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RESEARCH ARTICLE

Facies and Hydrocarbon Reservoir Rock Characterization of the Paleozoic Rocks of Peshawar Basin, Northwest Pakistan

Sajjad Ahmad* **Sohail Raza** **Suleman Khan**

Department of Geology, University of Peshawar, Khyber Pukhtunkhwa, 25120, Pakistan

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ABSTRACT

The present study details the facies description and hydrocarbon reservoir characterization of the Paleozoic rocks of Peshawar Basin, northwest Pakistan. The outcrop samples from the Cambrian-Devonian rocks along the famous Nowshera-Risalpur Road and Turlandi Village Section were investigated. The analysis of outcrop data revealed significant information regarding the facies and their depositional environments. Based on its detailed sedimentological data, it is believed that the Ambar Formation is deposited in shallow shelf-tidal flat settings, while the protolith of the Misri Banda Quartzite came from the wide beaches. The protolith of the Panjpir Formation was deposited in the shelf conditions, which shows an overall shallowing when moving up the section from the argillites and phyllites to crinoidal limestone. The Nowshera Formation was deposited as a reef complex on the shelf edge having reef core, reef breccia and a back-reef lagoon. The techniques of petrography, XRD and SEM were used for the bulk geochemical composition of the rocks focusing on their matrix, mineralogy, micro-porosity and pore-filling materials. The presence of micrite, goethite, kaolinite and illite as intergranular mass, dolomitization-induced porosity, twin cleavage plane and high dissolution porosity in the Ambar Formation can provide significant pore space to the reservoir fluids migration. Hematite with minor kaolinite, illite and chlorite as alteration products of unstable framework grains as intergranular mass and a deep seated burial diagenesis has minimized the reservoir potential in Misri Banda Quartzite. The coarse and fine calcite, dolomite, chlorite and kaolinite occur as pore-filling material between the framework grains while the high intensity of intragranular dissolution and micro intergranular connecting porosity in the Nowshera Formation makes it a promising reservoir.

*Corresponding Author:
Sajjad Ahmad,
Department of Geology, University of Peshawar, Khyber Pukhtunkhwa, 25120, Pakistan;
Email: dr.s_ahmed@uop.edu.pk

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1. Introduction

In the foothills of the Himalayas, the Peshawar Basin (Figure 1) includes the oldest exposed sequence of sedimentary and metasedimentary rocks. Marine evaporites (Salt Range Formation) can be found in the south, whereas deep water pelites can be found in the north. The entire sequence of Paleozoic-era strata can be found within the Peshawar Basin and along the hills that circle the basin on its eastern side. Waagen [1], Griesbach [2], Middlemiss [3], Wadia [4], Martin et al. [5], Davies and Ahmad [6], and Teichert and Stauffer [7] are credited with the first attempts to understand the stratigraphy of the Peshawar Basin. They also first reported the presence of Paleozoic rocks in the region. Burbank [8] described Pleistocene and Pliocene era sediments in 1983, and Tahirkheli and Burbank [9] did the same in 1985. In an effort to understand the local context of Himalayan stratigraphy, Fuchs [10] undertook a study in the Nowshera area. Hussain [11] created the regional geological map of the Nizampur region, which includes portions of the Attock, Mardan, and Peshawar districts. Pogue and Hussain [12] reconstructed the Nowshera region stratigraphy based on the discovery of Trilobite trace fossils. The structural events' timing in the foothills of the Himalayas was worked out by Yeats and Hussain [13]. Pogue and others [14] are responsible for the initial systematic attempt to understand the regionally applicable and coherent stratigraphy of the Peshawar Basin and surrounding regions. They completed a thorough sampling from several outcrops for a paleontological investigation, and as a result, they were able to modify the region's stratigraphic framework and carry out a regional correlation. The literature assessment makes clear that the petroleum geology of the study region has not yet been fully studied. Therefore, the assessment of the Peshawar Basin's hydrocarbon resource potential has received particular attention in this study.

2. Regional Tectonic Settings

A fairly large intra-mountain basin (more than 5500 km^2) named the Peshawar Basin is located near the southernmost tip of the Himalayas, northwest of the Kohat Basin (Figure 1). It is situated where the northern and southern edges of the Indo-Gangetic fore-deep, as well as the southern limit of the Hindu Kush-Himalayan Ranges, converge. The Peshawar basin is delimited by the Khyber range in the northwest, the Attock-Cherat range in the south, and the Swat range in the northeast along the margin of the basin, Quaternary fanglomerates were seen. The majority of such deposits in the basin's central region are fluvial micaceous sand, gravel, and lacustrine deposits. Small outcrops within the basin are the only places where the Paleozoic and older strata have been exposed. Pre-Cambrian to Early Mesozoic metamorphosed and igneous rocks in the Peshawar Basin are highly deformed and tightly folded. According to Treloar and Others [15] these rocks are thrust over the Kurrum-Cherat-Margalla ranges in the south. More than 300 meters of floodplain mudstone and siltstones with minor sandstone intercalations occupy the basin, which is overlaid by eroded Eocene limestone or Murree sandstone fanglomerates which are moving northward. Intruding metamorphosed Paleozoic sediments along fault zones are a few alkaline rock complexes that emerge towards the western edge of the Peshawar basin. The heavily deformed Murree sediments that make up the northern part of the Peshawar Basin indicate that the pre-existing fore-deep basin experienced severe deformation prior to the start of sedimentation in the newly created Peshawar Basin. At least 2.8 million years ago, sediments that filled the basin piled at a pace of 15 cm/1,000 years, totaling more than 300 m. The juxtaposition of metasediments from the Lesser Himalaya in the north and sediments from the Mesozoic to Neogene fold-belt in the south characterizes the southern edge of the Peshawar Basin. Ahmad and others [16] hypothesized that the marine shelf sedimentation of the Indus Basin was extended up to the Peshawar Basin during the Mesozoic. Under the Pre-Paleocene thrust nappes in the submerged Mesozoic marine strata, it is anticipated that a potential petroleum system may be present in the Peshawar Basin.

