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EXPLORING RESERVOIR HETEROGENEITY AND DIAGENETIC CONTROLS IN CHORGALI-SAKESAR CARBONATE FORMATION: A COMPREHENSIVE PETROPHYSICAL STUDY IN THE POTWAR BASIN, PAKISTAN

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Abstract

Potwar Basin is proven to be the most significant hydrocarbon potential resource area of the Indus Basin Pakistan, comprising of various carbonate oil and gas producing reservoirs of Eocene age. However, these reservoirs are depleting with unsustainable production rates, and low recovery factors, attributed to complex reservoir heterogeneity resulting from diagenesis. This study provides an integrated reservoir characterization of the Chorgali-Sakesar carbonate formation to analyze its diagenetic and mineralogical impact on reservoir quality. The comprehensive analysis includes petrography of thin sections, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS), Fourier Transformed Infrared Spectroscopy (FTIR), Gas permeability and Helium porosity measurements. Outcomes indicating an average porosity and permeability values of 5.31%, and 0.89mD respectively; revealing poor to moderate reservoir quality primarily influenced by secondary origin due to diagenetic alterations. Petrographic analysis classified the three discrete microfacies of dolo-mudstone to bioclastic pack-grainstone with distinct diagenetic features and micro-nano fossil assemblages, including bioclast, intraclasts, nummulites, Assilina, and LBFs. Diagenesis significantly impacts petrophysical properties, increasing reservoir heterogeneity through processes like micritization, cementation, and compaction. The specified depositional environment of the formation exposed the alteration during distinct diagenetic phases in marine, meteoric, and burial diagenetic settings. Pore morphology and mineralogy reveals the complex micro-pore structure with various carbonate mineral phases and cement types, further influencing reservoir heterogeneity and fluid flow potential. In conclusion, the CHG-SKR formation exhibits intricate reservoir heterogeneity and varied micro-pore structure due to diagenesis and depositional settings. Its non-uniform pore geometry, and low petrophysical properties resulting from rock compaction classified it as low-quality reservoir. The findings provide a solid foundation for addressing the key challenges in reservoir characterization, and accurately assessing reservoir quality, with implications to mitigate reservoir management risks, and improving productivity of indigenous resources. It offers valuable insights for optimizing resource extraction strategies in the exploration and exploitation of indigenous resources worldwide.

Keywords: Carbonate Formation, Diagenesis, Petrophysical Properties, Pore Morphology and Mineralogy, Potwar Basin, Reservoir Heterogeneity, Reservoir Characterization, Reservoir Quality.

1. INTRODUCTION

Reservoir characterization and quality assessment are the important parameters for the hydrocarbon production forecasts and reservoir management. Petro-physical characteristics are the key parameters for determining reservoir potential and recognized to have a big impact on reservoir development techniques [1]. Carbonate formations pose notable challenges in petroleum exploration and production due to their intricate reservoir complexity, influenced by both initial depositional features and subsequent diagenetic alterations. The reservoir characteristics are impacted by depositional environment, while post-depositional processes such as diagenesis and mineral precipitation further affects the reservoir quality [2, 3]. Evaluating the impact of reservoir heterogeneity on petro-physical characteristics, and its pore structure, present significant challenges due to the influence of diagenetic effects and depositional environment. These factors lead to microstructural variations and diverse pore geometries, complicating the assessment process [3-5]. Extensive sedimentation and diagenesis give rise to range of micro-pore grains leading to distinct variations in pore size, intricate pore interconnectivity, and dispersion. These alterations have the potential to significantly impact the petrophysical properties of the rock. [6, 7]. Similarly, conventional methods prove insufficient in assessing the petrophysical characteristics of carbonate formations, often limited to routine analysis. These methods lack the capacity to distinguish intricate variations in pore microstructure and permeability, crucial for understanding morphological features and fluid distribution in heterogeneous reservoirs. Consequently, specialized core analysis is required to ensure a comprehensive assessment. As a result, specialized core investigation protocols become imperative to achieve greater precise reservoir characterization. To comprehensively assess the diagenetic and mineralogical impact on petrophysical parameters and perform in-depth characterization, specialized core analysis techniques are essential. These methods enables more specific and extensive interpretation of reservoir quality [2,3, 8-10]. The present study employes integrated methodologies to evaluate the various characteristics of carbonate formation including petrophysical analysis, pore size distribution, thin section measurements, microstructure analysis, and assessment of diagenetic alterations [3, 11, 12]. The petrophysical features are important in determining fluid flow properties, influencing carbonate reservoir quality and productivity. These properties are crucial for predicting reservoir production, performance evaluation, and reservoir management [13-15]. Variations in these properties are influenced by depositional environments, diagenetic processes, and mineral precipitations, leading to significant changes in reservoir quality [2, 12], and becomes very challenging in analysis, measurement and interpretation [16, 17]. Consequently, a thorough investigation is necessary to understand these factors, including baseline properties and the impact of mineral precipitation, is essential for accurate assessment of reservoir production performance.

Chorgali-Sakesar formation (CHG-SKR), is well known to be the most productive hydrocarbon reservoir in the Potwar region, Indus Basin Pakistan [18, 19], contributing 80% to total field production. Its extensive fracture network supports major oil fields like Meyal and Fimkasar [20, 21]. This Eocene formation is characterized by complex lithology, and intricate pore and fracture networks, posing significant challenges for reservoir interpretation and field development strategies [22-24]. Substantially, characterizing these parameters of the carbonate formation posed significant challenges due to their heterogeneity, rock fabrics and intricate pore structure [19, 25]. This complexity is a result of the depositional conditions and diagenetic alterations that includes compaction, cementation, dissolution and different levels of dolomitization [22, 26, 27]. Numerous wells have been drilled in the CHG-SKR formation to compensate the hydrocarbon deficit of current energy demand. However, due to severe reservoir heterogeneity, an extensive fracture network, less effective porosity, and poor permeability, early water production occurs in these wells, leading to their abandonment [28, 29]. The well logging studies demonstrated the reservoir potential with various identified net pay zones, but did not identify their stratigraphic units' heterogeneity type properly [20, 30]; or determined reservoir complexities due to diagenetic alterations [31]. Petrography and pore morphology are the important tools that provides a solid foundation for identifying diagenetic interactions between rock units. Understanding the diagenetic relations and typical reactions that occur in carbonate rocks is crucial because they can change the texture of the rock and have an impact on the grains, matrix, cements, mineral precipitation, and evolution of petrophysical properties [31, 32]. This study provides a comprehensive database for CHG-SKR formation through integrated reservoir characterization. Further, it analyzes the impact of diagenetic on reservoir quality and enhance risk reduction in field development, facilitating resource development of carbonates through petro-graphical, pore-morphological, mineralogical, and petrophysical assessments.

