

Research Article

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An integrated analysis of mineralogical and microstructural characteristics and petrophysical properties of carbonate rocks in the lower Indus Basin, Pakistan

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Abstract: Carbonate rocks are believed to be proven hydrocarbon reservoirs and are found in various basins of Pakistan including Lower Indus Basin. The carbonate rock intervals of the Jakkher Group from Paleocene to Oligocene age are distributed in south-western part of Lower Indus Basin of Pakistan. However, there are limited published petrophysical data sets on these carbonate rocks and are essential for field development and risk reduction. To fill this knowledge gap, this study is mainly established to collect the comprehensive high quality data sets on petrophysical properties of carbonate rocks along with their mineralogy and microstructure. Additionally, the study assesses the impact of diagenesis on quality of the unconventional tight carbonate resources. Experimental techniques include Scanning Electronic Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS), and X-ray diffraction (XRD), photomicrography, Helium porosity and steady state gas permeability. Results revealed that the porosity was in range of 2.12 to 8.5% with an average value of 4.5% and the permeability was ranging from 0.013 to 5.8mD. Thin section study, SEM-EDS, and XRD analyses revealed that the samples mostly contain carbon (C), calcium (Ca), and magnesium (Mg) as dominant elemental components. The main carbonate components observed

were calcite, dolomite, micrite, Ferron mud, bioclasts and intermixes of clay minerals and cementing materials. The analysis shows that: 1) the permeability and porosity cross plot, the permeability and slippage factor values cross plots appears to be scattered, which showed weaker correlation that was the reflection of carbonate rock heterogeneity. 2) The permeability and clay mineralogy cross plots have resulted in poor correlation in these carbonate samples. 3) Several diagenetic processes had influenced the quality of carbonates of Jakkher Group, such as pore dissolution, calcification, cementation, and compaction. 4) Reservoir quality was mainly affected by inter-mixing of clay, cementation, presence of micrite muds, grain compactions, and overburden stresses that all lead these carbonate reservoirs to ultra-tight reservoirs and are considered to be of very poor quality. 5) SEM and thin section observations shows incidence of micro-fractures and pore dissolution tended to improve reservoir quality.

Keywords: permeability, porosity, mineralogy, stress sensitivity, petrophysics, diagenesis, petrography

1 Introduction

Characterization of carbonate reservoir rocks is essential for production forecasting and reservoir management. The petrophysical properties are known to have significant impact on reservoir development strategies and are essential for assessment of reservoir potential [1]. It is very challenging to assess the petrophysical properties, pore structure, and rock heterogeneity of hydrocarbon bearing carbonate rocks. As the carbonate rocks exhibit diversified pore sizes, pore geometry, and pore morphology, they are known to be the highly heterogeneous rocks [2, 3]. More specifically, the carbonate rocks exhibiting significant discrepancy in their pore size is due to the substantial sedimentation processes and diagenesis that may create microporous grains and diversified size of pores, leading to com-

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plex dissemination of pores and pore interconnectivity resulting into noticeable changes in their petrophysical properties [1]. The routine core analysis techniques are unsuitable to determine tight reservoir rocks petrophysical properties being practiced for performance analysis. Therefore, special core analysis techniques are needed to assess the tight carbonate rocks more appropriately. In addition, it is challenging to measure the permeability of tight carbonate rocks and describe its pore characteristics comprehensively by simple conventional core analysis techniques. This requires special core analysis techniques in order to measure petrophysical properties and to perform detailed characterization [1, 4]. Hence, the present study has assessed the carbonate rock properties by use of various integrated approaches. The most imperious petrophysical properties of carbonate rock are permeability, porosity, pore size distribution, microstructure, capillary pressure, and relative permeability [5]. Aforementioned rock properties play an important role on production forecasting and reservoir production performance predictions [6, 7]. They could be significantly changed due to the tectonic activities and diagenetic alterations [5, 8, 9]. Generally, the variations in petrophysical properties depend on depositional environment and diagenetic processes [5, 8, 9]. Discrepancies in rock petrophysical properties would occur due to depositional environments and diagenetic processes leading to the variations in reservoir quality [7]. It is challenging to characterize the pore microstructure and analyze the petrophysical properties of carbonate rocks [2, 7, 10]. Therefore, it is essential to better understand all those parameters that affect the reservoir production performance, such as permeability, porosity, and the impact of overburden stress. More specifically, the petrophysical characteristics have significant influence on carbonate reservoir productivity and are essential in predicting fluid flow properties. Therefore, an extensive study is required to better understand the microstructure, petrophysical properties of carbonate rocks, the flow properties within the porous and fractured formations and are substantially needed in assessing the carbonate reservoir characteristics [11]. This encompasses considerable understanding of the pore size; permeability, rock texture, and existence of natural fracture systems within carbonate formations.

It is reported that the tremendous oil and gas reserves accumulation have been discovered and reported within the carbonate bearing rock formations around the globe *e.g.* Russia, Kazakhstan, and North America [12]. It is anticipated that the carbonate reservoirs contain 60% oil and 40% gas reserves all over the world [12]. Among them, the Middle East (*e.g.*, Saudi Arabia, Oman, Iraq, Bahrain, Iran, United Arab Emirates, Qatar) carbonate rocks exhibits a

large amount of oil around 70% and the gas reserves are almost 90% [13]. Likewise, the substantial hydrocarbon potential have also been reported that exists in Pakistan within the carbonate reservoirs rocks [14, 15]. In Pakistan, the lower Indus Basin carbonates and Kohat-Potwar sub-basin are reported to be the main carbonate reservoirs that have been attracted by many exploration and production (E&P) firms for exploitation of hydrocarbon potential [14]. These carbonate reservoir rocks are highly fractured and pretending copious challenges in reservoir characterization, production and management and poses massive technical hindrance in exploitation and drilling [14]. The fractures have significant impact on controlling the production behavior of reservoir and field development, planning and facilities installation [7, 16]. Due to such complexities of carbonate reservoirs many petroleum E&P companies have been facing copious challenges in exploiting and developing highly heterogeneous carbonate reservoirs [17]. Some of the major technical and economic challenges faced by E&P industry are that these reservoirs contains very low hydrocarbon volumes, exhibits extremely tight permeability which requires expensive stimulation treatments, longer well cleanup periods, relatively higher costs to import technologies and obtain expensive services, less service provider competitors and material suppliers, due to very tight nature of reservoir early water production issues, lower gas rates, marginal profits, complex reservoir geology and complex petrophysics [15]. In this regard, prior to development of any carbonate reservoir, it is highly recommended to address all aforementioned challenges involved in exploitation and development of reservoirs by provide accurate rock properties [17]. Many E&P companies working in Pakistan to date have conducted numerous types of surveys and have conducted research that is more specifically concentrated on geological aspects of carbonate reservoirs [14, 18, 19]. However, the petrophysical properties, mineralogy and microstructural analysis of carbonate reservoirs have not been assessed appropriately with some exceptions of [15]. For efficient exploitation and development of hydrocarbon reservoirs, it is essential to assess the carbonate rock petrophysical and microstructural properties and the factors that affect the reservoir quality. The reservoir quality is directly related to the porosity and permeability of the reservoir and is necessary to explore those aspects that control these reservoir rock properties. Since the diagenetic changes significantly affect that reservoir quality, it must be also evaluated.