3. Stratigraphic Setup

In a younging up stratigraphic sequence, the Peshawar Basin contains the Cambrian (Ambar Formation), Mid Ordovician (Misri Banda Quartzite), Late Silurian (Panjpir Formation), and Late Devonian (Nowshera Formation) (Figure 2). Of particular mention is the absence of Precambrian (Manki, Shekhai and Dakhner Formations), Cambrian (Darwaza Formation), Early Ordovician (Hisartang Formation) and early-Mid Devonian (Inazari Formation) from the Peshawar Basin and characterizes the adjacent Attock-Cherat Ranges in the south of Peshawar Basin (Table 1).

3.1 Ambar Formation

It is a thick rock unit that is exposed in the form of isolated hillocks between the Nowshera and Swabi areas. The dominant lithology of the formation is thick bedded to massive sandy dolomite, having ripple marks, mud cracks and salt pseudomorphs (Figures 2–3). Minor shale and siltstone intercalations are also present.

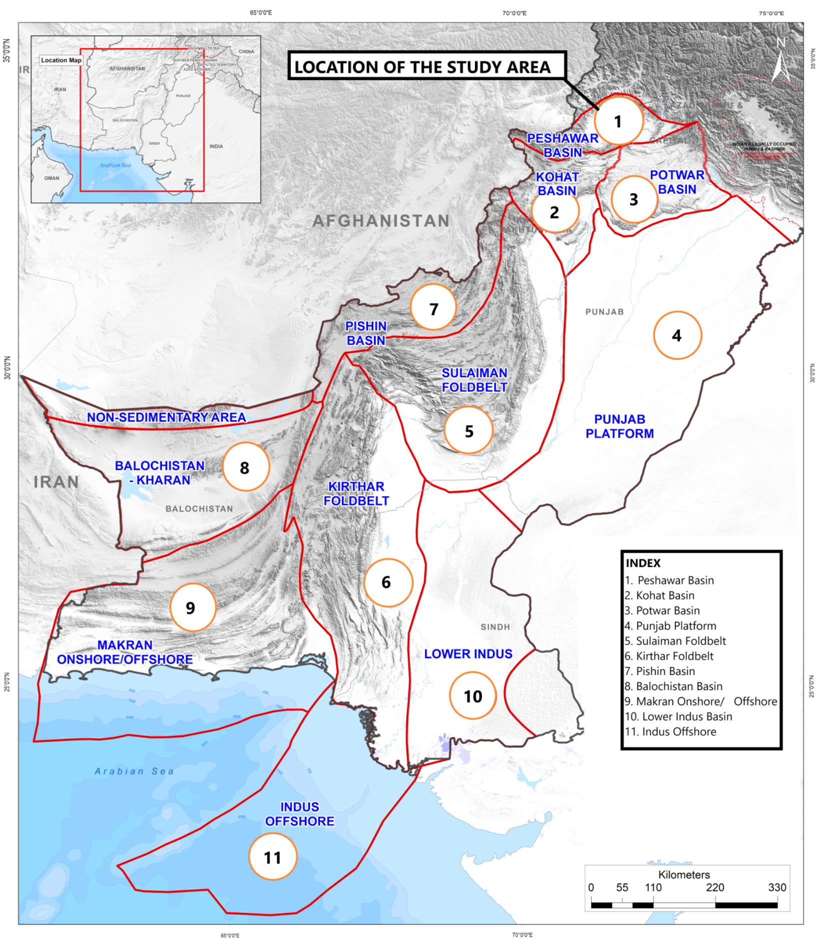

Figure 1. The map shows major sedimentary basins and actinomorphic terrains of Pakistan. The Peshawar Basin is located in the northwest of the Kohat Basin.

Table 1. The Paleozoic Stratigraphic framework of the Peshawar Basin and adjoining Attock Cherat Ranges, in north Pakistan.

Era	Epochs	Peshawar Basin and adjoining Attock-Cherat Range		
		Formation	**Lithology**	**Thickness**
Paleozoic	Devonian	Nowshera	Limestone, dolomite	30–215 m
	Silurian	Panjpir	argillie, phyllite, limestone, meta-sediments & quartzite	400–600 m
	Ordovician	Missri Banda	Quartzite	200–500 m
		Hissar-Tang	Argillites & quartzite	400–600 m
	Cambrian	Darwaza	Limestone, dolomite and maroon shale	500–760 m
		Ambar	Dolomite, quartzite and argillite	425 m

3.2 Misri Banda Quartzite

It is a dominantly arenaceous unit, bounded by unconformities, and lies between the underlying Ambar Formation (Figure 4) and overlying the Panjpir Formation. The formation contains feldspathic quartzite with thin intervals of argillites. The quartzite is cross bedded, and ripple marks are common. The lower contact is marked by argillites of the Ambar Formation whereas the upper contact is represented by a basal conglomerate. Based on the Cruziana *rugosa* fossils Ordovician age is assigned to this rock unit.

3.3 Panjpir Formation

This is dominantly an argillaceous unit lying between the Misri Banda Quartzite and the overlying Nowshera

Formation. The formation consists of argillites and phyllites; with interbeds of limestone in the upper part having crinoids (Figure 5). The lower contact was not exposed while its upper contact is gradational with the Nowshera Formation.