2. GEOLOGICAL CONTEXT OF THE STUDY REGION

The study area is situated within the Attock District of Punjab province, at latitude 33° 26' 30'' N and longitude of 72° 41'06'' E, in the Northern Potwar Deformed Zone (NPDZ) of the Upper Indus Basin of Pakistan [33]. The region is characterized by intricate, tightly folded structures, with southward overturning facilitated by steep angle faults. The Soan Syncline and Main Boundary Thrust mark the boundaries of the Potwar Plateau [34-37]. The geological history of this area dates back to the early Cretaceous period, marked by the collision of the Indian and Eurasian Plates, resulting the development of foreland basins in India and Pakistan, including Potwar Basin [37, 38], leading to diverse and deformed geological structures, as depicted in Figure 1. The study area consists of fluvial, deltaic, and shallow marine deposits from the Eocene period, primarily composed of carbonate formations from the Chorgali and Sakesar formations, as shown in the generalized stratigraphy of the region is shown in Figure 2. These formations are interspersed with shales and sandstones. The Chorgali Formation, particularly interesting, is a thick succession of carbonates divided into upper and lower parts, with evidences that suggesting their deposition in shallow marine to deltaic environments [2, 18, 39]. It overlies the Sakesar and Margala Hills Limestone of the Hazara Sub-basin, and is either covered by the Miocene Muree Formation or the middle Eocene Kuldana Formation [18, 40]. The Sakesar Formation, located in the Potwar Plateau, is a transitional phase from marine to continental depositional settings, characterized by nodular limestone with marl and shale interbeds, containing fossil evidence of marine and terrestrial organisms [41, 42]. The Chorgali and Sakesar Formations, located in the Northern Punjab region, hold significant hydrocarbon potential, hosting fields like Fimkasar, Dhulian, Miyal, Balkasar, and Dhakni, considering their stratigraphic and structural characteristics crucial for effective exploration and production strategies.

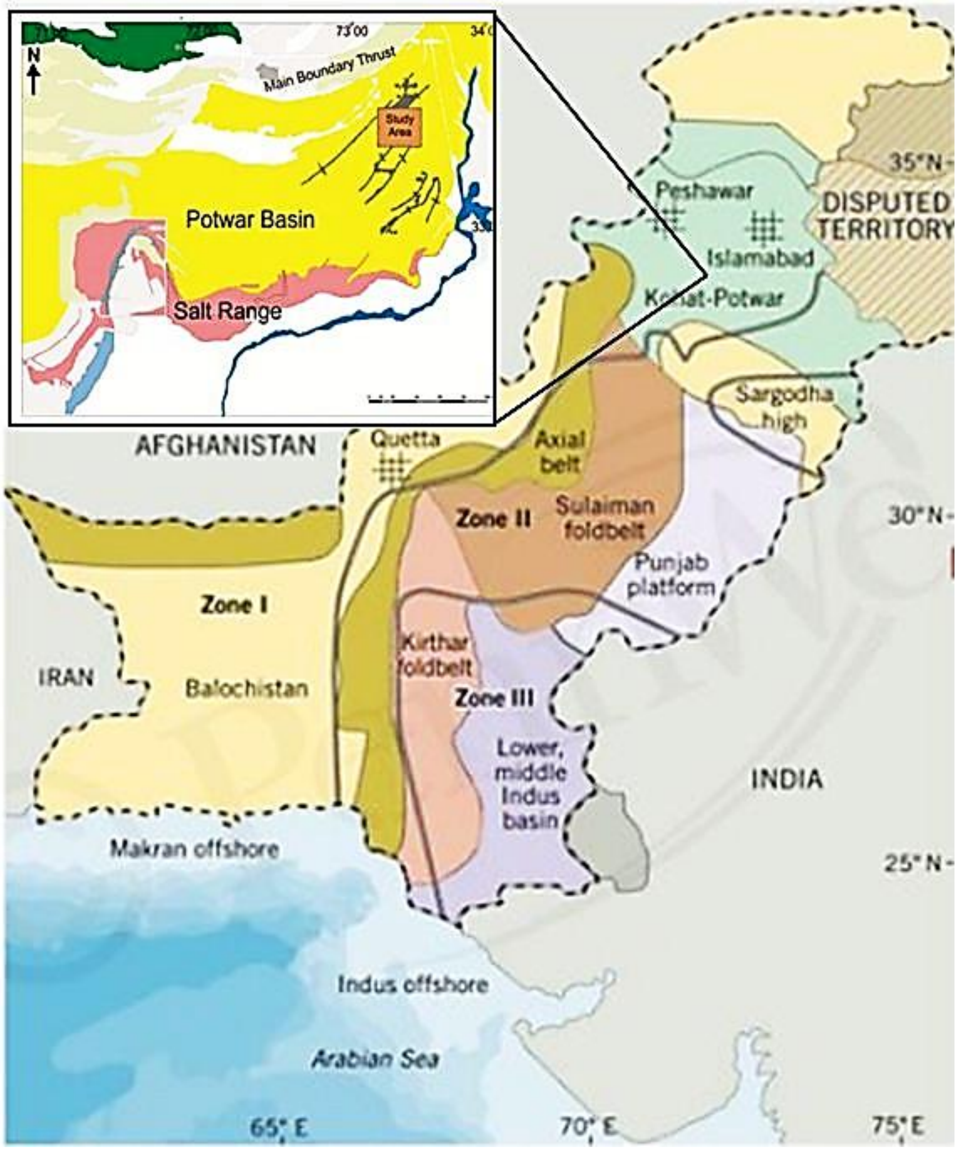

Figure 1: Pakistan Map Showing Tectonically Adjoining Regions of Study Area Exposing Out Crops of Northern Potwar Deformed Zone, Modified after Mahesar et.al, 2020 [43]

