



EVALUATING THE RESERVOIR POTENTIAL OF HABIB RAHI LIMESTONE FORMATION, LOWER INDUS BASIN, PAKISTAN: A COMPREHENSIVE DIAGENETIC, GEOCHEMICAL AND PETROPHYSICAL ANALYSIS

Faisal Hussain Memon^{1*}, Ghulam Abbas¹, Muhammad Furqan Qureshi², Shoaib Ahmed Memon¹, Khalil Rehman Memon² & Abdul Haque Tunio²

¹Petroleum and Natural Gas Engineering Department, Mehran UET, SZAB Campus Khairpur Mirs, Pakistan

²Institute of Petroleum & Natural Gas Engineering, Mehran UET Jamshoro, Pakistan

Article Info

*Corresponding Author

Email: faisalhussain@muetkhp.edu.pk

Abstract

The Lower Indus Basin, a significant hydrocarbon resource area in Pakistan, hosts numerous carbonate gas reservoirs. These reservoirs encounter challenges like depletion and unsustainable production rates due to complex geology and varying petro-physical characteristics, often leading to premature well abandonment. This study focused on the Habib Rahi Limestone (HRL) formation evaluation for reservoir quality assessment through geochemical, pore morphological, structural, diagenetic, and petrophysical properties. The geochemical analysis, including X-ray fluorescence (XRF), Scanning Electron Microscopy (SEM-EDS), revealed substantial CaO, SiO₂, Al₂O₃, and Fe₂O₃ concentrations, indicating an intermix of carbonate and siliciclastic materials, which adversely affect the reservoir potential. SEM and Fourier Transform Infrared Spectroscopy (FTIR) analyses demonstrated a complex pore structure with heterogeneous grain sizes, and varied pore types, complicating the fluid flow. Diagenetic alterations, as identified through thin section petrography, revealed that micritization and recrystallization reduced the pore size and connectivity, while dolomitization and fracturing enhanced secondary porosity but introduced significant heterogeneity. Petrophysical measurements, including reservoir quality index (RQI), specified a non-uniform pore-network, with average grain density 2.684 gm/cc, porosity of 11.84% and permeability of 3.16 mD, indicating poor to moderate reservoir quality. These findings underscore the critical impact of mineral authigenesis, complex pore morphology, and diagenetic processes on formation heterogeneity, reducing reservoir quality. This integrated approach unveils valuable insights into HRL's intricate nature, aiding a solid foundation for effective reservoir management and exploitation strategies.

Keywords

Habib Rahi Limestone, Geochemical, Morphology, Petro physical Characteristics, Reservoir Quality



1. Introduction

Reservoir characterization of carbonate rocks is crucial for accurate hydrocarbons production forecasts and effective reservoir management. Petro-physical properties are essential for evaluating reservoir potential and significantly influence the reservoir development strategies (Sun, Belhaj, Tao, Vega, & Liu, 2019). However, assessment of the inherent rock properties, as well as the heterogeneity and pore structure of reservoir rock, is challenging due to diagenetic effects and depositional environment that cause microstructural variations and diverse pore geometries. Significant sedimentation and diagenesis create various micro-pore grains and mineralogical changes, resulting in difference in pore size, complex pore interconnectivity, and pore dispersion, which alter the rock's petrophysical properties. The variability in mineralogical composition and micro-structure causes uncertainties that directly influence the reservoir potential. Thus, considering the interplay between depositional and diagenetic alterations are critical for refining reservoir quality predictions (Mahesar, Abbasi, Shar, & Shaikh, 2022; Shar, Mahesar, Abbasi, Narejo, & Hakro, 2021; Sun *et al.*, 2019). This study investigates the potential of HRL formation in the Lower Indus Basin, Pakistan, a substantial carbonate producing reservoir within the region. The formation represents an intricate carbonate unit with lithological heterogeneity and complicated pore networks due to its depositional history and subsequent tectonic effects, resulting in diverse reservoir quality across various sections (Khitab, Umar, Jamil, & Evaporites, 2020; Memon *et al.*, 2024). The study examines a specific section of the HRL formation, emphasizing on confined diagenetic and depositional features that influence the reservoir

potential. It integrates petrographic, geochemical, and petrophysical analyses, that provides valuable insights in to the studied section and similar formations, contributing to localized reservoir understanding and regional carbonate reservoir models. The variations in pore structure and grain morphology are crucial for fluid flow and reservoir performance, leading to complex network of micro to macropores, highlighting heterogeneity and connectivity within the rock matrix. Similarly, geochemical alterations such as mineral authigenesis and transformation of carbonate minerals into major oxides, significantly affect the reservoir quality by altering the petrophysical properties (Memon *et al.*, 2024; Nabawy, Abudeif, Masoud, & Radwan, 2022). Correspondingly, Standard core analysis techniques are inadequate in evaluating the complexities of petrophysical characteristics of carbonate rocks used in routine analysis, required unique core investigation procedures for more accurate characterization. Additionally, variations in pore-microstructure and permeability, which explain the morphological characteristics and fluid distribution of these heterogeneous reservoirs, cannot be precisely examined using conventional core analysis methods (Memon *et al.*, 2024; Rashid, Hussein, Glover, Lorinczi, & Lawrence, 2022). Therefore, specialized core analysis techniques are required to assess petrophysical parameters and perform an in-depth characterization, leading to more specific and extensive interpretations of the petrophysical properties. This study employs a range of integrated methodologies to evaluate the characteristics of carbonate rocks. The key approaches to characterize the HRL formation contained X-ray fluorescence (XRF) for mineralogical and elemental analysis, Scanning Electron Microscopy coupled

Energy Dispersive Spectroscopy (SEM-EDS) for micro-pore analysis. Fourier Transformed Infrared Spectroscopy (FTIR) utilized to examine pore structure and functional mineral groups assessment (Palabiran, Sesilia, & Akbar, 2016). Diagenetic features visualize through thin-section petrography, providing insights into grain-pore relationships. This methodology addresses the limitations of traditional core analysis, enhancing reservoir characterization accuracy and fluid flow prediction by offering comprehensive assessment of petrophysical properties, diagenetic processes, and reservoir heterogeneity (F. H. Memon, Tunio, Memon, Mahesar, & Abbas, 2023; Palabiran *et al.*, 2016). Diagenetic alterations and post-depositional changes impact the petrophysical, petrographic, morphological and geochemical parameters of carbonate rocks, complicating their analysis, measurement and interpretation (F. H. Memon, Tunio, Memon, *et al.*, 2023; Onuh, David, Onuh, & Technology, 2017; Palabiran *et al.*, 2016). More specifically, petrophysical features are crucial for determining fluid flow properties and significantly influence the carbonate reservoir quality and productivity (Skalinski & Kenter, 2015). Thus, it is essential to understand all contributing factors, including the base line properties and reservoir quality index, which have a substantial impact on reservoir performance. Carbonates hold significant hydrocarbon reserves globally, with the Middle East being a significant contributor (F. H. Memon, Tunio, Memon, *et al.*, 2023). Pakistan's Lower Indus Basin, with its extensive carbonate formations, including the Habib Rahi Limestone, presents significant potential for hydrocarbon production. The Habib Rahi formation's complex lithology and pore networks pose challenges in

interpretation and reservoir management. Primarily, the formation is composed of calcite, clays, and dolomites, influencing its heterogeneity. Its diverse pore structure and high energy environments, allowing calcareous and bioclastic debris accumulation in its depositional settings. Its petrophysical characteristics and reservoir quality are mainly influenced by depositional conditions and diagenetic alterations, necessitating detailed analysis for optimal exploration and development (Ghazi, Miraj, Ali, & Waqas, 2023; Khitab *et al.*, 2020). Petrography is a crucial method for identifying diagenetic interactions between rock units, particularly in carbonate rocks. Understanding these interactions provide solid foundation for mineralogical, morphological, and petrophysical changes which affect the reservoir rock quality (Memon *et al.*, 2024; Nabawy *et al.*, 2022). HRL formation have been studied for its reservoir potential. Several well log and outcrop studies have been conducted to assess its sedimentological, paleontological, depositional, and geochemical aspects in recent studies (Ghazi *et al.*, 2023; Khitab *et al.*, 2020). Although, the heterogeneity of the stratigraphic units within reservoir have not been adequately recognized, subsequently reservoir complexity remained poorly understood due diagenetic alterations and pore-structure modifications. The formation exposed substantial variations in lithology and intricate pore-geometry due to diagenesis, required a novel approach to understand the diagenetic effects on reservoir properties to develop strategy for enhancing hydrocarbons recovery efficiency (F. H. Memon, Tunio, Memon, *et al.*, 2023). The primary objective of the study is to evaluate the reservoir potential of the Habib Rahi Limestone formation in the Lower Indus Basin, using an

integrated approach for petrographic and geochemical and petrophysical analyses. The research aims to highlight the challenges posed by formation heterogeneity, diagenetic alterations, and depositional environment, significantly affecting the reservoir quality. This comprehensive dataset provides insights into reservoir complexities and factors influencing quality and performance. Subsequently, addressing the uncertainties about reservoir properties and fluid distribution. The findings provide solid foundation for reducing field development risks, and enhance resource development strategies for Pakistani carbonates.