3.4 Nowshera Formation

The Nowshera Formation is the youngest stratigraphic unit in the Peshawar Basin. The dominant lithology of the Nowshera Formation includes recrystallized limestone, dolomitic limestone (Figure 6), sandstone and calcareous quartzite and minor argillite. The Nowshera Formation is subdivided into reef core, reef breccia, and unfossiliferous carbonates. The Nowshera Formation has an unconformable contact with the overlying Jafar Kandao Formation in the north of Swabi. The unconformity is marked by cobbles of argillite in the quartzite-argillite matrix and a discontinuous conglomerate bed composed of pebbles.

Figure 2. Salt pseudomorphs can be seen in the dolomite of Ambar Formation in the Ambar Village Section.

Figure 3. A view of the ripple marks in the Ambar Formation in the Ambar Village Section.

Figure 4. The contact relationship of the Ambar Formation and Misri Banda Quartzite in the Turlandi Village Section.

Figure 5. A close view of the Panjpir Phyllites is exposed along the Nowshera-Risalpur Road Section.

Figure 6. The outcrop of Nowshera Formation, shows the marble facies along the Nowshera-Risalpur Road Section.

4. Materials and Methods

A total of twenty-eight outcrop samples from the Nowshera-Risalpur Road Section, the Turlandi Section, and the

Ambar Village Section, were thoroughly investigated for the assessment of the hydrocarbon reservoir rocks in the Peshawar Basin. At the Central Resource Laboratory of the University of Peshawar, all the samples were analyzed. The techniques of thin section petrography, X-ray diffraction (XRD) analysis, and Scanning Electron Microscopy (SEM) were used and the results were integrated to better understand the hydrocarbon reservoir characterization in the study area.

5. Results and Discussion

5.1 Facies and Depositional Environments

Ambar Formation

Siltstone Facies: This facies is dominantly composed of silty siliceous matrix (Plate 1, A) with some muscovite grains (Plate 1, B). Some iron stains and heavy minerals (pyrite) are also obvious in the facies. The Ambar Village section has more sandy/siliciclastic content that is fine-grained (Plate 1, C). The facies is characterized by veins filled with low Mg calcite crystals (Plate 1, D). The facies shows signs of a low grade of metamorphism. The facies is very fine-grained, have some heavy mineral concentrations and is devoid of any fauna. The facies therefore represents the inner parts of a restricted environment. The sand content, present only in the Ambar Village Section is derived from the fine sand beaches.

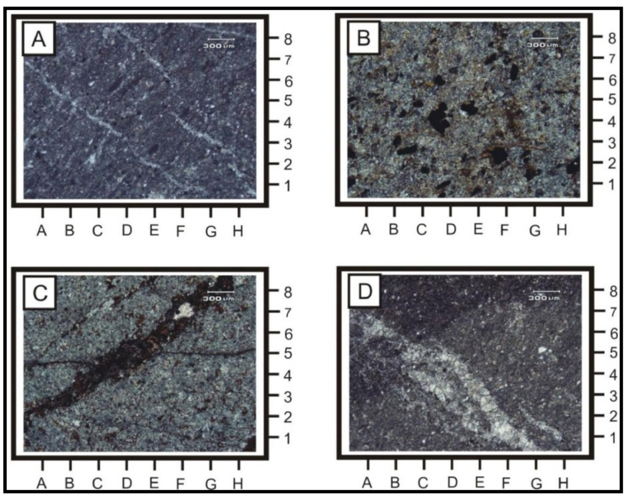

Plate 1. A: Photomicrograph showing the silty matrix in the siltstone facies of the Ambar Formation; B: the ferruginous mineral D4 and Muscovite mineral (D6); C: the ferruginous mineral filled fracture (D4); D: the calcite filled echelon fracture (D3).

Siliciclastic Lime Mudstone Facies: The facies is characterized by the dominance of lime mud (Plate 2, A) with varying amounts of siliciclastic input, in the form of quartz (Plate 2, B) and minor muscovite flakes, some unrecognizable bioclasts and ore minerals. The quartz grains are fine and sub angular to sub rounded (Plate 2, C). The facies is laminated (Plate 2, D) in one portion in the Ambar Village Section. The facies has a network of calcite filled vein that cross cut each other. Ferruginous stains and stylolites with ferruginous and clayey material are also obvious in the facies at different horizons. The facies contains an overall visual porosity of 2% in the thin section. The facies is mud supported and is almost devoid of any fauna and it seems to have been to have been deposited in the restricted parts of the ocean with elevated salinities and less circulation. The presence of lamination in the facies is an indication of the slow nature of deposition in this environment. This lagoon was supplied with siliciclastic input by fluvial and aeolian processes. The undulose extinction, displayed by quartz grains, is because of low grade metamorphism.

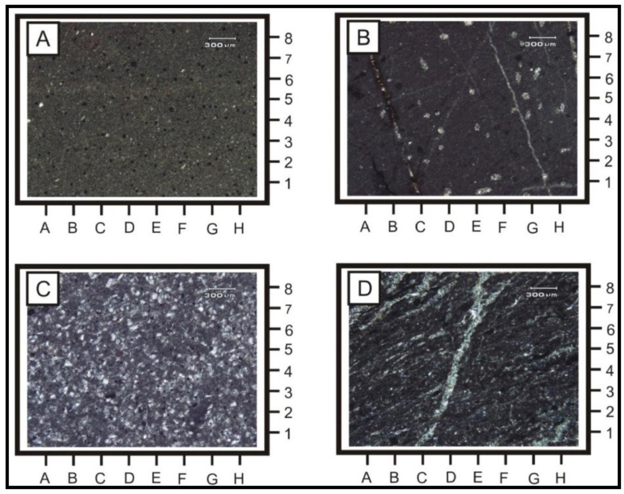

Plate 2. A: Photomicrograph showing the Lime Mudstone Facies of the Ambar Formation; B: the siliciclastic material (E4); C: fine silt size grains (B4); D: Photomicrograph showing the laminated fabric.

