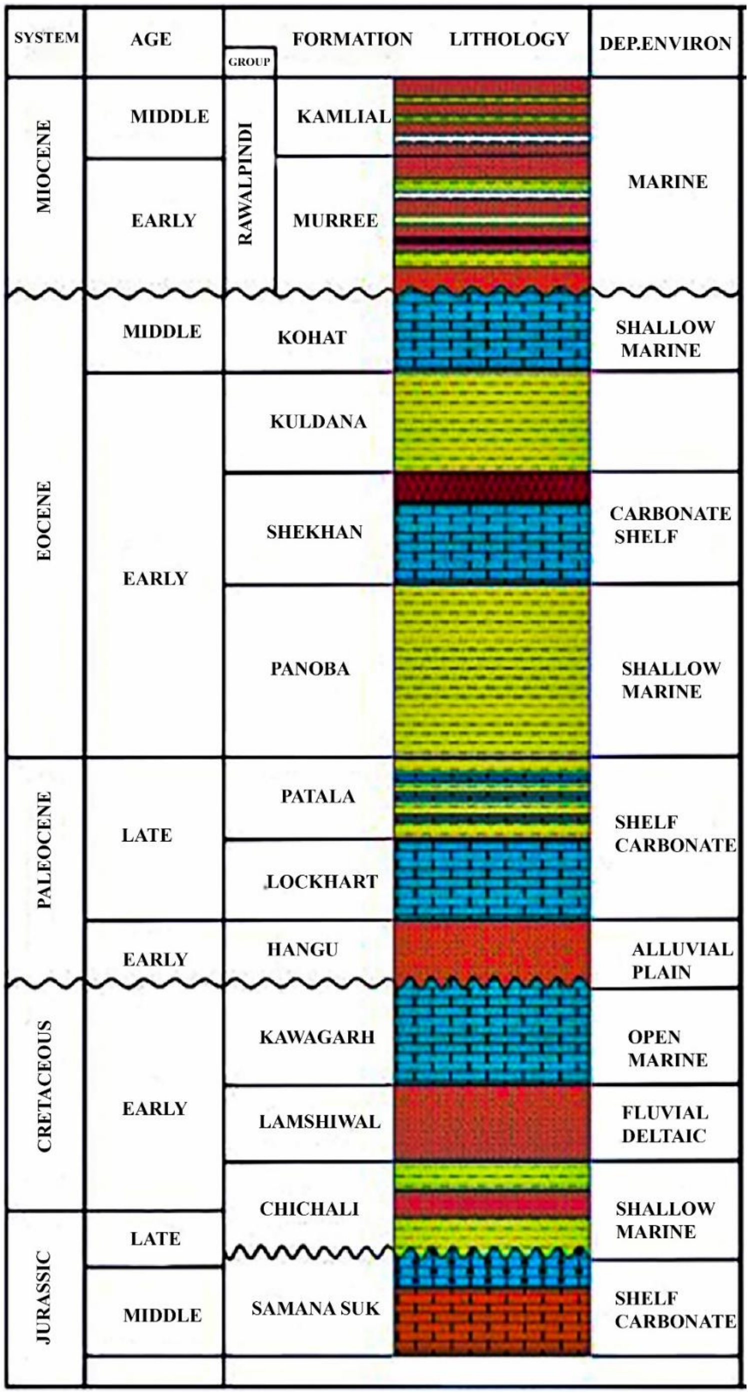

Figure.2.2 Stratigraphic column of Kohat basin along Kohat ranges (Yaseen et al., 2021).

CHAPTER 3

METHODOLOGY

The methodology of this study consists of laboratory studies and field work for the collection of samples.

3.1 Fieldwork

The field work was done to Kotal Pass, Kohat ranges in the Kohat sub-Basin. The samples were collected randomly from the outcrop and numbered respectively according to the point of collection. Excellent exposure of Paleocene Lockhart Limestone is exposed along the Kohat-Dara Adam Khel Road (Fig 3.1 A). Outcrop picture showing massive beddings as well nodularity of Lockhart Limestone in the Kotal section, Kohat Ranges, Kohat sub-basin (Fig 3.1 B), nodularity is one of main feature of Lockhart Limestone. Thin beds of shale embedded in massive limestone beds (Fig 3.2 A). Lockhart Limestone of Kotal section having abundance of fossil contents (fig 3.2 B).

Diagenetic features of Lockhart Limestone are also observed in the field which includes: stylolite, fractures, dissolution cavities, and calcite veins.

Stylolites are geological features found in carbonate rocks that result from pressure dissolution processes under the influence of overburden pressure (Fig 3.3 A). They can exhibit various forms, including hummocky, irregular, low and high-amplitude peaks, as well as irregular anastomosing patterns. Fractures are physical breaks or discontinuities in rocks that involve gaps in displacement across surfaces or narrow zones (Fig 3.3 B). The term "fracture" encompasses various types of generic discontinuities. In the Kotal Section of the Lockhart Limestone, extensive fracturing is observed. The presence and characteristics of fractures can be observed in the accompanying field images provided below.

Ground dissolution occurs when water passes through soluble rocks, leading to the formation of underground cavities and cave systems. Potentially resulting in localized collapse of the rocks and deposits. The Lockhart Limestone, like other soluble rock formations, can display dissolution cavities (Fig 3.4 A). These cavities were observed during field investigations, indicating the existence of ground dissolution processes in the area. Calcite veins in the Lockhart Limestone are primarily formed through diagenesis and dissolution processes. In Lockhart Limestone, there are numerous examples of cross-cutting calcite veins observed on the outcrop (Fig 3.4 B). These veins determine the complex and intersecting nature of the calcite vein network within the formation.

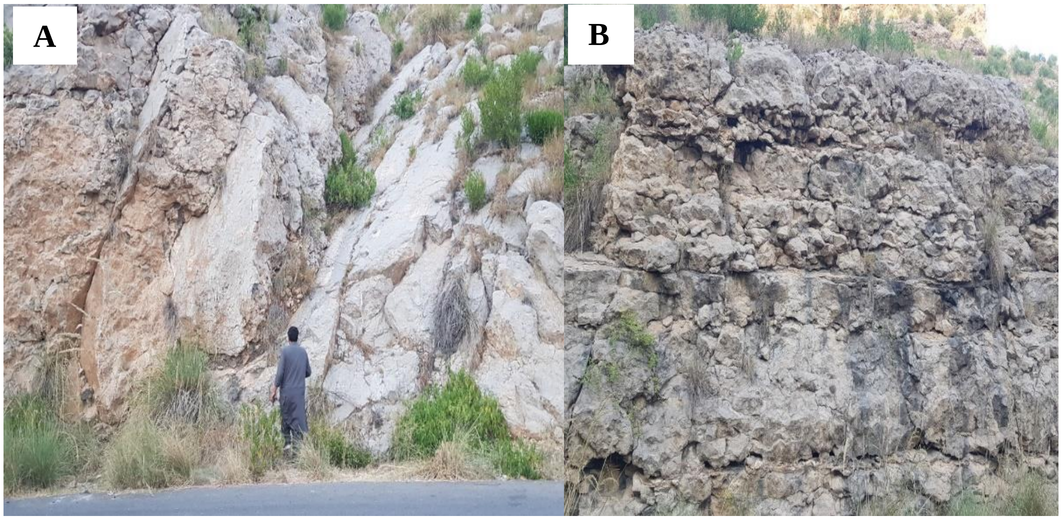

Figure 3.1 Field photographs (A) outcrop picture showing different limestone beds. (B) Outcrop picture showing massive bedding, nodularity of Lockhart Limestone

