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Structural Analysis and Reservoir Characterisation of Cretaceous Sequence in Kohala Bala, Khyber Pakhtunkhwa, Pakistan

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Original scientific paper

Bilal Ahmed[1]; Shahzad Bakht[2]; Sohail Wahid[1]; Muhammad Hanif[1]
[1] *National Centre of Excellence in Geology, University of Peshawar, Peshawar, Pakistan*
[2] *College of Earth Sciences, Jilin University, Changchun 130061, China, https://orcid.org/0000-0002-3201-1498*

Abstract
Southeastern Hazara is a portion of the Himalayan Fold-Thrust Belt, formed by the interaction of the Indian Plate with the Eurasian Plate. The present research was conducted to analyse the structural geometry and assess the reservoir potential of the Cretaceous sequence (the Chichali Formation and the Kawagarh Formation) in southern Hazara, Pakistan. The mapped stratigraphic units range from Late Jurassic, Samana Suk Formation to early Eocene, Margalla Hill Limestone, along with unconformities. The research area is under intense deformation and is characterised by the thrust faults with accompanying folds. The fore-thrust faults are steeply dipping towards the north with associated back-thrust dipping southward, and the folds are mainly asymmetric anticlines and asymmetric synclines along with a symmetric anticline (Barkot). The structures trend mainly NE-SW, indicating NW-SE compressive stresses. Reservoir quality is evaluated by using petrographic image analysis, SEM analysis, plug porosity, and permeability analysis. The porosity observed varies from 0.282% – 10.89%, 0.016% – 1.78% in the Chichali (sandstone) Formation and the Kawagarh (limestone) Formation, respectively. Simultaneously, the measured permeability in the Chichali and Kawagarh formations varies from 0–0.064 mD and 0–0.014 mD, respectively. The primary porosity type was intergranular/interparticle, intragranular, fracture, and vuggy porosity. SEM analysis shows that microporosity is present in the Cretaceous sequence and, calcite, dolomite, quartz, feldspar, and pyrite are the major minerals. The reservoir studies show that the Chichali Formation can be proven as a good (Tight) reservoir rock, and the Kawagarh Formation may be proven as a reservoir (if the fractures in the subsurface, formed by severe tectonic deformation are not filled with cementing material) and seal/cap rock.

Keywords:
Himalayan Fold-Thrust belt; reservoir characterisation; southern Hazara Pakistan; SEM analysis; plug porosity

1. Introduction

The research area Kohala Bala is located in southeastern Hazara surrounded by the Mansehra Metamorphic zone and Potwar Basin in the north and south, respectively (**Baig and Lawrence, 1987**). The research area is situated 42 kilometres southeast of Haripur between the latitude of 33° 50′ N to 33° 54′ N and longitude 73° 10′ E to 73° 14′ E in southern Hazara. The Nathiagali Thrust (NT) and Murree Fault also bound the research area from north and south, respectively (**Iqbal et al., 2007; Figure 1**). Southeastern Hazara is a small portion of the Himalayan Fold-Thrust Belt, formed by the collision of the Indian Plate and the Eurasian Plate (**Pennock et al., 1989; Grodner et al., 2021; Rehman et al., 2021**). **Waagen** (**1872**), **Wynne** (**1873; 1875**), **Middlemiss** (**1896**) and **Cotter** (**1933**) are considered the first geological researchers who explored the Hazara area. **Shah** (**1977**) renamed many formations, and the Stratigraphic Committee of Pakistan acknowledged his recommendations. A structural geological section of Murree-Abbottabad road was published by **Coward and Butler** (**1985**). It was suggested by them that the Hazara Hill Ranges is a chain of imbricate thrust faults, separated from the Main Boundary Thrust (MBT). The issues of stratigraphic nomenclature of the Hazara region were studied by **Butt** (**1972**). Various stratigraphic provinces and geological structures of Kuza Gali, Dunga Gali and Ayubia areas were established by **Ghazanfar et al.** (**1990**). **Burg et al.** (**2006**) proposed the structural fabrics of the Hazara Fold-Thrust Belt. The litho-biostratigraphic studies in the research area were carried out by **Munir et al.** (**1997**).

Latif (**1970, 1976**) contributed a detailed explanation of the stratigraphy of southeastern Hazara and mapped an extensive area of southeastern Hazara. He explained the stratigraphy of the area in the descriptive notes with a geological map. However, **Latif**'s (**1970**) map lacks some information, as formations were covered by thick alluvium. Nevertheless, due to advancements in road

Corresponding author: Shahzad Bakht
e-mail address: bakhtshahzad18@mails.jlu.edu.cn

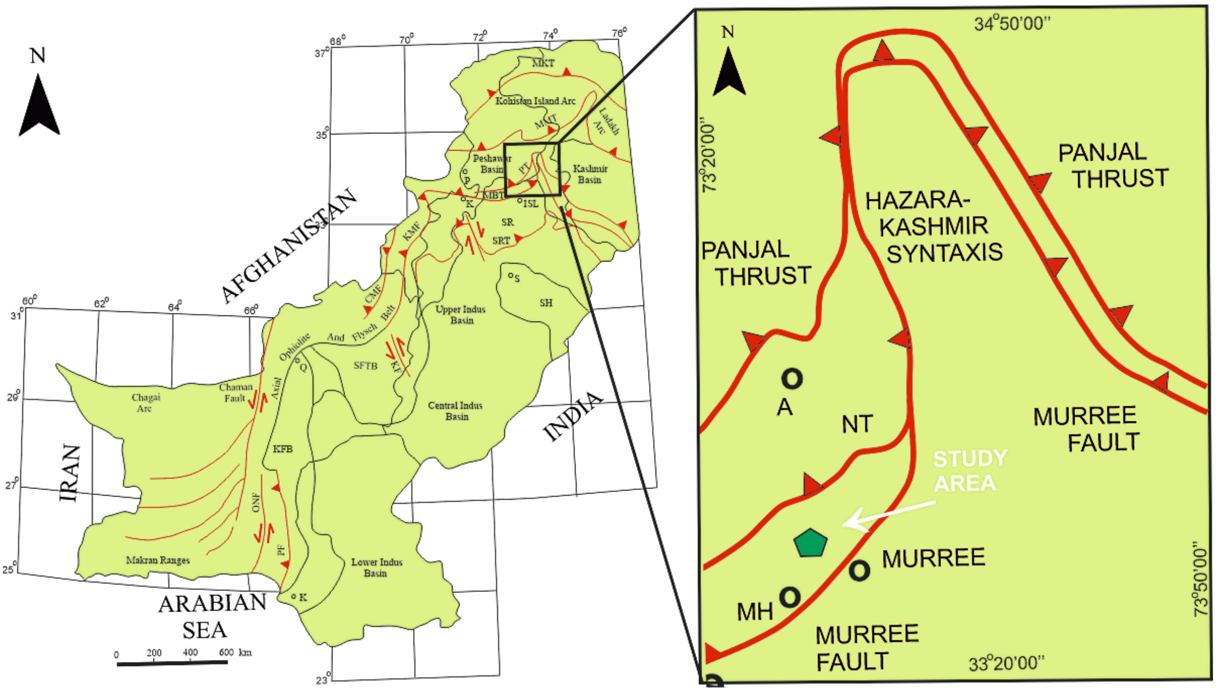


Figure 1: Map showing regional geology and tectonics of Pakistan. Research area is shown by box. (A) Abbottabad, (NT) Nathiagali Thrust, (MH) Margalla Hills. (After Khan, 2013)

networks, many formations have been exposed along the road cuts, especially in the Barkot section, and this information is needed to be updated. Moreover, Latif's geological map lacks information regarding structural geometry, which is the most important part for structural analysis. In this study, we have used Latif's base map (**Latif, 1970**) to update the missing information (see **Figure 3**). Stratigraphically, the area of southeastern Hazara represents a portion of the much larger sedimentary basin of Kohat-Potwar (**Ghazanfar et al., 1990**). **Khan** (**2007**) evaluated the Chichali Formation for its hydrocarbon potential in southern Hazara. **Akhtar et al.** (**2019**) worked on the stratigraphy and structure of the Dhamtaur area, explaining the structural features along with their subsurface projections. The stratigraphic sequence in southern Hazara ranges from Pre-Cambrian to Miocene. The middle to upper Paleozoic sequence is completely missing from the area, and other small disconformities are also present in southern Hazara (**Ghazanfar et al., 1990; Latif, 1970; Figure 2**). In addition, the units exposed in the research area range from late Jurassic Samana Suk Formation to early Eocene Margalla Hill Limestone (**Swati et al., 2014; Figure 3**). The Callovian disconformity separates the Chichali Formation from the underlying Samana Suk Formation in the Hazara area (**Shah, 1977; Figure 2**). However, the contact is conformable in the research area (Kohala Bala).

The Chichali Formation mostly consists of grey to black splintery shale and glauconitic sandstone. It also contains pyrite nodules and ferruginous concretions within the formation at various places. The thickness of the formation varies from 33m to 64m in the Hazara area (**Shah, 1977; Iqbal and Shah, 1980**). The Chichali Formation is rich in ammonites, belemnites and pelecypods accompanied by gastropods, brachiopods, vertebrate remains and foraminifera. The formation is exposed as thin bands due to tectonic compression, and erosion of incompetent lithology forms topographic depression. Petrographically, sub-rounded to sub-angular grains are observed in the Chichali Formation, and the grain sorting observed was moderate to poor. The maturity observed was from sub mature to mature, and it can be grouped into "quartz arenite" (**Pettijohn et al., 1987**). Laterite is dividing the Chichali Formation from the underlying Samana Suk Formation. This laterite was formed in the upper Indus Basin of Pakistan when the sub areal exposure of carbonate platform occurred (**Smewing et al., 2002**). The other facies observed during fieldwork are fine to medium grained glauconitic sandstone that is occasionally carbonaceous. The glauconite dominates throughout the formation. However, it is more abundant in the lower part of the formation than the top. The abundance of glauconite represents the slightly reducing shallow to moderate water conditions with low sedimentation influx. The carbonaceous green clay facies exist in the uppermost part of the formation, and belemnites and ammonite's shells are also present. The presence of phosphatic nodules and rich horizon of sulphur indicates that the facies was deposited under deep reducing conditions.

The Kawagarh Formation is one of the important formations in the Hazara Basin, which exhibits two different facies towards north and south of the Nathiagali Fault (**Ahsan and Chaudhry, 1998**). The composition

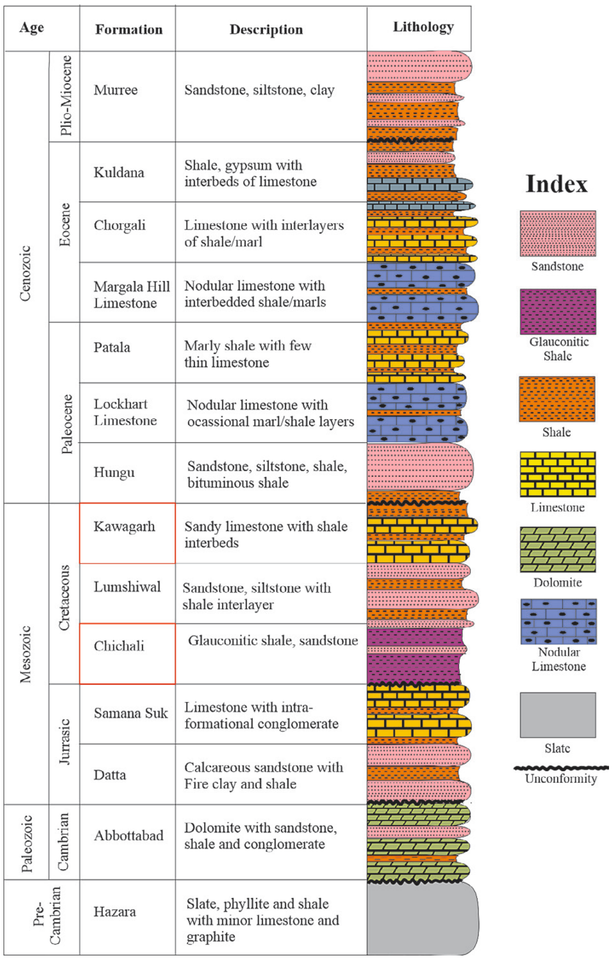


Figure 2: Showing stratigraphic column of southern Hazara, Pakistan. The red rectangles indicate the studied formations (Chichali and Kawagarh) (after Latif, 1970).

of the formation in the research area is limestone of olive-grey colour with intercalation of marl and calcareous clays. The main skeletal components of the Kawagarh Formation are planktonic foraminifera, calcareous dinoflagellate algae and shelly fauna. The skeletal debris of filaments, textularia, bryozoans, ostracodes and echinoids are also observed as a shelly fauna during petrographic studies. The formation has disconformable contact with both the lower Lumshiwal Formation and upper Hangu Formation. The thickness of the formation varies from 45m to over 200m in the Hazara region.