Dolomitized Ooidal-Peloidal Limestone Facies: The facies is characterized by the presence of carbonate allochems that include ooids and peloids (Plate 3, A). These grains are bounded by sparry cement along with intervening lime mud at places. The facies has packstone to grainstone textures. The ooids are radial with peloidal nuclei and some are micritized and converted into peloids. Both the micritized peloids and fecal pellets are present in the facies. In some horizons, the cementing material is replaced by dolomite of secondary origin (Plate 3, B). Some siliciclastic material in the form of angular to sub-rounded quartz is also present, some of which show undulose extinction. Ferruginous stains, stylolites and calcite filled veins are obvious in the facies at different places.

The facies is grain supported and are bounded by sparry calcite cement, some of which have been replaced by secondary dolomite (Plate 3, C) and some sand grains (Plate 3, D). The general absence of fauna, presence of faecal pellets, micritized nature of the grains and radial habit of the ooids indicate that deposition took place on hyper saline beaches of the lagoons. The presence of lime mud in some sections shows that this environment was subjected to fluctuating energy.

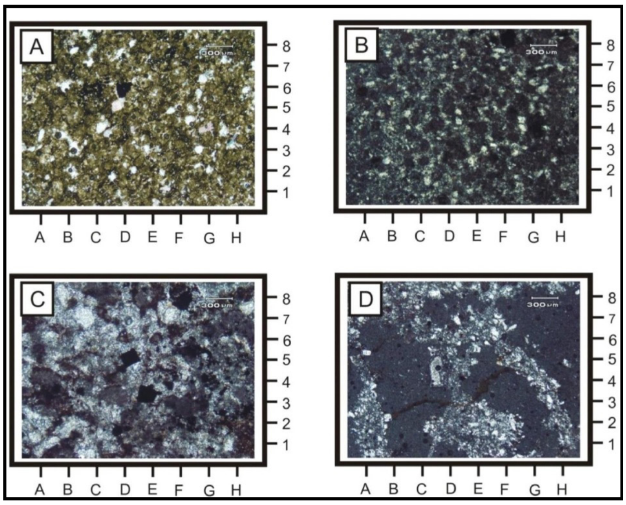

Plate 3. A: Photomicrograph showing the Ooids (C3) in the dolomitized Ooidal Peloidal Limestone Facies of the Ambar Formation; B: Peloids (D5) and siliciclastics (D4); C: Photomicrograph showing the dolomitized cement and pyrite (D5); D: siliciclastic material within the Ooidal Peloidal Limestone Facies.

Sandy Siliciclastic Mudstone Facies: The facies is a siliciclastic mudstone (Plate 4, A) that has some sandy patches of fine grained nature. It contains some amounts of muscovite, recrystallized biota and altered clays. The muscovite grains are aligned preferentially and show micro folding (Plate 4, B). The facies have some iron rich heavy minerals that exhibit a network of silica filled fractures.

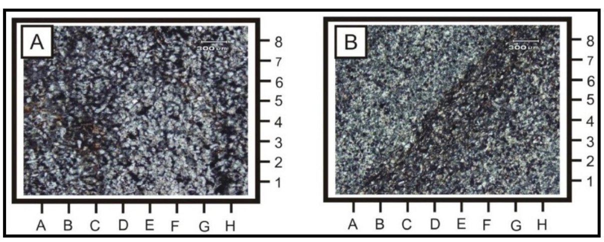

Plate 4. A: Photomicrograph is showing Fine Grained Sandstone Facies showing the siliciclastic input (E5); B: Muscovite flakes (D4).

The facies is siliciclastic mud supported and is devoid of fauna, except for some recrystallized bioclasts. The deposition took place in the inner parts of a lagoon. The minor siliciclastic input is probably derived from the fine grained siliciclastic beaches. The absence of planktons suggests an inner shelf lagoon environment rather than an outer shelf.

Missri Banda Quartzite

At the outcrop, this facies is composed of medium-thick bedded quartzose sandstone having ripple marks and cross beds at certain intervals. At the thin section level, this facies is dominantly composed of monocrystalline (90%) and polycrystalline (2%) quartz (Plate 5, A). The quartz is angular to subrounded, moderate to well sorted, tightly packed with straight to sutured contacts. A few quartz grains show undulose extinction. The feldspars (alkali feldspar and plagioclase) constitute about 10% of the facies. Altered clay lithic fragments constitute about 2% of the facies. A trace amount of muscovite (1%) is also present in the facies. Fracture porosity is present in the facies. The well sorted, sub rounded to rounded, rippled and cross bedded quartzose sandstone of the Misri Banda Quartzite is deposited on high energy beaches and foreshore environments.

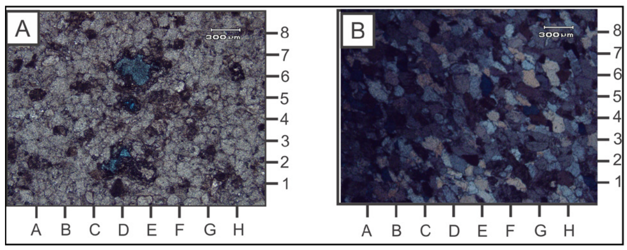

Plate 5. A: Photomicrograph is showing moderately sorted quartz, Dissolution porosity (EC57), Intraclats (D1) within the Qurtzite of Misri Banda Formation; B: Photomicrograph showing moderately the contacts between the quartz grains (XPL).

Panjpir Formation

Phyllites: The phyllites of the Panjpir Formation are dominantly composed of quartz and clays. The segregation of quartz and clays into separate layers is quite well developed but not to the degree of schistosity. Very fine mica is developed in the clay rich layers (Plate 6, A–D). Prominent segregation and the development of mica suggest that the Panjpir Phyllites have undergone the peak of low grade metamorphism.