The main aim of this study was to collect the high quality data on carbonate rock formations of Jakkher Group based on petrographic thin sections and petrophysical property measurement in order to understand the de-

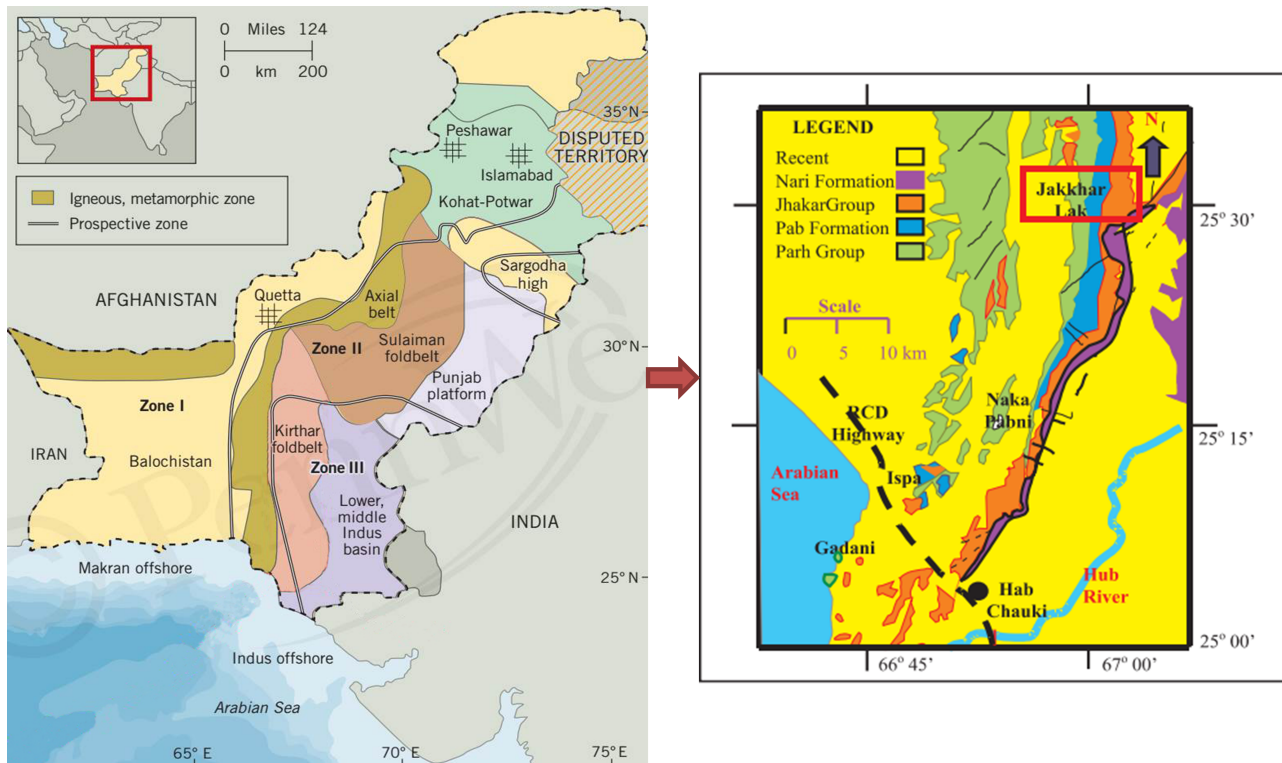


Figure 1: Geological map of sedimentary basins of Pakistan showing the location of study area [Modified after 29, 30].

positional textures, to visualize the porosity, and to assess the diagenetic features that influences the carbonate rock quality. Petrography is the valuable tool that offers fundamental base for discovering diagenetic relationships among the rocks [20]. It is essential to understand the diagenetic relationships and common reactions that take place in carbonate rocks, resulting into changes that may appear in rock texture affecting the grains, matrix, cements, porosity evolution, and permeability that ultimately affect the quality of reservoir rocks. In the literature, there are several good examples that highlight such information regarding carbonate rocks [21–23] and more exclusively, offers technique to visualize, as well as thinking about and comprehending the permeability, porosity evolution in carbonate reservoirs. The diagenetic analysis is the fundamental requirement for the feasibility of reducing exploration risks. Hence, the study has analyzed the main diagenetic processes that may have considerably affected the original rock fabrics and characteristics after deposition. Moreover, the study has supplemented by adding new knowledge on the various essential aspects of the reservoir rock such as presence of cement types, open and cemented fractures, diagenesis, as well as the influence of diagenesis on quality of reservoir rock to evaluate the potential of carbonate reservoirs in the region. Additionally,

the present study analysis offers a sound basis to evaluate the parameters that impact the fluid flow within carbonate reservoirs rocks along with diagenetic controls. Interestingly, the study would have significant implications in investment making decisions that would reduce the risk associated in the target reservoirs exploitation. Moreover, it provides a comprehensive understanding the carbonate rock petrophysical properties and impact of diagenesis on quality of the rock in the exploitation and development of unconventional tight carbonate resources. The findings of present study may have substantial implications for further development of newly discovered oil and gas fields to improve the performance predictions in the country and in region.

2 Geological Setting

The study area of this paper includes the southern part of Pab range which is in the west of Kirthar Fold Belt, and Jakkher pass Balochistan, Pakistan. Regionally, Kirthar Fold Belt is part of the north-south trending mountain belts in Pakistan linking the Himalayan orogeny with the Makran accretionary wedge (Figure 1). The map of generalized stratigraphic column of Lower Indus Basin of Pak-

Table 1: Specification of core sampling, testing, and number of samples selected for measurements.

Location	Stations	Sample ID	Core Length L (cm)	Helium Porosity	Gas Per-meability	XRD	SEM	Thin section	EDS
Jakkher Balochistan	1	18-JK-01	4.30	03	03	02	02	02	02
		18-JK-04	3.00	02	02	03	01	04	03
	2	18-JK-05	5.20	03	03	01	02	03	02
		18-JK-08	4.50	04	04	02	02	04	02
	3	18-JK-11	4.40	02	02	02	03	05	03
		18-JK-13	4.44	03	03	01	02	05	04

STRATIGRAPHIC NOMECLATURE OF AREA					
Era	Period and Symbol	Epoch	Group/Formation	Members	Lithology
CENOZOIC	Quaternary (Q)	Recent	Streambed Deposits (Qs)		Unconsolidated sand, gravel, pebble and clay.
			Alluvial Deposits (Qal)		Fine sand, silt and clayey material.
		Sub-Recent	Terrace Deposits (Qt)		Pebble, gravel and boulder of older rocks consolidated with sandy material.
	Tertiary (T)	Miocene	Gaj Formation	Mol Member	Limestone, marl with minor clay.
				Mundro Member	Predominantly shale/clay, with sandstone and minor marl.
		Oligocene	Nari Formation	Orangi Member	Multicoloured sandstone with subordinate shale and clay.
				Pir Mango Member	Limestone with shale and minor sandstone.
				Hub Member	Massive and resistant sandstone with subordinate shale.
				Tobo Member	Sandstone, sandy limestone and minor shale.
		Paleocene to Oligocene	Jakker Group		It consists of limestone and shale. lower part is characterized by the interbedded shale and sandstone(minor) with ferruginous nodules and upper part mainly consists of limestone.
Mesozoic	Cretaceous (K)		Pab Sandstone		Consists mainly of sandstone with subordinate shale, marly limestone and minor conglomerate.