2. Geological Settings of the Study Area

The Indus Basin is divided into three regions: Upper, Central, and Lower Indus basins. The Lower Indus Basin is further divided into central and Southern basins by the Sukkur Rift Zone, which includes the Jacobabad-Khairpur and Mari-Kandhkot highs. This study focuses on the eastern portion of the Jacobabad-Khairpur High, oriented in an NNW-SSE direction. The geological settings of the region are well presented in our previous study (F. H. Memon, Tunio, Mahesar, & Abbas, 2023). The study area is comprising of normal faults associated with some Horsts and Graben structures including Pano Akil graben, Mari-Kandhkot high and Khairpur – Jacobabad high, illustrated in Figure 1(a). Although, the study area is indicating the oldest Triassic age rocks as Wulgai and Dunghan Limestone, directly existing above the Middle Jurassic Chiltan Formation.

Further, it showing the well-known unconformity of K-T boundary formed during Cretaceous time throughout the Indus Basin (F. H. Memon, Tunio, Memon, *et al.*, 2023). This region is primarily exposed with Eocene outcrops, such as Pirkoh and Habib Rahi limestone formations, as illustrated in generalized stratigraphic column in Figure 1(b). Stratigraphically, it mostly contains shallow marine rocks of Eocene limestone and shale formation with sandstones as subsidiary interbeds in the lower part. The Habib Rahi Limestone, located in the Pano Akil graben, and is a significant hydrocarbons potential reservoir within the Mari-Kandhkot high, representing its complex carbonate lithology and intricate pore networks. Geologically, the framework of the HRL formation is primarily influenced by diverse depositional environment and subsequent diagenesis that results in reservoir heterogeneity. It composed of calcareous limestone, shales and dolomite layers, including calcites, clays, secondary dolomites and iron oxides, affecting its heterogeneity and reservoir potential. The post depositional diagenetic processes affected the micro-pore structure which includes inter-granular pore, moldic pores, and fractures (Ghazi *et al.*, 2023; Jadoon, Zahid, & Gardezi, 2013). Its varying lithologies and diagenetic effects require a comprehensive analysis to understand its reservoir quality. This study provides in depth characterization of the HRL, addressing its reservoir complexities and potential for indigenous resource development in the region.

workflow chart for integrated reservoir characterization is illustrated in Fig. The number of core samples utilized for this integrated study is well represented in Table 1, and the details of each

characterization method with specific procedures are provided in our recent publications (Memon *et al*, 2024).

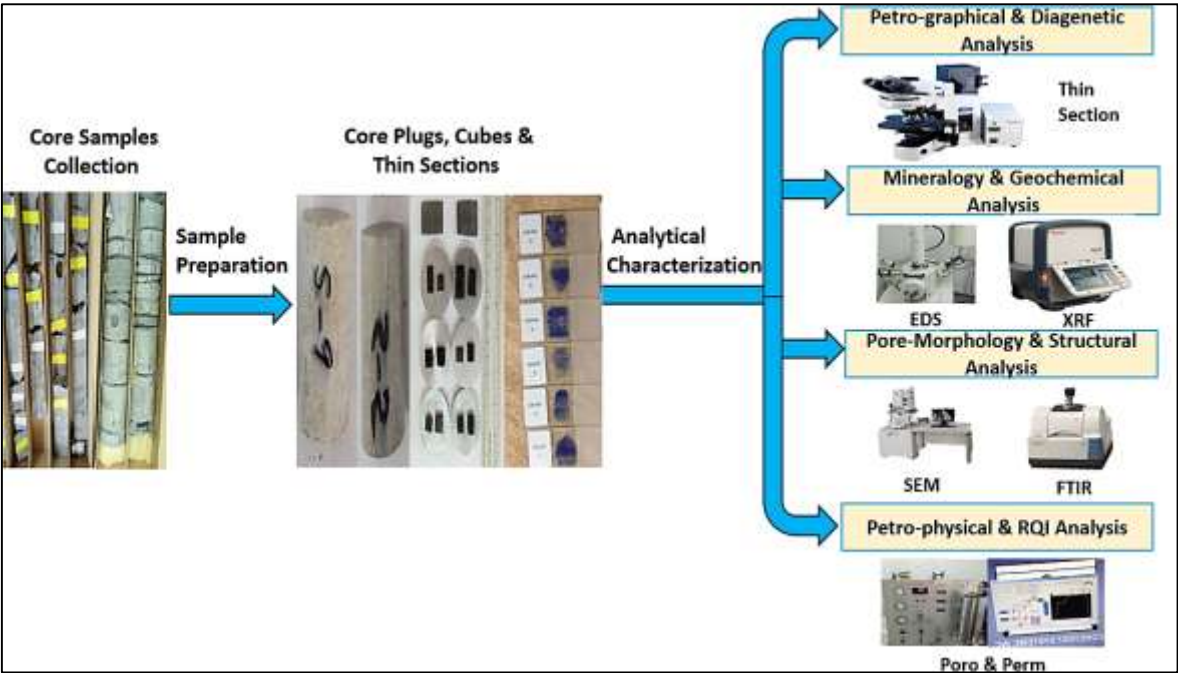


Figure 1: Comprehensive Illustration of experimental workflow chart.

Table 1: Details of core samples utilized for the different experimental methods in the study.

Sr. No.	Employed Experimental Method	No. of Samples Utilized
1	Thin Section Petrography	10
2	SEM & EDS	8
3	FTIR	6
4	XRF	6
5	Helium Porosity	7
6	Gas Permeability	7

3.1 Pore-morphological and Mineralogical assessment via SEM and EDS

The study utilized a JEOL- JSM-6590LV, Japan Compact field emission SEM technology for investigating the microstructure and diagenetic characteristics of samples. The system was integrated with QUANTAX system, an imaging interface

software for detailed visualization and analysis. This microanalyzer provided Energy Dispersive X-ray Spectroscopy (EDS) capabilities, allowing precise determination of elemental composition and understanding of mineralogical properties (F. H. Memon, Tunio, Memon, *et al.*, 2023).

3.2 Petrography as Thin Sections Measurement

The analysis involved an Olympus BX-51, Pittsford USA polarized light microscope to examine the stained thin sections, polished with carbon coatings. The microscope contains magnification range of 10x to 1000x pixels resolution with polarizing filters, and rotatable stage. A digital sight Nikon DS-U3 camera was attached for image analysis, capturing microphotographs of the microfacies thin sections through zooming. The use of polarized light microscopy to capture the rock's microstructure and understand the diagenetic processes influencing its current state, providing valuable insights into their petro-physical properties and overall reservoir quality.

3.3 Petro-physical Measurement

The petrophysical measurements of bulk density, porosity, and permeability were conducted to characterize the reservoir quality and understand its potential complexity. A PHI-220 Helium Porosimeter was used to determine the porosity of the core plugs, while gas permeability was measured using Temco GP-12-2631 gas permeameter at ambient conditions. The prepared core plugs were cleaned and dried to ensure the optimal conditions for precise and reliable measurements (F. H. Memon, Tunio, Memon, *et al.*, 2023).

3.4 Structural analysis via FTIR

The FTIR spectroscopy is a crucial technique for analyzing molecular composition, functional groups, and identification of various mineral constituents and their structural characteristics. An Attenuated Total Reflection (ATR) mode ALPHA Bruker, Germany was used to get the IR spectra. The sample powders

were placed on a diamond crystal and squeezed, where low wavenumbers enable deeper penetration of infrared light. This technique is used to analyze the absorption or emission of a sample by obtaining an infrared spectrum. The average of 24 scans with a spectral resolution of 2 cm^{-1} was used to create the spectra, and measured between 4000 cm^{-1} and 500 cm^{-1} . It provides detailed information about molecular composition, identifying the chemical bonds of organic compounds, and is particularly useful for analyzing molecular structure and composition.