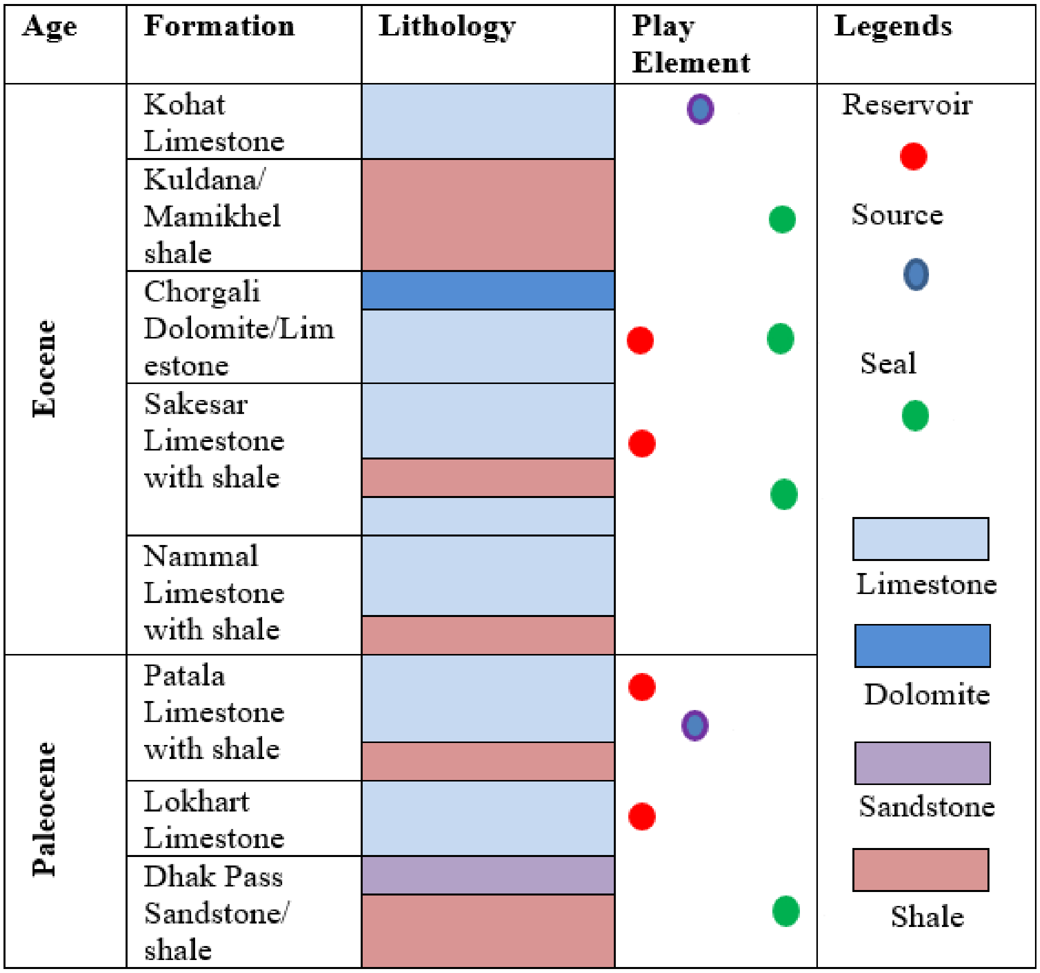

Figure 2: Generalized Stratigraphic Column of the Study Area

3. CORE SAMPLES COLLECTION, PREPARATION AND CLEANING

Reservoir core samples from the Eocene carbonate of Chorgali-Sakesar formation were collected from Meyal Oil field at various depths. These cores were sourced from the Petcorelab, Hydrocarbon Development Institute of Pakistan, (HDIP) Islamabad, with the approval from the Directorate General of Petroleum Concession (DGPC), Pakistan. Standard core preparation procedures, including core slabbing, plugging, trimming, and cleaning were conducted to ensure sample integrity.

Each plug was labeled for identification, cleaned using a Soxhlet extractor with toluene and ethanol to remove abrasions, and dried in an oven at 80°C for 48 hours. The samples typically 5.5cm length and 3.5cm diameter, were then cut into cubical core chips measuring of 2.6 x 2 x 2.3 cm for advance analysis, as depicted in Figure 3. This standardized approach aimed to maintain the consistency in testing procedures, ensuring accurate and representative data for subsequent analyses.

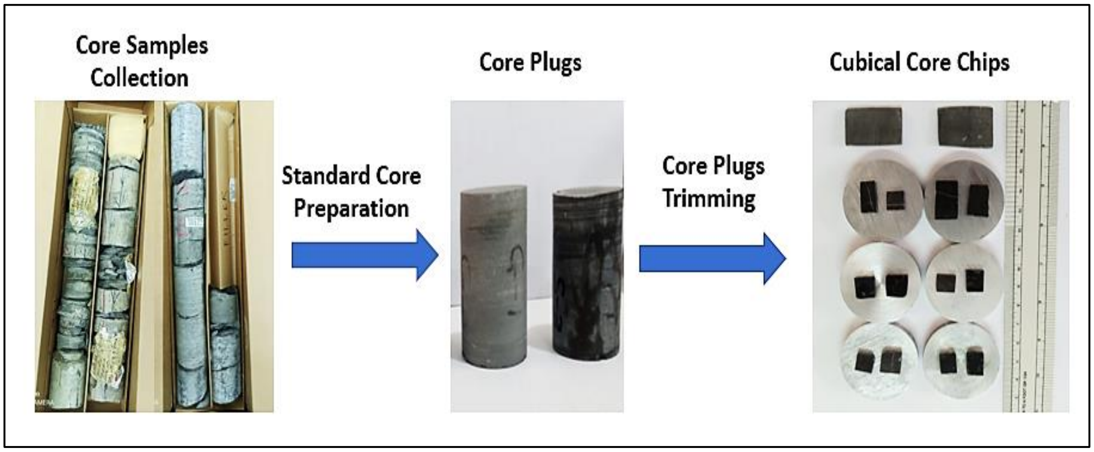

Figure 3: Illustration of Core Samples Preparation for the Study

4. EXPERIMENTAL PROGRAM

The core samples of Chorgali-Sakesar carbonate formation were analyzed through several techniques, as discussed below. The detail experimental analysis of the utilized core samples and work flow chart for petro-physical, petrographic and other different measurements with specific procedures of each given separately in Figure 4.

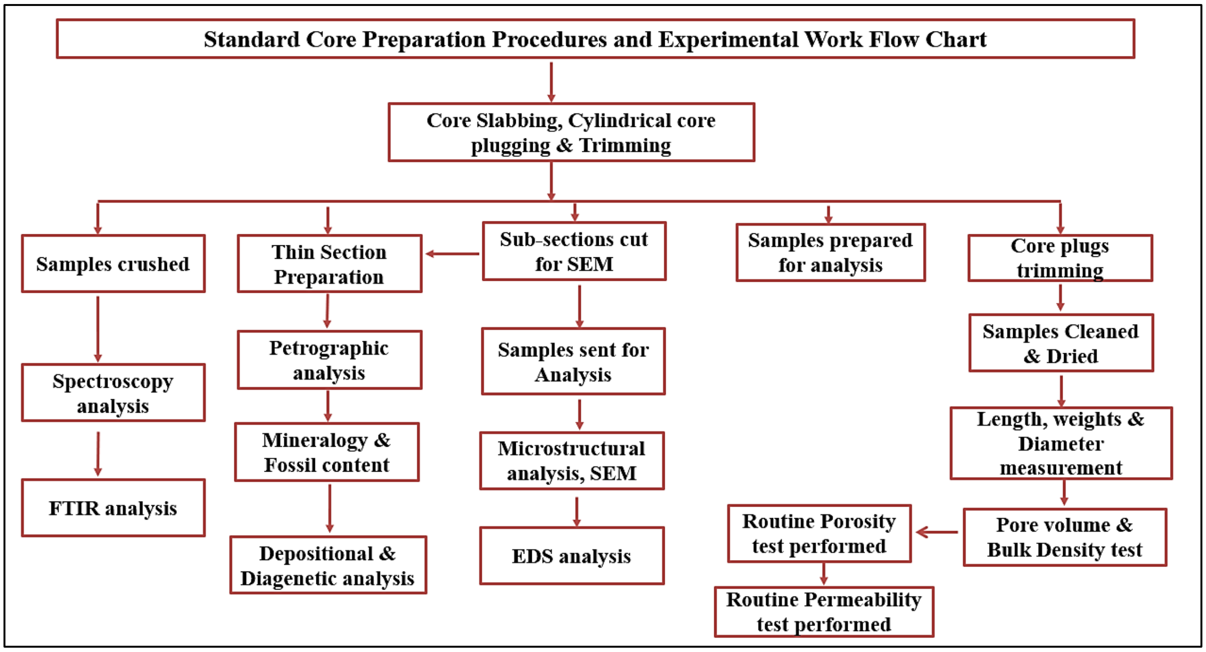

Figure 4: Comprehensive Illustration of Experimental Work Flow Chart

4.1. Petrography as Thin Sections Measurement

A number of 10 CHG-SKR polished stained thin sections with carbon coatings approximately 0.029 mm thick were prepared, using standard procedures. The carbonate thin sections were carefully examined under this study utilizing, Olympus BX-51 microscope, Pittsford USA. This tool has the magnification range of 10x to 1000x pixels resolution with polarizing filters, and rotatable stage. A digital sight Nikon DS-U3 camera was used for image analysis, capturing microphotographs of microfacies through zooming. Petrographic analysis of thin sections was conducted using Dunham's classification system [44].

4.2. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) as Pore-morphological and Mineralogical Assessment

A field emission JEOL- JSM-6590LV, Japan Compact SEM equipment was used to study the microstructure, mineralogy and diagenetic characteristics of the examined samples. The scanning electron microscope (SEM) is an imagining interface software linked with a QUANTAX system of micro analyzer as Energy Dispersive X-ray (EDS) for elemental analysis.

4.3. Fourier Transformed Infrared Spectroscopy Analysis

The FTIR investigations were carried out in Attenuated Total Reflection (ATR) mode using an infrared spectrometer named ALPHA (produced by Bruker, Ettlingen, Germany). To get the IR spectra, sample powders were placed on a diamond crystal and squeezed. In this technology, low wavenumbers enable deeper penetration of infrared light. 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}.