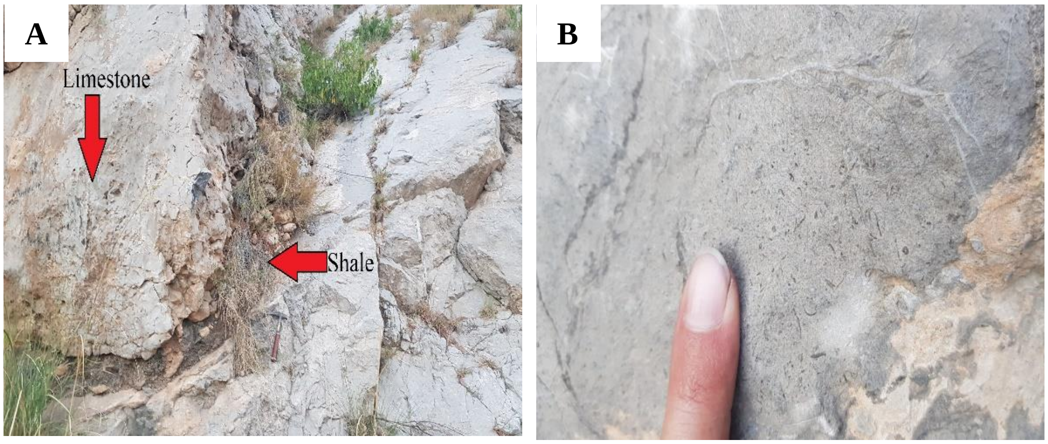

Figure 3.2 Field photographs (A) Outcrop picture showing limestone with inter bedded shale. (B) Representing fossiliferous limestone

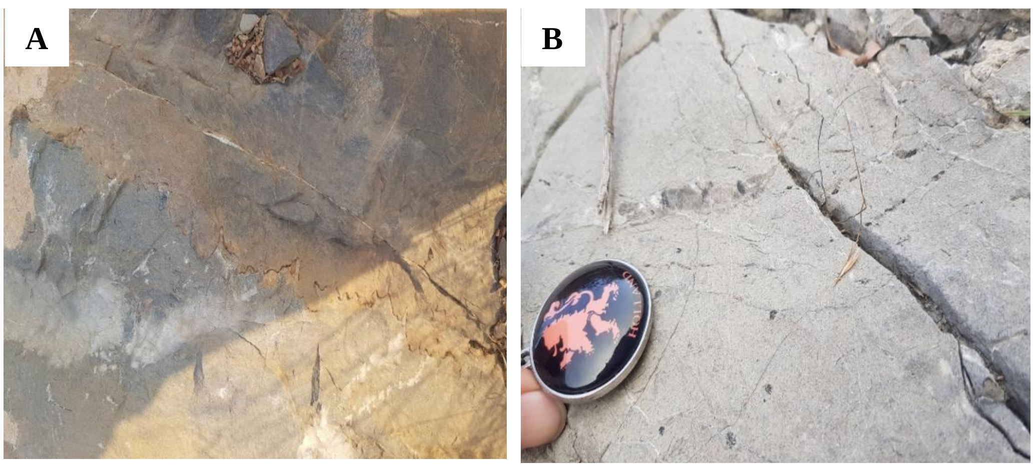

Figure 3.3 Field photographs (A) showing stylolites in the Lockhart Limestone observed in field. (B). Representing the fractures in limestone beds.

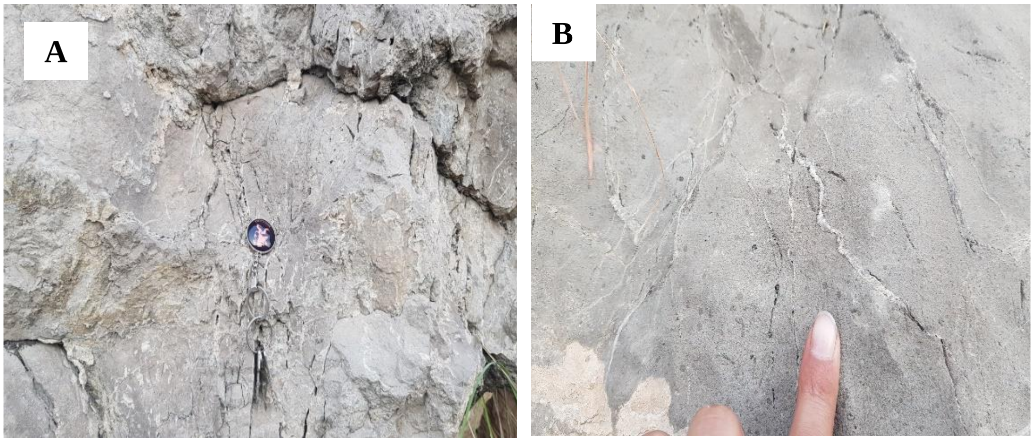

Figure 3.4 Field photographs (A) limestone bed displaying dissolution cavities observed in field. (B) Showing cross cut calcite veins in limestone.

3.2 Laboratory Work

The laboratory work for this study includes several analyses (Fig 3.7) namely Total Organic Carbon (TOC), Rock Eval Pyrolysis, and Vitrinite Reflectance (VR). These analyses are conducted to examine the geochemical data and aid in identifying the source rock potential of Lockhart Limestone. The workflow for the laboratory work can be summarized as follows.

3.2.1 Sample Preparation

Sample preparation comprises washing of samples, crushing, grinding, polishing, pulverization, contamination removal, drying and de-asphalting for various geochemical analysis. Outlined in API RP40.

3.2.2 Total Organic Carbon (TOC) through Direct Method

Total Organic Carbon (TOC) is indeed a key parameter used to quantify the amount of organic carbon present in a rock sample, typically expressed as a percentage (%). In the context of petroleum exploration, TOC serves as an indicator of the organic richness of a rock and plays a crucial role in assessing its potential as a source rock for hydrocarbon generation (Fig 3.5). To be considered a potential source rock for hydrocarbons, a sedimentary rock generally needs to exhibit a minimum TOC value of 0.5%. This threshold indicates that a sufficient quantity of organic matter is existing in the rock to serve as a potential source for hydrocarbon generation. By analyzing the TOC content of rock samples, geoscientists can evaluate the organic richness of a formation and determine its viability as a source rock within a petroleum play.