Bioclastic Wackestone Facies: The facies is composed of grains to matrix ratio of 1.5:8.5. The grains consist mainly of bioclasts of echinoderms (Plate 7, A), pelecypods (Plate 7, B), brachiopods, ostracods (Plate 7, C). The other grains include siliciclasts (Plate 7, D) of fine sand

and have angular to sub rounded shapes. These grains are embedded in a matrix of lime mud. The facies is mud supported and contains diverse fauna in the form of brachiopods and echinoderms. The facies thus represents a normal salinity low energy environment of the middle shelf environment.

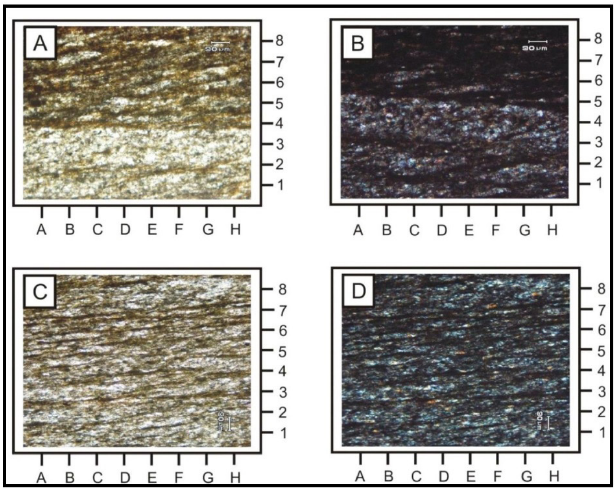

Plate 6. A, B: Photomicrograph showing the quartz, clays and mica rich layers in the Panjpir Phylites (PPL, XPL); C, D: preferred orientation of the quartz and clay layers (PPL, XPL).

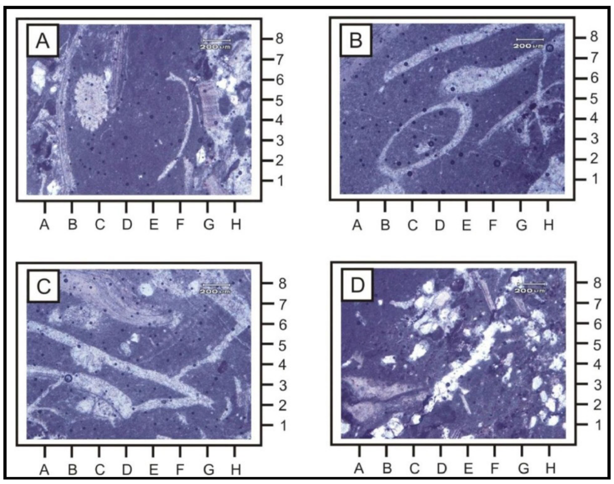

Plate 7. A: Photomicrograph showing the Bioclastic Wackestone Facies, confirming echinoderm spine (C5) within the Panjpir Formation; B: bivalve (E6); C: ostracode (F2) and brachiopod (C7); D: siliciclasts (H2) are common.

Nowshera Formation

Dolostone Facies: The dolostone is the most prevalent facies across the formation in both the Nowshera and Pir Sabak Village Sections. The dolomite (Plate 8, A) ranges in size from fine to medium sand and it is often pervasive, sometimes selective as well. The dolomite has replaced either the matrix or the grains or both. In some cases, the signs of the original precursor material are still obvious (Plate 8, B). Most of the dolomitization has taken place in the fine grained lime mudstones and wackestones. Some of the dolomite crystals are euhedral (Plate 8, C), ferroan and zoned. Silt size siliciclasts are found in some of the samples. Fracturing, though not common, is found in some parts of the facies (Plate 8, D).

The facies is characterized by fine to medium dolostones, some of which have euhedral crystals. The original precursor material, in some cases, is still obvious. The facies is therefore considered secondary in nature replacing the matrix and bioclasts of the mudstones and wackestones. The Magnesium rich fluids might have been circulated through the reef complex, particularly in the back reef portion.

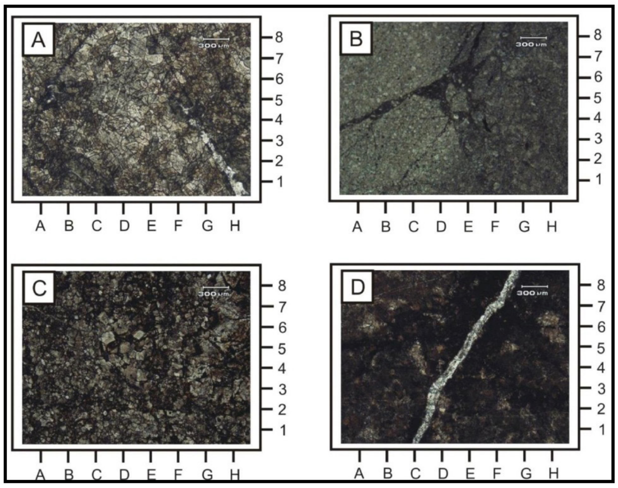

Plate 8. A: Photomicrograph showing the presence well developed dolomite crystals (D5) in the Dolostone facies of the Nowshera Formation; B: the original precursor (D5); C: Euhedral dolomites (DE56); D: Photomicrograph is showing the fractures (E5).

Recrystallized Bioclastic Wackestone/Mudstone Facies: The facies is represented by mud supported nature and have grains in the form of bioclasts. The facies is dolomitized (Plate 9, A) but the precursor facies is still evident. The bioclasts consist of crinoid's ossicles (Plate 9, B), bivalves (Plate 9, C), and gastropods. Most of these bioclasts are recrystallized but their outlines are still obvious (Plate 9, D). The facies is fractured in some horizons and stylolites are also obvious.