4.4. Petro-physical Measurement

For petro-physical measurement of bulk density, porosity, and permeability, obtained samples were made cleaned in Soxhlet extractor to get prevent from debris and foreign particles which could have affected the outcome. The cleaned samples were dried into humidity-controlled oven at 80°C for 48 hours.

4.5. Bulk Density Measurement

Rock samples' bulk volume (Vb), dimensions, and density were all calculated; the dry weight (Wd) of these samples was then calculated using an electronic balance of 0.1 mg precision and a digital caliper of 0.1 mm precision.

4.6. Helium Porosity Measurement

A PHI-220 Helium Porosimeter of Coretest Systems was used to determine the porosity of selected core plugs. The core porosity was determined by comparing the measured reference volume of the core plugs size with the calculated grain volume using Boyle's law method.

4.7. Gas Permeability Measurement

Gas permeability was measured using Temco GP-12-2631 gas permeameter at ambient conditions using Darcy flow equation of steady-state gas flow:

$$K_a = 2\mu_g Q_g L / A(P_1^2 - P_2^2) \qquad (1)$$

Where;

K_a = Air/ gas permeability, mD

μg = Gas viscosity, cp

Q_g= Gas flow rate, cc/sec

P_1 = Upstream pressure, psi

P_2 = Downstream pressure, psi

5. RESULTS AND DISCUSSION

5.1. Petrographic Description and Microfacies Analysis

The CHG-SKR formation samples underwent petrographic study through thin section analysis, revealing three distinct microfacies: dolomitized mudstone (MF1), bioclastic dolomite-wackestone (MF2), and bioclastic pack-grainstone (MF3). These microfacies provide insights into the depositional and diagenetic history of the rock formations, depicting a shoal and lagoon settings of middle outer ramp deposition.

MF1 displays dark brown dolo-mudstone with a diverse petrographic composition (5-10%), including neomorphosed foraminifera and other bioclasts. It exhibits fine-grained crystalline texture, and orthochems, predominantly displaying dolomitized micritic matrix of 85% and other cementing materials, as depicted in Figure 5(a-b). Additionally, features like stylolites, sparite cement, and ferruginous-filled calcite fractures were also identified, contributing a comprehensive understanding of its origin, mineralogical composition, and diagenetic history. MF2 was characterized by a dark brown to gray dolo-stone, signifying bioclastic dolomitized wackestone, with 25-30% allochems and a 60-70% iron and dolomite matrix. The microfacies was rich in allochemes such as large benthic forums (LBFs), bioclasts, and nummulites, as exposed in Figure 5(b-c). It revealed numerous diagenetic developments interrelated with a shoal setting, including micritization, neomorphism, calcite fractures, cementation, and stylolitization. Similarly, MF3 displays a light brown to gray colored, dolomitized bioclastic pack-grainstone texture, rich in micro-nano fossils such as LBFS, nummulites, algae, bioclasts, intraclasts, and bivalves. It characterized by medium-sized particles embedded in a dolomite matrix, containing 25%-30% cement and Ferron crystals, with allochems (60-65%), including undifferentiated bioclasts, and LBFs, as evidenced in Figure 5(e-f). Unlike MF2, MF3 also exhibits various diagenetic processes like, micritization, cementation, neomorphism, and stylolitization of shoal environment. The petrographic measurements of the distinguished microfacies are presented in Table 1. These observations are consistent with the previous studies in the region, presenting valuable insights into the geologic history and formation conditions of the microfacies [2,3,18, 45].

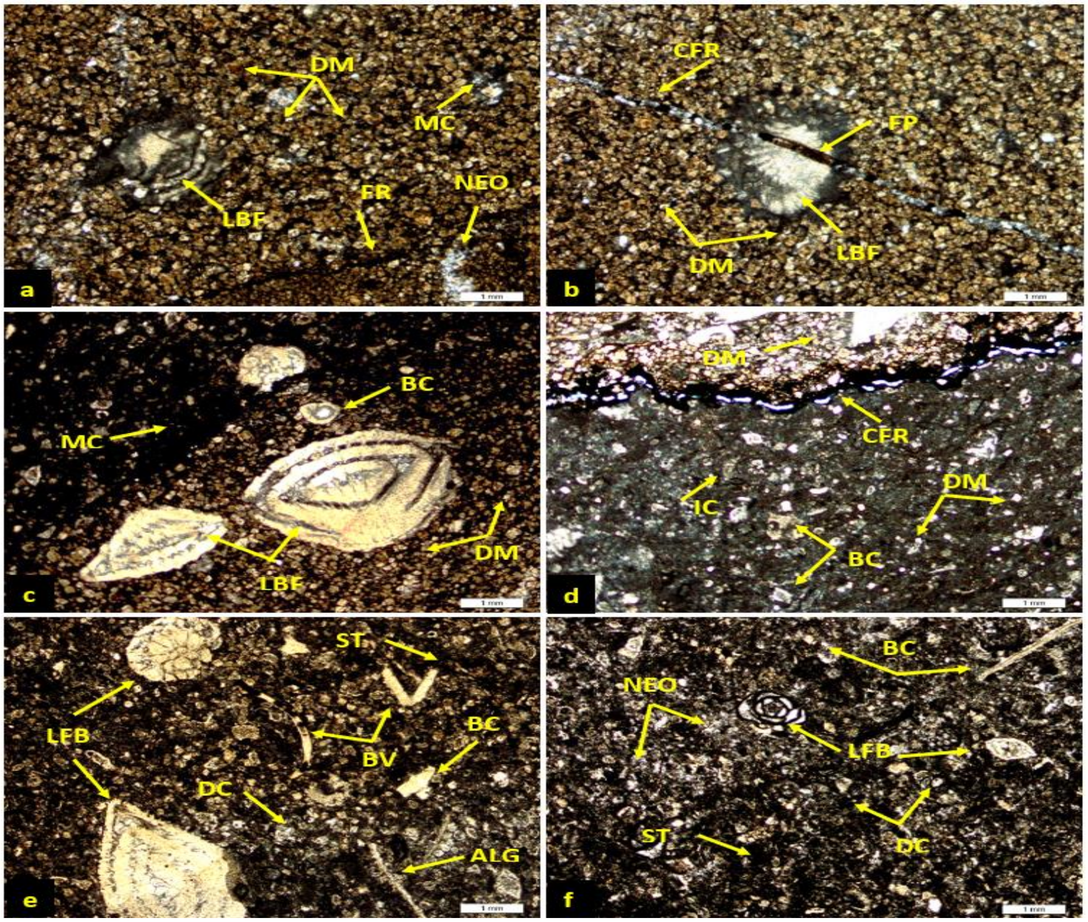

Figure 5: Chorgali-Sakesar Formation Microphotographs Exposing Identified different Microfacies MF1 (a-b), MF2 (c-d) and MF3 (e-f).

Stylolite disintegration (ST), Micrite mud (MC), Bivalves (BV), Intraclasts (IC), Micrite fracture (FR), Bioclasts (BT), Neomorphism (NEO), and Neo-morphed Algae (ALG), large benthic forums (LBF), Calcite filled fracture (CFR) Dolomite matrix (DM).

