Integrated Study to Assess the Diagenetic Impacts on Petro-Physical Characteristics and Reservoir Quality of Sukkur Rift Zone

Faisal Hussain Memon*, Abdul Haque Tunio*, Aftab Ahmed Mahesar*, Khalil Rehman Memon*, Ghulam Abbas**

*Institute of Petroleum & N. Gas Engineering, Mehran UET Jamshoro, Pakistan
**Petroleum and N. Gas Engineering Department, Mehran UET, SZAB Campus Khairpur Mirs, Pakistan

Abstract: Sukkur Rift Zone is proven to be the most significant hydrocarbon potential resource area of Lower Indus Basin of Pakistan. It comprises of various carbonate gas producing reservoirs of Eocene and Oligocene formations. These reservoirs are getting depleted due to reservoir heterogeneities and production complexities caused by diagenetic effects. In this study, an integrated reservoir characterization of Sui Upper (SUL) and Sui Main Limestone (SML) formations was carried out through pore morphology and mineralogical assessment by Scanning electron microscope (SEM), Energy dispersive X-ray spectroscopy (EDS) and Fourier transform infrared (FTIR). The impact of diagenetic alterations on reservoir quality was measured though thin section analysis, porosity and permeability measurement. SEM, EDS and FTIR analysis interpreted a fair pore-morphology and grain structure; predominantly composed of calcite and dolomite with other cementing materials. Petrography analysis revealed that gray colored mudstone to grainstone texture with numerous diagenetic features which reduces carbonate reservoir quality. The evaluated petro-physical properties indicating fair porosity and reduced permeability. The presented study will be beneficial to reduce the reservoir management uncertainties of carbonate reservoirs and also helps in improving the productivity of indigenous resources.

1. INTRODUCTION

Reservoir characterization of carbonate rocks is very important for hydrocarbons production forecasts and reservoir management. Petro-physical characteristics are key parameters for determining reservoir potential and have big impact on reservoir development techniques [1]. But, these parameters are mainly affected by reservoir rock heterogeneity and depositional environment [2]. Substantial sedimentation and diagenesis may produce variety of micro-pore grains that have different pore size, complicated pore interconnectivity, and pore dispersion, which may affect the petrophysical properties of rock [3, 4]. Furthermore, morphological characteristics and fluid distribution of these heterogeneous reservoirs cannot properly be examined using conventional core analysis methods [5]. It required in-depth characterization, i-e specialized core analysis techniques that leads to interprets the petrophysical properties more specifically and extensively [6, 7]. Permeability, porosity, pore size distribution, thin section measurement, microstructure

analysis, are the most significant challenging features for reservoir quality assessment and interpretation [8-11]. Therefore, a thorough investigation is necessary to understand the microstructure, rock texture, petrophysical features, pore throat geometry, natural fractures and their effects on fluid flow behavior in carbonate rocks.

According to reports, carbonates hold 60% oil and 40% gas reserves worldwide. Middle East show a significant amount of oil at around 70% and a considerable amount of gas is almost 90% [12, 13]. Pakistan's carbonates have a significant hydrocarbon potential; located in Baluchistan basin, Upper and Lower Indus basin. Numerous exploration and production (E&P) companies have drawn attention to these complex and fractured hydrocarbon potential carbonates [14-16]. They carried out extensive surveys and research projects, particularly focused on the geological and geophysical characteristics of these carbonate reservoirs [15]. But petro-physical characteristics, microstructural studies and mineralogy have not been properly evaluated to explore and develop hydrocarbon reservoirs more effectively. It is necessary to comprehend the pore morphology, depositional textures, petrophysical properties as well as diagenetic changes that have substantial impact on reservoir quality [17, 18].