The facies is supported by lime mud and bioclasts such as crinoids and mollusks. The crinoids are found in the reef flank beds [17]. The facies thus represent the reef flank/upper slope depositional environment.

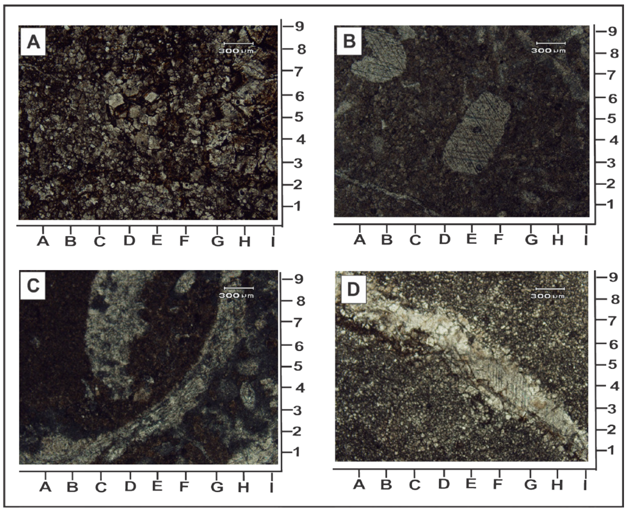

Plate 9. A: Photomicrograph shows the precursor dolomite within the Recrystallized Bioclastic Wackestone/Mudstone facies (E5); B: A view of the Crinoid ossicle (E4); C: Photomicrograph showing the bivalve fragment (F4); D: Photomicrograph is showing the recrystallized bioclast (E5).

Siliciclastic Dolostone Facies: This facies is restricted to the Pir Sabak Village Section and is composed of dolostones with substantial amounts of siliciclasts (Plate 10, A) in the form of quartz. The quartz grains, some of which are fractured (Plate 10, B), are fine-medium sand size, moderately sorted and range from sub-angular to rounded (Plate 10, C). These grains are set in a mix of fine grained dolomite and coarse calcite (Plate 10, D). The facies has a preponderance of quartz grains set in secondary dolomite and calcite. The secondary calcite is formed as a result of the circulation of Mg rich lagoon waters [18]. The facies represents the lagoon facies with some clastic input from the land area.

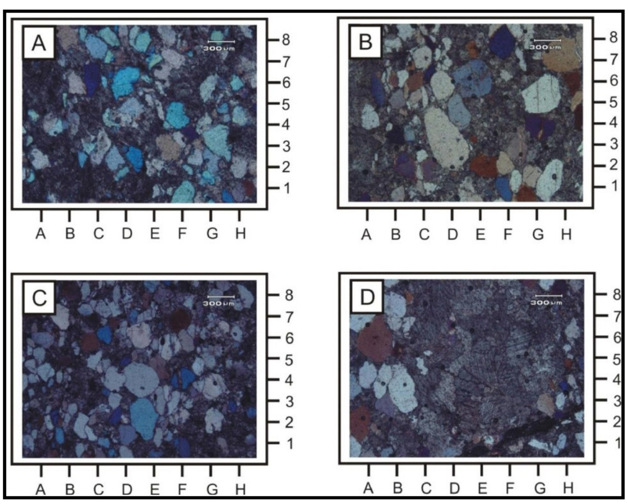

Plate 10. A: Photomicrograph showing the Siliciclastics Dolostone Facies; B: siliciclastic quartz (G5); C: well rounded quartz (E4); D: A view of the recrystallized calcite.

6. Hydrocarbon Reservoir Characterization

6.1 Ambar Formation

The Ambar Formation is mainly comprised of dolomite and argillite. The matrix is composed of ferruginous-clay, dolomite and micrite while the spar is present as fracture filling and as a product of neomorphism (Plate 11, A, B, C, D, and E). The XRD analysis indicates that the ferruginous clay matrix constitutes quartz, dolomite, goethite, kaolinite, albite and illite (Plate 11, F).

Dolomitization may increase the secondary porosity and is connected to the ferruginous matrix. When rocks are exposed sub-aerially to meteoric fluids in an exogenetic environment, porosity enhancement owing to dissolution may also happen to make up for this early porosity loss [19-21]. Twin cleavage plane and high dissolution porosity which is evident from the SEM images can provide significant pore space to the migrating hydrocarbons thus making it an excellent reservoir (Plate 11, G and H).

6.2 Misri Banda Quartzite

The feldspathic quartzite with subordinate argillite is the main lithology in Misri Banda Quartzite. The quartzite is tightly packed with concavo-convex to sutured contacts. Grains are mostly sub-rounded to rounded having the ability to adopt the closest packing upon increased pressure. At places, a small amount of ferruginous matrix is present along the fractures. Secondary dissolution porosity has been developed at the expense of the much unstable sedimentary lithics (Plate 12, A and B). A high concentration of quartz and a minor occurrence of microcline and hematite is also evident from the XRD analysis. A minor amount of kaolinite, illite and chlorite as alteration products of unstable framework grains (feldspar) are present which can affect the porosity (Plate 12, C). All naturally occurring smectite clays including kaolinite are susceptible to chlorite alteration [22,23]. In situations with high pH values and high Fe and Mg ion levels, smectite changed into chlorite. Chlorite-smectite mixed layer stage is when the transition typically takes place [24,25]. This process takes place at a low diagenetic temperature at a relatively shallow depth. In an environment with abundant Fe and Mg supply, kaolinite changed to chlorite with increasing burial depth and temperature [26,27]. Illite is present in the form of flaky pore lining material and partially covers a few of the pore spaces thus minimizing its reservoir potential (Plate 12, D). Being tightly packed, still there exists intergranular porosity between the stable grains (Plate 12, E) because the mineralogical, mature sandstone has the ability to retain a high amount of intergranular porosity at greater