The study examined the several microfacies of Chorgali-Sakesar formation, identifying the significant petrographic features with substantial variations in mineralogical composition, texture, and allochems content [2, 3]. It classified microfacies using Dunham classification, revealing grain size, cement type, and matrices [44]. Visual estimation charts provided semi-quantitative data on carbonate constituents [2, 46]. Diagenetic progressions like stylolization, neomorphism, dolomitization, and calcite-filled fractures impact porosity types, subsequently affecting the reservoir quality [2, 3]. Results indicates shallow marine environment with highly biomineralized by-products, micrite cement, limited water conditions, bioclasts, high-water conditions by the shoreline, and micritized allochems, suggesting low grains reworking in active environments. These outcomes offer crucial insights into depositional conditions, geological history, and assessment of reservoir effectiveness, essential for evaluation of reservoir integrity and management.

Table 1: Petrographic Details of the Examined Microfacies of Chorgali-Sakesar Formation [2].

Microfacies	**Carbonate Grains**			**Cement-Type**		**Visual Porosity**	**Pore-Type**	**Diagenetic Features**	**Depositional Environment**
Lithology	**Nummulite/ Assilina %**	**LBFs/ Alvulina %**	**Bio-clasts/ Intraclasts %**	**Calcite/ Iron %**	**Micrite/ Dolomite %**				
Bioclastic dolomite-mudstone	5%	2%	5%	30%	35%	porosity up-to 2%	Limited original porosity. Secondary porosity developed by stylolization	stylolization Neomorphism Intra- Calcite veins, Formational Clasts,	Shoal
Bioclastic dolomite wackestone	10%	15%	10%	10%	55%	porosity up-to 5%	Limited original porosity. Secondary pores advanced by grain dissolution	Dissolution, Cementation, Dolomitization Calcite vein,	Lagoon
Bioclastic pack-garinstone	20%	25%	25%	5%	25%	porosity up-to 2%	Partial original porosity. Secondary pores developed by dissolution	Dissolution, Dolomitization Cementation, Calcite vein,	Lagoon

5.2. Diagenetic Processes and Bio-stratigraphic Features

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. SEM and thin section analyses reveal several diagenetic growths, distinguished by strength grain bonds, and alter the primary pore-structure, resulting in development of tight reservoirs. Numerous diagenetic transformations such as cementation, micritization, dissolution, compaction, and dolomitization, alter the morphological changes in carbonate formations over time, as discussed follows.

5.2.1. Micritization

Micritization refers to an initial diagenetic phenomenon within the Chorgali-Sakesar Formation, significantly influences reservoir quality by modifying skeletal grain attributes and microbial presence. This process entails the breakdown of bioclasts, leading to the development of depositional micrite matrix, as illustrated in Figure 6(a-b). Its occurrence is predominantly linked to shallow marine settings, where endolithic organism activity results peloids development [2,3, 47].

5.2.2. Dissolution

The Chorgali-Sakesar Formation undergoes significant dissolution due to meteoric fluids, resulting in the leaching of metastable bioclasts, as evidenced in Figure 6. The initial disintegration of the micrite matrix is attributed to methane release from algae decomposition, commonly observed in lagoon depositional settings. [2, 47]. This phenomenon predominantly unfolds during early marine and meteoric diagenesis stages. Whereas, subsequent phases include dolomite grain breakdown, cementation, stylolitization, and fracture enlargement, indicating early diagenetic phase in burial settings, as depicted in Figure 6(a-c).

5.2.3. Cementation

Cementation is a prevalent process observed within the formation, characterized by calcite cementation, blocky, isopachous, and drusy-mosaic cements, as shown in Figure 6. Calcite fills fossil pores, forming granular and mosaic cement [2]. The dolomite crystals are evident in pack-grainstone microfacies with precipitation of blocky cement, while isopachous fibrous cement envelops the intraclasts, and bioclasts, progressively embedding the fossils, as observed in Figure 6(e-f).

5.2.4. Compaction

Compaction, a process caused by sediment pressure, significantly impacting the petrophysical parameters of the microfacies. Over time, sediments deposited, causing carbonate grains and minerals to compact and precipitate, ultimately affecting reservoir quality. Further, fractures and stylolites were observed within microfacies in Figure 6(c, e-f), which either enhance or diminish the reservoir potential, depending on the existing mineral matrix orientation and association [2, 48].

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5.2.5. Neomorphism

Neomorphism indicated the recrystallization of minerals to form new crystals, and is a common diagenetic phenomenon observed in the examined microfacies, as depicted in Figure 6(c,e-f). This process involves recrystallization of micrite muds, dolomite matrix, and iron oxide cement resulting in replacement of original textures into microcrystalline calcite [2]. In MF2, dolomite matrix exhibits neomorphic features with euhedral to subhedral morphology, indicating its occurrence during early diagenesis, depicted in Figure 6.

5.2.6. Dolomitization

Dolomitization replaces the calcium carbonate minerals with magnesium calcium carbonate, primarily observed in the MF2 and MF3 microfacies, as shown in Figure 6. Dolomitization leads to the substitution of native carbonate components in micrite muds with dolomite, succeeding development of dolomite crystals and dolomite matrix [2, 3]. Subsequently, enhances the petrophysical properties, depending on the extent of dolomite substitution and crystal magnitude [2, 49].

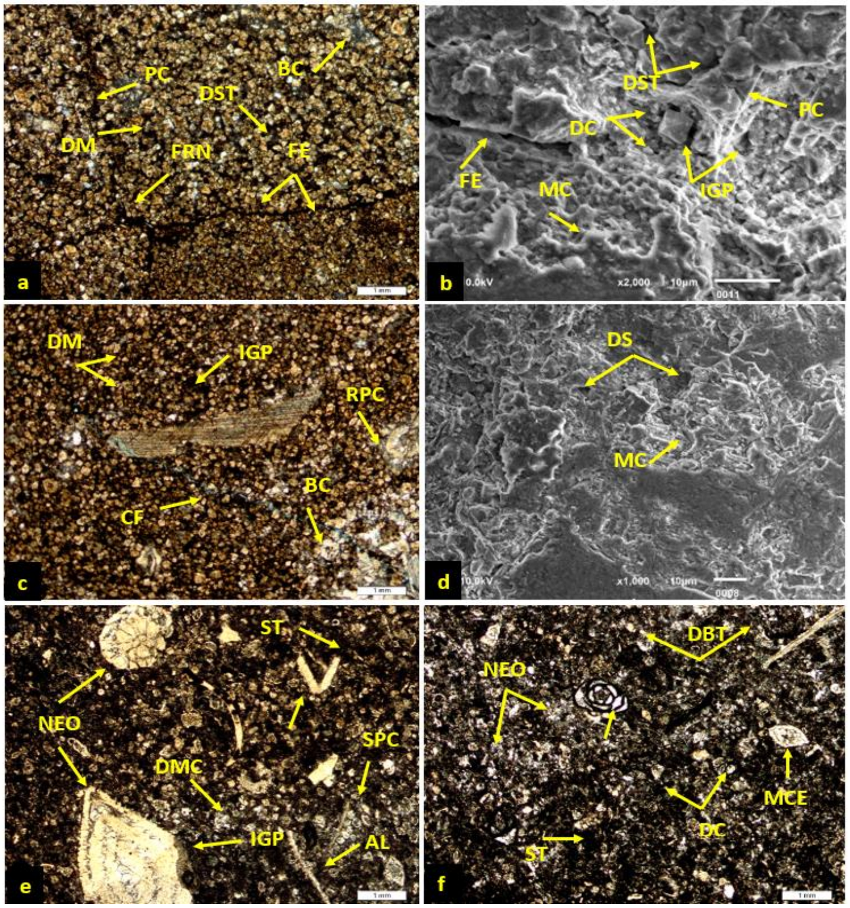


Figure 6: Thin Section (a, c, and e-f) and SEM (b and d) Microphotographs of the Chorgali-Sakesar Carbonate Formation Representing Diverse Diagenetic Features

Blocky cement (BC), Calcite filled fractures (CF), Micrite envelop (MCE), Cement micritization (MC), Dolomite crystals (DC), Intragranular pores (IGP), Dissolution of stylolite (DST), Fracture dissolution (FD), Dissolution of bioclasts (DBT), Drusy cement (DC), Dolomite crystals (FE-DC), Fracture enlargement (FE), Spar cement (SC), Physical compaction (PC), Replacement and recrystallization (RPC), Dissolution of micrite cement (DM).