Figure 2: Generalized tabulated nomenclature of the stratigraphic column of Jakkher Group carbonates.

istan is presented in Figure 2 that shows various formations distribution along with Jakkher Group carbonates. Generally, this region is being deformed obliquely as well as parallel to the regional plate motion vector [24, 25]. The Kirthar Fold belt and surrounding complex structural units have been formed during the collision between Indo-

Pak and Eurasian plates. The initial collision and subduction occurred in Paleocene to Eocene times, possibly along the N-S trending line of the Lasbela Ophiolite Belt, when the Indo-Pakistani plate was moving westwards [26]. The resulting N-S trending, easterly transported thrust faults and folds are the dominant structural elements in the re-

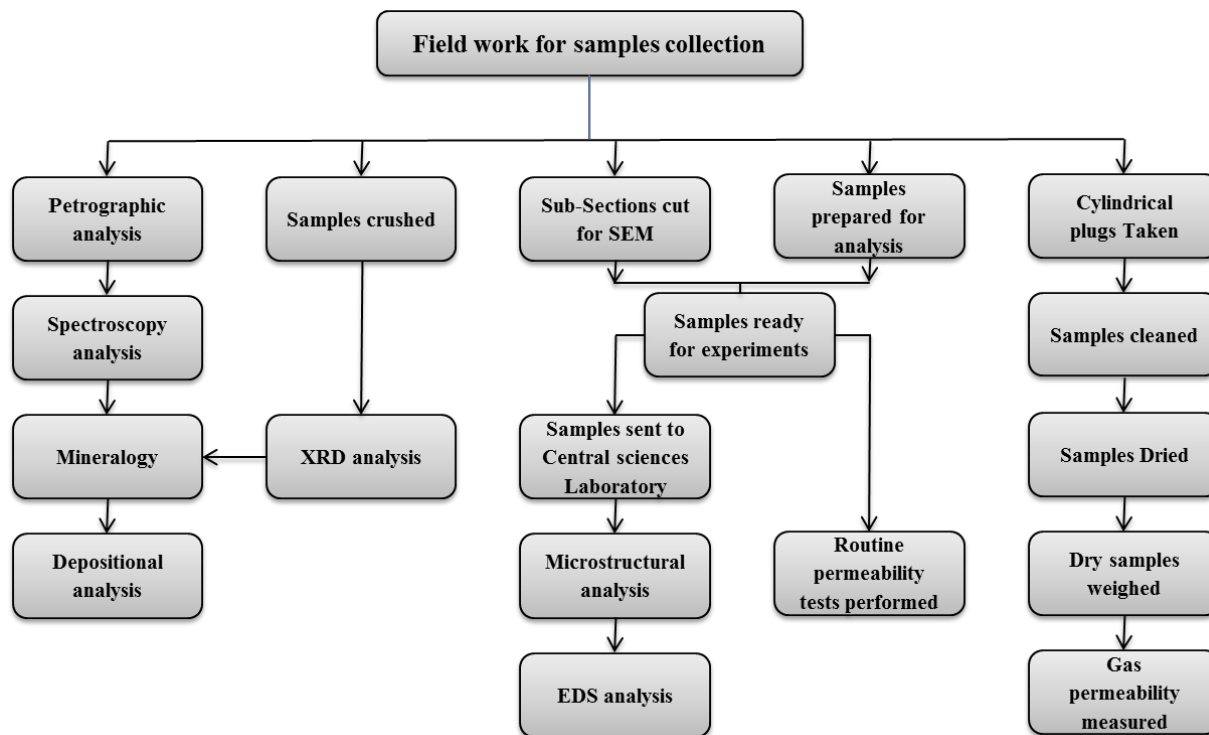


Figure 3: Illustration is the comprehensive experimental workflow.

gion. Kirthar Fold Belt is adjoined with Bela ophiolitic complex/Balochistan basin, lower Indus platform, Offshore Indus basin, and Sulaiman Fold belt in west, east, south, and north, respectively. The rocks overlying the basement of the Indo-Pakistan Plate are mainly consisting Mesozoic and Cenozoic age [26]. The Mesozoic sediments were generally deposited in marine geo-synclinal structure and partially pelagic origin. Likewise, the overlying Cenozoic rocks were mostly deposited under shallow water conditions [27]. Stratigraphically, the studied samples were taken from the limestone of Jakkher Group. This Group takes its name from a Jakkher Lak, a pass and peak in the southern Pab range [28]. The Jakkher Group lies on the eastern flank of Pab range and its stratigraphic position is in between Cretaceous Pab formation and Oligocene Nari formation. Therefore, it is specified that the age of Jakkher Group would range between upper Paleocene to early Oligocene. Likewise, the different fauna of Paleocene, Eocene, and Early Oligocene age have been reported in the Jakkher Group. The average thickness of Jakkher Group as measured at study area is 750 m, including 150 m upper limestone part and 600 m lower shale part. Furthermore, shale is predominant lithology at the north while limestone increases in proportion southward in Jakkher Group. The limestone of Jakkher Group is typically less sandy as

compared to other Paleocene limestone and it is massive and shows no nodularity.

3 Materials and Methods

Extensive laboratory analyses were conducted on selected samples of carbonates outcrop samples collected from southern Pab range Kirthar fold belt, lower Indus basin, Balochistan, Pakistan. The samples collected for analyses were ranging a typical size of 12 to 15 cm block. The number of samples analyzed for petrophysical properties measurements along with all other tests are provided in Table 1. The experimental flow chart is shown in Figure 3. The details of each experimental procedure are described separately.

3.1 Petrography

Petrographic studies of the selected samples were performed at the Geological survey of Pakistan, Karachi office. Leica optical microscope was used to identify minerals and fossils. Thin sections were prepared about to 0.03 mm thickness and were carefully studied under polarized microscopes.

3.2 Scanning Electron Microscopy (SEM) for Microstructural Analysis

The microstructure and diagenetic features of samples were examined using Scanning electron microscope (SEM). A JEOL-Japan Compact SEM at centralized sciences laboratory of University of Karachi, was used to observe microstructure and mineralogy of the samples. Polished thin sections were prepared for analysis and carbon coated and then these were examined using a JEOL, Tokyo, Japan Compact field-emission- SEM equipped with a link system Energy Dispersive X-ray microanalyzer (EDS). The purpose of SEM was to confirm the mineralogy obtained from XRD and to determine the diagenetic features of each sample that affect the reservoir quality and petrophysical properties of carbonate rocks. The main diagenetic processes that are responsible for altering the pore structure and carbonate reservoir rock properties were examined.

3.3 X-ray Diffraction (XRD)

Analysis for mineral composition of 1 cm^3 representative samples was undertaken from collected outcrop blocks. XRD experiments for rock mineral analysis were conducted by preparing powder of less than $20\text{ }\mu\text{m}$. XRD data was obtained using the spray dry technique using the X-ray Diffractometer PANalytical X'Pert Pro powder. The sample was powdered with 20 wt. % silicon, which acted as a standard. The powder of prepared samples was then sprayed in the furnace leading to formation of approximately $20\text{ }\mu\text{m}$ random sized grains with random orientations. These samples were then loaded into sample chamber and analyzed using diffractometer. The system prior to experiments and XRD results interpretations was calibrated using standard procedures. The minerals concentrations of samples obtained through diffraction patterns considering the intensity ratio of reference mineral and orientation.

3.4 Porosity

The plugs porosity was determined using the helium expansion porosimeter. The porosity was calculated using Boyle's law porosity and determined as the difference of the core plug bulk volume which was measured with a caliper, and grain volume was measured adopted the Boyle's law method. The principle involves the compression of gas into pores of rock samples. The experimental setup consists of two chambers. Initially, the helium gas was introduced into the two chambers and the valve

between chambers kept open. Same time was allowed for pressure stabilization. This was followed by placing the core sample inside one of the chamber at pressure p_1 , and was separated from the second chamber at pressure p_2 . After few minutes of pressure stabilization, the valve between chambers is opened and wait until the pressure equilibrate and to reach a final pressure p_f . The core sample pore volume was occupied by the helium gas used; hence the difference between the two test conditions would be the measure of the grain volume of the core.

3.5 Steady State Permeability Experiments with Tri-Axial Loading

Klinkenberg corrected steady-state gas permeability experiments were performed using an innovative permeability measuring experimental setup as shown in Figure 4. The system was calibrated prior to permeability measurement and tested for leaks. This system measures the permeability of samples of different sizes ranging from 2.5 cm and is capable of applying tri-axial loading through hydraulic pump. This setup is connected with gas cylinder to apply constant gas pressure and to record the stabilized gas rate at the outlet in order to measure the steady state permeability. The permeability measurements were made under different confining stress conditions. The experiments of the current study were performed applying different confining stress starting from 500 psi to maximum of 2500 psi with 500 psi incremental pressure.