Figure 3.5 Carbon and Sulfur analyzer CS-580 A (Helios) used for determination of TOC

3.2.3 Rock-Eval Pyrolysis

Rock-Eval pyrolysis is indeed a widely used technique in the field of organic geochemistry and petroleum exploration (Fig 3.6). It delivers valuable information about organic matter existing in sedimentary rocks, including its quantity, type, and thermal maturity level. The Rock-Eval pyrolysis process involves subjecting a small sample (typically around 100 mg) of the rock to controlled heating in a pyrolysis oven at a constant temperature. This process helps to assess several important parameters related to the organic matter within the rock. One of the key outputs of Rock-Eval pyrolysis is the estimation of thermal maturity. By heating the sample, the amount of free hydrocarbons released can be measured. This provides an indication of the thermal maturity of the organic matter and helps determine the stage of hydrocarbon generation. Additionally, Rock-Eval pyrolysis allows for the identification and quantification of hydrogen and oxygen-containing compounds present in the organic matter, known as kerogen. This information helps in characterizing the type and composition of the organic matter, which is crucial for evaluating its potential as a source rock for hydrocarbon generation. Overall, Rock-Eval pyrolysis is a valuable tool in assessing the hydrocarbon generation potential and thermal maturity of organic matter within sedimentary rocks, aiding in the understanding of source rock quality and petroleum system evaluation.

Figure 3.6 Rock Eval 6 used for determination of S1, S2, S3, and T_{max}

3.3 Organic Petrography

To prepare the rock sample for reflectance measurements, it undergoes a series of steps. First, the sample is crushed and then embedded in liquid polystyrene resin, which is set to be hardened. Once hardened, sample is ground using progressively finer carborundum paper to achieve a smooth surface. Subsequently, the sample is polished using successive rounds of finer alumina powders to obtain a highly reflective surface.

The reflectance values are recorded as a percentage of light reflected. In the analysis, the reflectance values are compared to optical standards, allowing for the assessment of the sample's reflectance characteristics. Changes in reflectance values that exceed a threshold of 0.1% (referred to as Vr 0.1%) are considered significant. Reflectance measurements are most reliable when the values exceed 0.5% (Vr 0.5%). For values below this threshold, other parameters and techniques are employed. It's worth noting that in immature rocks, where the organic matter has not undergone significant thermal alteration, the reflectance values tend to exhibit erratic changes with increasing maturity. Therefore, reflectance measurements alone may not provide a clear indication of the sample's maturity in such cases, and other parameters are utilized for assessment.

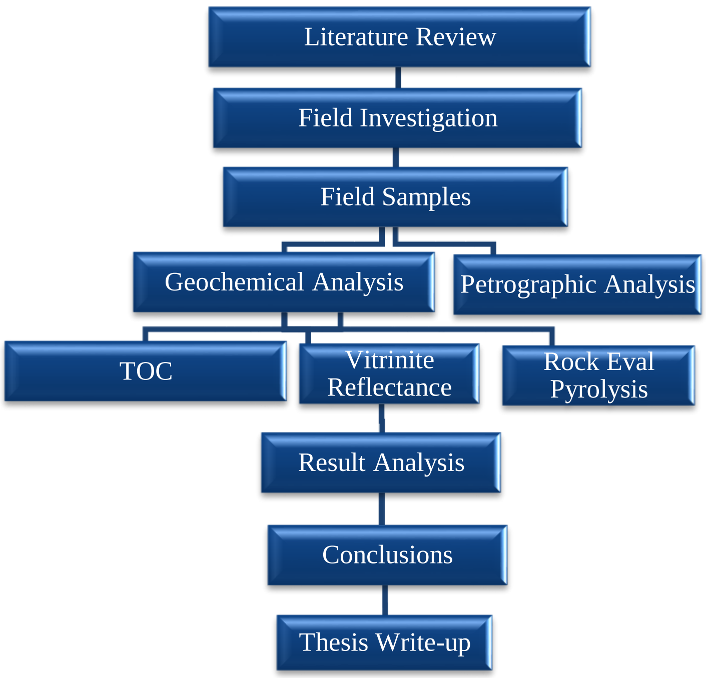

Figure 3.7 Methodology flowchart showing different steps of study.

CHAPTER 4

PETROGRAPHY

4.1 Petrographic Analysis

Petrography is a field of geology that involves the analysis of rocks and minerals using optical microscopes. Through petrographic analysis, valuable information about mineralogy, textures, associations, and microstructures can be obtained. This data plays a crucial role in determining the formation, alteration, and weathering processes that have influenced geological samples. By examining the mineralogy, texture, and associations of rock samples, petrographic analysis helps classify the samples and provides insights into their geologic history. This understanding is beneficial in various industries such as mining, quarrying, and oil and gas exploration, as it enables more effective exploration strategies.

In the case of the Lockhart Limestone, thirteen thin sections were prepared at Bacha Khan University Charsadda. These thin sections were then studied at the sedimentology laboratory of the National Center of Excellence in Geology (NCEG) at Peshawar University. During the microscopic examination of the thin sections, various characteristics of the Lockhart Limestone were observed, including fossils, fractures, dissolution cavities, calcitic veins, and other properties that provide insights into its formation and texture. Some notable features and fossils were highlighted in the thin sections, which possess distinct properties that can aid in identifying the age of formation or the depositional environment. Each thin section is assigned a unique number for reference and analysis purposes.