5.3. Diagenetic Evolution and Depositional Context Analysis

The study examined the diagenetic evolution and depositional settings of the studied formation, estimated to have been deposited about 37-39 million years ago [18]. The formation exhibits a second-order rise cycle of relative sea level, marked by composite transgressive zone arrangement and short-term fluctuations in the sea levels [2, 50]. The absence of a single event in the CHG-SKR formation could be attributed to local tectonic activity during Indian and Eurasian plate collisions [37]. The formation indicated an intricate diagenetic history, shaped by diverse diagenetic settings and tectonic activities, modify the primary sedimentary structures over time. The presence of bioclasts and intraclasts suggest wave-disturbed, shallow-water conditions distributed by waves, with sand shoals and grainstone facies separating open-marine and limited-marine environments. Dolomite crystals, neomorphism, and biotic components dissolution indicated burial settings during deposition below the storm wave base level, as depicted in Figure 7. Microfacies analysis unveils a dynamic depositional narrative within a marine setting, offering insight into sediments reworking and tranquil conditions that characterize the formation's environment and sequence.

Further, sequence of diagenetic developments was established to distinguish the paragenetic relations during analysis. The processes, including micritization, fracturing, cementation, compaction, vein filling, and dissolution, evidenced in diverse environments such as marine, meteoric, and burial settings, as illustrated in Figure 8. In marine environment, micritization of allochems, precipitation of isopachous fibrous cement, and matrix disintegration occur, resulting in the formation of a micrite envelope at the sediment-water interface. Isopachous calcite cement, prevalent in open sea environment, contributes to grain lithification and preservation of porosity [2, 51]. Preceding burial diagenesis, meteoric diagenesis is distinguished by dissolution and marine cementation, restricting pore space expansion or bridging associated with stylolites, dolomite, and fractures. Subsequently, pore-filling cement and blocky cement indicate shallow burial settings, featuring neomorphism, microfractures, displaced grains, and recrystallization [45]. Deep burial diagenesis, occurring at depths of hundreds of meters, involves processes such as calcite vein filling, stylolitization, and the formation of coarse-grained dolomite crystals. Dolomite formation is attributed to the release of Mg and Fe ions from clay during deep burial diagenesis, often associated with stylolites [2, 47].

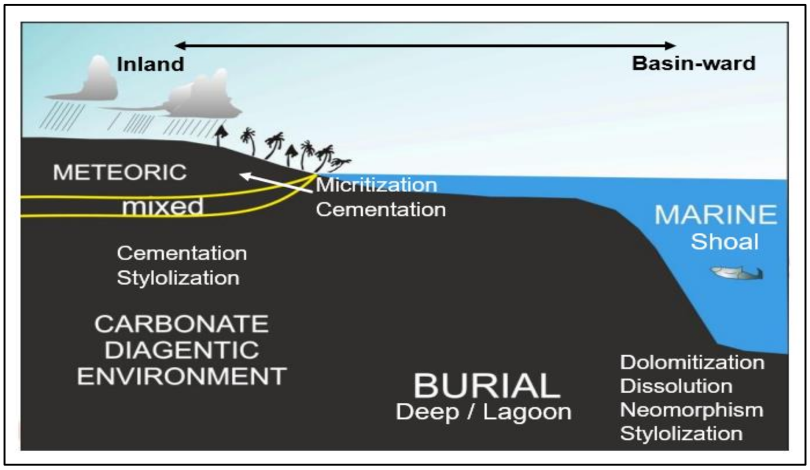
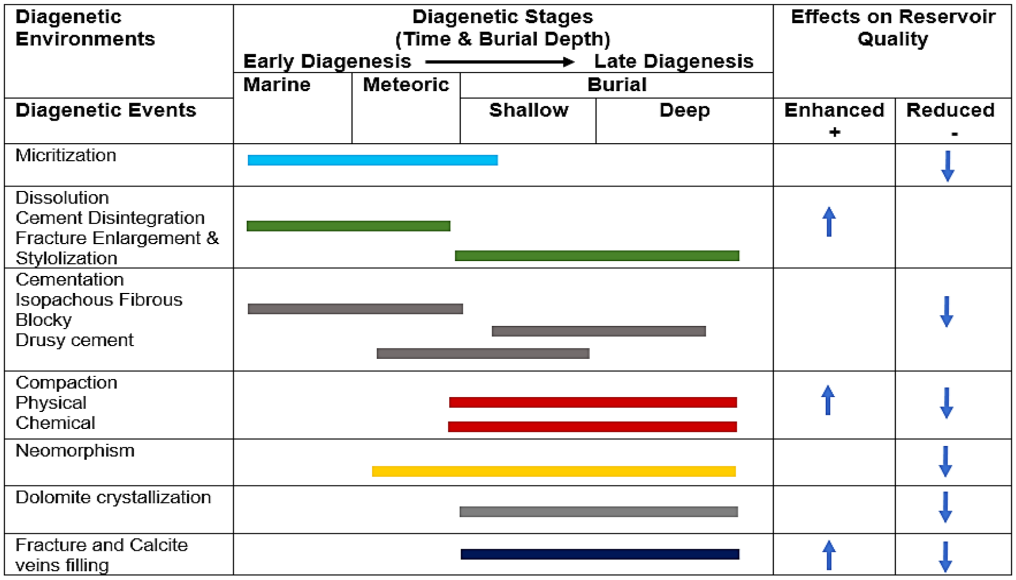


Figure 7: Diagenetic Environment and Depositional Phases Proposed for Chorgali-Sakesar Formation [52]



Diagenetic Environments	Diagenetic Stages (Time & Burial Depth) Early Diagenesis ⟶ Late Diagenesis				Effects on Reservoir Quality	
	Marine	Meteoric	Burial			
Diagenetic Events			Shallow	Deep	Enhanced +	Reduced -
Micritization						↓
Dissolution Cement Disintegration Fracture Enlargement & Stylolization					↑	
Cementation Isopachous Fibrous Blocky Drusy cement						↓
Compaction Physical Chemical					↑	↓
Neomorphism						↓
Dolomite crystallization						↓
Fracture and Calcite veins filling					↑	↓

Figure 8: Sequential Diagenetic Events under Varying Depositional Environment with their Impact on Reservoir Quality

5.4. Mineralogical and Morphological Assessment

The mineral constituents of Chorgali-Sakesar formation underwent a comprehensive and integrated analysis utilizing thin sections, FTIR, and SEM-EDS. Results revealed that the analyzed samples predominantly composed of calcite, dolomite, and an intermix of clay and cementing materials. Additionally, some clay and cementing materials (Al, Si, Mg) were detected in SEM-EDS patterns, shaping the grain structure of the carbonate rocks, as illustrated in Figure 9. The samples of the CHG-SKR exhibited a dolomite matrix composition, whereas, the presence of magnesium, aluminum, and silica suggests the occurrence of clay minerals mixed with siliciclastic influx indicate the formation of micrite

[3]. A detailed breakdown of the mineral composition of the examined samples from this carbonate formation, along with their respective weight percentages (%), is provided in Table 2. The pore morphology of the examined samples revealed a diverse pore-type structure within the formation, exhibiting differences in shape, connectivity, and distribution. This complexity in pore network primarily influenced by grains and minerals precipitation to form and various pore structures such as micro-macropore, inter-intra particles, moldic, vuggy, and fenestral pores [2]. The examined formation samples highlighted dolomite as the predominant mineral constituting the rock matrix, alongside common cement types including silica, calcite, and clay minerals. FTIR analysis demonstrated the dominance of dolomite as the primary mineral in samples, with different carbonate phases also identified by absorption bands distinguished in the analysis, in Figure 10. Different carbonate phases including calcite, dolomite was determined based on the peak wavenumbers of the absorption bands. Additionally, the absorption spectra of various detected minerals like feldspar, quartz, and kaolinite were recognized as non-carbonate clay classes in the analysis.