Sui Main Limestone is a productive gas reservoir with complex lithology and pore networks, leading to decline due to challenging development strategies [19, 20]. About 20 trillion cubic feet (TCF) of proven reserves had detected in 14 acquisitions in Pakistan with more than 5 TCF found in 625m thick SML in Baluchistan. The SML together with SUL is broadly spread in Lower Indus Basin and Baluchistan Basin; with low-permeability and heterogeneity of a field, Middle Indus Basin. Around 40 wells drilled to meet energy demand, but many found dry wells and abandoned due to reservoir heterogeneity, less effective porosity, and poor permeability[20, 21]. Many well log studies have been conducted in the area, but did not identified their stratigraphic units, heterogeneity type properly and lacking reservoir complexities due to diagenetic alterations [20, 22]. Therefore, this study provides a complete data base of integrated reservoir characterization of SUL and SML formations by conducting series of experiments on petro-graphical, pore-morphological, mineralogical and petro-physical assessment in

order to determine diagenetic impact on carbonate reservoir quality.

1.1. GEOLOGICAL SETTINGS OF THE STUDY AREA

The Lower Indus basin is divided into central and southern basins by the Sukkur Rift Zone, which mostly comprising of normal faults with associated Horst and Graben structures including Khairpur Jacobabad high, Pano Akil graben and Mari Kandhkot high. The research region is located in the eastern portion of Jacobabad Khairpur High in NNW-SSE, and is consistent with geological development of Lower Indus Basin. Geologically, the region mostly covered by rocks of Mesozoic succession which continues to the several thousand meter thick Jurassic sequences with few Triassic outcrops exceptions [23, 24]. Stratigraphically, this area is mostly

consisting shallow marine limestones of Eocene age and shales with sandstones as subsidiary inter beds in lower bottom as in Figure 1-B. Khairpur-Jacobabad high exposed with Eocene outcrops, except Main Sui lime stone which underlying approximately latitude 27° 55' to 28° 09' N longitude 69° 11' to 69° 31' E as reported by Geological Survey of Pakistan in Figure 1-A [25, 26]. The SUL sequence is composed of muddy to grainy limestone, while SML contains argillaceous to dolomite carbonate with variety of skeleton assemblages and discrete packs of diagenetically subpar Sui Main have been reported by few studies. In Pakistan's geological history, the petrophysical investigation of early Eocene SML was conducted previously in 1995 for hydrocarbon exploitation in studied zone; as this region has a significant economic impact of hydrocarbon potential for new discoveries as well [27].
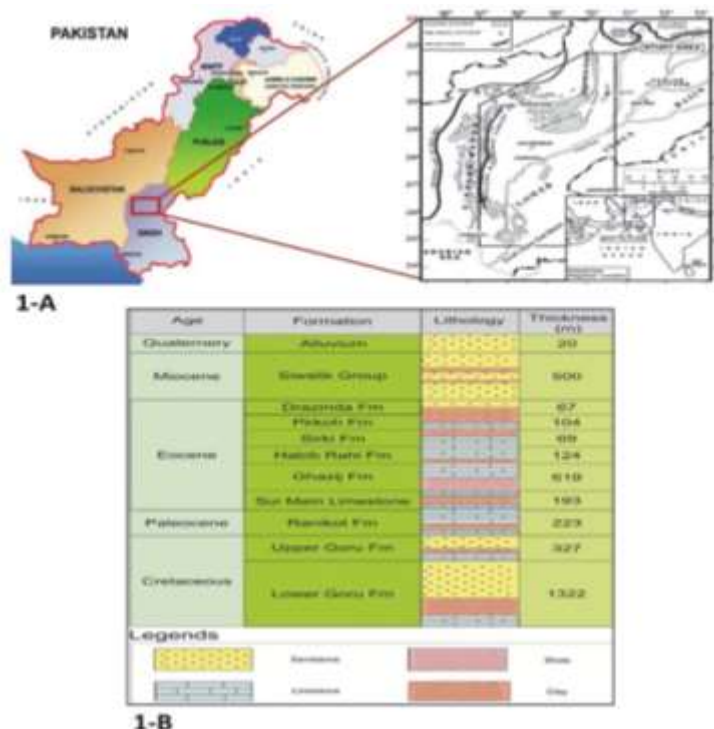

Figure.1-A   Pakistan map showing tectonically adjoining regions of study area exposing out crops of Sukkur Rift Zone [27] & Figure.1[b] Generalized stratigraphic column of the study area [28].