Mathematically, the gas permeability of the core samples was determined by adopting steady state procedure that can be described as follows;

$$k_g = \frac{2\mu LQ}{A(P_1^2 - P_2^2)} \quad (1)$$

where the flow rate is represented as Q that is related to the permeability k_g , core plug cross-sectional area is represented as A , gas viscosity is μ , pressure across the length of core is P_1 , which is upstream pressure and P_2 is the downstream pressure and length of the core samples is represented as L .

Further, the gas permeability measured was corrected for the gas slippage effects [31]. The phenomenon of gas slippage is described as when gas is allowed to flow through the very tiny pore capillaries with pore diameter similar to the mean free path of the gas molecules. The striking of gas molecules to the pore walls increases the flow rate of gas, which results in ultimate increase in gas permeability [32, 33]. Such increase in permeability resulting from molecules and pore walls interactions is most of

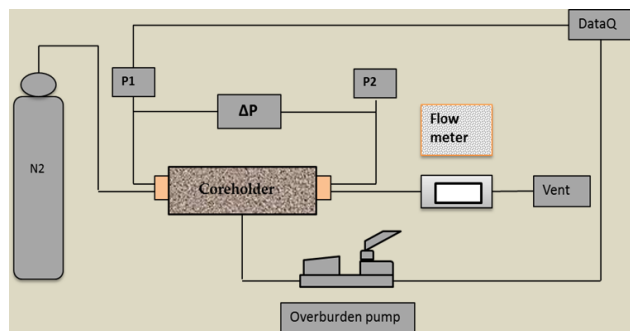


Figure 4: Schematic is the experimental setup for steady state permeability measurement under confining stress conditions, the P1 and P2 are the upstream and downstream pressures respectively.

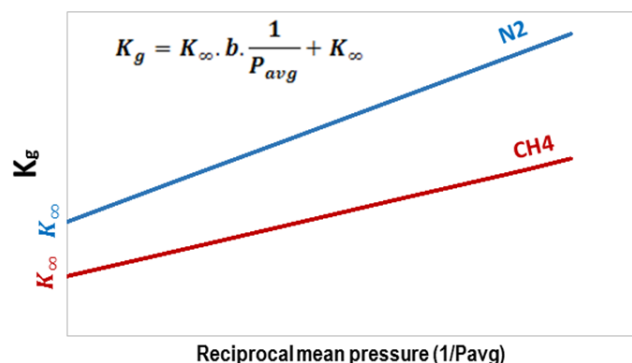


Figure 5: Illustration is an example of the Klinkenberg corrected permeability of sample using two different gases and different mean pressures [Modified after 34].

ten known as Klinkenberg's slippage effect (Figure 5) [31].

4 Results and Discussions

4.1 Petrography

Analysis of the carbonate samples from fossil assemblage and texture under petrographic microscope showed that these samples were deposited near fore-slope depositional environment according to [35] classification of carbonate rocks. The dolostone may be due to the increase of manganese content in sea water that would probably due to regression reducing the water depth. Thin section photomicrograph in Figure 6 displays the various petrographical descriptions and features of Jakkher Group carbonate rocks. Petrographic and SEM examination of the lower Indus Basin Jakkher Group rocks showed both primary and secondary porosity that was evident from micro-cracks and fractures. SEM observation showed that most of samples were exhibiting intergranular porosity along with as-

sociated micro pores exhibiting dense rock pore structure tending to very tight carbonate rocks. Further, it was noticed that some diagenetic processes have altered the rock porosity by precipitation and secondary filling of micrite muds within pore spaces resulting into the pore throats size reduction. Most of samples were very low in porosity and permeability due to the diagenetic alterations. These Jakkher Group carbonate rock features observed from thin section analysis and petrographical point of view are shown in Table 2 and Figure 6.

4.2 Mineralogy

Thin section study, SEM-EDS, and XRD studies have shown that the minerals in the Jakkher Group carbonates include the, calcite, dolomite and intermixes of clay and cementing materials as dominant mineral components [Figure 7 and Figure 8]. In addition, the aluminum (Al), silicon (Si), irons (Fe), and intermixes of clay and cementing materials were also noticed [Table 3]. These observed minerals establish the carbonate rock framework grains along with the minor amounts of clay and intermixes of cementing materials. The detailed descriptions and characteristics of some selected carbonate samples are provided in Table 3. An XRD study carried out confirmed that rocks mainly composed of the CaCO_3 limestone rock as shown in Figure 7.

The quality of the carbonate reservoirs essentially depends on the mineral constituents, rock texture, depositional settings, and diagenetic modification of porosity and permeability [36]. Porosity and permeability are two main petrophysical properties that are partly controlled by the textural characteristics of grain arrangement, size of the grains, shape and grain packing [36]. The grain textural properties are also influenced by the rock deposition that eventually is influenced by lithified actions, such as aging, mineral cementation, mineral compositional changes [37]. The presence of different minerals affects the reservoir quality in different ways in subsurface [38]. Some mineral components and their contents have great influence on the pore microstructure and have impact on fluid flow properties in the subsurface reservoirs. The reservoir rock permeability, porosity and sealing capacity could also be affected by the mineral compositions [37, 39]. Mineralogy has significant role in sediment diagenesis and controlling the fluid flow through rocks. The fluids that flow across the sedimentary environments brings different changes by cementations, dissolutions, particle movements, and authigenesis of minerals [38].

Table 2: Detailed petrographic observations of Jakkher Group carbonate samples from thin sections photomicrography analysis

S.No.	Sample ID	Petrographic description
1	18-JK-01	It is a Ferro-Bio-Micrite, limestone. Shows considerable variation in mineral assemblages. Bioclasts of Nummulites with other unidentified broken forams and some algal fragments are cemented by Ferroan rhombic sparry calcite. The rock in Dunham classification falls in the category of Packstone.
2	18-JK-04	Silty Pel-Micrite Rock. Intraclast of silt sized quartz grains cemented by micrite calcite. Iron concretions are present among quartz grains. A considerable amount of peloids are in micrite mud. This rock is wackestone according to dunham classification.
3.	18-JK-05	The rock is Bio-Micrite Limestone. Rock is highly fractured. Bioclasts of Discocyclinoid with other broken foraminifera shells cemented in a dense micritic mud. An oolite filled with sparite. Pellets are visible in micrite at places. This rock is wackestone according to dunham classification.
4.	18-JK-08	The rock is sparse bio-silty micrite. Silt sized quartz grains are abundantly present. Algal fragments and Nummulites bioclasts are identifiable. Rock is cemented dominantly by micrite with minor washing by sparite. A wackestone cluster of spherical grains in micrite mud bounded with iron oxide meniscus cement. It falls in wackestone category of Dunham classification.
5.	18-JK-11	This rock is classified as dolostone. The rock is fine grained dolostone. Dolomite crystals are sub-hedral to Euhedral shape, mostly Mg rich with a few Fe rich crystals. Crystal distribution is loosely packed. Fabric is peloidal. Cement is micrite.
6.	18-JK-13	This falls under the limestone classification of carbonate rocks. The rock is sparse bio-micrite. bioclasts of Nummulites and Algae are frequently present. Rock is cemented dominantly by micrite with minor washing by sparite. It falls in wackestone category of Dunham classification.

Table 3: Scanning electron microscopy (SEM-EDS) analysis from the Jakkher Group carbonates.