3.5 X-ray Florescence Spectroscopy (XRF)

The Habib Rahi carbonate samples underwent whole-rock X-ray fluorescence (XRF) analysis using a Thermo Scientific Niton FXL, FM-XRF analyzer spectrometer. The samples were ground into a fine powder, placed in plastic XRF sample cups, and calibrated. High-energy X-rays were used to emit secondary X-rays, determining the characteristic energy and intensity of each element. The analysis provided quantitative data on major oxides and trace elements, crucial for understanding mineralogical composition and assessing reservoir quality impact.

3.6 Reservoir Quality Index

Reservoir quality index or hydraulic flow unit is the measure of storage capacity and fluid conductivity of the rock based on its porosity and permeability values. The storage capacity determines from effective porosity and reservoir extent whereas fluid deliverability is influenced by reservoir permeability. The RQI can be calculated from the equation (Onuh *et al.*, 2017).

$$RQI = 0.0314 \sqrt{\left(\frac{K}{\phi}\right)} \quad 1.1$$

Where, RQI denotes the reservoir quality index measured in micrometer (μm), K is the permeability of the core samples expressed in millidarcy (mD), and ϕ represents the porosity in fractions.

4. Results and Discussion

4.1 Petrographic and Diagenetic Analysis

The study examines the Eocene carbonate samples from the Habib Rahi Limestone formation in the Sukkur Rift Zone, focusing on the Mari-Kandhkot High region. The petrographic analysis was conducted to understand diagenesis, depositional environment, and the impact of primary mineralogical structure on reservoir porosity and quality. The examined samples specifically representing its emphasis on localized section rather than entire deposits of the HRL, providing comprehensive understanding of complexities while ensuring the relevance of findings to analogous carbonates. The samples were primarily composed of carbonate minerals like calcite, dolomite, clay and cementing materials including smectite, illite, huntite, and ferric oxides, resulting from recrystallization and diagenetic processes, contributing to reservoir heterogeneity. Petrographic and microfacies analysis reveals that formation was deposited in marine environment, with fossil accumulations and surface features observed under microscopy. While the occurrences of dolomite crystals, likely due to increased manganese levels in seawater, supports the marine setting. Dunham's classification was used to categorize carbonate

microfacies in Habib Rahi Limestone, revealing diverse composition and texture, with various petrographic characteristics and diagenetic features (Khalid, Ehsan, Khurram, Ullah, & Ahmad, 2022). The microfacies analysis revealed that several allochems with proportion generally less than 85%, ranging from bioclastic packstone to grainstone, as identified in Fig. 2. These allochems include Assilina, Miliolid, Alvulina, Nummulite, brachiopod fragments, and broken bioclasts, as well as non-skeletal allochems like peloids and intraclasts. The fragmented assilinal grainstone microfacies is characterized by over 75% biogenic grains, including benthic forums and broken bioclasts. The bioclastic pack-grainstone exhibited LBFs, nummulite, alvulina and milliods structure embedded with micrite mud. The planktonic forums wackestone/packstone shows over 60% skeletal allochems, primarily planktonic forums. The nummulitic wacke-packstone features dark gray limestone with 55% of nummulites, LBFs skeletal grains and fine to medium-sized particles embedded with calcite, micrite cement, and various bioclasts. The bioclastic packstone is light gray with fine to medium-sized particles and micro-nano fossils assemblages. These findings offer insights into the depositional environments and diagenetic processes that have shaped the reservoir properties of the formation, and addressing the detailed description of the study (Khalid et al., 2022; Memon et al, 2024).

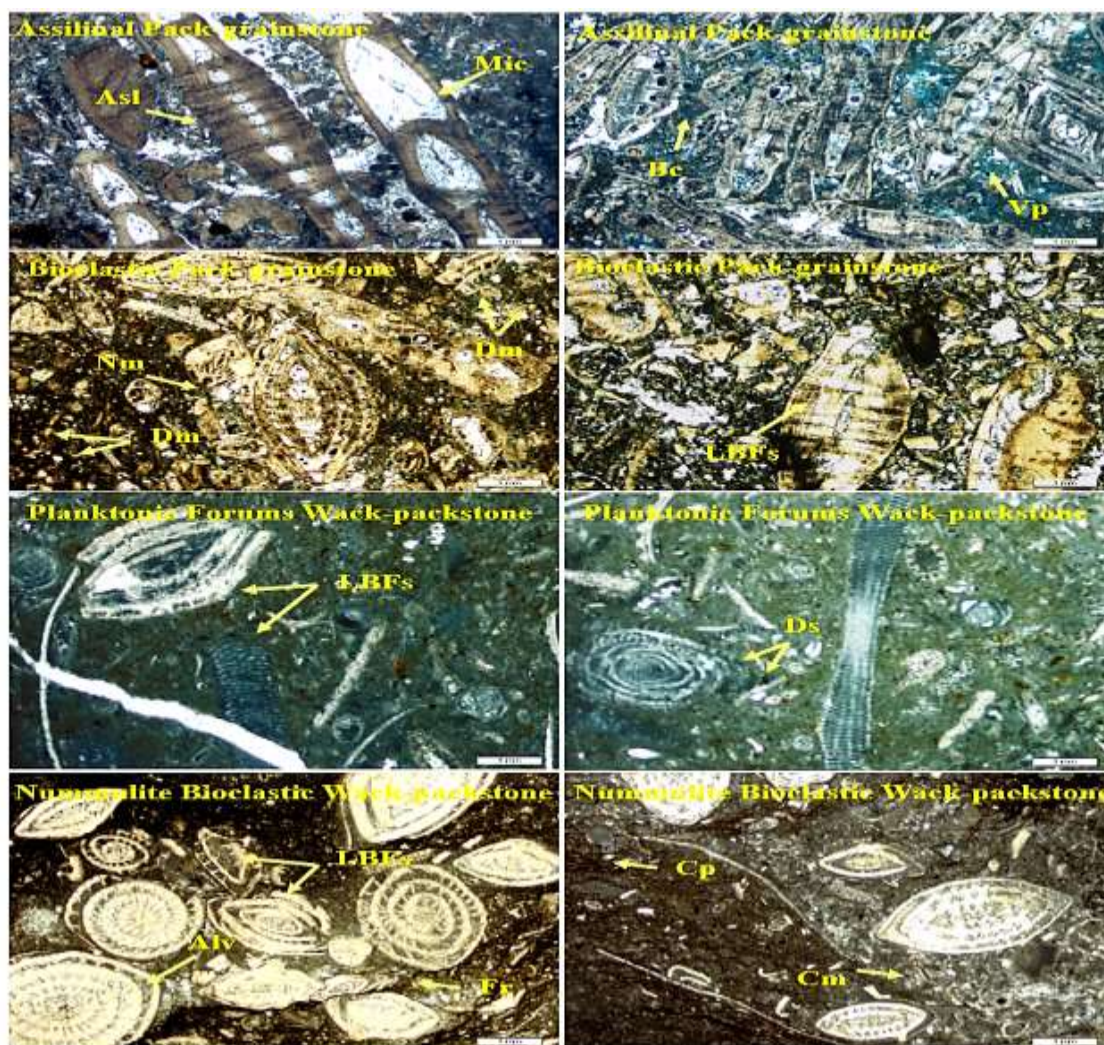


Fig. 2 Petrographic illustration of the examined samples of HRL formation displays different identified microfacies in thin section microphotographs; assilina (Asl), bioclasts (Bc), micritization (Mic), visual porosity (Vp), Nummulites (Nm), dolomites (Dm), large benthic forams (LBFs), dissolution (Ds), alvulina (Alv), fracture porosity (Fr), compaction (Cp), and cementation (Cm).

Diagenesis begins during sediment-water interaction and continues to post-deposition, significantly impacts the petrophysical properties and reservoir heterogeneity. This complexity leads to reduced petrophysical, and pore-morphological characteristics, ultimately affecting the reservoir quality (F. H. Memon, Tunio, Memon, *et al.*, 2023). Various diagenetic transformations, such as cementation, micritization, dissolution, compaction, and dolomitization, contribute to morphological changes in the examined carbonate formation over time,

illustrated in Fig. 2. Micritization observed to an early diagenetic phenomenon within the examined samples, significantly influences reservoir quality by modifying skeletal grain attributes and microbial presence. It predominantly linked to shallow marine settings and involved breakdown of bioclasts, leading to the development of depositional micrite matrix, as illustrated in Fig. 2. Cementation was also observed a dominant process characterized by calcite cementation, which infills the fossil pores, forming granular and mosaic cement (Ghazi *et al.*, 2023; F. H.