2. EXPERIMENTAL DETAILS AND METHODOLOGY

2.1   Materials
The selected carbonate cylindrical core plugs of 5.5cm length to 3.5cm diameter of Sui Upper and Sui Mai Limestone from different well depths were utilized and underwent different sample preparation procedures for extensive laboratory scale analysis.

2.2   Methods

2.2.1   Petrography Measurement
Polished thin sections with carbon coatings were utilized for this analysis; approximately 0.029mm thick stained thin sections were prepared and carefully examined using a

Polarized Microscope BX-51. Petrographic determination involves the identification of mineral composition, fossils content and evidences of diagenetic alterations.

2.2.2   Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) Measurement
SEM was used to study the samples' microstructure, mineralogy and diagenetic characteristics using a JEOL- JSM-6590LV, field emission Japan Compact SEM equipment; imagining interface software which is linked with a QUANTAX system of micro analyzer as Energy Dispersive X-ray (EDS) analysis.

2.3   Petro-Physical Measurement

For petro-physical measurement of bulk density, porosity and permeability, obtained samples were 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.

2.3.1   *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.

2.3.2   *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 assessed by the difference of measured reference volume of the core plugs size, and the calculated grain volume using the Boyle's law method[29].

2.3.3   *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:

$$Ka = 2\mu\ Qb\ Pb\ L\ /\ A\ (P21\text{-}P22)\ldots\ldots\ldots\ldots\text{Eq. 1.1}$$

Where;
Ka = air/ gas permeability, Darcy
Ug = gas viscosity, cp
Qb = referenced flow rate to Pb, cc/sec
Pb = standard reference pressure for mass flow meters, =1.0 atm
P1 = Upstream pressure, atm

2.4   *Fourier Transformed Infrared Spectroscopy Analysis*
The FTIR investigations were carried out in ATR (Attenuated Total Reflection) mode using a portable infrared spectrometer named ALPHA (produced by Bruker, Optik GmbH, Ettlingen, Germany). 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}.

3.   RESULTS AND DISCUSSION

3.1   *Petrography and Diagenetic Analysis*

The petrography findings show that these formations were primarily composed of calcite, dolomite with few smectite, illite, huntite and ferric oxides also observed. Surface features and fossils deposited, indicating marine environment with subsequent dolostone due to manganese levels in seawater. In petrographic analysis, carbonate facies categorized by Dunham's classification showing muddy to wackestone texture for SUL samples. Whereas SML indicates bioclastic pack stone to grainstone texture. The distinct description of thin section microphotograms of selected carbonate samples illustrate in Table 01. Majority of samples had microcracks and fractures exposed to both primary and secondary porosity. Additionally, it was observed that certain diagenetic developments change the rock's porosity through precipitation and subsequent pore filling of micrite muds, led to reduction in pore throats size and affect permeability as well; shown in figure 2.

The primary diagenetic characteristics of carbonate rocks were visible in morphology analysis and thin sections measurement as shown in figure 3. Fragments of carbonate rocks and surrounding muds are highly bio-mineralized products of marine environment found in analysis. Diagenesis can produce carbonate deposits with complex petrophysical characteristics, and it has a significant impact on reservoir quality [20]. The stronger grain interactions reflect a suitable diagenetic development was observed by petrography and SEM interpretations. Extremely fine-grained sediments and diversified clay minerals were also observed usually form very tightly reservoirs with low porosity and low permeability. Additionally, a very fine mixture of terrigenous sediments was also seen with carbonates; combined with micrite mud and illite-smectite grain coatings on carbonate minerals.