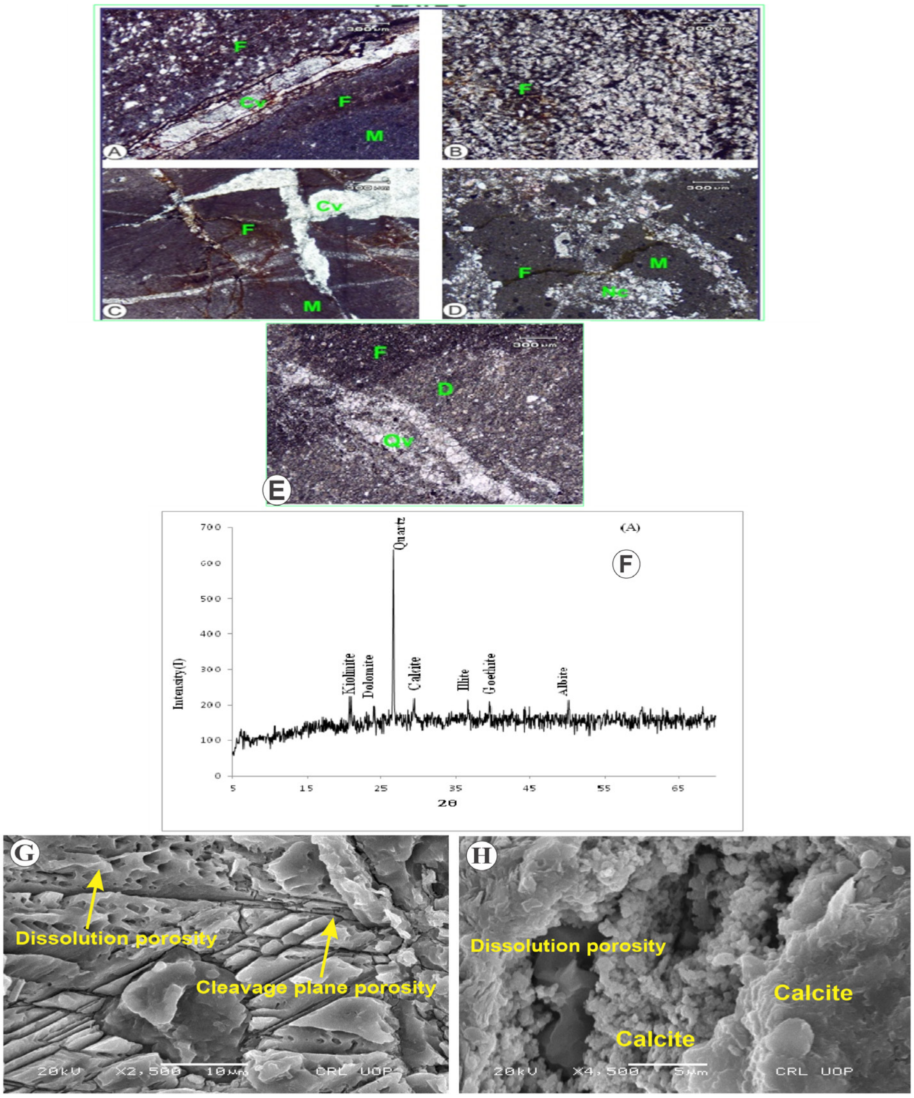

Plate 11. A, B, C, D, and E are representing the Photomicrographs of Ambar Formation, various blocks of cement matrix types, Ferruginous clays (F). Micrite (M), Calcite filled Veins (CV), Dolomite (D) and calcite; F: The XRD results showing the bulk rock geochemistry of the Ambar Formation; G, H represent the SEM images focusing the Dissolution and cleavage plane porosities and calcite mineral.

burial depth. According to earlier research, chlorite coatings, particularly in deeper reservoir sandstones are significant contributors to anomalous porosity and permeability. The Presence of chlorite and sutured contacts between quartz grains are indicative of deep burial diagenesis and very low grade metamorphism, which may have obliterated the depositional porosities to a great extent.

6.3 Nowshera Formation

Limestone, dolomite, and quartzite are the main lithologies in the Nowshera Formation. Between the framework grains, coarse and fine calcite, dolomite, and ferruginous clays are present as pore fillers (Plate 13, A and B). Chlorite and kaolinite may have been created by the alteration of alkali feldspar or unstable clastic framework grains, as shown by the XRD study in Plate 13, C. According to Foscolos [28], certain fluids produced during burial diagenesis aid in the alteration of clay minerals, such as the transformation of smectite to illite. The burial depth and temperatures had a significant impact on how quickly kaolinite turned into chlorite. Almost no porosity is present at the thin section level. However, SEM analysis shows that the carbonate of the Nowshera Formation possesses a high amount of intragranular dissolution porosity and micro intergranular connecting porosity (Plate 13, D and E). The primary porosity has been reduced as a result of high temperature recrystallization, which alters the size, shape, and lattice of the crystals without altering their mineralogy.