Numerous researchers, including **Latif (1970)**, **Fatmi (1972)**, **Butt et al. (1990)**, **Khan (2007)**, **Ahsan (2008)** and **Rehman (2009)**, gave contributions on the Cretaceous sequence regarding its depositional environments, microfacies analysis, biostratigraphic zonation and diagenetic setting in Hazara fold-thrust belt. However, no one gave significant importance to the reservoir quality of the Cretaceous sequence, structural geometry, and potential hydrocarbon structural traps, if they exist. Moreover, no detailed map of the study area regarding the structural styles has been prepared. This research work aims to delineate the reservoir quality of the Cretaceous sequence and analyse the structural geometry of the study area. This study provides help to understand the overall structure of the Kohala Bala. In addition, it provides insights for understanding petroleum potential, and possible hydrocarbon traps for the Chichali Formation and the Kawagarh Formation.

2. Methodology

The methodology includes both fieldwork and laboratory work. In the fieldwork, geological mapping of the research area is done at a scale of 1:50,000 with the help of topographic maps and existing available geological maps as a base map. Traverses were made to document structural features along with road cuts and streams which provide good exposures across the regional strike. The geological map was prepared by using GIS (Arc Map 10.4.1), and Corel Draw X7 portable graphic software was used to construct geological cross-sections. Two transects have been marked along with line AB and CD, perpendicular to the structural trend on the map, respectively (see **Figures 4** and **5**).

A total of 57 samples were collected during fieldwork. Thirty-six samples were collected from the Chichali Formation and twenty-one samples were collected from the Kawagarh Formation at the Barkot section (see **Figure 6A**). Selective sampling has been carried out based on the lithological variation in the field and group BC (Barkot Chichali) and BK (Barkot Kawagarh) was formed for three samples each based on petrographic similarities. All samples were analysed during petrographic image analysis. Based on the petrographic studies, eighteen samples were selected from the Chichali Formation, and nine samples were selected from the Kawagarh Formation for plug porosity and permeability analysis. In addition, twenty-one samples were selected for SEM analysis from the Chichali Formation (fifteen samples) and the Kawagarh Formation (six samples).

Most of the laboratory work, i.e. rock thin section preparations, petrography, microscopic photography, SEM analysis, was done at the petrography laboratory and SEM laboratory of the National Centre of Excellence (NCE) in Geology, University of Peshawar. The petrographic study was carried out with the help of a digital camera fitted Nikon Polarising microscope at NCE. The different types of pore spaces filled with the blue dye are used to recognise the different porosity types. SEM of selected samples was performed using the SEM microscope (JEOL JSMIT 100), present at the NCE in Geology, University of Peshawar, to identify the various minerals and morphology of the cement, pore, and minerals.

Petrographic image analysis for the reservoir characterisation was carried out using the Image J software. The methodology was used by **Hayat et al., 2016; Grove et al., 2011; Haeri, 2015**. Image J porosity analysis is a relatively new computerised approach. The Image J software works on JavaScript, and the pores spaces are calculated from the microphotographs. The Image J requires high-resolution microphotographs. The microphotographs were imported into the software, and the command of the Colour threshold was applied. Then the threshold of blue colour was adjusted as the sample's pore spaces were filled with blue dye. Lastly, the threshold was adjusted and the command of analysed particles was applied. The obtained results in the column of "percent area" are the quantitative porosity of the analysed sample.

The plug porosity and permeability of the rock samples were measured at the Hydrocarbon Development Institute of Pakistan laboratories (HDIP). The porosity and permeability of selected rock samples were analysed by using a porosimeter of the Pore Master Series. The plug permeability test of the rock samples was also measured at HDIP laboratories using a permeameter.

3. Results

3.1 Important Structural Features

The research area is situated at Hazara Fold-Thrust Belt and has experienced extreme distortion and shortening, as shown by many thrust faults and several folds at large and small scales (see **Figure 1**). The general orientation of these structures is NE-SW, representing compressional forces in the direction of northwest-southeast. The main structural features of the research area are discussed below.

3.1.1 Fault Structures

The research area is characterised by numerous reverse faults that comprise the Jabri Thrust, Kohala Thrust-1, Kohala Thrust-2, Rupper Fore-Thrust and Barkot Back-Thrust Faults (see **Figure 3**). Many strata are steeply dipping towards the south. The deformed Samana Suk Formation is present in the northernmost part of the study area. The northernmost thrust of the research area is Jabri Thrust Fault, which brought the Samana Suk Formation over Lockhart Limestone along the thrust. The folding in Lockhart Limestone represents that it has experienced plastic and ductile deformation.

The Jabri Thrust is northeast-southwest oriented, and it is dipping at about 63° towards the north (see **Figure 4; Figure 5**). In cross-section AB, the Jabri Thrust is present north of Dotara overturned Anticline and Samana Suk Formation is thrust over the Lockhart Limestone along this thrust. However, in cross-section CD, the Samana Suk Formation is missing, and the Chichali Formation is thrust over the younger Lockhart Limestone.

Kohala Thrust-1 and Kohala Thrust-2 faults occur south of the Jabri Thrust Fault and the Kohala overturned Syncline. The Samana Suk Formation is thrust over the Kawagarh Formation along the Kohala Thrust-1 Fault (see **Figure 6b**). The orientation of thrust is also northeast-southwest with a dip of 60° towards the north. In both cross-sections AB and CD, Kohala Thrust-1 shows same structural geometry (see **Figure 4; Figure 5**). The Kohala Thrust-2 Fault is present to the south of Kohala Thrust-1. It runs parallel to the Kohala Thrust-1 Fault and has the same orientation. This thrust brought the Kawagarh Formation over the younger Margalla Hill Limestone in both cross-sections AB and CD (see **Figure 4; Figure 5** and **Figure 6c**).

The Barkot Back-Thrust is present to the south of Kohala Thrust-2 Fault and Barkot Anticline. Along this fault, the lower Paleocene Lockhart Limestone is thrust above the younger upper Paleocene Patala Formation. The Barkot Back-Thrust is northeast-southwest orientated with a dip of 66° towards the south and is present in both cross-sections AB and CD and depicts the same geometry. In cross-section AB, the Samana Suk Formation, the Chichali Formation, the Kawagarh Formation, and the Lockhart Limestone is present in a conformable sequence to the south of the Barkot Back-Thrust. The lower Cretaceous Lumshiwal Formation and Rupper Thrust is missing in this cross-section (see **Figure 4; Figure 5**). To the south of Barkot Back Thrust, the Rupper Thrust Fault is present. The Samana Suk Formation brought over Margalla Hill Limestone along the Rupper Thrust Fault. This thrust also has a northeast-southwest orientation and is dipping 80° towards the north (see **Figure 5**). The Rupper Thrust Fault is present in the southern part of cross-section CD.

3.1.2 Fold Structures

The major overturned thrust related folds include Dotara overturned Anticline, Dotara overturned Syncline, Kohala overturned Anticline, Kohala overturned Syncline, and Barkot Anticline (see **Figure 3; Figure 4; Figure 5**).

Dotara overturned Anticline and Dotara overturned syncline occurs northwest of the study area (south of Jabri Thrust Fault), near the village Dotara. In Dotara overturned anticline, the core is occupied by Lockhart Limestone while Patala Formation covers its flanks. The orientation of the fold axis is northeast-southwest, similar to the orientation of the region. The Dotara overturned anticline is present in both cross-sections AB and CD (see **Figure 4; Figure 5**).

Dotara overturned syncline is present to the south of Dotara overturned anticline. In this syncline, Patala Formation occupies the core of the fold, and Lockhart Limestone is present on the limbs. The orientation of the fold axis is similar to the orientation of the Dotara overturned anticline. The Dotara overturned syncline is present in both cross-sections AB and CD (see **Figure 4; Figure 5**).

The Kohala overturned anticline is present in the middle of the mapped area and south of Dotara overturned syncline. The Cretaceous Kawagarh Formation occupies

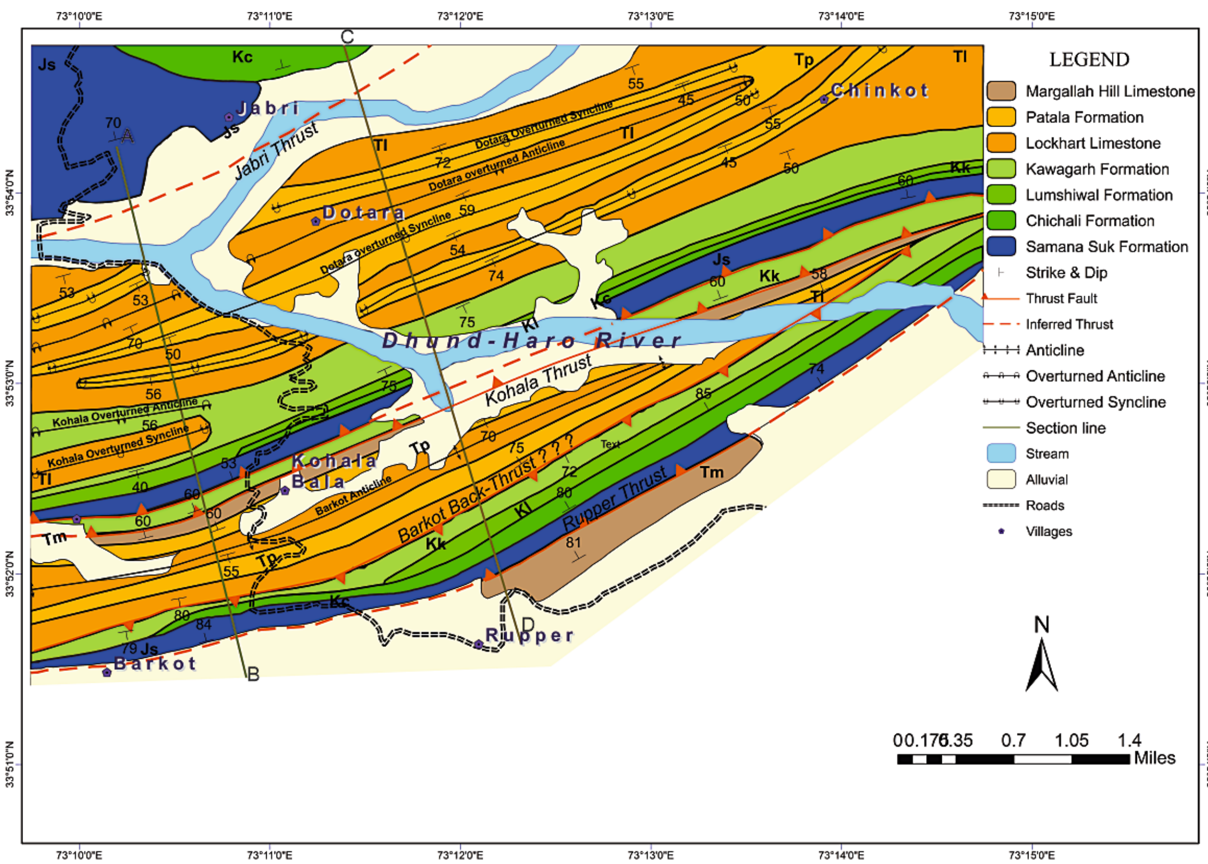


Figure 3: Geological map of the research area (modified after Latif, 1970). AB and CD showing the transects position.