Table.01: Petrographic details of SUL & SML formations for thin sections study

Sr. No	Sample ID	Petrographic Details
1	22-SUML-01	Gray colored bio-silty mudstone texture as Dunham classification with iron clay and fine grained to medium size calcite matrix. Clear visual porosity observed with some calcite filled vein fractures as diagenetic features.
2	22-SUML-02	Dark colored silty Pel-micrite limestone having LBFs and nummulitic bioclasts mudstone to wackestone texture. Fined grain rounded to Euhedral Spar cement micrite matrix and iron clay. Calcite filled fractures porosity, neomorphism and dolomization observed in analysis.
3	22-SUML-10	Gray colored bio-micrite silty limestone with Discocyclinoid bioclastic wackestone texture by Dunham classification. Broken neomorphosed foraminifera shells cemented in micrite mud with Pellets are visible.
4	22-SML-05	Grayish bio-micrite limestone with Assilinal and Nummulitic bioclast packe to grainstone texture. Iron clay medium sized rounded to rhombo-hedral dolomite matrix with visual fennistral and matrix porosity observed.
5	22-SML-06	Bio-micrite silty limestone showing a wackestone to packestone group of round grains in micrite muds confined with iron oxide cement, pyrite and dolomite matrix. Nummulites and assillinal bioclasts are distinct with vugy and calcite filled fracture network observed in analysis.
6	22-SML-07	Dark grey tint bio sparse micrite limestone with fine garin to medium sized calcite and iron matrix. Larger

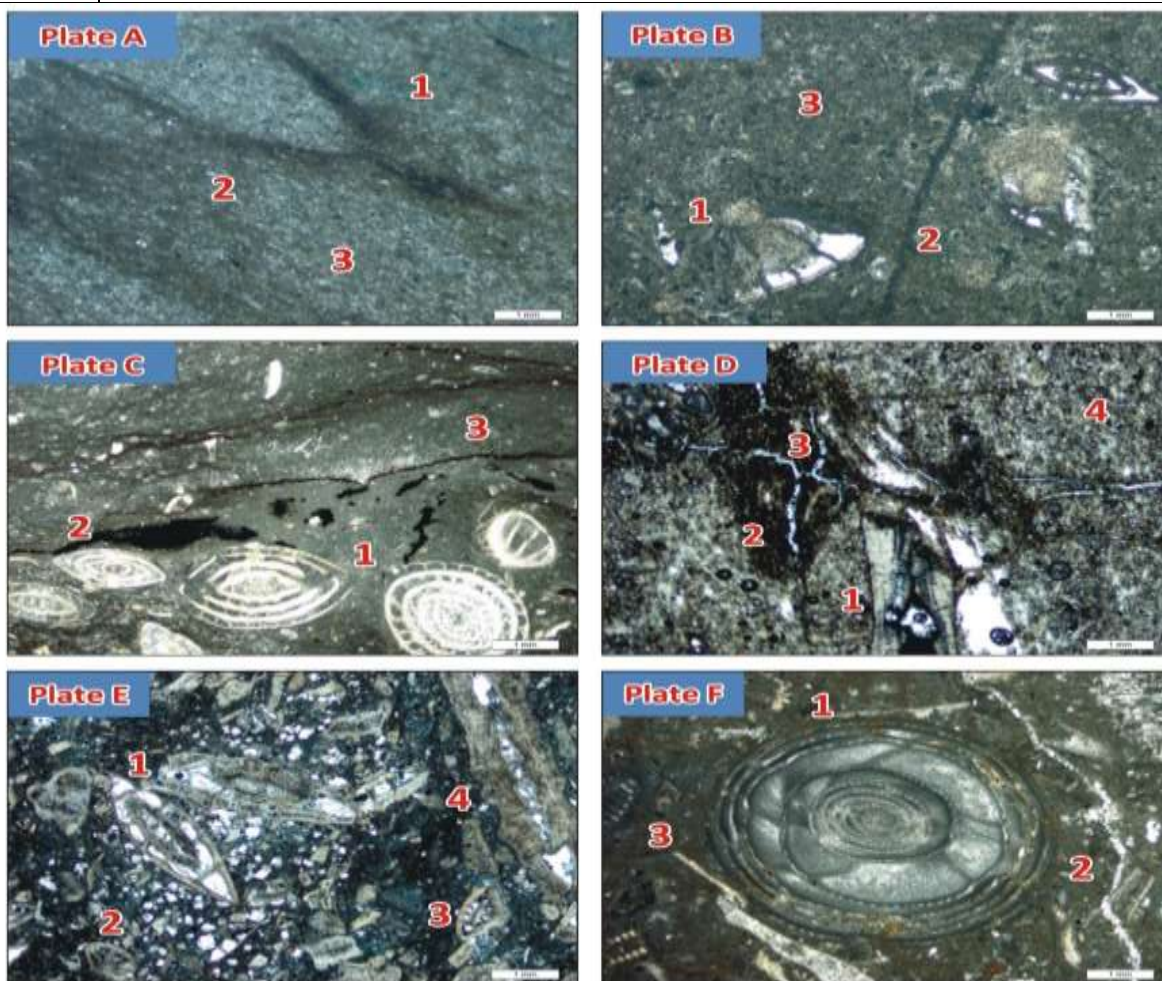|		benthic alveolina, algal and foraminiferal wacke-packestone texture with micrite fractures with iron oxides meniscus cement are also identified.