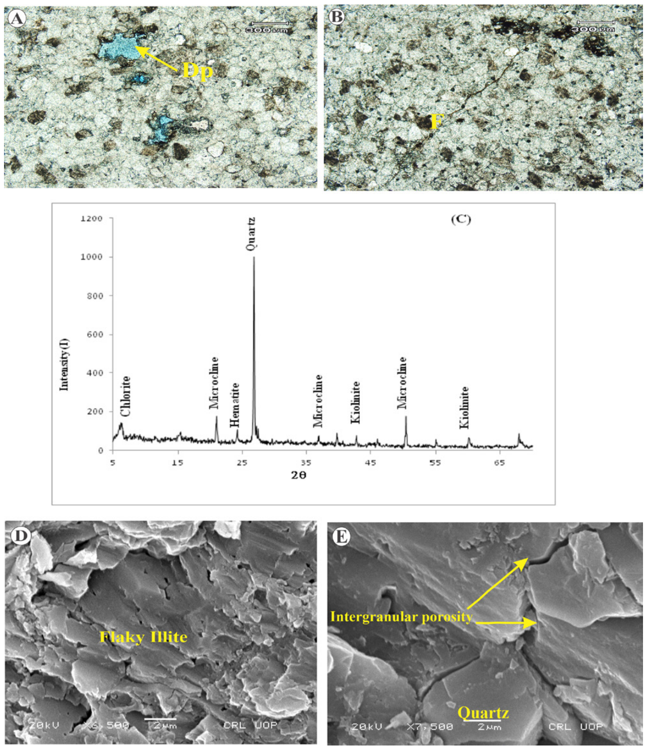

Plate 12. A, B: Photomicrographs of the Misri Band Quartzite showing tightly packed quartzite with dissolution porosity (Dp) and ferruginous clays (F); C: The XRD data are showing the bulk rock geochemistry of the Quartzite rocks; D, E: represent the SEM images showing the pore filling illite and inter-granular porosity.

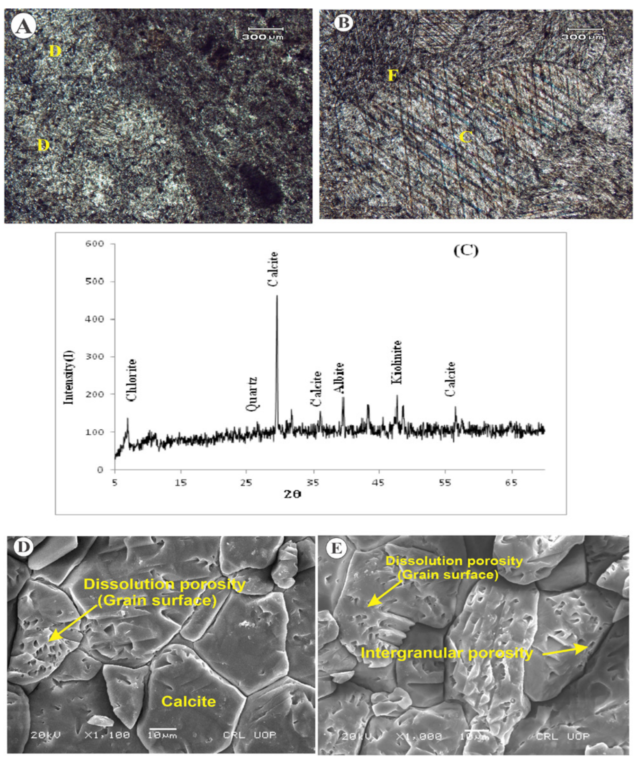

Plate 13. A, B: Photomicrographs of the Nowshera Formation illustrating its pore filling material, Calcite (C) Ferruginous clay (Fc) and dolomite D; C: The XRD data showing the bulk rock geochemistry of the Nowshera Formation lithologies showing the bulk geochemistry; D, E: represent the SEM images of the Nowshera Fm illustrating the dissolution and inter-granular porosities.

7. Conclusions

Hydrocarbon reservoir characterization has gained significance as numerous oil fields are getting mature around the world. The development of petroleum geology and reservoir characterization over time provides insight into how these issues have been overcome and what new methods and technologies will be used in the future. Integrated sedimentogoloical, mineralogical and Nano porosity analysis of the Cambrian-Devonian clastic-carbonate mixed lithofacies of the Peshawar Basin in Pakistan has been seen as a significant tool in characterizing the hydrocarbon reservoirs in the study area.

The following conclusions are drawn from current investigations.

- The Ambar Formation is characterized by a mix of siliciclastics and carbonates. The siliciclastic lime mudstones and ooidal peloidal limestones represent the carbonate portion of this shelf in the form of hyper saline lagoons and beaches. Whereas the fine grained sandstone, siltstone and sandy siliciclastic mudstone occupied the clastic dominated beach and lagoon environments. The deposition of formation, therefore, took place in the clastic and carbonate dominated near shore waters of the shelf.
- The XRD analysis indicated the presence of dolomite, micrite; goethite, kaolinite and illite are present as an intergranular mass while calcitic spar is present as fracture filling and a product of neomorphism in Ambar Formation. Dolomitization induced porosity, twin cleavage plane and high dissolution porosity confirmed from SEM image can provide significant pore space to the fluids creating it good reservoir.
- The deposition of the Missri Banda Quartzite occurred on the sandy beaches. The thin section of Misri Banda Quartzite shows lithic fragments dissolution. Hematite with some minor amount of kaolinite, illite and chlorite as alteration products of unstable framework grains as an intergranular mass in Misri Banda Quartzite confirmed from XRD analysis. Deep seated burial diagenesis has minimized the reservoir potential of the unit. It is concluded that Missri Banda Quartzite is a moderate Reservoir.
- The reefal buildups (Dolomites and carbonates) of the Nowshera Formation contain both coarse and fine calcite, dolomite, chlorite and kaolinite that occur as pore filling material between the framework grains. The SEM images display a high amount of intragranular dissolution and micro intergranular connecting porosity in the Nowshera Formation which makes it a promising reservoir.

Author Contributions

Sajjad Ahmad conceptualized this research and drafted this manuscript. Sohail Raza completed his MS Geology research in this area of investigation while Suleman Khan's Contribution in the geological fieldwork and subsequent laboratory work are highly appreciated. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be made available on request.

Conflict of Interest

There is no conflict of interest.

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