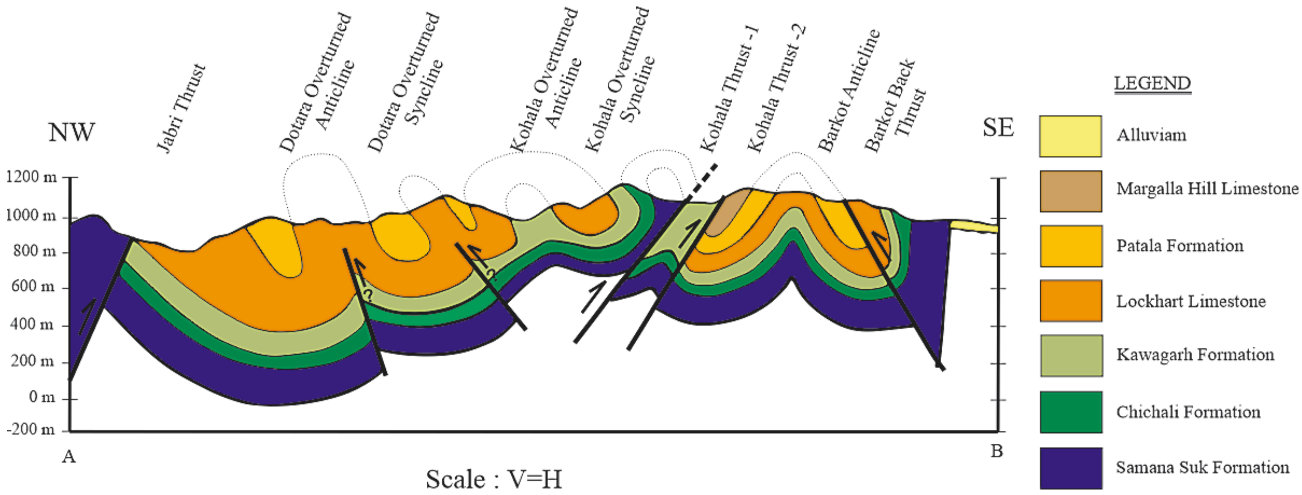


Figure 4: Geological cross-section along line AB of Figure 3

the core of the Kohala overturned anticline, and Lockhart Limestone is present on the limbs. The Kohala overturned anticline is present in cross-section AB and is missing in the cross-section CD (see **Figure 4; Figure 5**).

The Kohala overturned syncline is present adjacent to the Kohala overturned anticline. The Lockhart Limestone is present in the core, and the limbs are occupied by the Kawagarh Formation, the Chichali Formation and the Samana Suk Formation. The Kohala overturned syncline is also present in cross-section AB and is missing in cross-section CD (see **Figure 4; Figure 5**).

The Barkot Anticline is the southern-most fold of the research area, near the village Barkot (see **Figure 3**). The Barkot Anticline has the older Lockhart Limestone in the core. However, the limbs of the anticline are comprised of the younger Patala Formation. The Barkot Anticline is present in both cross-sections AB and CD (see **Figure 4; Figure 5**).

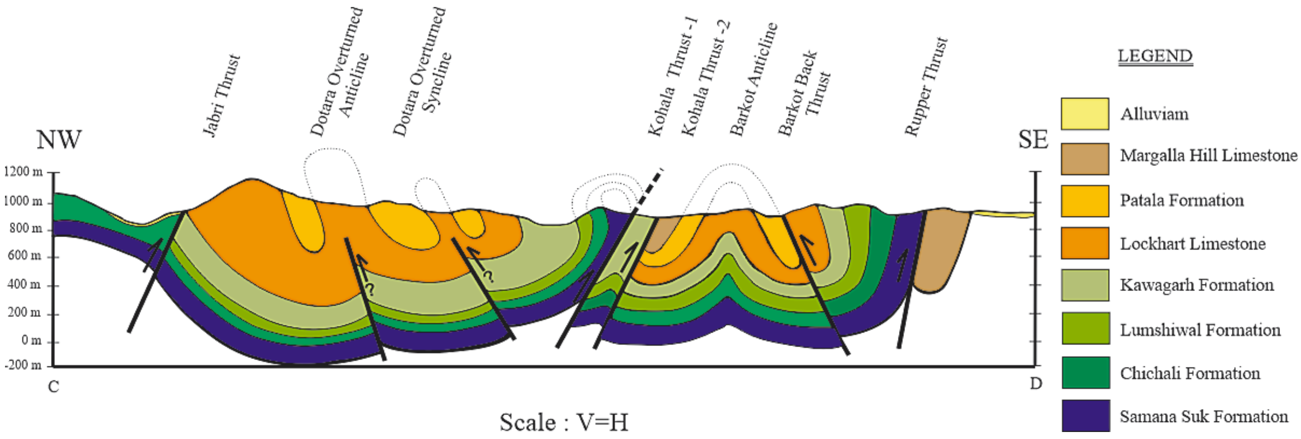


Figure 5: Geological cross-section along line CD of Figure 3

3.2 Reservoir Characterisation

The Chichali Formation and the Kawagarh Formation were evaluated for reservoir potential. There are several methods that are used to delineate the reservoir quality. Petrographic Image Analysis, SEM Analysis, Plug Porosity Analysis and Plug Permeability Analysis are used to delineate the reservoir quality. Petrographic image analysis was carried out in both Chichali (sandstone) Formation and Kawagarh Formation to reveal particle size, porosity between particles, linked and unlinked vugs/cavities. The analysis was also performed to observe the fractures and their connectivity (permeability) and other diagenetic features influencing reservoir quality.

The petrographic image analysis reveals that the common porosity type observed in lower Cretaceous clastic are inter-granular, micro-pores, fractures, dissolution, or vugs (see **Figure 7; Figure 8**). The total optical porosity measured in the Chichali Formation ranges from 0.282% – 10.89%. In the upper part, the late-stage dissolution or vug-type porosity mainly enhances the reservoir quality of the Chichali Formation (see **Figure 7; Figure 8**). The samples from the middle-upper part of the Formation showed good secondary porosity. Most fractures are un-

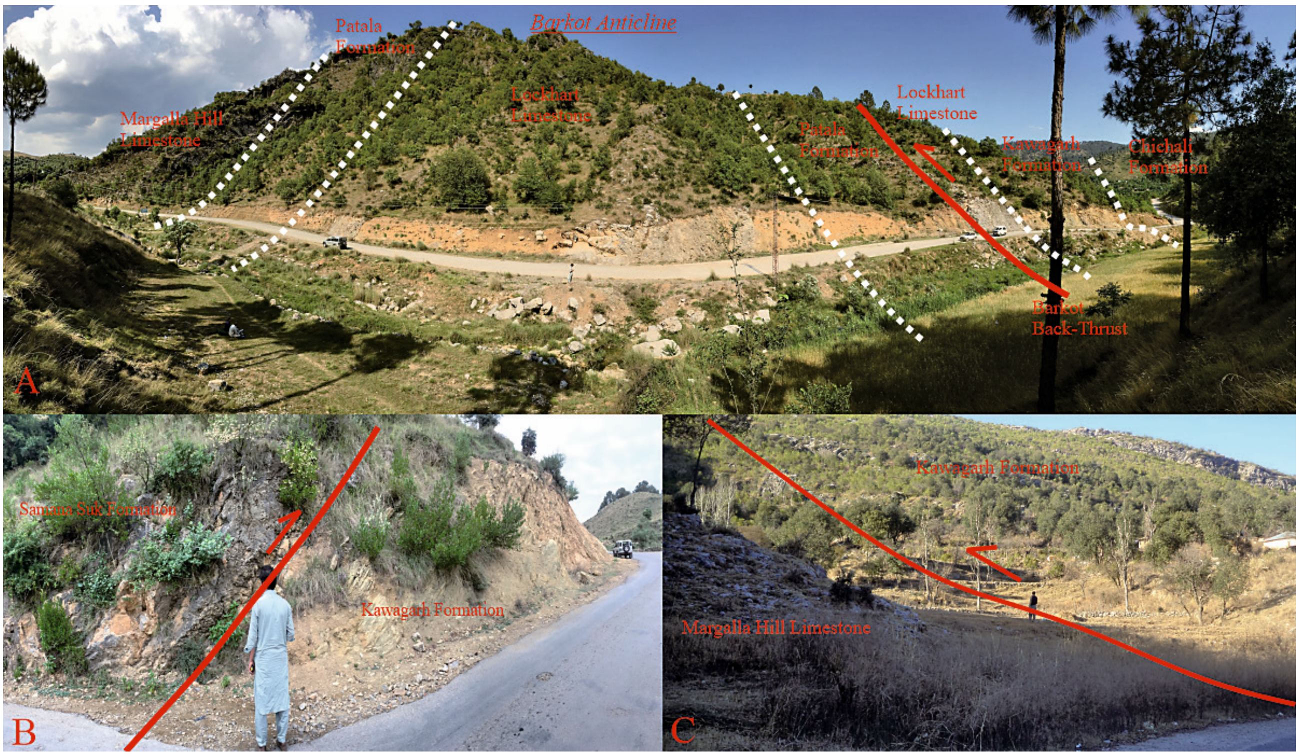


Figure 6: (A) East looking view of the Barkot section where rocks are folded into an anticline along with back thrust (Lockhart Limestone thrust over the Patala Formation). (B) North looking view of outcrop where the older Samana Suk Formation thrust over the younger Kawagarh Formation in Kohala Bala (Village). (C) North looking view of the outcrop where the Kawagarh Formation thrust over the younger Margalla Hill Limestone along Kohala Bala-Jabri (Village) road.