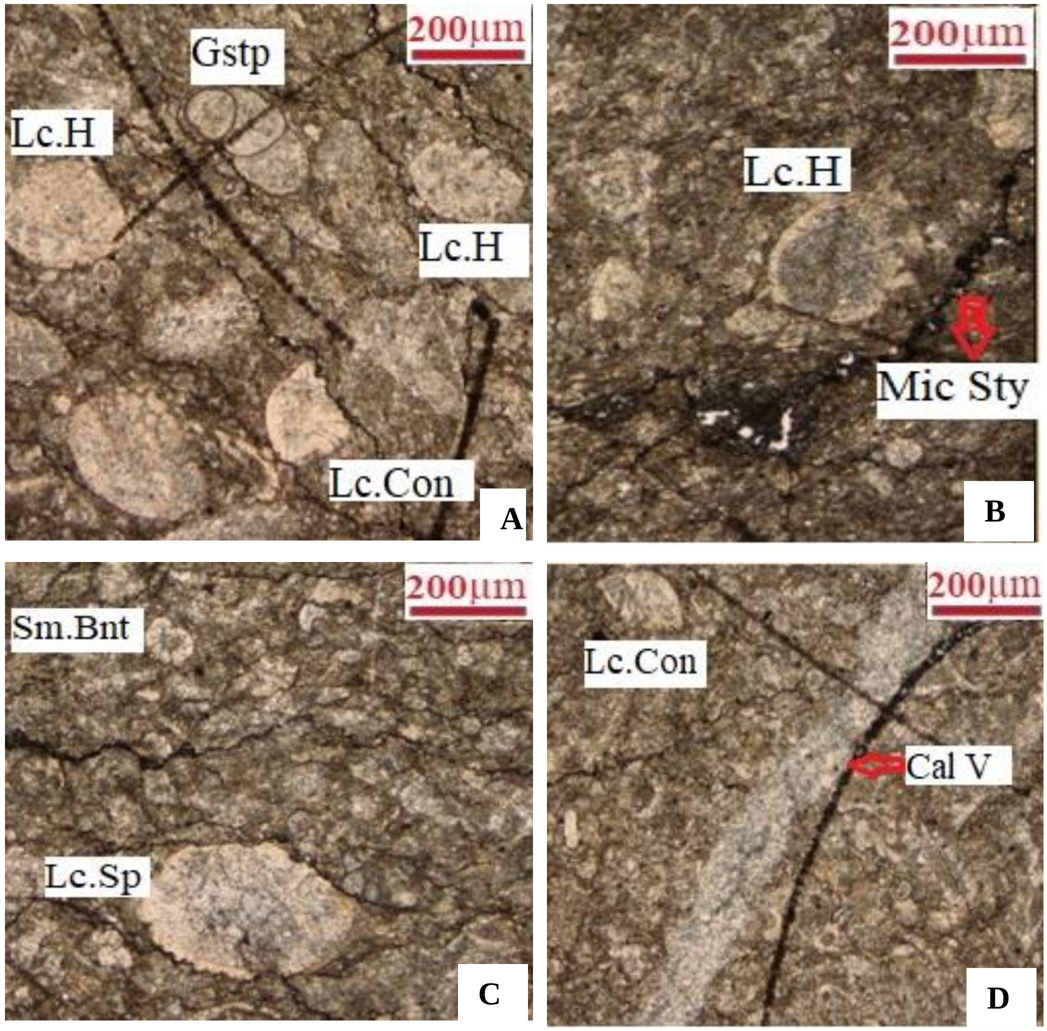

Figure 4.1 Photomicrographs. (A) Lockhartia Hemai (Lc.H), Gastropods (Gstp), Lockhartia Conditi (Lc.Con). (B) Lockhartia Hemai (Lc.H), microstyllolites (Mic Sty). (C) Small benthic (Sm.Bnt), Lockhartia Sp (Lc.Sp). (D) Lockhartia Conditi (Lc.Con), calcitic vein (Cal V).

4.1.1 Bioclastic Wackestone-Packstone

Plate S2 is basically Bioclastic Wackestone-Packstone, it includes 6 photomicrographs, (A) there are two clear species of Lockhartia Hemai (Lc.H), Gastropods (Gstp), Lockhartia Conditi (Lc.Con) with microstyllolites of low amplitudes. (B) In this a clear specie of Lockhartia Hemai (Lc.H), with microstyllolites (Mic Sty) of high amplitudes. (C) In this we have Small benthic (Sm.Bnt) fossils and also a fossil of Lockhartia Sp (Lc.Sp) with microstyllolites of low amplitudes. (D) In this photomicrograph we have a fossil of Lockhartia Conditi (Lc.Con) and also it contain a calcitic vein (Cal V) (fig 4.1).

4.1.2 Bioclastic Packstone

The plate S3 is Bioclastic Packstone which includes (A) Calcitic vein (Cal V) with low amplitude microstyllolites and replacement is also occurred in this plate. (B) In this photomicrograph small benthic foram (Sm.Bnt), some broken fragments of fossils and a calcite vein (Cal V) is passed through it. (C) In this photomicrograph fossil of Cebiside (Ceb), Taxtularia Sp (Tst.Sp), and Lockhartia Sp (Lc.H) can be seen much clearly in addition with them we also have some broken fragments and a calcite vein is passed through. (D) There is small benthic foram (Sm.Bnt) fossil and a diagonal calcitic vein (Cal V) is passing through it (fig 4.2).

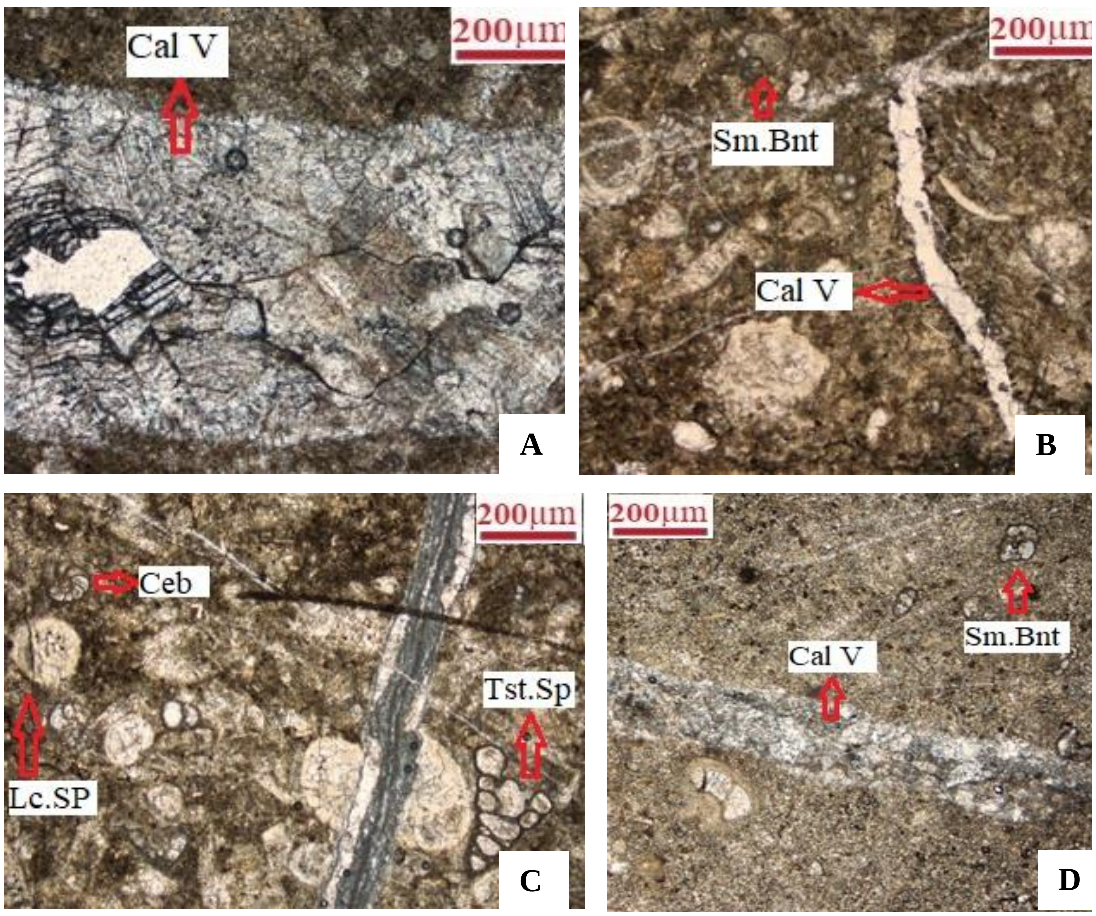

Figure 4.2 Photomicrographs. (A) Calcitic vein (Cal V). (B) Small benthic foram (Sm.Bnt), calcite vein (Cal V). (C) Cebiside (Ceb), Taxtularia Sp (Tst.Sp), and Lockhartia Sp (Lc.H). (D) Small benthic foram (Sm.Bnt), calcitic vein (Cal V).