S.No.	Sample ID	Description
1	18-JK-01	This has shown calcite and clay mineral forms the bulk of photograph area. Clay mineral is most probably chlorites. SEM-EDS analysis, the minerals observed are Ca and C indicate calcite and high amounts of Si, Al, and K indicates clay content.
2	18-JK-04	The above photomicrograph shows the major areas are occupied by calcite. The EDS graph displays relatively high percentages of Ca and C indicating calcite. Other detected elements such as Si Al, and Fe are probably due to intermixed clay content. Mg is probably the part of calcite.
3.	18-JK-05	In the SEM photograph, calcite is intermixed and covered up with clay content probably smectite. SEM-EDS analysis indicates the Ca and C peaks for calcite. Elements of Si, Al, Na, K, and Fe probably belong to smectite. Small quantity of Mg observed may either be part of calcite or smectite.
4.	18-JK-08	The above photograph shows almost all the area is occupied by calcite. SEM-EDS analysis shows high detections of Ca and C referring to calcite, while Mg may be part of Calcite.
5.	18-JK-11	This sample reveals that calcite forms the bulk of photograph area. Small detrital quartz grains are also visible. SEM-EDS analysis indicates relatively high percentages of Ca and C showing calcite composition. Mg may be the part of Calcite. Si and Al is probably the part of clay content.
6.	18-JK-13	In this sample the calcite mineralogy is prominent as seen in SEM photomicrograph forming bulk area. The EDS analysis indicates the high Ca and C values of calcite. Small quantity of Mg probably is part of calcite and Al indicates clay impurity in sample.

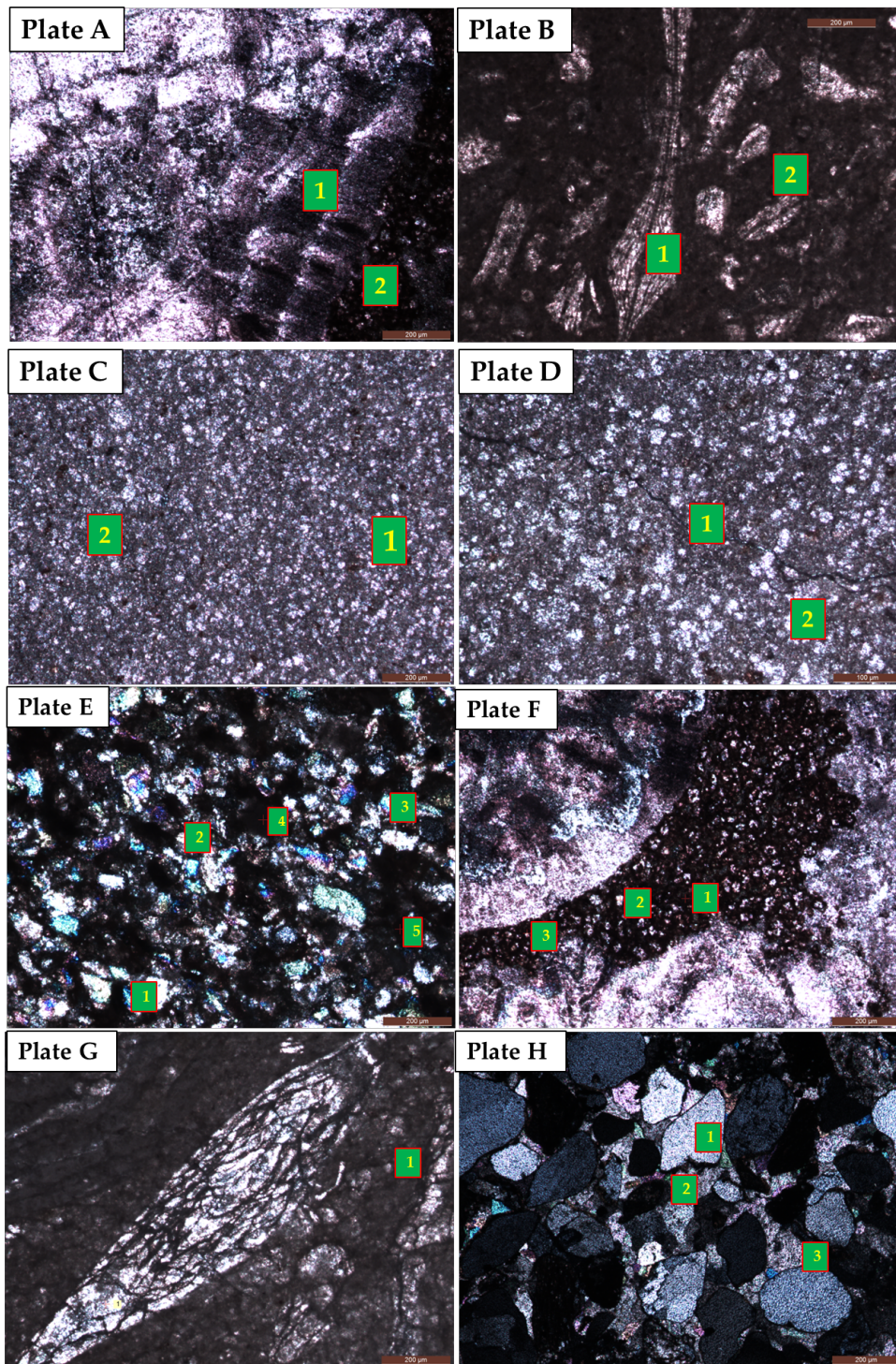
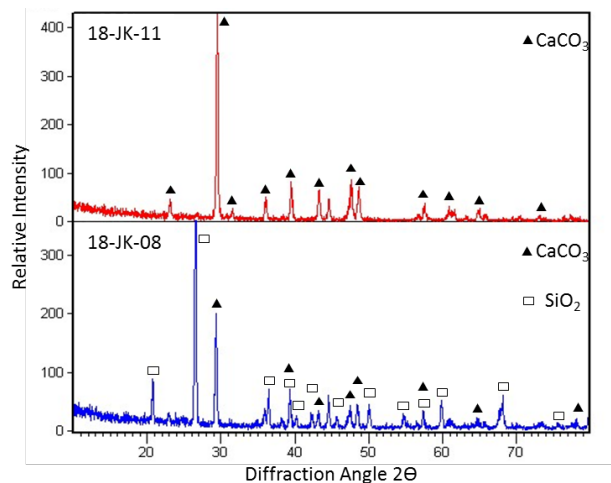


Figure 6: Thin section photomicrograph displays the petrographical description of carbonate rocks showing: **[Plate A]** point 1 displays the Nummulite and point 2 is Dolomite Rhomb. **[Plate B]** displays Discocyclus at point 1 and point 2 is the Peloidal Micrite. **[Plate C]** shows at point 1 are the Mg-Rich Dolomite crystal and at 2 is the Fe-Rich Dolomite crystal. **[Plate D]** the image shows the micro crack, fracture filled with carbonaceous material; and the point 2 displays the Calcisphere. **[Plate E]** observations are as 1, 2, 3, Quartz Crystals; 4, Micrite and point 5 is the Fe-Rich Dolomite Crystal. **[Plate F]** inside the image points 1, 2, 3, are the dolomite crystals surrounded by washed Nummulite walls. **[Plate G]** image displays the fractured Nummulite at the center surrounded by fine micrite mud. **[Plate H]** shows the Quartz crystal with calcite cement surrounded by coarse micrite mud. **The scale bar = 20µm.**

Table 4: Basic properties of the samples obtained.