Memon, Tunio, Memon, *et al.*, 2023). The observed dolomite crystals are evident in pack-grainstone microfacies with precipitation of cement envelopes the bioclasts, embedding the fossils, as observed in Fig. 2. The compaction is caused by sediment pressure, significantly impacting the petrophysical parameters within microfacies. Over time, sediments deposited, causing carbonate grains and minerals to compact and precipitate, ultimately affecting reservoir quality. Further, fractures were observed which either enhance or diminish the reservoir potential, depending on the existing mineral matrix orientation and association. While dissolution developments, enhance the secondary porosity, though cementation and micritization affecting fluid flow and storage capacity by reducing the pore connectivity (Ghazi *et al.*, 2023). Neomorphism indicated the common diagenetic phenomenon observed in the examined microfacies, involving recrystallization of minerals to form new crystals. It involves micrite muds, dolomite matrix, and iron oxide cement resulting in replacement of original textures into microcrystalline calcite. The dolomite crystals exhibit neomorphic features with euhedral to subhedral morphology, indicating its occurrence during early diagenesis, depicted in Fig. 2. Cementation fills pore spaces with minerals, reducing porosity and permeability. Micritization converts carbonate grains into microcrystalline calcite, reducing pore size and connectivity. Dissolution enhances or reduces porosity by creating secondary pore spaces for hydrocarbon storage, depending on nature and intensity of the process. Whereas, compaction rearranges grain packing, further decreasing porosity and permeability. Dolomitization replaces calcium carbonate with dolomite, altering pore structures and reservoir properties (Ghazi *et al.*,

2023; F. H. Memon, Tunio, Memon, *et al.*, 2023). The diagenetic alterations significantly influence the petrophysical properties and increase the reservoir heterogeneity, that tends to complicate fluid flow within carbonates. Further, it modifies pore structures, reduces porosity and permeability, and strengthens grain bonds, leading to the formation of tight reservoirs, as observed through SEM and thin section analyses (Khitab *et al.*, 2020; F. H. Memon, Tunio, Memon, *et al.*, 2023). This comprehensive petrographic and diagenetic analysis of the Habib Rahi formation reveals the intricate relationship between various processes and their impact on reservoir quality. The findings provide a strong framework for predicting reservoir quality by examining rock type, diagenetic developments, and their role in void space formation. This localized study offers valuable insights into the geological history and evolution of the formation, aiding in reservoir prediction and hydrocarbon recovery optimization to manage carbonate reservoirs effectively.

4.2 Mineralogy and Geochemical analysis

The Habib Rahi Limestone (HRL) carbonate samples were thoroughly analyzed using various methods, including Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), X-ray Fluorescence (XRF), and thin sections. The results showed that calcite and dolomite are the dominant minerals, along with cementing materials and clay content. EDS analysis also revealed the presence of aluminum (Al), silicon (Si), iron (Fe), sodium (Na), and potassium (K), which contribute to the carbonate rocks' grain structure. While concentrations of calcium (Ca) and magnesium (Mn), corresponds to the abundance of calcite with some dolomite, as depicted

in Figure 3(b). The major and trace elements examined by these with their compositions are represented in **Error! Reference source not found.** The XRF analysis of the Habib Rahi Limestone (HRL) formation provides a detailed geochemical breakdown, revealing a primary composition of carbonate minerals like calcite and dolomite, along with significant silicate content, as illustrated in Figure 3 (a). The high CaO percentage (59.97%) indicates the formation's carbonate nature, while the significant SiO₂ (25.385%) content suggests the integration of siliceous materials, likely from detrital quartz or silicate minerals. This contributes to the grain structure and influences the formation's mechanical strength and stability. Additionally, the samples also contain Al₂O₃ (10.798%), Fe₂O₃ (1.663%), TiO₂ (0.849%), and K₂O (0.733%), which are aluminosilicate minerals. Al₂O₃ specifies the clay content and its impact on petrophysical properties, while Fe₂O₃ indicates iron-bearing minerals, which affect the rock's color, diagenetic processes, and magnetic properties, observed in the analysis. TiO₂ and K₂O, in smaller amounts, suggest accessory minerals like rutile and potassium feldspar, which influence the rock's geochemical behavior and diagenetic history (Hosseininejad, Pedersen, Spencer, & Nicolas, 2013). These minerals are essential for understanding the rock's petrophysical properties. The

XRF results reveal trace elements and oxides, such as MnO (0.078%), SrO (0.315%), and SO₃ (0.136%), which provide insights into the diagenetic environment and processes that affect reservoir quality. Manganese (Mn), strontium (Sr), and sulfur (S) are associated with specific diagenetic alterations and mineral phases (Yu et al., 2021). Manganese represents substitute for calcium in carbonate minerals, suggesting redox conditions during diagenesis. Strontium is found in aragonite and be traced for recrystallization processes. These trace elements help reconstruct the diagenetic history and environmental conditions (Steinmann et al., 2020; Yu et al., 2021). The findings provide the detailed mineralogical assessment of the examined carbonate samples, and explores the impact of mineral authigenesis on diagenetic alterations. Calcite being primary matrix, controls the pore-structure through reprecipitation and dissolution processes. Dolomitization caused by megnesium enriched fluids, often modifys the pore structure and primary porosity. The relationship between hutite and ferric oxides enhance the cementation process, reducing pore connectivity and mechanical properties. While clay swelling causes by illite and smectite through pore plugging, reducing permeability, and complecating the fluid flow pattern (Memon et al, 2024; Rashid et al., 2022).

Table 2 Mineral constituents of Habib Rahi formation including major oxides and elemental composition by XRF and EDS patterns.

Major and Trace Oxides (XRF Analysis)		Elemental Composition (EDS Analusis)	
Oxides	%	Elements	%
CaO	59.97	Carbon	1.08
SiO ₂	25.385	Oxygen	56.72
Al ₂ O ₃	10.798	Aluminum	6.36
Fe ₂ O ₃	1.663	Silicon	21.68

TiO ₂	0.849	Calcium	9.34
K ₂ O	0.733	Potassium	2.80
MnO	0.078	Iron	3.52
Oxides	%	Carbon	1.08
CaO	59.97	Oxygen	56.72

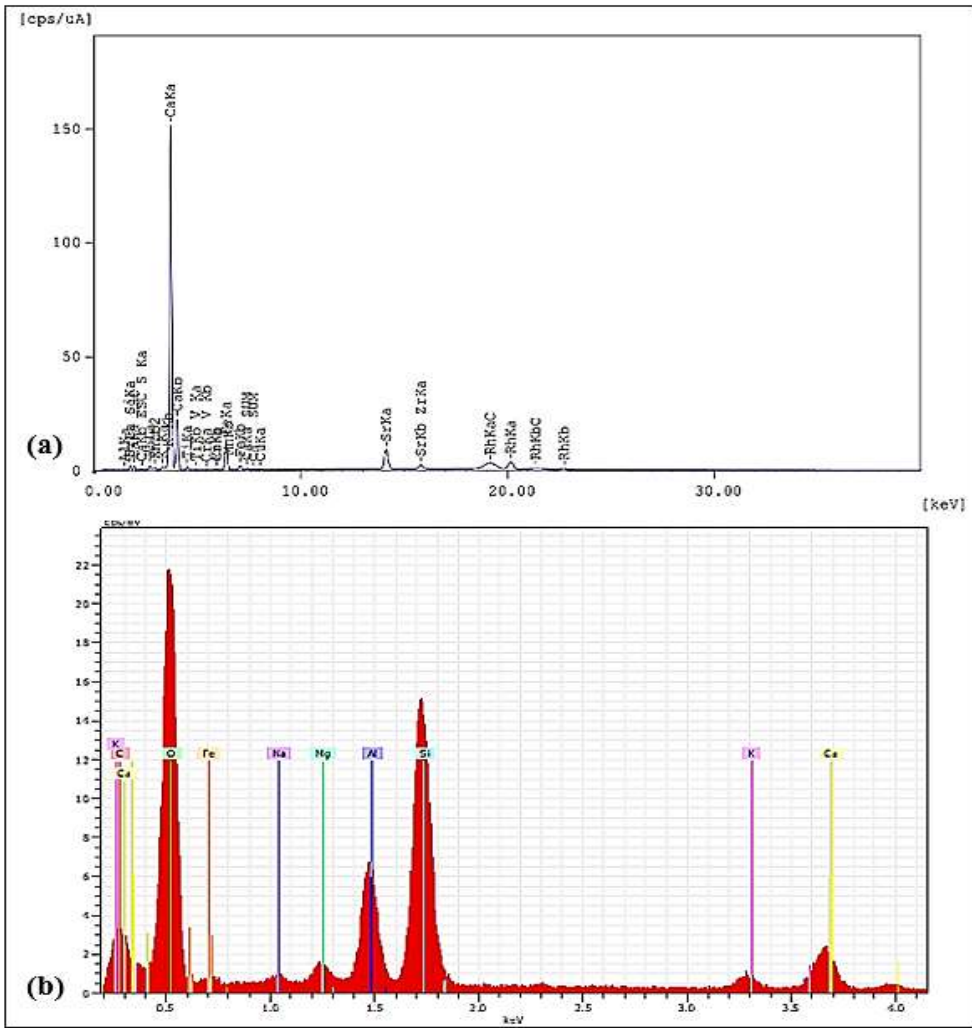


Figure 3: Mineralogy of the Habib Rahi Limestone formation (a) XRF analysis (b) EDS patterns.