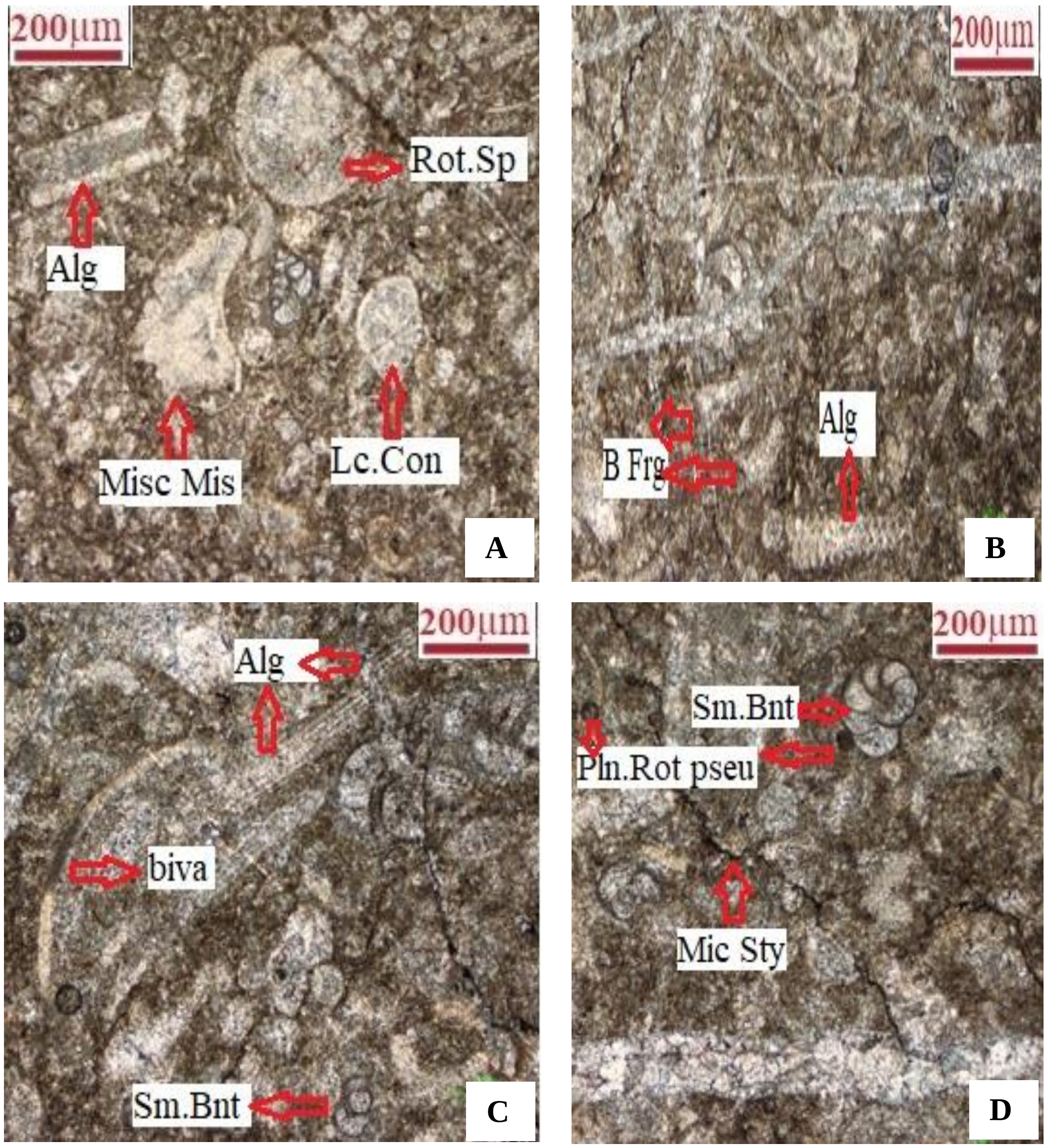

Figure 4.3 Photomicrographs. (A) Algal filaments (Alg), miscellanea Miscella (Misc. Mis), Lockhartia Conditi (Lc.Con), Rotalia Sp (Rot. Sp). (B) Algal filament (Alg), bioclastic fragments (B Frg). (C) Algal filaments (Alg), bivalve (Biva), and small benthic foram (Sm.Bnt). (D) plano-rotalites pseudomorphs (Pln.Rot pseu), small benthic forams (Sm.Bnt), microstyllolites (Mic Sty).

4.1.3 Bioclastic Wackestone

Plate S7 is a Bioclastic Wackestone and it consists of four photomicrographs which can be used to describe its features. (A) This photomicrograph contains various fossils of algal filaments (Alg), miscellanea Miscella (Misc. Mis), Lockhartia Conditi (Lc.Con), Rotalia Sp (Rot. Sp), with other bioclastic broken fragments. (B) In this we have algal filament (Alg), and it contains abundance of bioclastic fragments (B Frg). (C) In the third one we have fossils of algal filaments (Alg), bivalve (Biva), and small benthic foram (Sm.Bnt) also it includes microstyllolites. (D) The fourth photomicrograph we have fossils of plano-rotalites pseudomorphs (Pln.Rot pseu) which is an index fossil of late Paleocene age, small benthic forams (Sm.Bnt) and microstyllolites (Mic Sty) of low amplitudes and a calcite vein is crossing through it (fig 4.3).

CHAPTER 5

HYDROCARBON GEOCHEMISTRY

5.1 Geochemical Analysis

The geochemical analysis of Lockhart Limestone was carried out in G & R Labs of Oil and Gas Development Company Limited (OGDCL) Islamabad, Pakistan. The geochemical analysis of Lockhart Limestone includes determining of TOC (Total organic carbon) and Rock eval, the total number of samples for the TOC were 13 and based on the TOC results five samples were selected for the Rock eval. The above-mentioned analysis was carried out by grinding of the samples to powdered form.