S. No.	Sample ID	L (cm)	D (cm)	Area (cm ²)	Dry Wt. (g)	Density (g/cc)
1	18-JK-01	4.30	3.8	11.34	155.45	2.71
2	18-JK-04	3.00	3.5	9.62	89.14	2.68
3	18-JK-05	5.20	3.7	10.75	168.5	2.62
4	18-JK-08	4.50	3.8	11.35	172.20	2.60
5	18-JK-11	3.20	3.5	9.62	92.35	2.65
6	18-JK-13	4.20	3.8	11.34	130.18	2.64

**Figure 7:** Illustration is the XRD results from two of the Jakkher Group carbonate samples.

The samples showed that the dominant minerals are calcite and minor dolomite accompanied by some other accessory minerals. The dominating elements observed from SEM-EDS patterns are Ca, C, and Mg, showing the carbonate rock assemblage [Figure 8]. The Al was found in some of the studied samples, which indicates that the minor intermixed clay minerals are associated with samples. The Si observed from EDS patterns showed the siliciclastic influx within the carbonate rock samples. The SEM photographs revealed the main diagenetic features of the carbonate rocks. Carbonate rock fragments and associated mud are highly bio-mineralized yields of the existing marine organisms. Diagenesis can result into complex petrophysical properties of carbonate sediments and has strong influence on porosity and permeability impacting on the quality of carbonates reservoirs [20]. Thin sections petrographic analysis and scanning electron microscopy interpretations emancipated that the closer grain contacts, indicating a low diagenetic evolution. Despite the fact, the original sedimentary features such as well-sorted, very fine grained sediments along with their diversified inter-

mixed sediments set out these reservoirs very tight exhibiting low permeability and low porosity reservoirs. It also showed very fine mixed terrigenous sediments with carbonates. Fine terrigenous components mixed with micrite cement, and also the grain coatings of illite-smectite on carbonate crystals. The Si element observed from SEM-EDS graphs shows the siliciclastic influx within the carbonate rock along with some ferrous materials. SEM studies shown that accordion-shaped calcite fragments were also noticed in sample 18-JK-01 in some places (Figure 8). The SEM-EDS analysis of sample 18-JK-01 shows the occurrence of kaolinite clay in form of booklets crystal flakes. Furthermore, the kaolinite clay has tendency to appear as an extra mineral that has tendency to reduce the permeability and porosity of carbonate reservoir rocks.

4.3 Porosity and Permeability

The basic properties of the samples of Jakkher Group are presented in Table 4. Few samples from Jakkher Group were sandy to argillaceous carbonates and most of them were exhibiting high volume of pure calcite and were characterized by a relatively low grain density of 2.70 g/cm³. The grain density for the samples exhibiting calcite minerals is of 2.81 g/cm³ on average. Furthermore, the grain boundary fractures could be observed within these carbonates from images of thin sections resulting into different porosity types. These samples were noticed that they developed two types of porosities (i) the porosities developed under the existence of microfractures and were ranged from 2.55 to 12.82%, with an average value of 3.86%, (ii) the porosities which developed in absence of micro-cracks and were ranging from 2.12 to 8.5% with an average value of 4.5%. Similarly, we observed a big variation in permeability values, the permeability measured were ranging from 0.013 to 5.8 mD for those samples without micro-cracks. The samples with obvious microfractures were exhibiting high permeability values and were discarded

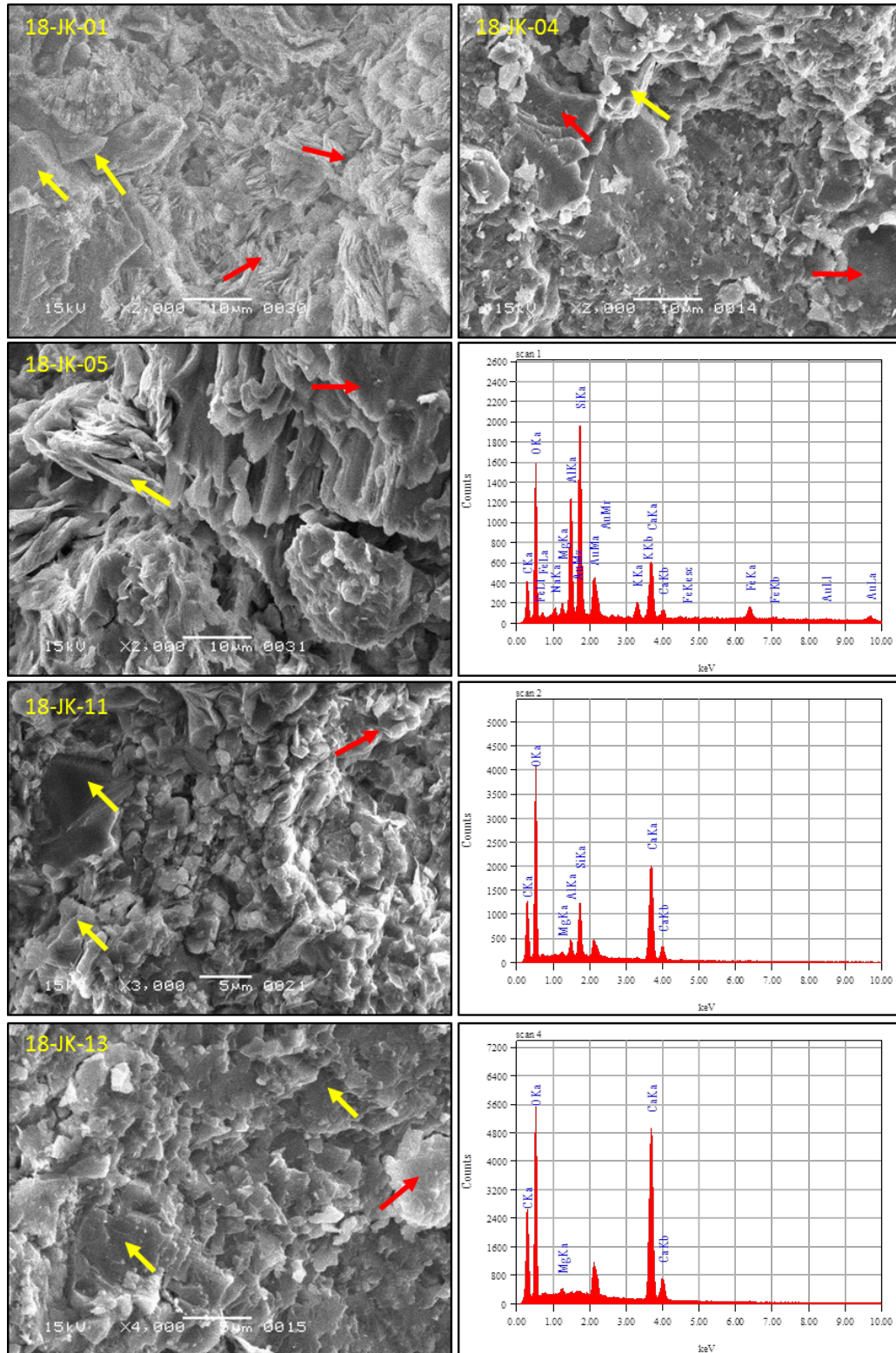


Figure 8: The microstructure and mineral compositions identified via EDS patterns and from SEM results are shown in Figure. The mineral contents in SEM photomicrograph of Jakkher carbonates; (18-JK-01) yellow arrows show calcite and red arrows show clay (chlorite). (18-JK-05) yellow arrow shows clay content and red arrow shows calcite; (18-JK-11) yellow arrows show coarse grained calcite and red arrow shows micritic calcite. (18-JK-13) all arrows show sparry calcite; (18-JK-04) all arrows show calcite, yellow shows the cleavage face of calcite grain; (18-JK-13) the arrow shows sparry calcite. In Figure the EDS patterns shows the dominating elements are Ca, C, and Mg.

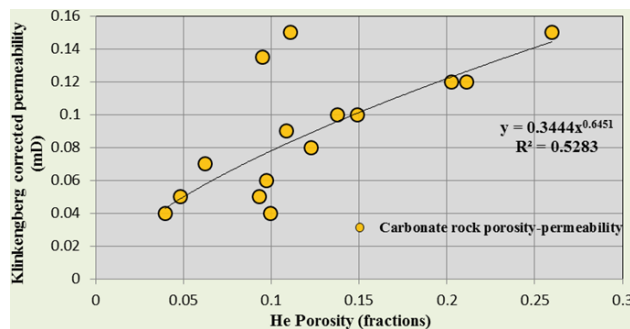


Figure 9: The illustration of the relationship between Klinkenberg corrected permeability (nitrogen) and porosity (Helium).

from the analysis. Though, the samples with open microfractures permeability were determined as higher values ranging from 12.5 to 25 mD with an average value of 15.5 mD. Moreover, the porosity and permeability results obtained shows relatively linear trend line when plotted on a semi-logarithmic graph, and the fitted correlation between values shows the power law relationship (Figure 9). However, the permeability and porosity data plotted did not appear in the linear relationship due to rock heterogeneity. The diagram of permeability-porosity scatter shows that the carbonate rocks studied encompass different pore size and pore-throat geometries.