Further, the mineralogical composition was also analyzed using EDS patterns and thin section microphotographs. The carbonate rock exhibited an intermix of biogenic and authigenic minerals, with calcite as the primary rock-matrix mineral (F. H. Memon, Tunio, Memon, *et al.*, 2023). The EDS patterns also highlighted the detectable amount of Al, Na, Si, and K indicated the influence of silici-clastic minerals and clay intermixing. This mineralogical

interplay affects the rock mechanical properties and diagenetic pathways that ultimately influence the quality of the carbonate reservoir. The detailed geochemical analysis by EDS and XRF has been associated with petrographic observations, providing a comprehensive understanding of the HRL Formation's mineralogical composition, and diagenetic alterations. Several observed diagenetic processes like dissolution, cementation and recrystallization

integrated with mineral compositions affecting the reservoir flow geometry, and shape of void space architecture. These findings offer deeper insights into reservoir quality, mechanical properties, and fluid flow behavior, subsequently, enabling accurate reservoir characterization, effective resource management, and optimized extraction strategies.

4.3 Pore Morphological and Structural analysis

The Habib Rahi Limestone (HRL) Formation's microstructure and mineral composition were studied using SEM and FTIR techniques. SEM images revealed a complex network of pore types, impacting the formation's petrophysical properties. FTIR analysis further elucidated mineral phases, identifying functional groups and variations that correlate with observed structural changes and diagenetic processes. The examined samples exhibited a complex network of pore types, including micropores to macropores, interparticle to intraparticle, moldic, vuggy, and fenestral pores, observed from SEM results in Figure 4. It was observed from the SEM results that micropores contribute to storage capacity, while macropores enhance permeability. Interparticle and intraparticle pores influence the fluid flow properties, while moldic and fenestral pores increase the reservoir heterogeneity. The variations in grain packing, grain size, and sorting affect the overall petrophysical properties. Cementation by calcite mineral reduces the pore space, while induced calcite and tectonic fractures indicated post-depositional structural changes. It was also detected during SEM analysis that these observed fractures contributed 10-15% of the total void space in some samples, estimated through Baccelle and Bosellini chart (Bacelle & Bosellini, 1965), while remaining void space dominated by inter-

intragranular pores. These findings explicitly simplify the ratio fracture void space relative to pore space, providing contribution of fractures to petrophysical properties, and clear understanding of the pore network within reservoir. The analyzed fractures significantly enhance the permeability by introducing anisotropy in fluid flow pattern, underlining the dual role of fractures in improving and complicating the reservoir potential. FTIR analysis complements the SEM results to identify the mineral phases and structural variations in HRL samples, including major carbonate minerals like calcite, and non-carbonate clay minerals like quartz, feldspar, and kaolinite (Barton, Yang, & Barton, 2014; F. H. Memon, Tunio, Mahesar, *et al.*, 2023). The study further analyzed the mineral structures using spectral bands, revealing compositional changes and the presence of monovalent or divalent cations combined with carbonate ions to form different carbonate minerals. Rhombohedral carbonates, such as calcite, dolomite, magnesite, siderite, and rhodochrosite, crystallized in the R-3C group. Despite site symmetry variations caused by divalent elements, these carbonates showed structural similarities. FTIR spectra showed that these variations did not affect molecular symmetry. Six active vibrational modes were detected, supporting the presence of complex carbonate mineral phases within the HRL Formation. The spectral bands at 1437 cm^{-1} and 3417 cm^{-1} are attributed to asymmetric C–O stretching and symmetric O–H stretching, representing the characteristic absorption feature of carbonate groups. These absorption bands indicate varying degrees of diagenetic alteration, including substitution of cations like Ca, Fe, Mg, and Mn within the carbonate lattice, as illustrated in Fig. These substitutions impact crystal symmetry and lattice

vibrations, as evidenced by six active modes in the FTIR spectra: two external crystal lattice vibrations

and four internal vibrations within the carbonate group.

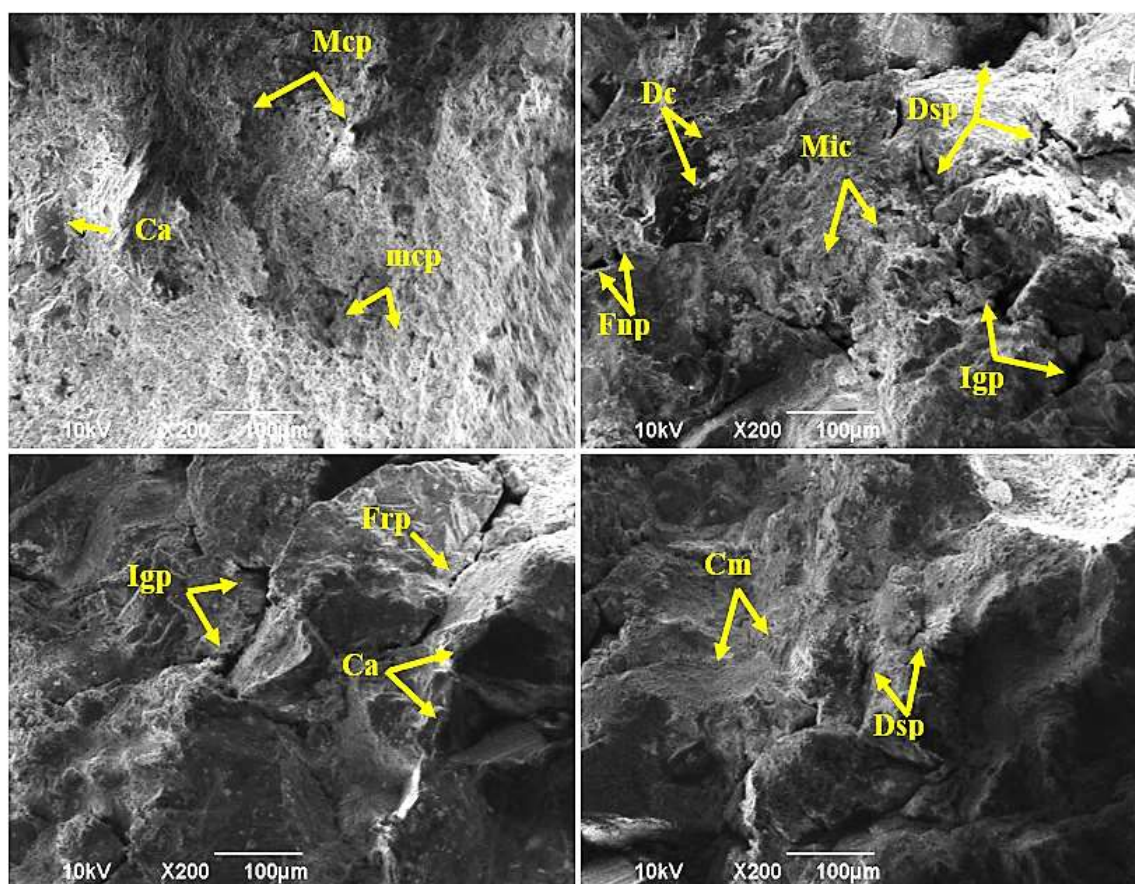


Figure 4: SEM analysis representing the complex pore-morphology of the examined formation including micropores (mcp), macropores (Mcp), calcite mineral (Ca), micrite mud (Mic), dissolution pores (Dsp), intragranular pores (Igp), fenestral pores (Fnp), dolomite crystal (Dc), fracture pores (Frp), and cementation (Cm).