Figure.2   Petrographic description shown in thin section microphotographs displays: [Plate A] point 1displays visual porosity, points 2 showing intermix of clay minerals and point 3 is calcite matrix. [Plate B] displaying the Nummulite at point 1, clay filled vugy fracture at point 2 and iron matrix at point 3. [Plate C] point 1 depicts the neo-morphed Nummulites, pyrite at point 2 and a long vugy fracture at point 3. [Plate D] point 1 displays Assillinal bioclasts, clay minerals at point 2, point 3 showing calcite fractures with fenistral porosity and dolomite crystals at point 4. [Plate E] Assillinal bioclasts at point 1, Mg-rich rhombo-hedral dolomite crystals at point 2, point 3 denotes visual porosity effects and clay minerals at point 4. [Plate F] Alvulina at point 1, calcite filled fracture at point 2, and micrite mud, bioclasts and iron matrix at point 3.

3.2   *Mineralogy and Geochemical Analysis*

The mineral constituents of SUL and SML carbonate samples were dominated by calcite and dolomite, with other minerals like aluminum, silicon, potassium and iron also identified. FTIR analysis identifies functional groups of carbonate phases and comparing their chemical compositions with spectral bands to identify compositional changes in mineral structures. The carbonates possess a variety of monovalent or divalent cations and one of $(CO_3)^{-2}$ ions which combine to form carbonate minerals. Calcite, dolomite, magnesite, siderite, and rhodochrosite are rhombohedral carbonates that crystallized in R-3 group. Due to changes made by divalent elements like Ca, Fe, Mg and Mn in the crystalline structure; dolomite and ankerite minerals had differing site symmetry but retain structural similarities. The observed molecular symmetry was unaffected by site symmetry variation as given in Figure.4. The mineral configuration, rock structure, depositional environments, porosity and permeability, grain packing, size, and grain arrangement; all have a significant role in reservoir quality [30]. Minerals have a significant impact on reservoir rock properties; that controlling the fluid flow performance in porous media. Mineralogy controls fluid movement through rocks and sediments diagenesis through particle motions, cementations, dissolutions, and mineral authigenesis [31]. The observed mineralogy showed that Ca, C, Fe and Mg are the dominant elements found in SEM-EDS patterns, indicating the presence of carbonate rocks in figure.3. While Si, Al and Na were also exposed in several samples, indicating intermix of clay minerals with silici-clastic inflow, as detected from EDS patterns. Observed samples also contained highly bio-

mineralized products of marine environment with strong affinity to several identified minerals and grain interactions