From few thin sections analysis of Figure 6 Plate D displays the micro fractures resulting into high permeability values. The permeability and porosity data cross plotted showed few outliers in the Figure 9 that was due to micro cracks as observed from thin section analysis. Furthermore, it is highly recommended that the impact of grain boundary fractures could be analyzed within these carbonates by preparing the polished surface thin sections. The permeability measured exceeding 20 mD is not included in the plot of permeability-porosity because this was resulting in big scatter on chart. The reason of such high permeability in the samples was the existence of obvious microfractures and micro-cracks as observed from one of the thin sections. These naturally fractured reservoirs would exhibit high permeability values and are expected to produce at commercial rates without application of fracturing the reservoirs for increasing permeability.

4.4 Klinkenberg Corrected Permeability and Slippage Parameters

There are many studies that have described the gas slippage effects particularly within tight gas sandstones and several models have been developed [40]. However, it is ex-

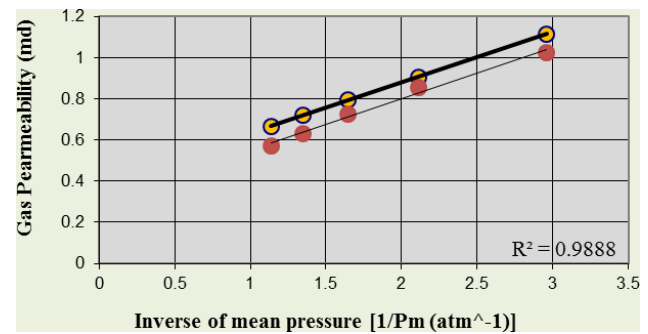


Figure 10: Illustration shows the Klinkenberg corrected gas permeability of the carbonate samples.

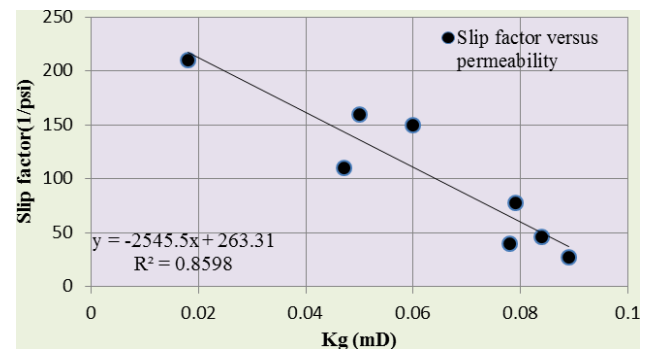


Figure 11: Illustration shows the relationship between carbonate rock permeability and gas slippage factor.

remely important to analyze the gas slippage phenomena associated to tight carbonate rocks for permeability prediction and accurate assessments. In public domain, there are numerous correlations that narrate the gas slip factor and permeability relation describing the sandstone rocks relationship [31–33, 41–46]. The values of some slippage parameters along with gas permeability obtained under varying overburden stress conditions. The relationship concerning to the permeability coefficients k_g of the samples 18-JK-01 and 18-JK-03 using nitrogen gas as pore fluid as a function of reciprocal of average pore pressure under varying pore pressure conditions is presented in Figure 10. The relationship between gas permeability and gas slip factor developed and found that there was scatter in permeability and slippage factor data (Figure 11). Such scatter in slippage parameters and permeability could be the results of carbonate rock heterogeneity and non-uniqueness of the pore size within studied samples. Hence, it is obvious that the permeability result would not be estimated from existing empirical correlations accurately due to carbonate rocks exhibits large heterogeneity and varying pore morphology. Additionally, in literature various researchers has attempted to provide with improved slippage estimation relation by inclusion of other parameters such as in

model of Sampath and Keighin [42] porosity is included this might work well for sandstone rocks. Since carbonates are highly heterogeneous rocks having fractures and secondary porosity, these empirical relations might not fit well. It is highly recommended where necessary to measure these petrophysical properties in the laboratory to appropriately analyze the reservoir behavior and to predict the future performance.

4.5 Effect Of Overburden Stress

The permeability reduction due to overburden stress could significantly affect the overall output of the ultra-tight permeability reservoirs [29, 47, 48]. There have been few papers that have addressed stress sensitivity in impact on oil and gas reservoirs in Pakistan; this requires more researches attention in order to develop stress sensitivity low permeability reservoirs. Studies [29, 47, 49] have shown that the tight, low permeability reservoirs are more sensitive to the overburden stress than conventional reservoirs. The elements responsible for decreasing the permeability due to applied stress are the pore size and pore throat. However, the samples recovered from subsurface may results in formation of the micro-cracks. If confining stress is applied in laboratory, the micro-fractured samples will results in more reduction at higher overburden stress [47, 49]. From experimental observations, the absolute gas permeability has shown reduction for both samples of carbonate with increase in net stress (Figure 12). The net stress is characterized as following equation

$$\sigma' = \sigma_c - n_k P_p \quad (2)$$

where $n_k = 1$. Proposing a new conceptual model to describe the combined effect of stress, pore pressure, and slippage factor, we are capable of simulating the stress effect and slippage parameters effects. The experiments

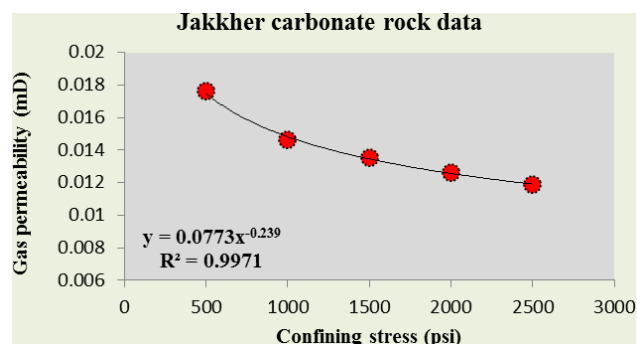


Figure 12: The plot shows the permeability stress sensitivity of carbonate rocks.

were performed to explore the implications of model for permeability stress sensitivity of carbonate samples coupling with other variables. This model shows the permeability decline in particular to ultra-low permeability carbonate rocks with increasing overburden stress. The model is expressed using the following equation,

$$K_{\infty} = K_a \left[1 + \frac{b}{P_m} \right] \cdot (\sigma_c - n_k P_p)^{-\gamma} \quad (3)$$

In above equation, K_a represents the apparent permeability of the rock formations extrapolated to zero net stress, the stress sensitivity exponent is represented as γ and P_m represents the mean pressure and b is the gas slippage factor and is the slippage corrected permeability.

It was observed that the permeability increases when the pore pressure was decreased even at in-situ stress, such increase in permeability was the results of gas slippage [29, 50, 51]. However, we realized that the absolute permeability of carbonate samples decreased with increase in net stress. Hence, it is clear that net effect is the reduced permeability with increase in net stress at lower ranges of stress. It was because the gas slippage effects were low due to the high pore pressure. At higher net stresses and low confining stresses, the increased flow due to slippage balances the reduction of slip corrected permeability leading to increased values of permeabilities. Stress sensitivity of permeability to low permeability tight sandstone reservoirs is well documented [48, 49], however; the permeability measurement at in-situ stress is very challenging. In present study on carbonate samples permeability (Figure 12), we found that there was greater extent of permeability reduction at lower overburden stress which is due to the microfractures existence as micro-crack was observed in one of the sample. Micro-cracks could have formed along the grain boundaries of the samples that resulted in increased in permeability at lower confining stress. Other authors [47] also reported that the effect of confining stress on samples permeability is controlled by presence of micro cracks. The main explanation of changes in gas permeability will be the result of changes in effective stresses, pore pressures and are essential for assessing their impact on reservoir quality by considering their relationship between gas permeability, stresses and gas slippage.