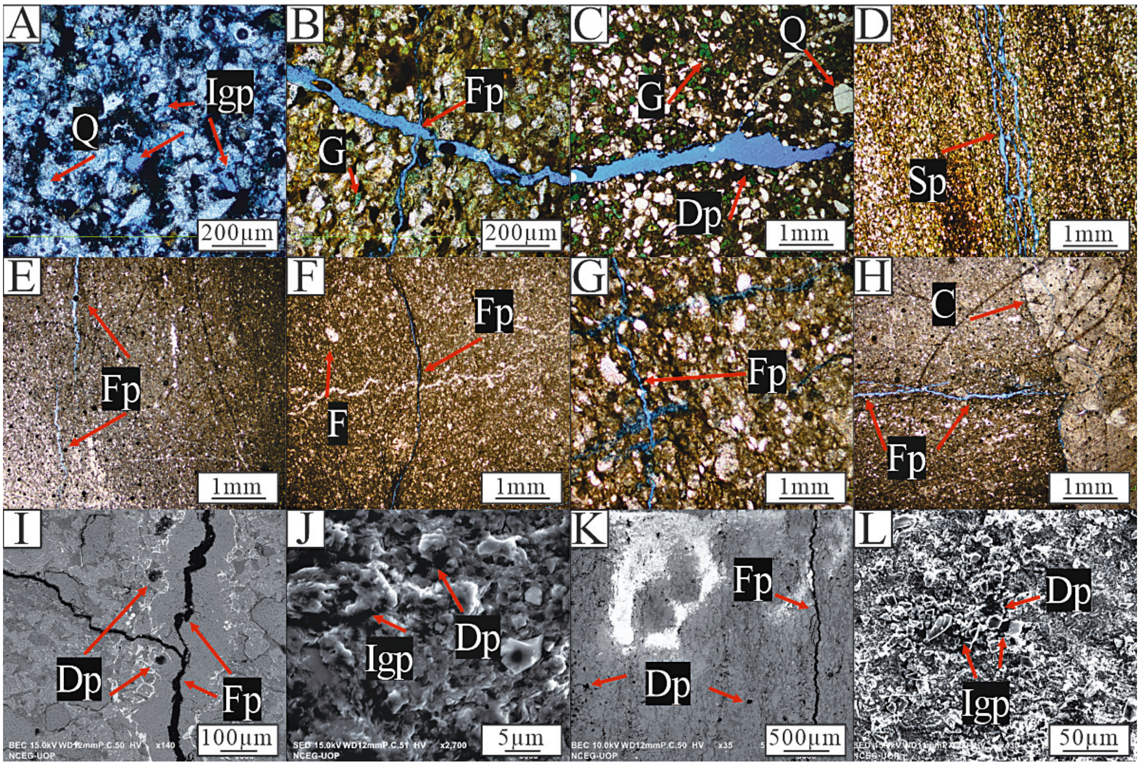


Figure 7: The blue color (A, B, C, D,) shows different types of porosity and permeability in the Chichali Formation and (E, F, G, H) of the Kawagarh Formation from the Barkot section, while (I, J) show SEM backscattered electron composition images (BEC) of the Chichali Formation and (K, L) of the Kawagarh Formation. (Dp= dissolution porosity, Igp= Inter-granular porosity, Fp= fracture porosity, Sp= secondary porosity, Q= quartz, G= glauconite, C= calcite, F= Forams)

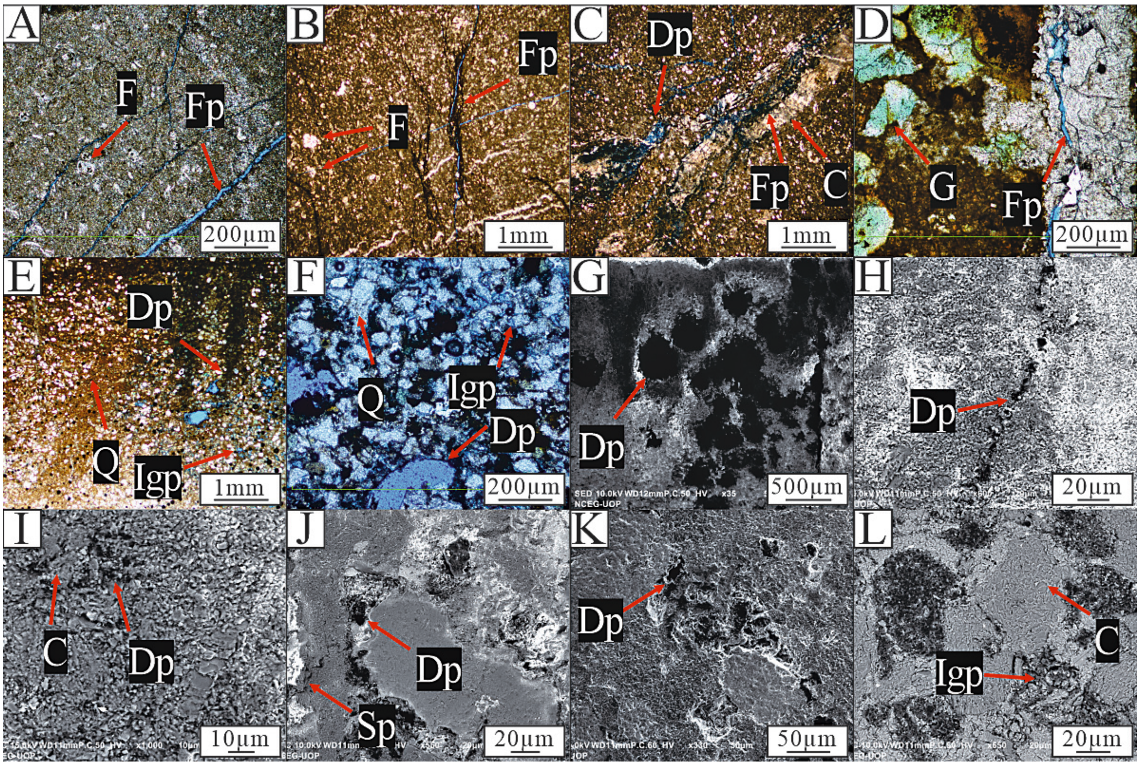
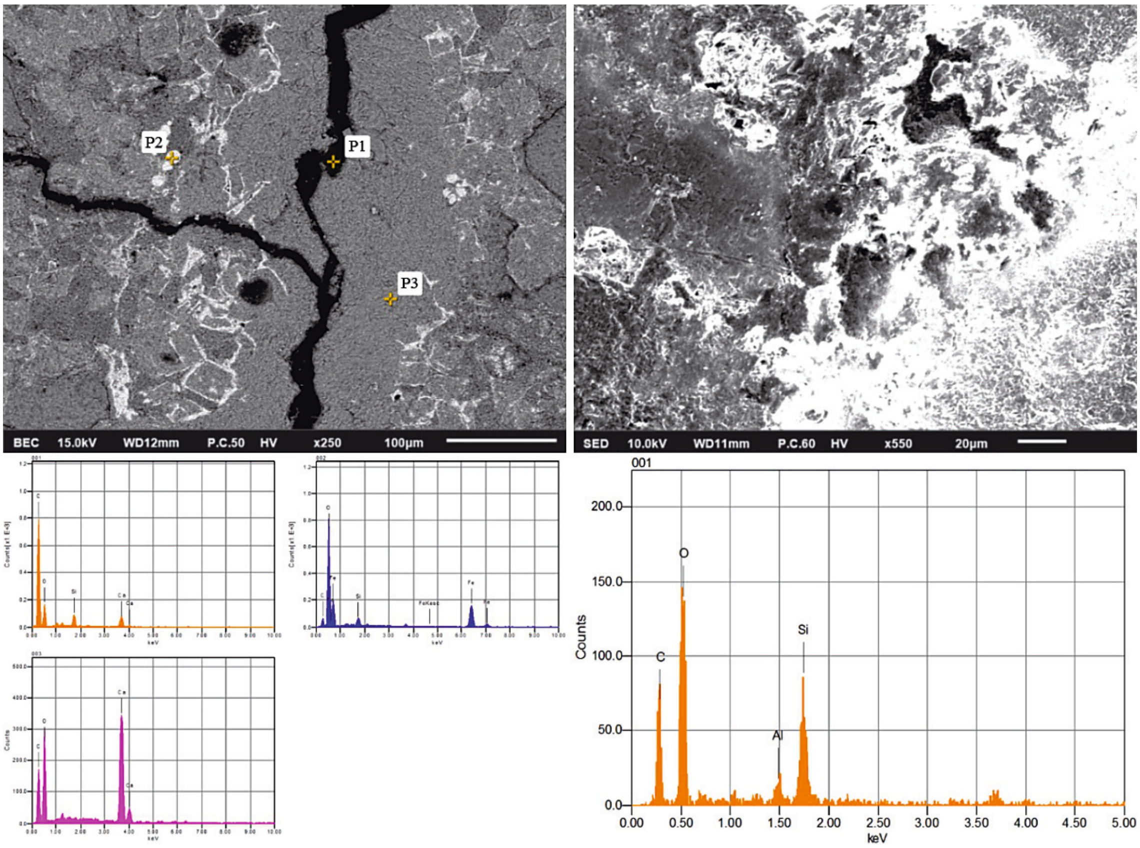


Figure 8: The blue color (A, B, C,) shows different types of the porosity and permeability in the Kawagarh Formation and (D, E, F,) of the Chichali Formation, while (G, H, I,) show SEM backscattered electron composition images (BEC) of the Kawagarh Formation and (J, K, L) of the Chichali Formation. (Dp= dissolution porosity, Igp= Inter-granular porosity, Fp= fracture porosity, Sp= secondary porosity, Q= quartz, G= glauconite, C= calcite, F=forams)



	CaO	O	C	SiO2	FeO
001	10.26	0.00	82.10	7.65	
002			11.00	6.49	82.50
003	75.30	0.00	24.70		
Average	42.78	0.00	39.27	7.07	82.50
Deviation	45.99	0.00	37.72	0.82	0.00

Formula	mass%	Atom%	Sigma	Net	K ratio	Line
C	36.29	45.97	0.17	1849	0.0079061	K
O	47.58	45.24	0.50	3837	0.0509189	K
Al	2.56	1.45	0.22	501	0.0059038	K
Si	13.56	7.35	0.48	2480	0.0320511	K
Total	100.00	100.00				

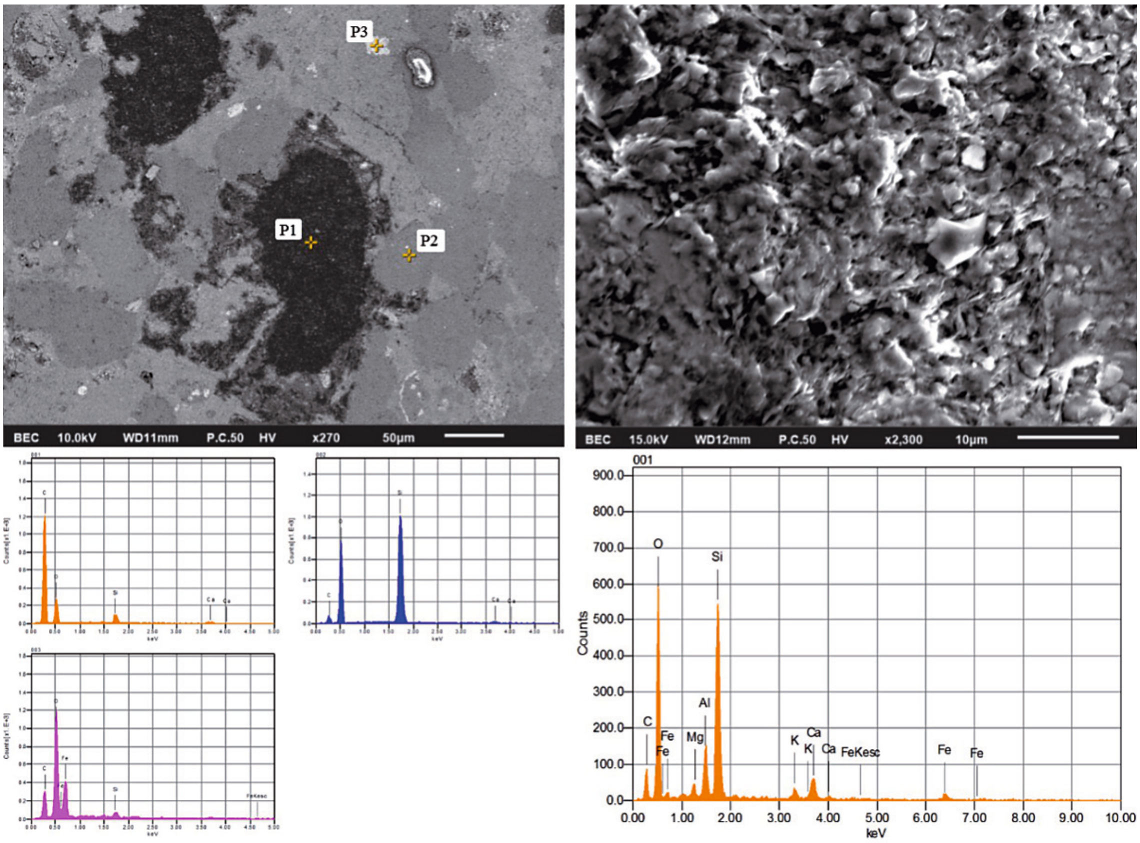
Figure 9: Shows SEM images and EDX results of the Chichali Formation (filling minerals are quartz, feldspar, calcite, and dolomite).

filled and connected, and late-stage dissolution of the fabric also results in the formation of vugs which enhances the porosity. The primary porosity observed is less as compared to secondary porosity and is only found in the upper part of the formation. In contrast, the impact of diagenesis (cementation and compaction) is negative, and results in destroying the total porosity in the lower part of the formation (see **Figure 13**). The dolomitisation is also observed in many thin sections, but its impact on porosity was negligible as the grains are not completely dolomitised (see **Figure 13**).