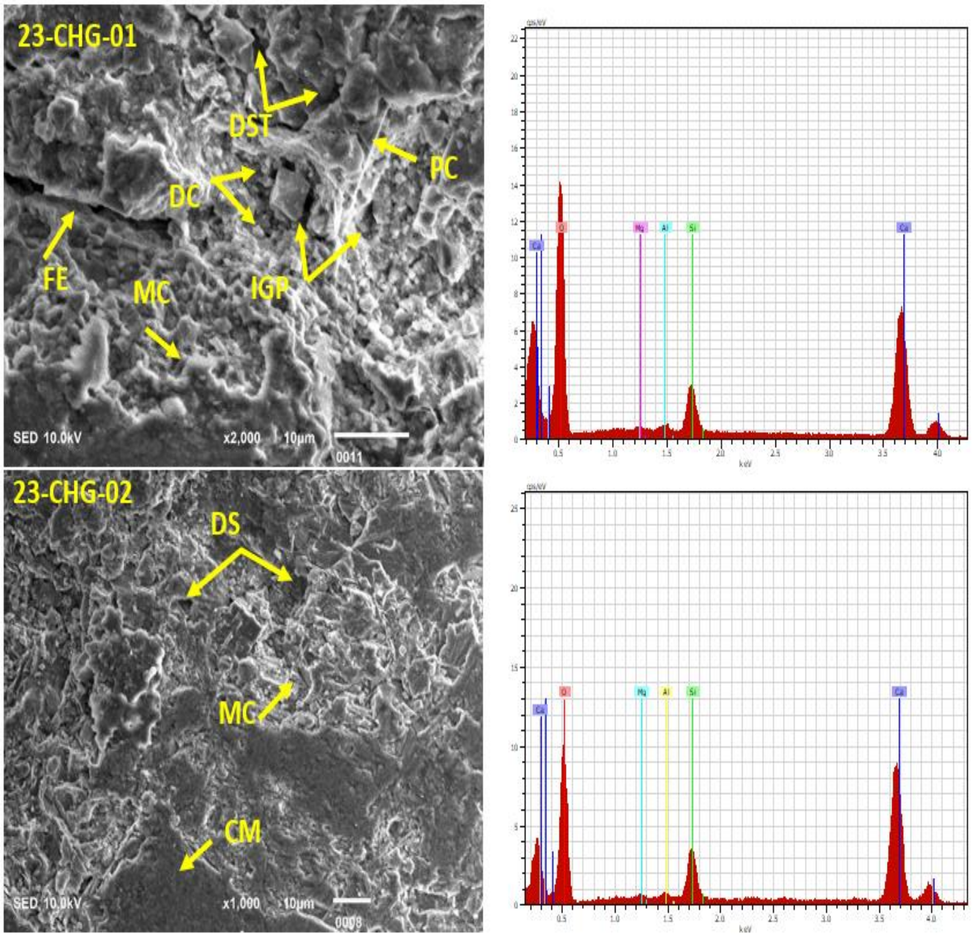


Figure 9: SEM and EDS Shapes of the Examined CHG-SKR Formation Samples, Representing Several Diagenetic Features and Minerals

Clay minerals (CM), Dissolution (DST), Dolomite crystals (DC), Fracture enlargement (FE), Micritization (MC), Intragranular pores (IGP), Physical compaction (PC).

Table 2: Mineral Composition of Chorgali-Sakesar Formation

Element	Atomic No.	Mass Norm. %	Weight, %
Oxygen	8	52.64	58.42
Carbon	6	6.67	6.17
Calcium	20	37.15	32.44
Magnesium	26	0.23	0.45
Aluminum	13	1.28	0.97
Silicon	14	2.03	1.55

The FTIR analysis of samples from the CHG-SKR formation revealed a variety of carbonate phases, with calcite being the most common, as shown in Figure 10. High magnesium content results in a range of high-Mg calcite bands, with Ca^{2+} ions replaced by Mg^{2+}, at increasing wavenumbers of 2500 cm^{-1}, and 3100 cm^{-1}, while huntite and magnesite peak wavenumbers are greater than dolomite [53]. This phenomenon has also observed in different carbonate solid solution (binary and ternary) systems [54, 55]. Similarly, several structural variations in different carbonate groups were identified, including symmetric and asymmetric C-O bending at 728 cm-1 and 881 cm^{-1}. Whereas spectral bands at 1437 cm^{-1} and 3417 cm^{-1}, corresponding to asymmetric C-O stretching and symmetric O-H stretching, as illustrated in Figure 10. According to mineralogical analyses, the most prevalent carbonate minerals in Chorgali-Sakesar formation include calcite, dolomite, micrite muds, and clay minerals which impact the reservoir quality through precipitation [2, 55-57]. Moreover, other minerals such as terrigenous sediment, kaolinite clay, grain coatings, and huntite minerals, also influence the quality of carbonate reservoir.

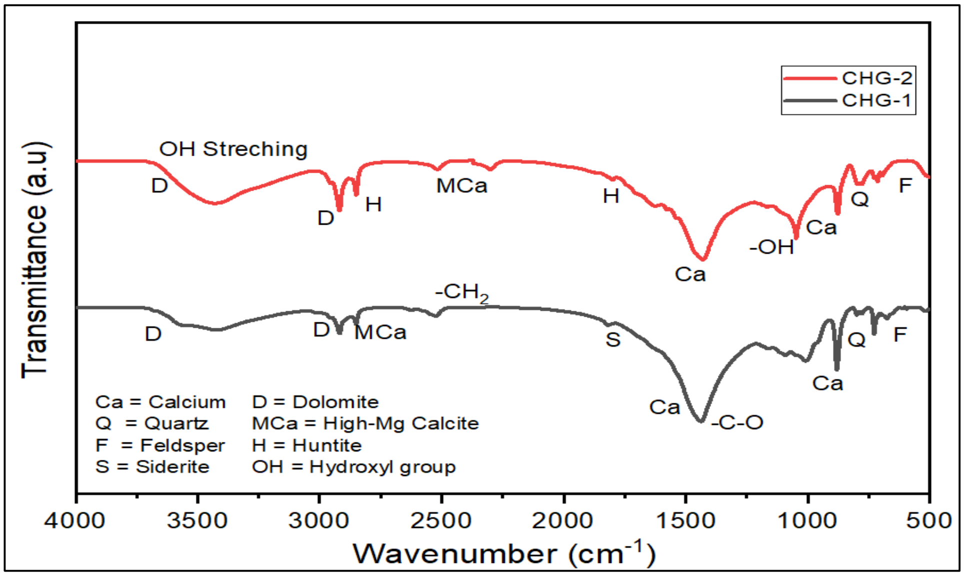


Figure 10: FTIR Analysis of the Chorgali-Sakesar Carbonate Formation Core Samples