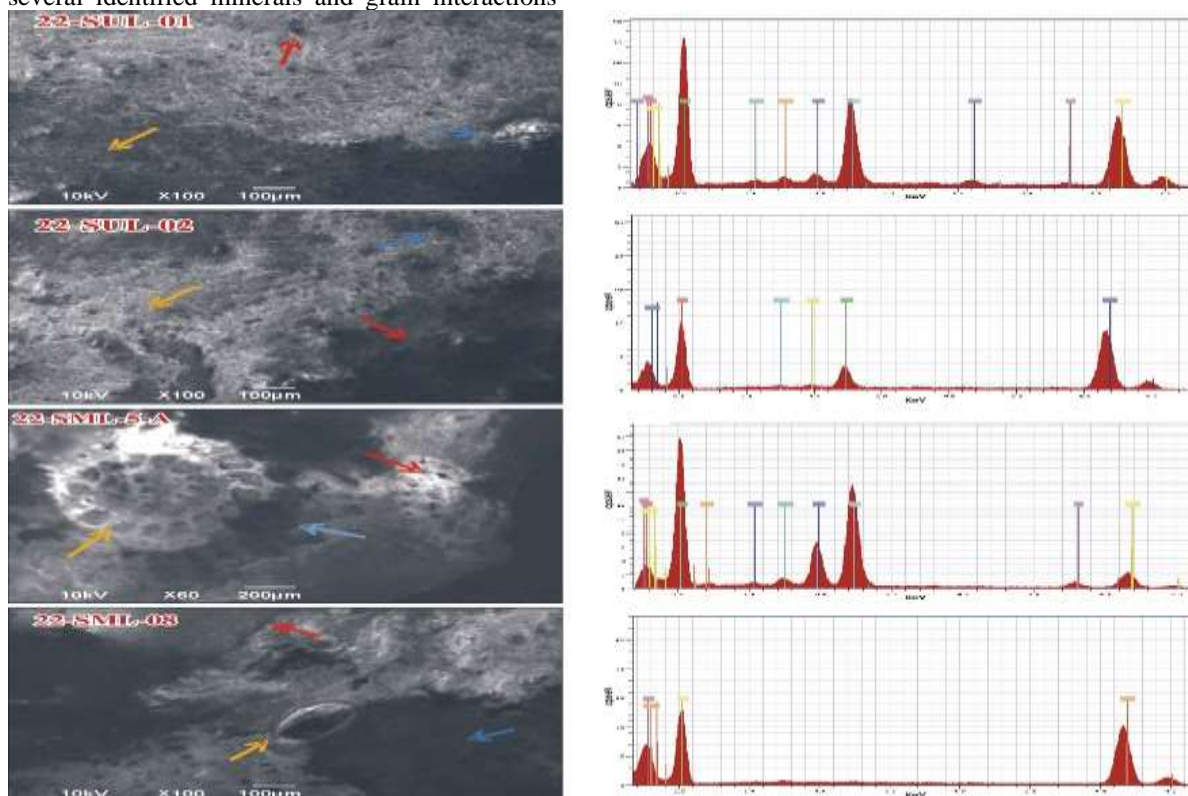that affect the carbonate reservoir quality.

Figure.3 Displays the results of the SEM-EDS study of SUL and SML formations indicating by different colored arrows; (22-SUL-01) red arrow shows micro pores, blue indicates low Mg-calcite, and yellow is clay minerals. (22-SUL-02) red arrow shows micrite calcite, brown indicates illite smectite and yellow represents clay minerals. (22-SML-05); yellow arrow describes large benthic forums as fossil content, red indicating intra-fossil fenistral porosity and blue arrow is secondary porosity. (22-SML-08); yellow arrow showing micrite bubble with iron clast, red arrow describing microfracture and blue denotes only C as clay mineral as in EDS analysis.
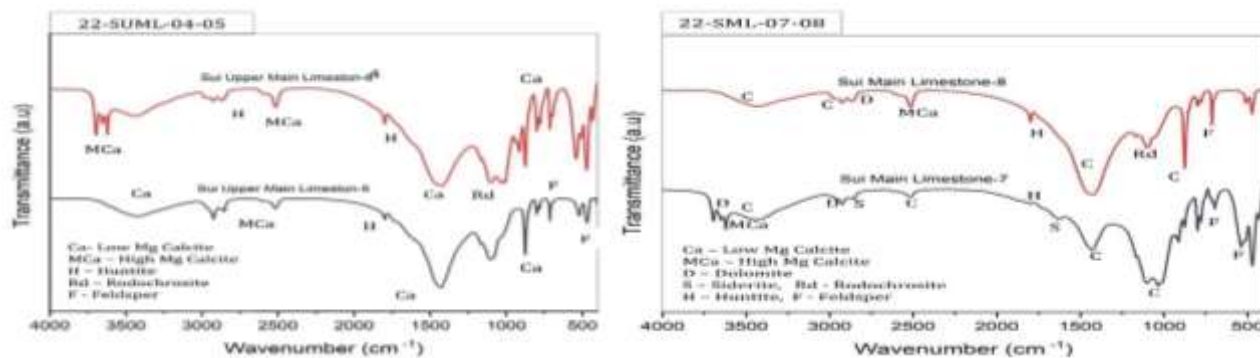