5.2 Total Organic Carbon (TOC)

Total organic carbon results revealed butimen and kerogen content existing in source rock and indicate total amount of organic matter (Peters and Cassa, 1994). According to Peters (1986) carbon should be bonded with hydrogen for generation of petroleum in source rock (Fig 5.1). The value of the TOC indicates the quality of the source rock Table 5.1 shows the chart of different types of source rock according to TOC value. The results of carbon analysis indicates changes in organic richness of Lockhart Limestone as shown in table 5.2. The results of the samples shows TOC values ranging from 0.43-0.20 %. The results of TOC are put in diagram accordingly which shows the quality of TOC.

Table 5.1 Geochemical Parameters describing Kerogen type and character of expelled products (Peter and Cassa, 1994).

Kerogen Type	**HI** (mg HC/g TOC)	**Main expelled product at peak Maturity**
I	>600	Oil
II	300-600	Oil
II/III	200-300	Mixed Oil and Gas
III	50-200	Gas
IV	<50	None

Table 5.2 Parameters used in determination of quality of source rock (Peters, 1994).

Quality	**TOC (wt. %) Shale**	**TOC (wt. %) Carbonates**
Poor	0-0.5	0.0-0.2
Fair	0.5-1.0	0.2-0.5
Good	1.0-2.0	0.5-1.0
Very good	2.0-5.0	1.0-2.0
Excellent	>5.0	>2.0

Table 5.3 TOC results of samples from Lockhart Limestone.

S. No	**Sample #**	**Lithology**	**% TOC**
1	S # 1	Bioclastic Wackestone	0.32
2	S # 2	Bioclastic Wackestone-Packstone	0.30
3	S # 3	Bioclastic Packstone	0.28
4	S # 4	Bioclastic Packstone	0.30
5	S # 5	Bioclastic Wackestone-Packstone	0.23
6	S # 6	Bioclastic Packstone	0.43
7	S # 7	Bioclastic Wackestone	0.26
8	S # 8	Bioclastic Wackestone	0.32
9	S # 9	Bioclastic Wackestone	0.22
10	S # 10	Bioclastic Wackestone	0.26
11	S # 11	Bioclastic Wackestone-Packstone	0.28
12	S # 12	Bioclastic Wackestone	0.24
13	S # 13	Bioclastic Wackestone	0.20

5.3 Rock Eval Pyrolysis

In the previous chapter, we discussed the Rock Eval technique, which provides valuable insights into the chemical characteristics of a source rock. This technique involves analyzing the generated hydrocarbons trapped within the kerogen structure and assessing the thermal maturity of the source rock. The Rock Eval technique utilizes several parameters to evaluate the source rock. These parameters include:

i. S1 peak: This peak indicates the amount of free hydrocarbons present in the sample.
ii. S2 peak: The S2 peak represents the remaining hydrocarbons that are still confined within the sedimentary unit. These hydrocarbons are generated because of heating through pyrolysis. Additionally, the S2 peak provides information about the oxygen content within the kerogen.
iii. S3: This parameter indicates the amount of carbon dioxide (CO_2) released during pyrolysis.
iv. Tmax: Tmax refers to the pyrolysis temperature at which the S2 peak is obtained. It provides an important measure of the thermal maturity or level of organic matter conversion within the source rock (Welte and Tissot, 1984).

By analyzing these parameters, the Rock Eval technique offers insights into the hydrocarbon potential, thermal maturity, and composition of the source rock. Five samples are selected from the 13 samples on the basis of their TOC result. The results from the Rock Eval Pyrolysis is shown in Table 5.3 having values of different parameters.

Table 5.4 Rock Eval parameters of outcrop samples of Lockhart Limestone.

S.No	**Sample #**	**% TOC**	**S1**	**S2**	**S3**	**Tmax (°c)**	**PI**	**OI**	**HI**	**GP (S1+S2)**
1	S # 1	0.32	0.02	0.06	0	474	0.24	0	18.75	0.08
2	S # 2	0.30	0.02	0.04	0	324	0.3	0	13.3	0.06
3	S # 4	0.30	0.02	0.03	0	483	0.33	0	10	0.05
4	S # 6	0.43	0.04	0.12	0.06	446	0.23	14	28	0.16
5	S # 8	0.32	0.01	0.03	0	483	0.28	0	9	0.04

5.3.1 Genetic Potential (GP)

Genetic potential of formation, represented by sum of S1, S2 values, indicates the amount of petroleum (oil and gas) that can be generated by the kerogen within the formation under suitable temperature conditions and over a sufficient period of time (Fig 5.2). This potential is influenced by external factors such as climate, topography, and biological associations. To quantitatively evaluate the genetic potential, a standard pyrolysis technique is employed. This technique involves subjecting the rock samples to controlled heating in order to analyze the amounts of hydrocarbons released during the pyrolysis process. By measuring the S1 and S2 values obtained from the pyrolysis, geologists can estimate the potential quantity of petroleum that the kerogen within the formation is capable of generating. The genetic potential assessment provides valuable information for understanding the hydrocarbon potential of a formation and plays a crucial role in petroleum exploration and resource evaluation. The detail of genetic potential is given in table 5.6 (Peters, 1986).

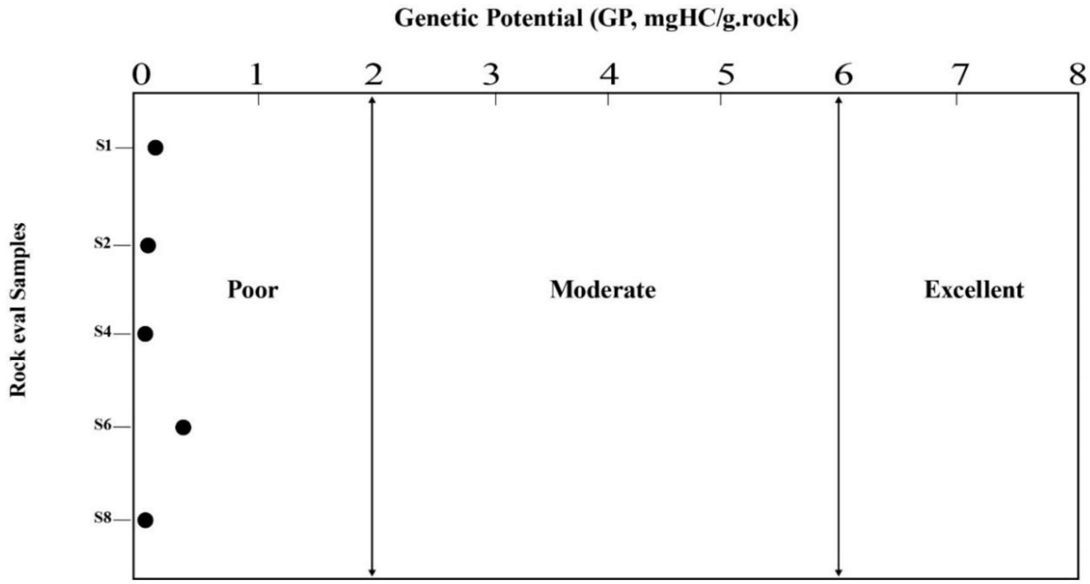

Figure 5.1 Genetic potential of the analyzed samples from Lockhart Limestone from the studied area (Welte & Tissot, 1984).