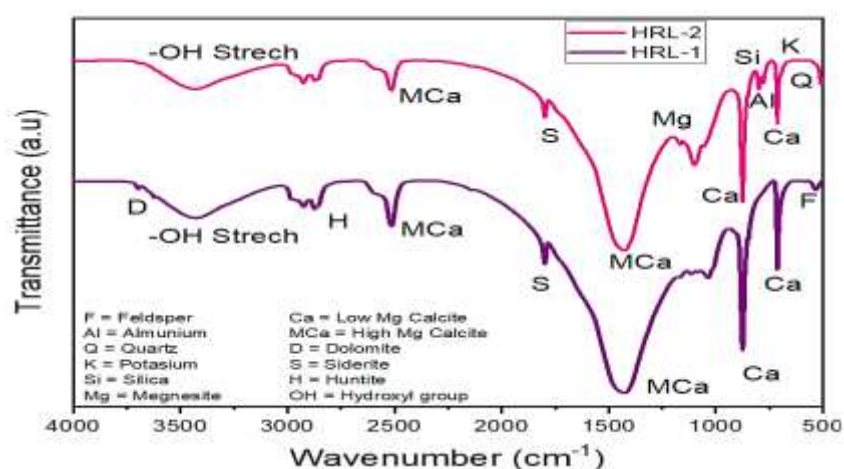


Figure 6:FTIR analysis of the HRL formation samples.

Further, the study was associated with thin-section petrography to analyze the impact of diagenesis on morphological features. The pore and structural characteristics are shaped by diagenetic processes such as micritization, cementation, dissolution, and fracturing. Cementation precipitates the carbonate minerals within pores, affecting porosity, while micritization converts grains to micrite, further reducing porosity and creating a rigid rock structure. Dissolution processes enhance porosity but cause irregular pore shapes and connectivity issues. Induced calcite and tectonic fractures in thin sections indicate significant diagenetic alteration, reflecting past tectonic activities and fluid movements (Memon *et al.*, 2024; Salah, Janjuhah, Sanjuan, Maalouf, & Environment, 2023). These fractures can enhance permeability but complicate the pore structure. The combined effects of these processes result in a complex interplay of porosity and permeability, ultimately affecting the reservoir quality. The fractures and heterogeneity in pore types posing challenges to fluid flow predictability. Understanding these complex factors are essential for developing effective hydrocarbon extraction strategies and improving reservoir management, focusing on quantifying micro-structural variations and developing predictive models for reservoir behavior.

4.4 Petrophysical and Reservoir Quality Index

(RQI) Analysis

The petrophysical properties of the Habib Rahi Limestone (HRL) formation were assessed using scalar (density and porosity) and directional measurements (permeability). The carbonate core samples showed average densities of 2.684 g/cc, with a weak correlation between bulk density and porosity,

as depicted in Fig(a). This suggests significant variations in mineralogical compositions, grain shapes, packing arrangements, and fabric within the formation, leading to a non-uniform and diverse pore structure (Memon *et al.*, 2024). The HRL samples had an average porosity of 11.84%, with a permeability of 3.16 mD, indicating moderate reservoir quality. Further, the visual porosity estimates of bioclastic wackestone using baccelle and Bosellini chart, exhibited the higher porosity values of 10-15 % due to enhanced secondary pores caused by dissolution. While grainstone microfacies exposed lower porosity of 8-12 % due to cemented and micritization (Bacelle & Bosellini, 1965). The observed micropores in the analysis related to storage capacity, whereas macropores contributed to fluid flow. The variations in pore structure are primarily associated to depositional and diagenetic processes, affecting the reservoir quality. SEM and thin section analyses revealed that various porosity types, highlighting the heterogeneity of pore structures within the formation, which significantly influences its fluid flow properties (K. R. Memon *et al.*, 2021). The study found a linear relationship between permeability and porosity in a reservoir, with a weak correlation coefficient, due to variations in pore size and pore throat networks that reducing the effective porosity, as evidenced in Fig(b). This suggests the diverse mineralogical structure of the reservoir and inherent heterogeneity that controls fluid flow properties. The presence of micro cracks was confirmed through thin section and SEM analysis. The dual porosity characteristics, matrix and fracture porosity, further complicate the relationship, making understanding these interactions crucial for optimizing hydrocarbon recovery and effective reservoir management.

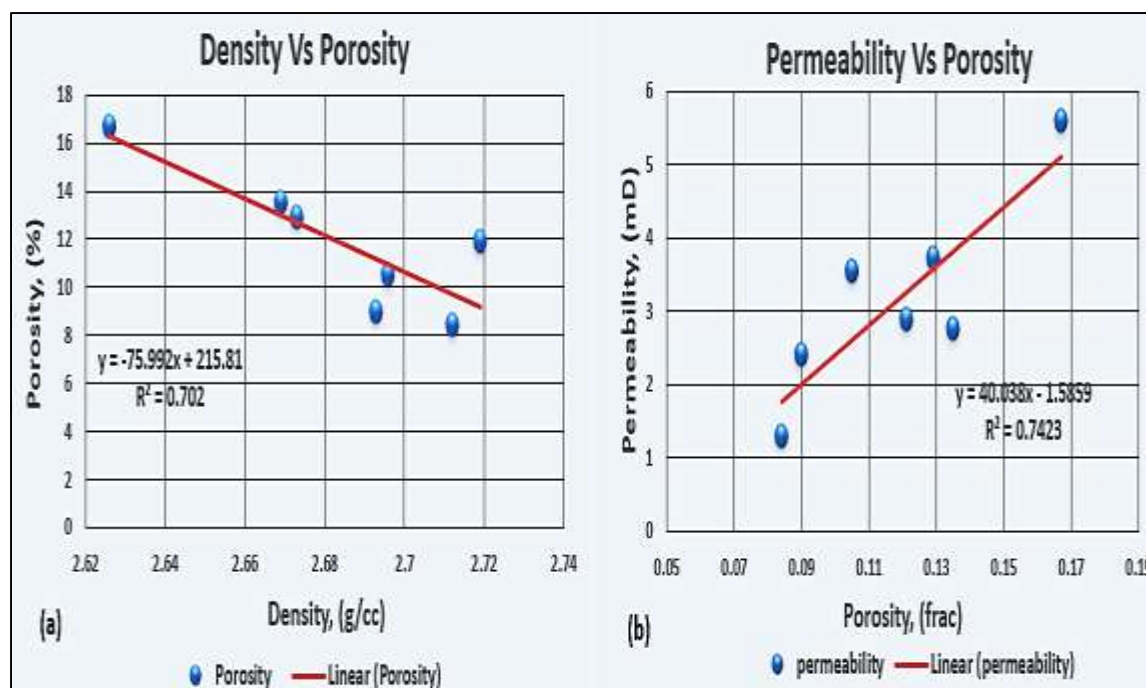


Figure 7: Petrophysical analysis of the HRL formation (a) Porosity versus Bulk Density, (b) Porosity versus Permeability.

The RQI analysis for the Habib Rahi Limestone was examined to analyze the influence of diagenetic features on reservoir quality using Eq. 1.1, focusing on the relationship between porosity, permeability, and their effective flow units. Subsequently, providing insight into the reservoir's fluid transmission capacity derived from petrophysical measurement. The analysis found a linear relationship between RQI and porosity in HRL formation, but weaker correlation coefficient suggest that porosity is significantly influenced by diagenetic alterations, as evidenced in Fig(a). The positive slope of 11.275 indicates that as porosity increases, the RQI also increases, indicating the porosity substantially affecting the fluid transmission capacity of the reservoir. However, the low R^2 value suggests that porosity alone doesn't strongly predict RQI due to diagenetic processes that introducing heterogeneity to the formation. The intercept of 3.7237 indicates the baseline RQI value, indicating the inherent quality of the reservoir before

considering porosity variations (Onuh *et al.*, 2017). This reservoir heterogeneity is characterized by variations in mineralogical composition, grain size, and pore structure, tends to reduce effective porosity and distressing overall reservoir quality. Further, the diagenetic processes like cementation and micritization also influence this relationship to reduce effective porosity and enhanced localized permeability but contributing to irregular pore network (Abuseda, Kassab, LaLa, & El Sayed, 2015; Memon *et al*, 2024). Similarly, permeability values directly correlate with RQI, indicating its importance in determining reservoir quality. However, the correlation is found to be moderate, as illustrated in Fig(b), indicating the complex nature of the pore system within HRL formation. The positive slope of 0.4268 indicates that permeability more significantly influences the reservoir quality than porosity alone. While the intercept of 3.7104 indicates the initial RQI value, indicating that reservoir characteristics remain

independent of permeability changes (Abuseda *et al.*, 2015). Other factors like clay minerals, bioclasts, and diagenetic alteration also influence permeability, highlighting its importance in reservoir quality assessment. The RQI analysis reveals the diverse and heterogeneous nature of the HRL formation, with weak to moderate correlations between RQI, porosity,

and permeability indicating the reservoir's complexity influenced by various geological and diagenetic processes. The finding underscores the importance of integrating petrographic, petrophysical and geochemical analyses to develop the comprehensive assessment of the reservoir.