The petrographic image analysis of the Kawagarh Formation reveals that the common porosity types are interparticle, fractures, and vugs (see **Figure 7; Figure 8**). The total optical porosity measured in the Kawagarh Formation ranges from 0.016% – 1.78%. The secondary (fracture) porosity is mainly present in the Kawagarh Formation, while the effect of diagenesis (cementation) greatly influences the porosity by filling the fractures and the pore spaces with calcite and dolomite and destroying the overall porosity, created by dissolution (see **Figure 7; Figure 8; Figure 13**).

SEM analysis with EDX shows that the major elements in the Chichali Formation and the Kawagarh Formation are calcium, carbon, silica, oxygen, magnesium, aluminium, iron, potassium, and sodium (see **Figure 9; Figure 10; Figure 11; Figure 12**). The results show that the major minerals present in the Chichali Formation and the Kawagarh Formation are quartz, feldspar, calcite, dolomite, pyrite, and clay minerals. SEM analysis reveals that micropores are present in the Chichali Formation and the Kawagarh Formation along with fractures (see **Figure 7; Figure 8; Figure 9; Figure 10; Figure 11 and Figure 12**). Dolomitic rhombs and stylolites are also observed in SEM analysis, and inter- crystalline porosity is also present. SEM analysis also shows that initially pores are created by dissolution and then filled during the diagenesis, consequently destroying the porosity of rocks (see **Figure 7; Figure 8; Figure 9; Figure 10; Figure 11 and Figure 12**).

From the plug porosity analysis, low to fair porosity is observed in the Chichali Formation, whereas very poor porosity is observed in the Kawagarh Formation. Measured porosities from selected samples of the lower Cretaceous Chichali Formation range from 1.142 – 9.374% and



	Fe	O	C	Si	Ca
001		27.43	66.04	3.81	2.72
002		43.58	11.94	41.84	2.65
003	63.70	23.62	11.44	1.24	
Average	63.70	31.55	29.81	15.63	2.68
Deviation	0.00	10.60	31.38	22.73	0.05

Formula	mass%	mol%	Cation	Sigma	Net	K ratio	Line
C	22.28	60.20	0.00	0.11	1742	0.0002562	K
O							
MgO	2.44	1.97	0.66	0.13	1222	0.0003250	K
Al2O3	9.22	2.94	1.97	0.24	4673	0.0010852	K
SiO2	48.00	25.93	8.69	0.56	2034	0.0050183	K
K2O	2.51	0.86	0.58	0.14	1074	0.0005251	K
CaO	8.46	4.90	1.64	0.26	3128	0.0016328	K
FeO	7.09	3.20	1.07	0.31	888	0.0012833	K
Total	100.00	100.0	14.61				

Figure 10: Shows SEM images and EDX results of the Chichali Formation (filling minerals are quartz, feldspar, clay, calcite, pyrite and dolomite).

the Upper Cretaceous Kawagarh Formation ranges from 0.406 – 1.236% (see **Figure 14**). From the plug permeability analysis, poor permeability is noted in both the Chichali Formation and the Kawagarh Formation. Measured permeability of the selected samples from the Chichali Formation range from 0 – 0.064 mD and the Kawagarh Formation range from 0 – 0.014 mD. The composition of the Kawagarh Formation is mainly mudstone and the depositional environment is deep marine. The sediments are light brown to grey, very fine grained, hard, and compact, thus making it a poor reservoir. However, during diagenesis, the formation undergoes deep burial conditions from marine settings, affecting the reservoir potential. The main reason for this poor porosity and permeability is the effect of diagenesis, which significantly leads to the loss of porosity and permeability. Petrographically, large calcite filled veins and fractures are observed, which indicates that initially large fractures were created due to tectonic activity (also observed fractures on outcrop). However, later, during diagenesis, these pore spaces were filled by fluid flow (cementation) (see **Figure 13**), resulting in destroying the overall porosity and permeability. Conversely, the dissolution of these minerals can significantly increase the porosity and permeability and can enhance the reservoir quality.

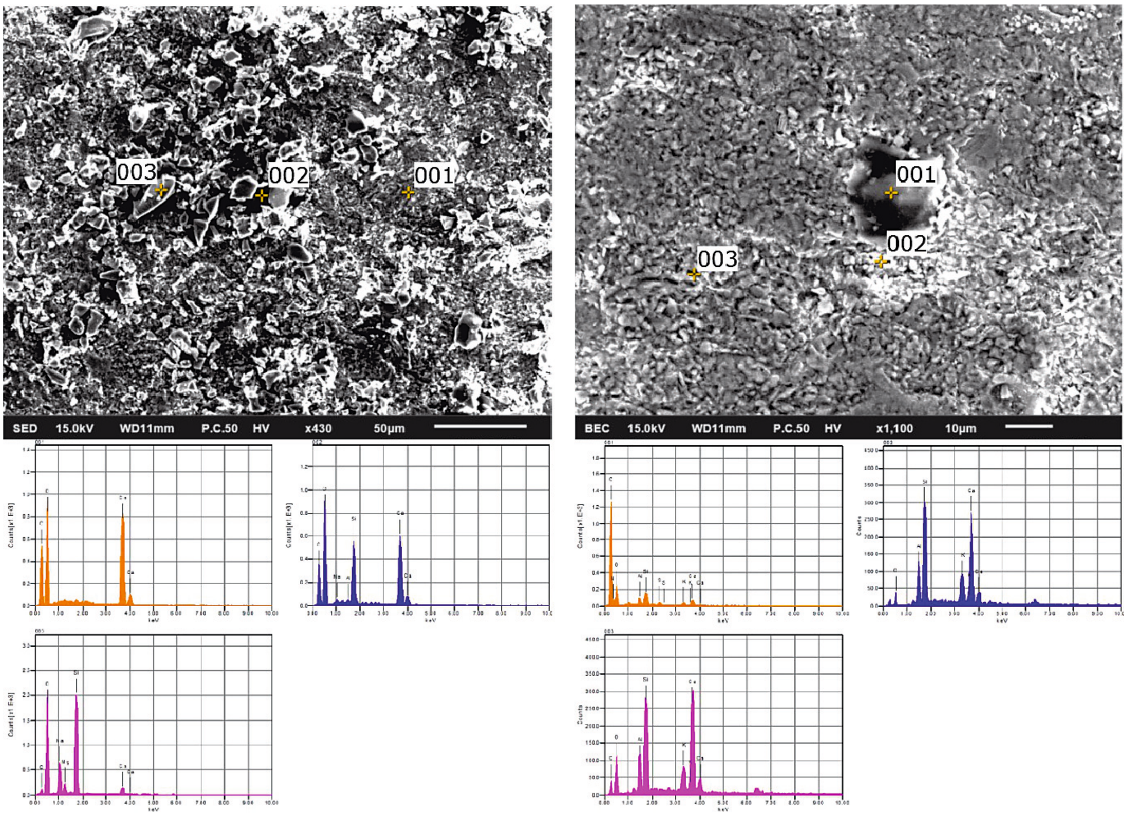
3.3 Diagenesis Impact on Reservoir Quality

Diagenesis affects reservoir quality either by enhancing or destroying the porosity by a variety of physical and chemical processes (**Taghavi et al., 2006; Ahr, 2008; Tavakoli et al., 2011; Abuseda et al., 2015**).

3.3.1 Factors Enhancing Porosity

3.3.1a Dissolution

In both formations, fabric-selective dissolution is observed, which results in isolated vugs and moldic poros-



	O	C	Na	Mg	Al	Si	Ca
001	53.70	18.81					27.49
002	49.46	19.99	0.87		0.39	8.07	21.23
003	51.34	8.03	10.09	1.87		24.68	4.00
Average	51.50	15.61	5.48	1.87	0.39	16.37	17.57
Deviation	2.13	6.59	6.52	0.00	0.00	11.75	12.16

	CaO	O	C	N	Al2O3	SiO2	SO3	K2O
001	4.79	0.00	76.73	5.23	3.00	6.51	2.43	1.32
002	43.54	0.00			10.18	33.99		12.2
003	45.75	0.00	7.28		8.86	28.28		9.84
Average	31.36	0.00	42.00	5.23	7.35	22.92	2.43	7.81
Deviation	23.04	0.00	49.11	0.00	3.82	14.50	0.00	5.76

Figure 11: Shows SEM images and EDX results of the Kawagarh Formation (Filling mineral are calcite along with quartz and feldspar).

ity. Enlarged fractures are also created by dissolution in both formations, but in the Kawagarh Formation, vugs are mainly occupied with calcite cement, and very little porosity is preserved. In addition, vugs and fractures in the Chichali Formation are slightly filled with silica cement, but most of these fractures are unfilled, resulting in increased porosity and permeability. Dissolution in the Chichali Formation also enlarges the interparticle pores, resulting in large, connected vugs (see **Figure 7; Figure 8; Figure 13**). The dissolution observed in both formations is most probably related to the effects of undersaturated meteoric water.