Table 5.5 Immature organic matter types and production Index (Welte and Tissot, 1984).

Organic Matter Type	**Production Index**
Type I	<0.10
Type II	0.10-0.15
Type III	0.25-40

5.3.2 Hydrogen Index (HI)

Hydrogen index (HI), calculated as S2÷TOC X 100, is a parameter utilized to describe the origin of organic matter and provide an estimation of its maturation level. In geological samples, a typical HI value is greater than 600. When the HI value falls under 150 mg/g, it suggests that the rock has the potential to generate gas, indicating the presence of type III kerogen. A HI value ranging from 150 to 300 indicates a mixture of type III and type II kerogens, with the capability to generate both oil and gas. If the HI exceeds 300 mg/g, it signifies a favorable potential for oil and gas generation. A HI value exceeding 600 mg/g indicates the presence of type I kerogen, making it a pure source for oil. These HI values serve as indicators of the organic matter's composition and its ability to generate different hydrocarbon products (gas, oil, or a combination) based on their respective kerogen types (Peters, 1986).

5.3.3 Maximum temperature (Tmax)

T_{max} parameter is derived from Rock Eval pyrolysis that signifies peak temperature at which the S2 peak reaches its maximum value. It serves as a maturity index for organic matter present in rock samples, providing insights into the quality of the organic material. By indicating the thermal history and degree of transformation, Tmax offers valuable information about the maturity level and hydrocarbon generation potential of the organic matter. Analyzing Tmax values enables geologists and petroleum experts to assess the thermal maturity of the organic material, aiding in the evaluation of its potential as a hydrocarbon source and contributing to a comprehensive understanding of the geological history of the studied area. In table 5.5 maturity stages of rock samples associated to Vitrinite reflectance and Tmax are shown (Ghori, 1998).

Table 5.6 Maturity stages related to Vitrinite reflectance and Tmax. (Ibrahimbas and Reidiger, 2004).

Stages of Maturity	**Vitrinite Reflectance Ro (%)**	**Tmax (°C)**
Immature	0.2-0.6	<435
Mature	0.9-1.35	435-470
Early	0.6-0.65	435-445
Peak	0.65-0.9	445-450
Late	0.9-1.35	450-470
Post mature	>1.35	>470

5.3.4 Oxygen Index (OI)

The oxygen index, calculated as S3/TOC multiplied by 100, is a parameter employed to evaluate the oxygen content and richness in source rocks. It provides insights into the quality and thermal maturity of the source rock. The oxygen index is often used in conjunction with the hydrogen index to assess the characteristics and maturation level of the organic material present in the rock. By analyzing both the oxygen index and hydrogen index, geologists can gain a more comprehensive understanding of the source rock's composition, thermal maturity, and hydrocarbon generation potential (Ghori, 1998).

5.3.5 Production Index (PI)

Production Index (PI), which is calculated as S1÷ (S1+S2), represents pyrolysis yield and reflects amount of free hydrocarbons to total amount of hydrocarbon compounds (Frobes, 1988: in Othman, 2003). PI is influenced by the types of organic matter present in source rock along with its burial history, including temperature and time (Welte & Tissot, 1984). PI provides insights into thermal maturity level of organic compounds within source rock and can also indicate existence of migrated hydrocarbons. Immature Type I and Type II organic matter typically yield PI values of less than 0.1, which gradually increase to 0.4 during catagenesis. By assessing the PI, one can gain information about the thermal maturity level of the organic matter, as well as evaluate the potential presence of migrated hydrocarbons.

Table 5.7 Evaluation of source rock on the basis of genetic potential. (After Welte & Tissot, 1984).

Genetic Potential (mg HC/g.Rock)	**Source Rock Evaluation**
>6	Good
2-6	Moderate
<2	Poor

Based on the above results of the Rock eval pyrolysis samples three cross plots are made and those values are inserted which can be seen in the diagrams.

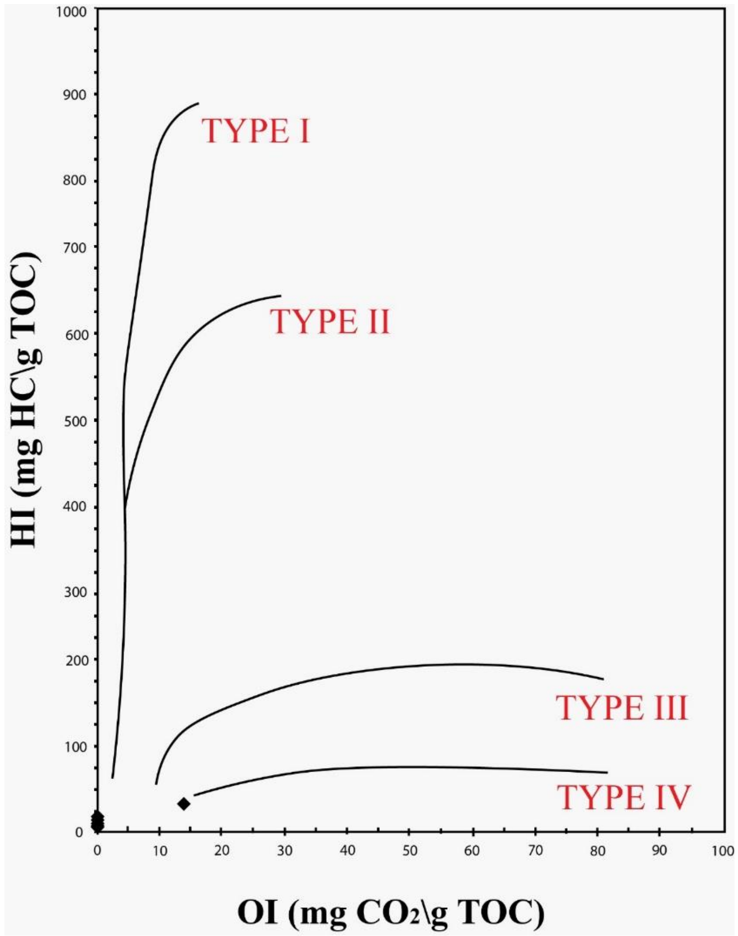

Figure 5.2 Cross plot of Hydrogen Index (HI) vs Oxygen Index (OI) of the studied formation (Barham et al., 2022).

The results shown in above figure 5.2 clearly indicates that all of the five samples are in the limits of kerogen type IV which are also known as inert as they are unable to generate or expel hydrocarbons as all samples have Hi values less than 50 (Peter and Cassa, 1994) (Fig 5.2).