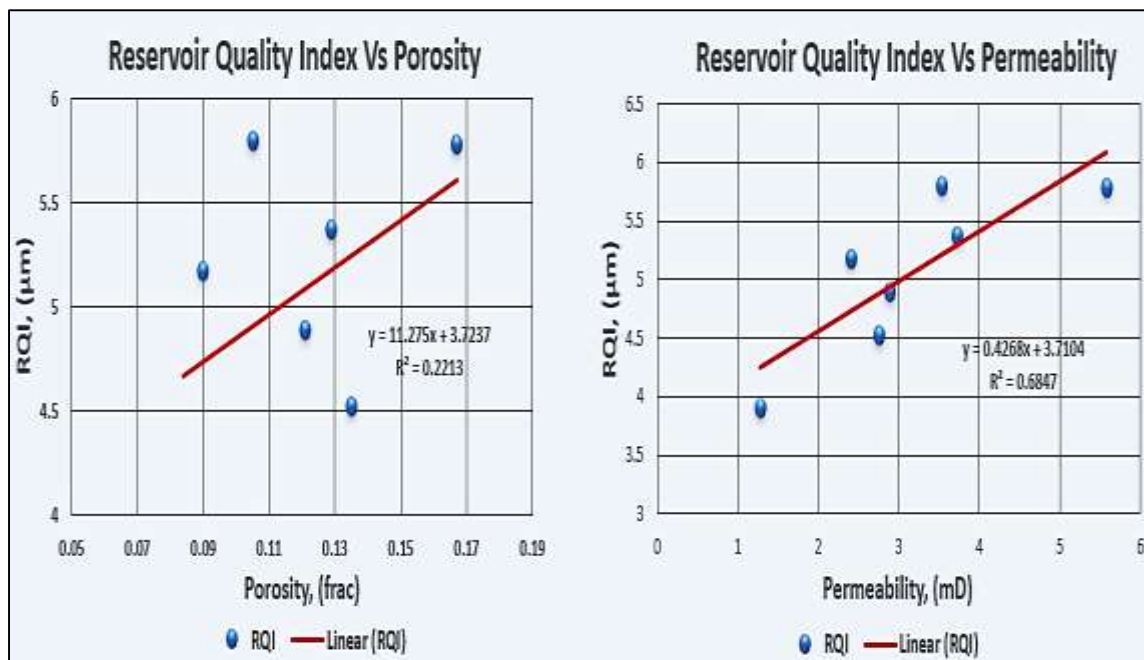


Figure 8: Reservoir quality analysis of the HRL formation (a) RQI versus Porosity, (b) RQI versus Permeability.

4.5 Implications for Reservoir Quality

Assessment

The study emphasizes the importance of understanding the petrophysical parameters of carbonate formation to assess its reservoir quality. Diagenetic processes significantly influence reservoir quality by altering fundamental properties like porosity and permeability, which are crucial for predicting performance and planning extraction strategies (Abro, Shar, Lee, & Narejo, 2019). The formation exhibits various diagenetic processes, including micritization, dolomitization, neomorphism, recrystallization, compaction, and calcification.

Cementation, caused by clays and iron oxides intermixing with calcite and clays, significantly affects the permeability and porosity of the carbonate rock samples. Subsequently, reducing reservoir quality by filling pore spaces and reducing fluid storage and transmission capacity (Abuseda *et al.*, 2015; F. H. Memon, Tunio, Memon, *et al.*, 2023). The XRF revealed a complex mixture of carbonate and siliciclastic materials, with CaO and SiO₂ being significant in the analysis. Other oxides like Al₂O₃, Fe₂O₃, TiO₂, and K₂O contribute to a heterogeneous pore structure. The samples showed low primary porosities due to intergranular, micropores, and nano-size pore throats,

resulting in dense, and diverse pore networks, as evidenced by SEM analysis. This indicating the significant heterogeneity in pore-connectivity and distribution, which further complicates fluid flow and reservoir performance (Abro *et al.*, 2019; K. R. Memon *et al.*, 2021). The variations in pore-morphology create a non-uniform and heterogeneous structure. FTIR analysis confirms the presence of carbonate phases and non-carbonate clay species, revealing chemical interactions contributing to the pore morphological variations (Abbas *et al.*, 2023). The combination of SEM and FTIR analyses underscores the complex relationship between mineralogical composition, pore morphology, and structural characteristics that affect the reservoir quality. The petrophysical measurements demonstrate the further complexity of the examined formation due to varying density, porosity, and permeability determinations. The average density is 2.684 gm/cc, with a weak correlation between bulk density and porosity. The porosity is 11.84% and permeability is 3.16 mD, indicating low to moderate reservoir quality. The Reservoir Quality Index values show weak to moderate correlations with porosity and permeability, highlighting the need for advanced stimulation techniques to improve reservoir quality and hydrocarbon recovery. This integrated analysis evaluates the HRL reservoir, highlighting challenges from diagenetic alterations, intricate pore structures, and mineralogical heterogeneity. Subsequently, providing understanding crucial for developing effective reservoir management strategies, guiding future exploration and production efforts for efficient and sustainable resource utilization. Further, it also emphasizes the need for hydraulic fracturing and liquid nitrogen cracking to enhance reservoir quality

and recovery efficiency, laying the groundwork for future research and informed decision-making in reservoir exploitation and management. To assess the reservoir quality of studied carbonate formations, it was very necessary to have the knowledge of reservoir's petrophysical parameters which are heavily influenced by diagenetic processes. Diagenetic processes primarily affect the reservoir quality by increasing or decreasing the basic petro-physical properties like porosity and permeability; that provide the basis for static or dynamic reservoir models (Abro *et al.*, 2019). Several diagenetic processes like micritization, dolomitization, neomorphism, recrystallization, compaction and calcification were the most significant diagenetic shift seen in the studied carbonate reservoirs. More precisely, the cementation was caused by the intermixing of clays and iron oxides in the pores, pore throats and fractures with calcite and clays. All of these had a severe impact on the examined carbonate rock samples' permeability and porosity that tends to diminish the quality of reservoir (F. H. Memon, Tunio, Memon, *et al.*, 2023). Additionally, the samples also showed low primary porosities that were mostly caused by intergranular, micropores, and nano size pore throats, which led to tightly compacted denser rocks. These carbonates became very tight diagenetically and require hydraulic fracturing for improving reservoir quality and recovery efficiency. The permeability and porosity of the rocks were significantly reduced in several samples by clay and micrite mud intermix and making them low to moderate quality reservoirs. Moreover, the crucial aspects on the reservoir rock, including cement types, fractures types, diagenesis and its effect on reservoir quality. The current study provides a solid foundation for evaluating the variables that affect fluid

flow inside carbonate reservoir rocks as well as diagenetic controls thorough special core analysis; which would be having a big impact on investment choices and lower the risk involved in exploiting the target reservoirs.

5. Conclusions

This characterization of Habib Rahi Limestone (HRL) offers valuable insights into its petrophysical properties, diagenetic processes, mineralogical composition, pore morphology, and reservoir quality through an integrated approach. Following are the key conclusions have been drawn for this study:

1. The HRL formation has been significantly impacted by diagenetic processes such as micritization, dolomitization, neomorphism, recrystallization, compaction, and calcification, which have reduced porosity and permeability due to extensive cementation by clays, iron oxides, and calcite within pore spaces. The cementation process, along with other diagenetic alterations, has resulted in dense, tightly compacted rock formations with low primary porosities, causing challenges to fluid storage and transmission.
2. A complex mix of carbonate and silici-clastic materials observes within the HRL formation, including CaO, SiO₂, Al₂O₃, Fe₂O₃, TiO₂, and K₂O, contributing to mineralogical variations. This diverse mineral composition, including calcite, dolomite, and clay minerals, contributes to the heterogeneity of the pore structure and influences the reservoir's petrophysical properties.
3. The SEM analysis revealed a complex network of pore types, including micropores,

macropores, inter-particle, moldic, vuggy, and fenestral pores, reflecting the non-uniform and heterogeneous nature of HRL formation. FTIR analysis confirmed the presence of carbonate phases and non-carbonate clay species, elucidating the chemical compositions and functional groups, contributing to the overall pore structure and connectivity. These findings reflect the significance of void space complexity in reservoir performance prediction.