3.3.1b Dolomitization

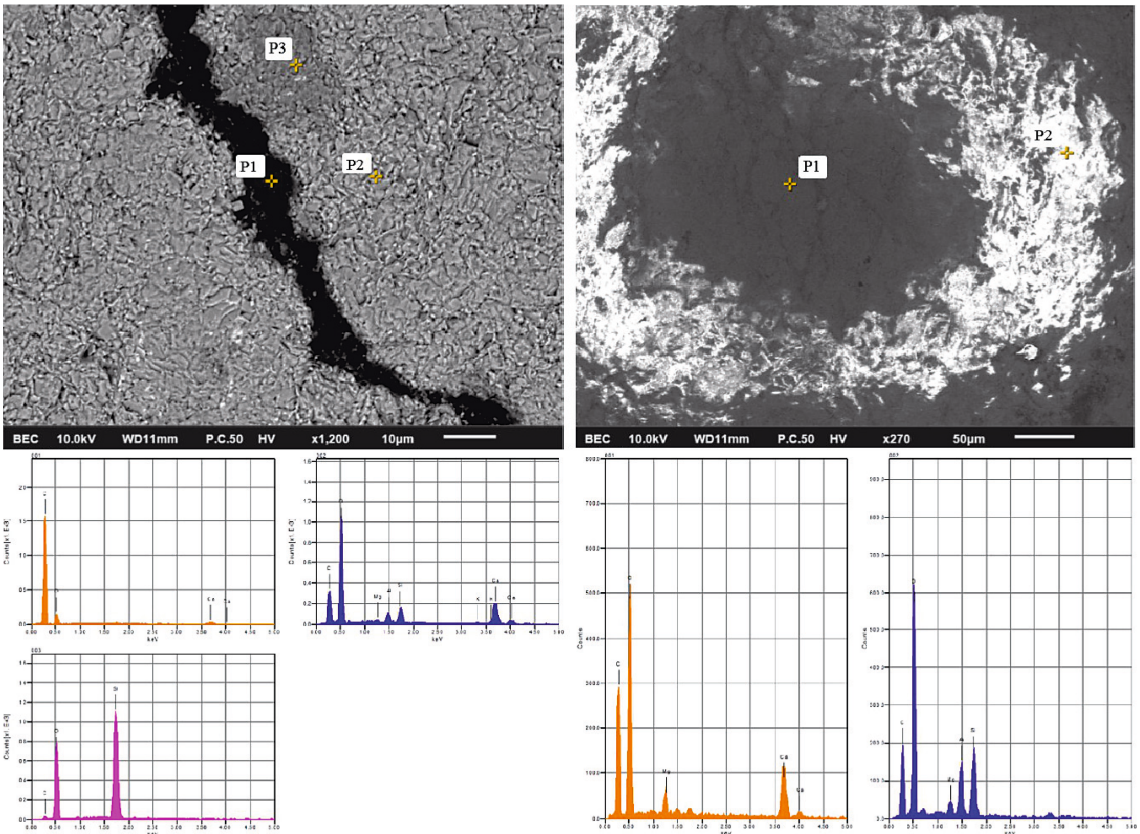
The porosity and permeability of rock generally increase when the dolomitization of limestone and calcite cement of sandstone occurs. The rock's grain volume is decreased up to 13% by dolomitization and creating more porosity (**Chilingar and Terry, 1964**). However, the dolomitization impact in the lower part of the Chichali Formation and the middle-upper part of the Kawagarh Formation is not very significant as the grains are partially dolomitised. Petrographically, euhedral, subhedral, and anhedral rhombs were recognised as dolomitic crystals (see **Figure 9; Figure 13**).

3.3.1c Fracturing

The fractures observed in the Cretaceous rocks (the Chichali Formation and the Kawagarh Formation) are extensional in nature, which may be tectonically related, occurring in association with folds. Fractures are mostly filled with calcite, dolomite, and ferruginous cementing materials, which cause the reduction of the pore network and affect the reservoir quality. Simultaneously, some fractures are unfilled, which enhances the porosity and permeability of the rock, which is significant for producing hydrocarbons (see **Figure 7; Figure 8; Figure 9; Figure 13**). **Racey et al.** (**2001**) also reported in the Tunisian fields of El Garia. Some of the allochems are cross-cut by fractures and represent multistage fracturing.

3.3.1d Stylolites

Stylolites are formed by a physiochemical process caused by deep burial compaction (**Buxton and Duncan, 1981**). Petrographically, the wavy structure in the



	CaO	O	C	MgO	Al2O3	SiO2	K2O
001	8.14	0.00	91.86				
002	49.57	0.00	25.10	1.60	7.06	13.91	2.76
003		0.00	5.76			94.24	
Average	28.85	0.00	40.91	1.60	7.06	54.07	2.76
Deviation	29.30	0.00	45.17	0.00	0.00	56.80	0.00

	O	C	Mg	MgO	Al2O3	SiO2	Ca
001	50.75	23.72	2.43				23.09
002	0.00	45.94		3.94	18.13	31.99	
Average	25.37	34.83	2.43	3.94	18.13	31.99	23.09
Deviation	35.88	15.71	0.00	0.00	0.00	0.00	0.00

Figure 12: Shows SEM images and EDX results of the Kawagarh Formation (Filling mineral are calcite along with quartz and feldspar).

Kawagarh Formation (see **Figure 13**). Mostly, stylolites are filled with calcite and oxide-rich elements. However, some are porous, resulting in a significant increase in porosity.

3.3.2 Factors Destroying Porosity

3.3.2a Compaction

Excessive overburden pressure on sedimentary rocks causes the development of a variety of compactional textures and fabrics. Compactional processes and their products are categorised into two groups, such as mechanical and chemical compaction. Mechanical compaction took place after the deposition and was observed in Cretaceous rocks (the Chichali Formation and the Kawagarh Formation) by the close packing of grains and fracturing (see **Figure 13**). Chemical compaction takes place at greater depths (several hundred meters). Chemical compaction in Cretaceous rocks (the Chichali Formation and the Kawagarh Formation) was observed by stylolite and grain suturing, formed by pressure dissolution (see **Figure 13**).

3.3.2b Cementation

Cementation occurs mainly during the early to middle stages of diagenesis. In the Chichali and Kawagarh formations, calcite cement, quartz overgrowths, ferroan dolomite, iron oxide cement, glauconitic cement and micritic mud are identified (see **Figure 13**). During the early stage of marine diagenesis, coarse calcite glauconitic cementation develops (**Rahman et al., 2016**). The brown to dark brown ferruginous cement is also observed. Ferruginous cement is also causing leaching. The cement is concentrated along with fractures and stylolite seams. The interstitial pores of the sandstones are filled with calcite and dolomite. The siliceous cement is present as a quartz overgrowth in the sandstone of the Chichali Formation. Silica overgrowth is most probably formed during deep burial compaction when a siliceous solution is released by pressure dissolution of quartz grains sediments (**Turner, 1980**). After silica cement is precipitated, iron-oxide is precipitated along with dolomite (**Arif et al., 2009**). In the Chichali Formation, iron oxide/hydroxide cement is present in a much

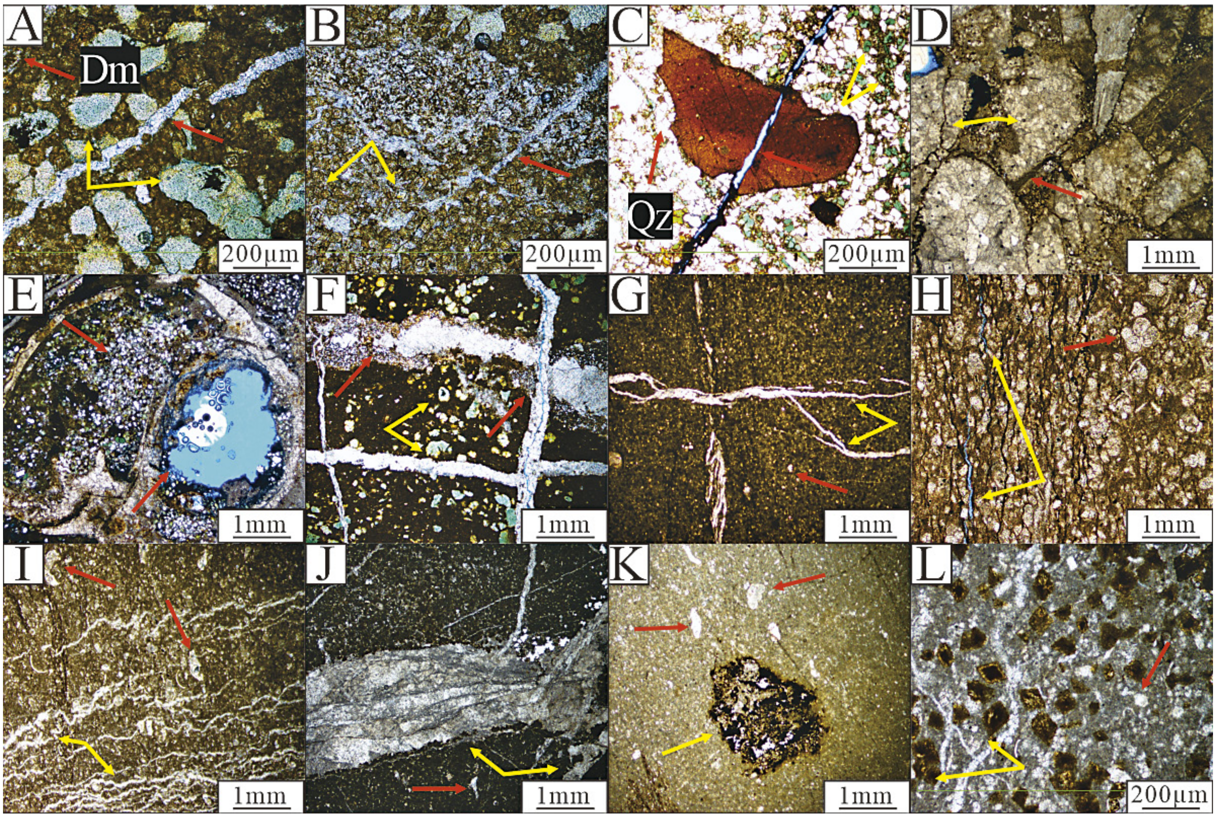


Figure 13: Photomicrographs of diagenetic features in the Chichali Formation (A, B, C, D, E and F) and the Kawagarh Formation (G, H, I, J, K and L). The yellow arrows (A, C and F) show glauconite A) Vein filled with quartz cement, Dm=dolomitic rhomb, B) Well developed dolomitic rhombs (yellow) and cross-cut filled veins (red), C) Late stage developed fracture preserving porosity (red), Qz=quartz, D) Recrystallized bioclasts (yellow) with sutured contact (red), E) Dissolution of bioclast preserving porosity, F) Large quartz filled veins displaced and fractured later showing porosity (red). The red arrows (G,H,I,J,K and L) show planktonic forams while the yellow arrows show G) Fracture filled with calcite, H) Thin but numerous micro stylolites showing porosity, I) Network of stylolites filled with calcite cement, J) Cementation in large fracture, K) Large pyrite nodule and L) Rhombs of planar to euhedral dolomites

higher quantity as compared to the Kawagarh Formation. During post-uplift, surface water causes the dissolution of oxide cement and enhances the secondary porosity of the rock, ultimately providing a path for hydrocarbon migration (**Ali et al., 2021**). Cementing material such as carbonate-clay mix matrix is abundant in the Kawagarh Formation and scarce in the Chichali Formation (see **Figure 7; Figure 8; Figure 9; Figure; Figure 13**), which is the product of early-stage marine diagenesis. Inter-granular porosity is considerably reduced by all these types of cement (**McLane, 1995; Bathrust, 1982**). Cementation has highly decreased the porosity in Cretaceous rocks (the Chichali Formation and the Kawagarh Formation) (see **Figure 7; Figure 8; Figure 13**).

4. Interpretation and Discussion

4.1 Structural Analysis

This tectonic activity has caused an intense deformation in southeast Hazara. During mapping, deformation was observed by intraformational folds within the formations and by macroscopic folds and thrust slip faults.

Zahid et al. (**2009**) have worked on the geometry of southern Hazara by investigating the cleavage data of Hazara slates. He proposed that Hazara slates are comprised of three sets of cleavages (S1, S2, and S3). He explained that S1 cleavage was well developed in comparison to the S2 and S3 cleavage set. Both the S2 and S3 cleavage set showed a conjugate pattern. On the basis of cleavage studies, he proposed that two phases of deformation occurred in Hazara slates. The first phase and the primary deformation occurred during pre-Cambrian time as recognized by S1 bedding parallel cleavage. The second phase of deformation is the result of Himalayan deformation inferred by less developed S2 and S3 cleavage set. It is inferred that these less developed sets S2 and S3 are also present in overlying Mesozoic-Cenozoic sequence (**Akhtar et al., 2019; Ali, 2014**).