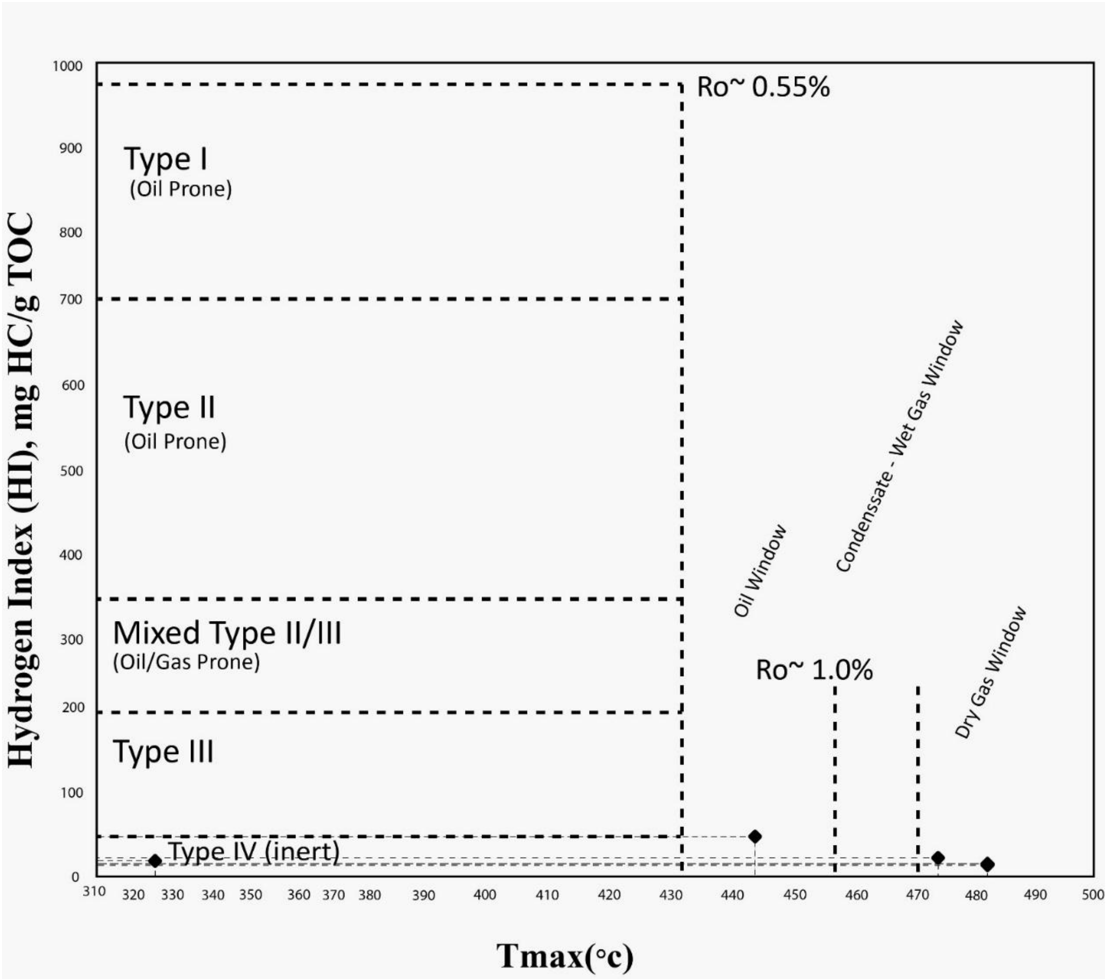

Figure 5.3 Cross plot of Hydrogen Index (HI) vs Tmax of the studied formation (Frobes et al., 1988).

The S#1 sample Tmax value is 474°C, it is Type IV kerogen. The S#2 sample indicated in cross plot lies in the range of Type IV kerogen which is also called Inert as its hydrogen index value 13.36 while its Tmax value is only 324°C. Similarly the value of S#4 its hydrogen index is 10 and its Tmax is 483 °C it also lies within the range of Type IV kerogen. The S#6 has hydrogen index of 28 and Tmax of 446 °C and its kerogen type is Type IV. The S#8 sample has hydrogen index of 9 and Tmax value of 483 °C, it is a Type IV kerogen (Fig 5.4).

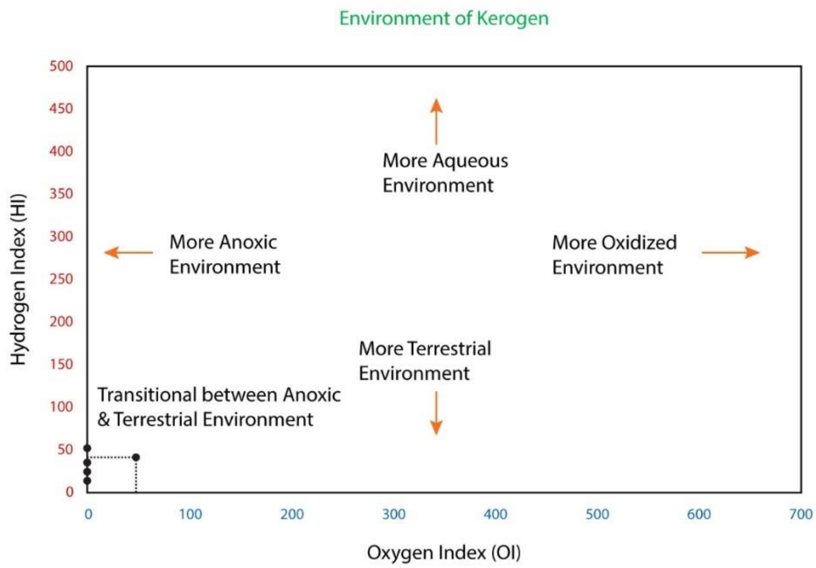

Figure 5.4 Depositional environment of kerogen in Lockhart Limestone in the studied area (Frobes et al., 1988).

In the above figure (Fig 5.5) the samples are in the Transitional between Anoxic & Terrestrial environment.

CONCLUSIONS

Upon the end of the research the following conclusion is taken

- Lockhart Limestone contains bioclastic Wackestone, bioclastic Packstone, and bioclastic Wackestone-Packstone.
- TOC results of the samples were not that good as expected for a good source rock
- Rock eval pyrolysis result of the five samples were also not up to the point which makes Lockhart Limestone a poor source rock.
- In petrography different fossils were found including Lockhartia Sp, Lockhartia Conditi, Lockhartia Hemai, Ostracod, Taxtularia, Small and large benthic forams, Gastropods, Bryozoans, plano-rotalite pseudomorphs, Algal filaments.
- Also contains diagenetic features like fractures, calcite veins, dissolution cavities, stylolites.
- Total of 13 samples were collected, TOC and Rock eval pyrolysis were run over these samples.
- TOC results of the samples were not that good as expected for a good source rock.
- From the Genetic potential cross plot the values lies within the poor section.

- The type of kerogen is Type IV.
- Mostly it lies within the Inert (having no potential) zone.
- The environment of the Lockhart Limestone is transitional between Anoxic & Terrestrial environment.

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