5.5. Petrophysical Measurement

The scalar measurements (density and porosity) and directional measurements (permeability) on the carbonate samples from the Chorgali formation were conducted to evaluate the petrophysical properties. The samples examined had average densities of 2.657 gm/cc and a linear inverse correlation between bulk density and porosity with a weaker association, as shown in Figure 11. This indicates the diversity in mineralogical compositions, grain shapes, packing arrangements, and fabric, leading to a non-uniform and diverse pore structure [5, 6, 58]. The porosity measured averaged 5.88%, with an average permeability of 0.89mD. Comparatively, wackestone and packstone microfacies exhibited slightly greater plug porosity values than the grainstone microfacies. Visual porosity assessments ranged from wackestone to grainstone, identifying intracrystalline, intergranular, and dissolution porosities, as discerned through SEM and thin section analyses [2, 59]. Cross-plotted permeability and porosity data showed a linear relationship with a weak coefficient due to variations in pore size and pore throat network, as shown Figure 11. Subsequently, indicating the diverse mineralogical structures, and reservoir heterogeneity, which significantly influenced fluid flow properties. This complexity of pore structure was evident through porosity and permeability relationships. The deviations in the data points were detected, indicating the occurrence of micro cracks, validated by thin section and SEM analysis [3, 60].

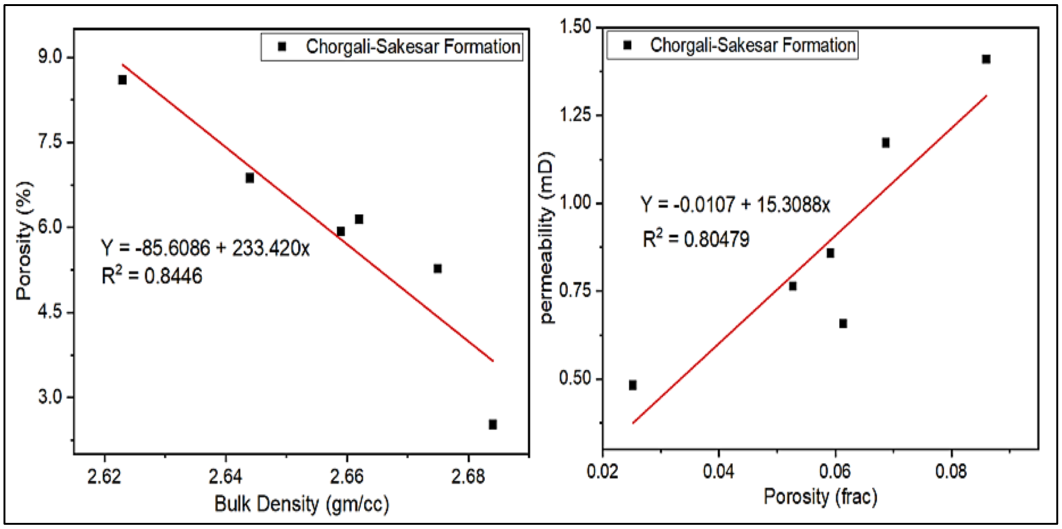


Figure 11: Bulk Density, Porosity and Permeability Relationship of Chorgali-Sakesar Formation

5.6. Implication For Reservoir Quality Assessment

An integrated and comprehensive study was undertaken to characterize the reservoir of the Chorgali-Sakesar formation from Meyal oil field Potwar Basin, Pakistan, focusing on diagenetic, and mineralogical impact on its reservoir quality. Diagenetic processes primarily affect the reservoir quality by influencing the basic petro-physical properties like porosity and permeability; providing the basis for static or dynamic reservoir conditions [61].

The formation exhibits diverse microfacies depositions influenced by marine, meteoric, and burial diagenesis, affecting the reservoir potential. Several diagenetic processes like dissolution, compaction, and dolomitization affect the reservoir quality, with early to late-stage cementation reducing petrophysical properties. Rock compaction decreases the porosity, while micro-fractures and stylolites accumulation may enhance porosity at different stratigraphic stages. However, deep burial activities can overfill fractures with calcite cement, further impacting the reservoir quality [2, 60]. Petrophysical and petrographic analyses show decreased intergranular porosity and permeability, with dolomitization potentially reducing reservoir quality while dissolution may improve it [2, 58]. Marine organic compounds precipitating with carbonate minerals, affecting the reservoir quality, while rock lithification processes and mineral compositional changes significantly impact grain textural qualities, as observed in the analysis. Mineral composition, rock structure, depositional environments, and diagenetic changes play crucial roles in carbonate reservoir quality. The fluid flow in porous media is controlled by rock diagenesis and mineral authigenesis, affecting the reservoir rock properties and fluid flow performance [58, 62]. The observed mineralogy revealed that calcite and dolomite are predominant minerals, with intermix of clay and cementing minerals as silici-clastic inflow inside the carbonate rock samples. The samples analyzed show low primary porosity and permeability, resulting in denser carbonate rocks. These carbonates became tight diagenetically, and require hydraulic fracturing for improving reservoir quality and recovery efficiency [3, 58]. The decline in petrophysical properties is due to micro-nano scale intergranular pores and pore throats, significantly impact the reservoir potential. The presence of clay and micrite muds further contributes to permeability variations, affecting reservoir quality. Moreover, rock compaction causes grain boundaries to converge, reducing petrophysical properties and making them low-quality reservoirs. This study explores the microscale variations in reservoir properties due to diagenesis and minerals' authigenesis, providing insights into larger-scale depositional environments with distinct geological histories. It highlights the impact of diagenetic processes and mineral precipitation on the reservoir quality. This has implications for lowering the risk of reservoir management uncertainties and improving the choices for exploring and exploitation of indigenous resources in the country.

6. CONCLUSIONS

A comprehensive and integrated reservoir study was conducted on petro-graphical, pore-morphological, mineralogical and petrophysical properties of CHG-SKR formation to investigate the reservoir quality assessment and the factors affecting the fluid flow within carbonate reservoirs.

1. The petrographic analysis concluded that the examined microfacies ranged from mud-dolostone to grainstone textures in marine shoal to lagoon deposits, featuring micro to nano fossil assemblages. The medium to fine-grained particles include rounded to rhombohedral dolomite crystals and calcite, associated micrite matrix, large benthic foraminifera (LBFs), bioclasts, and cementing materials, highlighting the complexity of the reservoir.

2. The examined samples indicated poor morphological structure with complex pore-network, variations in shape, connectivity, and distribution within the formation. The examined samples were predominantly composed of dolomite and calcite minerals, having strong affinity with grains, clay, and cementing minerals, that increasing the reservoir heterogeneity.
3. FTIR spectroscopy identified the predominance of dolomite mineral and diverse range of carbonate phases, with calcite being prevalent. Structural variations and identification of various carbonate cements with several observed minerals highlight the complexity of the formation that corresponds to complex geologic history and depositional settings.
4. The complex interplay of diagenetic processes intensifies the reservoir heterogeneity by influencing the petrophysical properties and becomes crucial for effective reservoir performance management.
5. The petrophysical analysis of the formation showed an average porosity of 5.13% and an average permeability of 0.89 mD, indicating significant heterogeneity. This complexity is attributed to various diagenetic processes and the interplay of factors such as mineralogical composition, fossil content, crystal size variations, clay content, and pore structure distribution.
6. The identification of micro cracks suggests potential complexities in fluid flow behavior, resulting in moderate to poor quality reservoir. The weaker correlation between bulk density and porosity suggests non-uniform and heterogeneous pore structures.

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Disclosure Statement

The authors declare no potential conflict of interest.

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