4.6 Controls On Fluid Flow Properties

The main reservoir rock parameters of fluid flow are the permeability which is controlled by its pore size and by pore-throat [52, 53]. In order to assess the impact of the processes that control the fluid flow in carbonate reservoirs

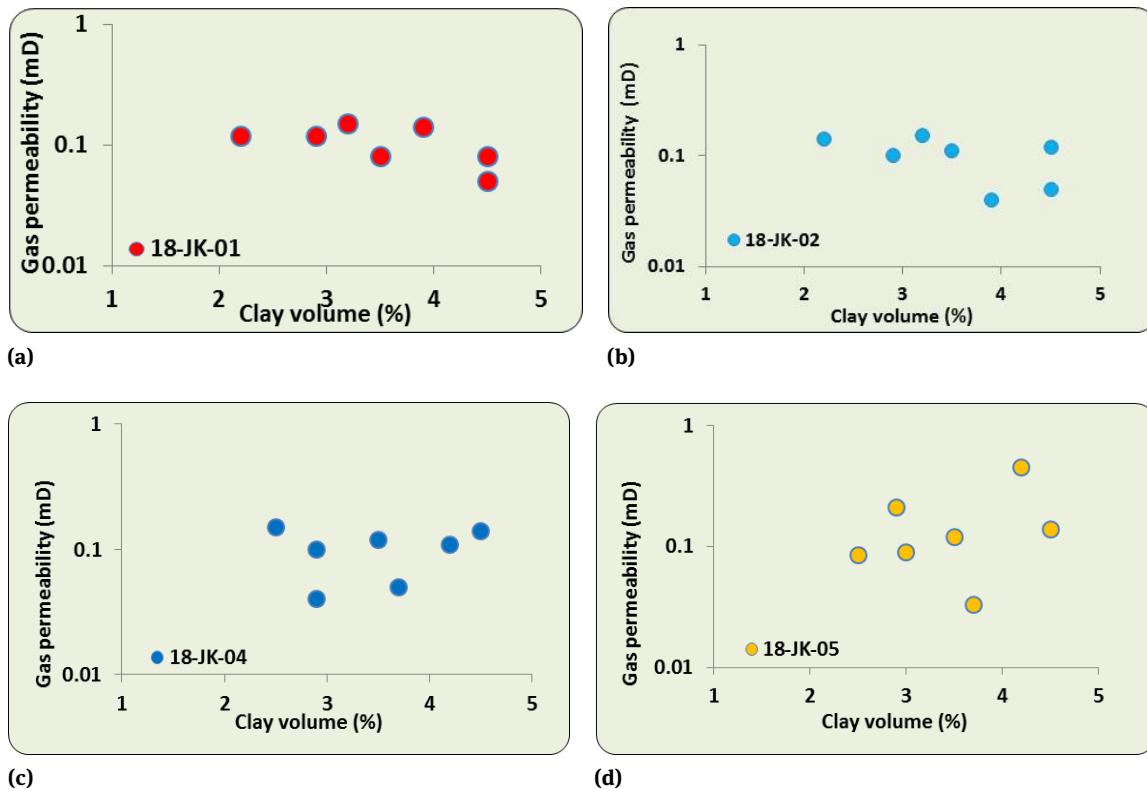


Figure 13: Illustration shows permeability relation to clay volume.

and the associated features that are responsible in changing the pore sizes are essential to explain. Several publications have addressed the fluid flow behavior and its control by pore size changes, changes in rock permeability and pore connectivity [52]. The pore structure of carbonate rocks is diversified due to the heterogeneity of the rock textures. None of the samples have displayed macro sized pores as observed from thin section analysis with one exception which tended to micro-crack. The micro and nanopores are common in carbonate with some exceptions of nano and meso-pores [54].

An attempt was made to find the correlation between the rock-clay mineralogy impacts on permeability. The permeability data did not appear a relation with clay mineralogy and the correlation was very poor. This could be the results of rock heterogeneity as reported by other authors [7]. In addition, the permeability relationship of each sample with clay mineral show a clear scatter in correlation between measured permeability and the observed minerals (Figure 13). This shows that the mineralogy does not play any role in controlling the permeability and fluid flow within these rock types. However, the pore size and pore connectivity have significant impact on controlling the fluid flow behavior within these rocks [1].

4.7 Implication for Reservoir Quality

In order to determine the quality of reservoir rock, it is essential to have information about the reservoir petrophysical properties which is largely affected by the diagenetic processes. The main petrophysical properties such as porosity and permeability are mainly be affected by diagenetic processes [38]. Diagenetic changes may either increase or decrease aforementioned petrophysical properties of any reservoir. The most important diagenetic changes observed within Jakkher Group carbonate were the micrite mud cementation; compactions as well as up-lifting and fracture nummulites at the centre were surrounded by fine micrite mud. More specifically, the cementation observed was the calcite, clays, and intermix of clays into pores associated iron oxides. These all acted to decrease the permeability and porosity of studied carbonate rock samples. Further, at few places, the samples were exhibiting primary porosities that were mainly due to intergranular, micro pores and nano size pore throats resulting into densely compacted tight rock. This is evident from samples porosity and permeability values which were very low and revealed that these carbonates are tight if developed will produce at very low flow rates until unless hy-

draulically fractured. Moreover, the clay mineralogy found to have very scattered distribution as observed from the Figure 13.

Due to overburden stresses and compactions, the grain boundaries of rocks get closer to each other making these rocks less permeable and are thought to be poor quality reservoirs [29, 50, 51, 55]. The stress sensitivity experiments on these carbonate rocks conducted showed significant decrease in permeability. These results have implications that if rocks are deeply buried and burial depth further progresses, these results into reduction in primary porosity due to overburden stresses and rock compaction. In samples studied in the study, there was also cement that has acted to decrease the additional compaction. In some sample, intermix of clay and micrite played a significant role in decreasing the permeability and porosity. More specifically, the pores and pore throats of tightly packed carbonates are very small and have resulted to act these reservoirs of poor quality.

5 Conclusions

An integrated study was conducted on petrophysical, petrographical and mineralogical properties to analyze parameters influencing the fluid flow within carbonate reservoir rocks. In addition, the impact of overburden stresses variation on permeability of carbonate rock analyzed and the following conclusions were drawn.

1. Thin section study, SEM-EDS, and XRD analyses revealed that Jakkher Group carbonates were mainly composed of calcite and dolomite, the proportions of associated minerals were in order of quartz, kaolinite, ferric oxide and illite-smectite. The intermix of clay, cementing materials, and the siliciclastic influx affected the quality of carbonate reservoir rock by cementation. Presence of micrite muds and grain compactions due to overburden stresses has tended poor quality reservoirs.
2. The factors controlling the permeability of carbonate rocks are diagenetic alterations and depositional environments. These factors change the rock textures and these could be responsible in changing rock flow properties e.g. rock permeability due to cementation, compaction and consolidation, leading to modification of petrophysical properties of the carbonates. The low permeability of these samples could be the results of diagenesis alterations.
3. The Klinkenberg corrected permeability values shown decrease corresponding to an increase in

overburden stress resulting into an increased slip-page factor was noticed.

4. The permeability data and clay mineral contents were plotted to see the impact on permeability of carbonate rocks. This has shown very little impact on permeability of carbonate rocks because the clay was found in very small quantity in these tight carbonate rocks.
5. Most of the carbonate samples were exhibiting tight permeability with some exception of higher permeability that was the incidence of micro-fractures; micro-crack tended these carbonates of improved reservoir quality.

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