4. The HRL formation exhibits diverse petrophysical behaviors, with average densities of 2.667 gm/cc and a weak correlation between bulk density and porosity, indicating variability in mineral composition and pore-structure. The examined porosity values range from 5.32 to 7.84% and permeability was 1.59 mD. The Reservoir Quality Index (RQI) values showed a weak to moderate correlation between porosity and permeability, highlighting the variability in reservoir quality due to diagenetic heterogeneity.
5. The heterogeneity in HRL formation, characterized by diverse mineralogical structures, grain shapes, packing arrangements, and fabric, significantly affects fluid flow properties. The complex pore structure complicates fluid movement prediction and reservoir performance, emphasizing the need for detailed reservoir characterization and modelling.

This integrated analysis of the Habib Rahi Limestone (HRL) reservoir reveals substantial challenges due to diagenetic alterations and mineralogical

heterogeneity. It emphasizes the need for hydraulic fracturing and other stimulation techniques to enhance reservoir quality and recovery efficiency. Further, the study signifies the larger dataset and statical analyses requirement to enhance conclusions, developing a strong framework for future exploration, reservoir management and effective resource utilization.

6. Acknowledgements

The authors would like to gratefully acknowledge the Mehran University of Engineering and Technology, Jamshoro, Pakistan for co-operation in conduct of research. The authors also thank to Hydrocarbon Development Institute of Pakistan (HDIP), Islamabad for providing public domain data source to carry out the research.

References

- Abbas, G., Tunio, A. H., Memon, K. R., Mahesar, A. A., Memon, F. H., & Abbasi, G. R. J. A. o. (2023). Modification of cellulose ether with organic carbonate for enhanced thermal and rheological properties: Characterization and analysis. 8(28), 25453-25466.
- Abro, W. A., Shar, A. M., Lee, K. S., & Narejo, A. A. (2019). An integrated analysis of mineralogical and microstructural characteristics and petrophysical properties of carbonate rocks in the lower Indus Basin, Pakistan. *Open Geosciences*, 11(1), 1151-1167.
- Abuseda, H., Kassab, M. A., LaLa, A. M., & El Sayed, N. A. (2015). Integrated petrographical and petrophysical studies of some Eocene carbonate rocks, Southwest Sinai, Egypt. *Egyptian Journal of Petroleum*, 24(2), 213-230.
- Bacelle, L., & Bosellini, A. J. A. U. F., NS, sez. IX., Sci. Geol. Paleont. (1965). Diagrams for visual estimation of percentage composition in sedimentary rocks [Diagrammi per la stima visiva della composizione percentuale nelle rocce sedimentarie]. 1, 59-62.
- Barton, I. F., Yang, H., & Barton, M. D. (2014). The mineralogy, geochemistry, and metallurgy of cobalt in the rhombohedral carbonates. *The Canadian Mineralogist*, 52(4), 653-670.
- Ghazi, S., Miraj, N., Ali, S. H., & Waqas, M. J. P. J. o. H. R. (2023). An Appraisal of Microfacies and Depositional Environment of the Early Eocene Habib Rahi Limestone, Sulaiman Range, Pakistan. 26, 16-16.
- Hosseininejad, S., Pedersen, P. K., Spencer, R. J., & Nicolas, M. P. (2013). Use of XRF elemental data to quantify mineralogy and reservoir properties of an Upper Cretaceous oil and gas shale reservoir, eastern Saskatchewan and south western Manitoba. Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference.
- Jadoon, Q. K., Zahid, M., & Gardezi, R. (2013). Petro physical analysis of Habib Rahi Limestone of Mari Gas Field using open hole wire line logs of well Mari Deep-06 Central Indus Basin Pakistan (a case study). *GeoConvention*, 2013, 1-9.
- Khalid, P., Ehsan, M. I., Khurram, S., Ullah, I., & Ahmad, Q. A. J. F. i. E. S. (2022). Reservoir quality and facies modeling of the early Eocene carbonate stratigraphic unit of the Middle Indus Basin, Pakistan. 10, 1063877.
- Khitab, U., Umar, M., Jamil, M. J. C., & Evaporites. (2020). Microfacies, diagenesis and

- hydrocarbon potential of Eocene carbonate strata in Pakistan. 35(3), 70.
- Mahesar, A. A., Abbasi, G. R., Shar, A. M., & Shaikh, M. A. (2022). Morphological and petrophysical evaluation of tight gas resources and energy production in Pakistan. *Mehran University Research Journal Of Engineering & Technology*, 41(3), 168-174.
- Memon et al. (2024). Exploring Reservoir Heterogeneity and Diagenetic Controls in Chorgali-Sakesar Carbonate Formation: A Comprehensive Petrophysical Study in the Potwar Basin, Pakistan. *Jilin Daxue Xuebao (Gongxueban)/Journal of Jilin University (Engineering and Technology Edition)*, 43(07-2024), 84-106. doi:DOI: 10.5281/zenodo.12703874
- Memon, F. H., Tunio, A. H., Mahesar, A. A., & Abbas, G. (2023). Integrated Study to Assess the Diagenetic Impacts on Petro-Physical Characteristics and Reservoir Quality of Sukkur Rift Zone. 19(ISSUE 02 FEBRUARY 2023), 1858- 1865.
- Memon, F. H., Tunio, A. H., Memon, K. R., Mahesar, A. A., & Abbas, G. J. M. (2023). Unveiling the Diagenetic and Mineralogical Impact on the Carbonate Formation of the Indus Basin, Pakistan: Implications for Reservoir Characterization and Quality Assessment. 13(12), 1474.
- Memon, K. R., Ali, M., Awan, F. U. R., Mahesar, A. A., Abbasi, G. R., Mohanty, U. S., . . . Keshavarz, A. (2021). Influence of cryogenic liquid nitrogen cooling and thermal shocks on petro-physical and morphological characteristics of Eagle Ford shale. *Journal of Natural Gas Science and Engineering*, 96, 104313.
- Nabawy, B. S., Abudeif, A. M., Masoud, M. M., & Radwan, A. E. (2022). An integrated workflow for petrophysical characterization, microfacies analysis, and diagenetic attributes of the Lower Jurassic type section in northeastern Africa margin: Implications for subsurface gas prospection. *Marine and Petroleum Geology*, 140, 105678.
- Onuh, H. M., David, O. O., Onuh, C. Y. J. J. o. P. E., & Technology, P. (2017). Modified reservoir quality indicator methodology for improved hydraulic flow unit characterization using the normalized pore throat methodology (Niger Delta field as case study). 7, 409-416.
- Palabiran, M., Sesilia, N., & Akbar, M. (2016). An analysis of rock typing methods in carbonate rocks for better carbonate reservoir characterization: A case study of Minahaki Carbonate Formation, Banggai Sula Basin, Central Sulawesi. Paper presented at the 41th Scientific Annual Meeting of Indonesian Association of Geophysicists (Pit Hagi) Lampung,(Aip Conference Proceedings).
- Rashid, F., Hussein, D., Glover, P., Lorinczi, P., & Lawrence, J. (2022). Quantitative diagenesis: Methods for studying the evolution of the physical properties of tight carbonate reservoir rocks. *Marine and Petroleum Geology*, 139, 105603.
- Salah, M. K., Janjuhah, H., Sanjuan, J., Maalouf, E. J. B. o. E. G., & Environment, t. (2023). Impact of diagenesis and pore aspects on the petrophysical and elastic properties of

carbonate rocks from southern Lebanon.
82(3), 67.

deposits in northern Guizhou, South China.
136, 104259.

Shar, A. M., Mahesar, A. A., Abbasi, G. R., Narejo, A. A., & Hakro, A. A. A. D. (2021). Influence of diagenetic features on petrophysical properties of fine-grained rocks of Oligocene strata in the Lower Indus Basin, Pakistan. *Open Geosciences*, 13(1), 517-531.

Skalinski, M., & Kenter, J. A. J. G. S., London, Special Publications. (2015). Carbonate petrophysical rock typing: integrating geological attributes and petrophysical properties while linking with dynamic behaviour. 406(1), 229-259.

Steinmann, J., Grammer, G., Brunner, B., Jones, C., Riedinger, N. J. M., & geology, p. (2020). Assessing the application of trace metals as paleoproxies and a chemostratigraphic tool in carbonate systems: a case study from the “Mississippian Limestone” of the midcontinent, United States. 112, 104061.

Sun, H., Belhaj, H., Tao, G., Vega, S., & Liu, L. (2019). Rock properties evaluation for carbonate reservoir characterization with multi-scale digital rock images. *Journal of Petroleum Science and Engineering*, 175, 654-664.

Yu, W., Polgári, M., Fintor, K., Gyollai, I., Szabó, M., Velledits, F., . . . Du, Y. J. O. G. R. (2021). Contribution of microbial processes to the enrichment of Middle Permian manganese