Figure.4 FTIR analysis of selected carbonate samples indicating different carbonate phases observed showing various peaks of spectral bands determined by wavenumbers.

3.3 Porosity and Permeability Measurement

The observed SUL and SML samples had relatively average densities of 2.664 g/cc and 2.706g/cc. Bulk density and porosity relationship was performed to identify the degree of reservoir homogeneity and observed relationships were linear inverse with somehow weak correlation for SUL and SML respectively. Since, the analyzed pore structure was predicted to be non-uniform and heterogeneous; that showing the rock samples had variable mineralogical structure, grain shape, packing, and fabric as observed in figure.5. Moreover, thin section photographs indicating that obtained samples were mostly altered diagenetically and possess low dual porosity characteristics. The average matrix porosity was 14.7% and 15.1% and average permeability of 3.34mD and 4.25mD for SUL and SML formations respectively as in figure.5.

Whereas, average fracture porosity was 5.84% and 3.58% with average permeability of 2.39mD and 1.18mD respectively for SUL and SML formations. The measured porosity of rock reflects pore volume, whereas the measured permeability reflects the pore throats size. Plate C in thin sections analysis (Figure.2) shows long micro fractures that result in high permeability values from study of SUL, while SML showing induced calcite filled vein fractures due to overburden stress and few observed micro cracks that cause the reservoir heterogeneity. Little deviation in the cross-plotted permeability and porosity data was observed by micro cracks, as seen in thin section analysis, and shown in Figure.5. Due to variety of pore size and pore throat network, the plotted permeability and porosity data did not show a linear connection and demonstrate a direct and power relationship in the examined carbonate samples with a weak relationship. The rock permeability values were not significantly influenced by porosity in investigated formations, but fine clay concentrations and pore throat sizes may indicate such cases.
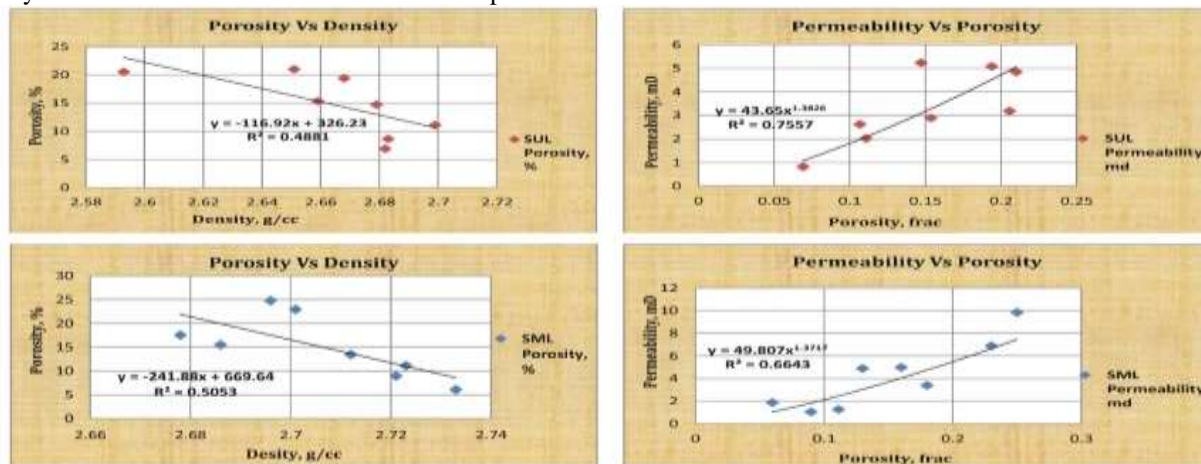