In the Hazara region, two different stages of northwest-southeast oriented compression are responsible for the formation of folds. The initial southeast directed stresses were related to the southeast directed thrusting of the NT with an imbricated hanging wall. Whereas the second stage results in the formation of north verging back-folds that locally fold the NT and its imbricates, resulting in dipping towards the south, and appearing as normal faults in the field (**Latif, 1970; Calkins et al., 1975; Coward et al., 1988**). Mesozoic and Tertiary rocks exposed between the MBT and the NT and have been deformed by many stages of N–S compressional stresses, resulting in the formation of both north and south verging coaxial folds and associated thrust faults (**Pogue, 1994**). The back folding of previously south vergent structures results in the formation of moderate to steep southward dips on the constituent faults of the MBT zone in the Margalla and Kohat hills (**Latif, 1970; Coward et al., 1988**).

The present study shows that the orientations of the mapped structures in the research area coincide with the changing orientation of the Main Boundary Thrust. The folds and faults of NE –SW trends are in concurrence with **Kazmi and Rana** (**1982**). The structural synthesis indicates that the research area is under NW–SE directed compressive stresses which results in the formation of NE–SW oriented structures. The first stage of deformation is distinguished by northwest-directed movement, as evidenced by back-thrust and overturned folds verging northwest (see **Figure 4; Figure 5**). These north verging folds and southward dipping back-thrust in the hanging wall of Main Boundary Thrust may have been related to the late Miocene back-folding period that followed south directed thrusting along the MBT (**Pogue, 1994; Saboor et al., 2015**).

The northwest verging overturned folds are cross-cut by comparatively younger southeast verging fore-thrusts (see **Figure 4; Figure 5**). The general translation of deformation during this younger structural event is directed south-eastwards. All the observed thrusts are out of sequence thrusts that occurred in MBT's deformed thrust sheet and may be associated with the increase in the decollement dip above the basement (**McDougall and Hussain, 1991; Saboor et al., 2015**).

The fore-thrusts are typically detached within the Jurassic and Cretaceous sequence. They have superimposed the dominant lithologies of Samana Suk Formation (sandy limestone/calcareous sandstones), the Chichali Formation, and the Kawagarh Formation on top of the younger formation. The back-thrusts are oriented similar to the other structures but with opposite vergence. The back-thrusting activity is likely to be responsible for the toppling of the Dotara, and Kohala folds in the northwest direction.

In terms of hydrocarbon potential, the anticlines in the subsurface can be possible structural traps for future hydrocarbons explorations if further evaluated. The Barkot Anticline may be a promising structural trap for the Chichali Formation, as it has the potential of (tight) reservoir rock. Most of the sandstone fractures were unfilled and provided good paths for fluid flow. The Kawagarh Formation overlies the Chichali Formation, and the results indicate that it has very low or no porosity and permeability, as fractures are mostly filled with cementing material. However, it may be suitable as a barrier/ seal rock by preventing the fluids from moving to the surface (**Downy, 1994**). In addition, the area is under the influence of intense tectonic activity (compressional stresses), as seen by folding and faulting. The intensity of compaction is increased by tectonic compression. Conversely, tectonic activity positively enhances the reservoir potential by producing fractures and folds in low permeability reservoirs (**Dan et al., 2013**).

4.2. Reservoir Potential

The age equivalent formations of the Cretaceous age in the Lower Indus Basin are potentially rich in hydrocarbons. **Khan** (**2007**) evaluated shales of the Chichali Formation for its hydrocarbon potential in southern Hazara. He has proposed that the Chichali Formation depicts a very well to excellent source prospect based on measured organic carbon content, and it falls within the gas window, observed by Tmax and vitrinite reflectance value. He also claimed that the oil and gas generated during thermal maturation might have migrated and accumulated within the potential traps of the overlying and adjacent areas.

Hashmi et al. (**2018**) evaluated the lower Cretaceous for its reservoir nature and concluded that it might prove as a good reservoir. The results obtained from petrographic image analysis, SEM analysis, plug porosity analysis show promising results of 0.282% – 10.9% optical porosity and 1.142 – 9.37% plug porosity (see **Figure 14**). However, the plug permeability results were not promising and ranged from 0 – 0.064 mD and 0 – 0.014mD in the Chichali and Kawagarh formations, respectively. The main diagenetic features observed in the Chichali Formation was compaction, dolomitisation, cementation, dissolution, brecciation, stylolites, fractures, and hairline to large calcite veins. The porosity observed in the Chichali Formation was inter-granular, micropores, fractures, and dissolution/vuggy. The intergranular porosity primarily exists in the upper part of the formation, and pores are well connected, providing a suitable medium for fluid flow (permeability). The micropores were found in all the samples, and most of the pores were isolated and not well connected. The fracture porosity was limited to the lower-middle part of the formation and affected most of the grains fabric. Moreover, most of the fractures were unfilled and well-connected. However, some were filled with mineral cement. The dissolution/ vuggy type porosity was also observed, and most of the vugs were unfilled. The dissolution porosity is mainly limited to the formation's middle to the upper part, and most of the dissolution is fabric selective (dissolving biolistic chamber).

Maqsood et al. (**2016**) worked on the Kawagarh Formation in the Hazara Basin and proposed that the formation has a good reservoir quality with 14% porosity. He claimed that the late diagenetic process (mainly dolo-

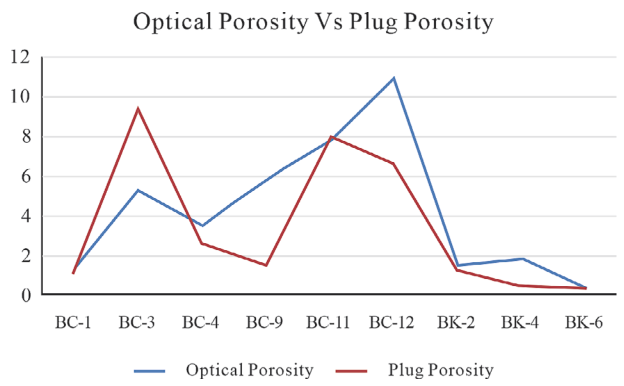


Figure 14: Shows a comparison of Optical porosity and Plug porosity observed in the Chichali Formation(BC-1, BC-3, BC-4, BC-9, BC-11 and BC-12) and the Kawagarh Formation (BK-2, BK-4 and BK-6) in the Barkot section.

mitization) was responsible for enhancing the porosity. In contrast, the reservoir quality of the Kawagarh Formation measured in the research area does not show promising results. The Kawagarh Formation revealed very low 0.016% – 1.78% optical porosity and 0.406 – 1.23% plug porosity (see **Figure 14**). In addition, permeability values range between 0 – 0.014mD. The formation has a very fine micritic texture. The formation showed much less visual porosity in the form of fractures, interparticle, and vugs. The interparticle and vuggy porosity is present in a small amount in the middle to the upper part of the formation. However, fracture porosity was observed throughout the formation. This porosity is greatly affected by the late diagenetic process. Initially, well cementation of very fine micritic cement reduces the pore spaces. Finally, during burial diagenesis, the remaining micropores are also destroyed by overburden/mechanical pressure as observed by large numbers of solution seams, and micro-stylolites produced by pressure dissolution. Large numbers of connected fractures formed by tectonic forces and dissolution were later filled with calcite cement. Moreover, SEM analysis reveals that micro-porosity is still present in the formation but not in much quantity.

The sandstone of the Chichali Formation has shown good porosity compared to the limestone of the Kawagarh Formation because both primary and secondary porosity were preserved. However, no primary porosity was present in the Kawagarh Formation, and secondary porosity, which was created by fracturing also destroyed by the filling of cement. In addition, the permeability of the formation is not good and can be categorised as a tight reservoir (**Lucia, 1995**). In the Hazara Basin, the sandstone is overlain by carbonaceous clay of the Chichali Formation and the limestone facies of the Kawagarh Formation (which has very low/negligible porosity and permeability) may act as a permeability barrier and sealing horizons for the Chichali Formation. Therefore, this sandstone may act as a potential reservoir in the subsurface of the study area.

5. Conclusions

The mapped stratigraphy is ranged from the late Jurassic Samana Suk Formation to the Early Eocene Margallah Hill limestone with unconformities (the Hungu Formation). The deformation includes successive folding and faulting represented by fore thrusts, overturned folds, and back thrusts. The SEM and thin section study reveal that the main porosity types that exist in the Chichali Formation and the Kawagarh Formation are inter-crystalline/ inter-particle, intra-crystalline /intra-particle, fracture, and vuggy. Petrographic image analysis, SEM analysis, plug porosity and permeability analysis indicate that the Chichali Formation has the capability to accumulate hydrocarbons and can be a good (tight) reservoir. Simultaneously, the Kawagarh Formation lacks the characteristics of reservoir rock and can act as a seal rock. It is mainly consisted of very fine grained mudstone. In addition, during diagenesis, the formation underwent deep burial conditions from marine settings, which resulted in affecting the reservoir potential. The porosity increased and decreased in many phases but was ultimately destroyed by cementation. The effect of the severe deformation and dissolution of precipitated minerals may increase the reservoir quality if it is not affected by diagenesis (cementation). Based on the geological cross-section, the presence of subsurface folds related traps within the Cretaceous sequence makes this area a promising region for future hydrocarbon exploration.

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6. References

Abuseda, H., Kassab, M. A., LaLa, A. M. and El Sayed, N. A. (2015): Integrated petrographical and petrophysical studies of some Eocene carbonate rocks, Southwest Sinai, Egypt. Egyptian Journal of Petroleum, 24(2), 213-230.

Ahr, W. M. (2008): A new genetic classification of carbonate porosity and its application to reservoir characterisation. In American Association of Petroleum Geology Annual convention (Abstract), San Antonio, Apr, 20-23.

Ahsan, N. (2008): Facies modeling, depositional and diagenetic environments of Kawagarh Formation, Hazara Basin, Pakistan, University of the Punjab, Lahore, Pakistan.

Ahsan, N. and Chaudhry, M.N. (1998): Facies and Microfacies analysis of Kawagarh Formation of Hazara Basin, Pakistan. 13th Himalaya-Karakoram-Tibet Workshop, Abstract, Geological Bulletin, Peshawar University, 31, 5-6.

Akhtar, S., Rahim, Y., Hu, B., Tsang, H., Ibrar, K. M., Ullah, M. F. and Bute, S. I. (2019): Stratigraphy and Structure of

Dhamtaur Area, District Abbottabad, Eastern Hazara, Pakistan. Open Journal of Geology, 9(01), 57.

Ali, F. (2014): Tectonic evolution of the Margala hills and a part of the south eastern Hazara ranges, Pakistan. University of Peshawar, 81-85p.

Ali, M., Weihua, B., Kaikai, Y. and Panni, M. S. K. Pore structures and reservoir characteristics of volcanic rocks in the Carboniferous Batamayineishan Formation in Shuangjingzi area, eastern Junggar Basin. Rudarsko-geološko-naftni zbornik, 2021, 36(5).

Arif. M., Ali, B. and Khan, M. (2009): Petrography of sandstone of the Lower Cretaceous sequence from the Samana Range, Hangu, north-western Pakistan: Implications for provenance, diagenesis and environments of deposition. Pakistan Journal of Hydrocarbon Research, 19, 01- 09.

Baig, M. S. and Lawrence, R. D. (1987): Precambrian to early Paleozoic orogenesis in the Himalaya. Kashmir Journal of Geology, 5, 1-22.