Figure.5   Relationship between Porosity versus Bulk Density and Permeability versus Porosity

3.4   Implications for Reservoir Quality Assessment

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 variation in basic petro-physical properties like porosity and permeability. That provides the basis for static or dynamic reservoir models. Several diagenetic processes like micritization, dolomitization, neomorphism, recrystallization, compaction and calcification ware the most significant diagenetic shift observed in studied carbonate reservoirs. More precisely, the cementation was caused by intermixing of clays and iron oxides in pores, pore throats and fractures. All these had a severe impact on permeability and porosity that tends to diminish the quality of reservoir. Additionally, the samples 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 rocks were significantly reduced in several samples by clay and micrite mud intermix and making them low to moderate quality reservoirs.

4.   CONCLUSIONS

Based on integrated reservoir characterization for petrography, pore-morphology and petrophysical characteristics of SUL and SML formations; following conclusions are drawn.

1. SEM-EDS analysis interprets the fair to good pore-morphological structure in selected carbonate formations; predominantly contains calcite and dolomite minerals. The magnitudes of related minerals like ferric oxide, illite-smectite and micrite muds also present. The bioclasts, cementing materials, and intermix of clay invasion by cementation, micritization and grain compactions as a result of overburden stresses has diminished the reservoir quality.

2. Petrography reveals that SML formation possessed packestone to grain stone texture while SUL, contained mudstone to packestone texture; analyzed in thin sections. The particle size found to be medium- to fine-grained, rounded to rhombo hederal dolomite crystals and calcite, associated with micrite matrix, LBFs & bioclasts of fossils and cementing materials of iron oxides & clay minerals.

3. Obtained spectra from FTIR analysis of SUL and SML indicating, the minerals constituents as proportions of limestone with low magnesium calcite, high-Mg calcite, dolomite, huntite, siderite and feldspar.

4. The average porosity values of SUL and SML formations were 14.7%, 15.1%, and average permeability of 3.34mD, 4.25mD respectively. The petro-physical characteristics are consistent with petro-graphical features and permeability dependent on effective porosity specifying poor to moderate reservoir quality. Majority of the outlined porosities are of secondary source, including fennisteral porosity, vugs, molds, fractures, calcite filled fractures and channel porosity.

It is also concluded that diagenetic alterations and depositional environments affect reservoir quality, with some processes enhancing porosity and permeability like leaching and dissolution effect; while others reducing them by mechanical infiltration of clays, compaction, cementation, and recrystallization. Moreover, this study provide new knowledge on crucial aspects of reservoir rock, including cement types, fractures, diagenesis, fluid flow and diagenetic controls through special core analysis that allowing for better investment choices and lower risk involved in exploiting the target reservoirs.

DECLARATION OF COMPETING INTEREST
The authors affirm that they have no known financial or interpersonal conflicts that could have influenced their research.

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Authors

First Author – Faisal Hussain Memon, M.E, IP&NGE, Mehran UET Jamshoro,

Second Author – Abdul Haque Tunio, PhD, Institute of Petroleum & N. Gas Engineering, Mehran UET Jamshoro,

Third Author – Aftab Ahmed Mahesar, PhD, IP&NGE, Mehran UET Jamshoro,

Fourth Author – Khalil Rehman Memon, PhD, IP&NGE, Mehran UET Jamshoro,

Fifth Author – Ghulam Abbas, M.E, Dept: Petroleum & N. Gas Engineering, Mehran UET, S.Z.A.B Campus, Khairpur,

Correspondence Author- Faisal Hussain Memon,