Bathurst, R. G. C. (1982): Genesis of stromatactis cavities between submarine crusts in Paleozoic carbonates mud builds ups. Journal of the Geological Society, 139, 165-181

Burg, J. P., Jagoutz, O., Dawood, H. and Hussain, S. S. (2006): Precollision tilt of crustal blocks in rifted island arcs: Structural evidence from the Kohistan Arc. Tectonics, 25(5).

Butt, A. A. (1972): Problems of stratigraphic nomenclature in the Hazara District, N.W.F.P., Pakistan. Geological Bulletin of Punjab University, 9, 65-69.

Butt, A.A., Sameeni, S.J. and Ghazi, S. (1990): An appraisal of the geology of Hazara Arc, Northern Pakistan. Geological Bulletin of Punjab University, 25, 27-32.

Buxton, T. M. and Duncan, F. S. (1981): Pressure solution features in shallow buried limestone. Journal of Sedimentary Petrology, 51, 19-26.

Calkins, J. A., Offield, T. W., Abdullah, S. K. and Ali, S. T. (1975): Geology of the southern Himalaya in Hazara, Pakistan, and adjacent areas (No. 716-C). U.S. Geological Survey Professional Paper, 716-C, 29.

Chilingar, G. V. and Terry, R. D. (1964): The relationship between porosity and chemical composition of carbonate rocks. Petroleum Engineering, 54, 341-342.

Cotter, G. D. P. (1933): Geology of part of Attock district west of longitude 72°45' E. Geological Survey of India Memoirs, 55, 2, 63-161.

Coward, M. P. and Butler, R. W. H. (1985): Thrust tectonics and the deep structure of the Pakistan Himalaya. Journal Geology, 13, 415-420.

Coward, M. P., Butler, R. W. H., Chambers, A. F., Graham, R. H., Izatt, C. N., Khan, M. A. and Williams, M. P. (1988): Folding and imbrication of the Indian crust during Himalayan collision. Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences, 326, 1589, 89-116.

Downy, M. A. (1994): Hydrocarbon seal rocks. AAPG mem. 60, 159-164.

Fatmi, A. N. (1972): Stratigraphy of the Jurassic and lower Cretaceous rocks and Jurassic ammonites from northern area of West Pakistan. British Mus. Nat. Hist., Bull, (Geol.), 20, 7, 229-380

Ghazanfar, M., Chaudary, M. N., Pervaiz, K., Qayyum, M. and Ahmed, R. (1990): Geology and Structure of Kuza-Dunga Gali-Ayubia Area, Hazara-Potwar Basin with a reference to Hydrocarbon Prospects of Attock-Hazara Fold and Thrust Belt, Pakistan. Journal of Hydrocarbon Research, 2, 2, 43-55.

Grodner, M. W., Clarke, S. M., Burley, S. D., Leslie, A. G. and Haslam, R. (2021): Combining topology and fractal dimension of fracture networks to characterise structural domains in thrusted limestones. Journal of Structural Geology, 153, 104468.

Grove, C. and Jerram, D. A. (2011): jPOR: An Image J macro to quantify total optical porosity from blue stained thin sections. Computers and Geosciences, 37, 1850-1859.

Haeri, M. (2015): Image J Plugin for analysis of porous Scaffolds used in tissue engineering. Journal of Open Research Software, 3(1).

Hashmi, S., Jan, I., Khan, S. and Ali, N. (2018): Depositional, diagenetic and sequence stratigraphic controls on the reservoir potential of the Cretaceous Chichali and Lumshiwal formations, Nizampur Basin, Pakistan. Journal of Himalayan Earth Sciences. 51, 44-65.

Hayat, M., Rahman, M. U., Abdullah, K., N. A. and Ali, F. (2016): Sedimentology, sequence stratigraphy and reservoir characterisation of Samana Suk Formation exposed in Namal Gorge Section, Salt Range, Mianwali, Punjab, Pakistan. International Journal of Economic and Environmental Geology, 7, 1-15.

Iqbal, M., Baig, T. and Khan, M. R. (2007): Petroleum potential of Kalachitta-Margala hills range and adjoining Peshawar-Hazara Basin, Pakistan. SPE-PAPG Annual Technical Conference, Islamabad, 121-128.

Iqbal, M.W.A. and Shah, S.M. I. (1980): A guide to the stratigraphy of Pakistan, 51-57p.

Kazmi, A. H. and Rana, R. A. (1982): Tectonic Map of Pakistan, 1:1,000,000. Geological Survey of Pakistan, Quetta, Pakistan.

Khan, M.I. (2013): Quantitative Analysis of the Joints and their Scaling Relationship within the Lumshiwal Formation along the Samana Anticline, Samana Range, Orakzai Agency, N.W.F.P, Pakistan, 20p.

Khan, S. (2007): Evaluation of Chichali Formation as a Source Rock for Hydrocarbon generation in the Southern Hazara, NWFP, Pakistan, unpublished thesis, NCEG, University of Peshawar, Peshawar.

Latif, M. (1970): Explanatory notes on the geology of southeastern Hazara to accompany the revised geological map, Wein Jb. Geol. B.A. Sonderban., 15, 5-20.

Latif, M. (1976): Stratigraphy and micropaleontology of the Galis Group of Hazara, Pakistan. Geological Bulletin of Punjab University, 13, 1-64.

Li, D., Dong, C., Lin, C., Ren, L, Jiang, T. and Tang, Z. (2013): Control factors on tight sandstone reservoirs below source rocks in the Rangzijing slope zone of southern Songliao Basin, East China. Petroleum Exploration and Development, 40, 6.

Lucia, F.J. (1995): Rock-Fabric Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization.

American Association of Petroleum Geologists Bulletin, 79, 1275-1300.

McDougall, J. W. and Hussain, A. (1991): Fold and thrust propagation in the western Himalaya based on a balanced cross section of the Surghar Range and Kohat Plateau, Pakistan. AAPG bulletin, 75(3), 463-478.

McLean, D. (1995): Provenance of reworked palynomorphs from the Greenmoor rock (Langsettian, late Carboniferous) near Sheffield, England. Review of Palaeobotany and Palynology, 89, 305-317.

Middlemiss, C. S. (1896): The Geology of Hazara and the Black Mountains. Geological Survey of India Memoirs, 26, 302.

Munir, M. H., Baig, M. S. and Qureshi, M. A. (1997): Lower Tertiary litho-biostratigraphy of the Bagla-Kohala-Bala Area, Haripur Hazara (NWFP), Pakistan. Geological Bulletin of Punjab University.

Pennock, E. S., Lillie, R. J., Zaman, A. S. H. and Yousaf, M. (1989): Structural interpretation of seismic reflection data from eastern Salt Range and Potwar Plateau, Pakistan. AAPG bulletin, 73(7), 841-857.

Pettijohn, F.J., Potter, P.E. and Siever, R. (1972): Sand and sandstone. Springer Science & Business Media.

Pogue, K.R. (1994): Stratigraphic and structural framework of Himalayan foothills, Northern Pakistan. Ph.D. thesis, Oregon State University, USA.

Rahman, M. U., Ali, F. and Hayat, M. (2016): Diagenetic Setting, Dolomitisation and Reservoir Characterization of Late Cretaceous Kawagarh Formation, Khanpur Dam section, Hazara, Pakistan. International Journal of Economic and Environmental Geology, 7(2), 1-15.

Rehman, S. U., Ahsan, N., Shah, M. M., Munawar, M. J., Miraj, M. A. F., Rehman, F. and Mahmood, K. (2021): Depositional environments and microfacies of the upper Turonian–Maastrichtian Kawagarh Formation, Kalachitta Range, Lesser Himalayas, Pakistan. Australian Journal of Earth Sciences, 68(7), 1017-1030.

Rehman, S.U. (2009): Microfacies and depositional environments of Kawagarh Formation exposed at Chinali and Khariala, Northwest Lesser Himalaya, Pakistan. Unpublished M.Phil thesis, University of the Punjab, Lahore, Pakistan, 97p.

Saboor, A., Ali, F., Ahmad, S., Haneef, M., Hanif, M., Imraz, M. and Sadiq, I. (2015): A preliminary account of the Middle Jurassic plays in Najafpur Village, southeastern Hazara, Khyber Pakhtunkhwa, Pakistan. Journal of Himalayan Earth Science, 48(1).

Smewing, J.D., Warburton, J., Daley, T., Copestake, P. and Ul –Haq, N. (2002): Sequence stratigraphy of the southern Kirthar fold belt and middle Indus basin, Pakistan. Geological Society, London, Special Publications, 195, 273-299.

Swati, M. A. F., Haneef, M., Ahmad, S., Latif, K., Naveed, Y., Zeb, W., Akhtar, N. and Owais, M. (2014): Diagenetic analysis of the Early Eocene Margala Hill limestone, Pakistan: A synthesis for thin section porosity. Journal of Himalayan Earth Sciences, 47(2), 49-61.

Taghavi, A. A., Mørk, A. and Emadi, M. A. (2006): Sequence stratigraphically controlled diagenesis governs reservoir quality in the carbonate Dehluran Field, southwest Iran. Petroleum Geoscience, 12(2), 115-126.

Tavakoli, V., Rahimpour-Bonab, H. and Esrafili-Dizaji, B. (2011): Diagenetic controlled reservoir quality of South Pars gas field, an integrated approach. Comptes Rendus Geoscience, 343(1), 55-71.

Turner, P. (1980): Continental red beds (Developments in Sedimentology). Elsevier, 29.

Waagen, W. (1872): Rough section showing the relations of the rocks near Murree (Mari) Punjab. Geological Survey of India Records, 5, 15-18.

Wynne, A. B. (1875): Notes on the Tertiary zone and underlying rocks in the northwest Punjab. Geological Survey of India Records, 10 (3), 107-13.

Wynne, A.B. (1873): Notes from progress report on the geology of parts of the upper Punjab. Geological Survey of India Records, 6 (3), 59-64.

Zahid, M., Ahmad, S., Ali, F. and Rehman, G. (2009): Structural geometry of a part of the southeastern Hazara Fold-Thrust Belt, Khyber Pakhtunkhwa, Pakistan. Pakistan Journal of Hydrocarbon Research, 19.

SAŽETAK

Strukturna analiza i karakterizacija ležišta kredne sekvencije u Kohala Bala, Khyber Pakhtunkhwa, Pakistan

Jugoistočna Hazara predstavlja dio himalajskoga borano-navlačnoga pojasa nastaloga interakcijom indijske ploče s euroazijskom pločom. U okviru ovoga istraživanja analizirana je strukturna geometrija i potencijal ležišta kredne sekvencije (formacija Chichali i Kawagarh) u južnoj Hazari, Pakistan. Kartirane stratigrafske jedinice kreću se od gornje jure, formacija Samana Suk, do donjega eocena, vapnenac Margalla Hill, zajedno s diskordancijama. Područje je istraživanja intezivno deformirano, a karakteriziraju ga reverzni rasjedi s pratećima borama. Prednje su navlake strmo nagnute prema sjeveru s pripadajućim pozadinskim navlakama nagnutim južno, dok su bore predstavljene asimetričnim antiklinalama i sinklinalama zajedno sa simetričnom antiklinalom (Barkot). Strukture su uglavnom položene SI – JZ, što upućuje na pojavu tlačnih naprezanja smjerom SZ – JI. Kvaliteta ležišta ocijenjena je analizom petrografskih slika, SEM analizom te analizom šupljikavosti i propusnosti. Vrijednosti variraju od 0.282 % do 10.89 % u formaciji Chichali (pješčenjaci) i 0.016 % do 1.78 % u formaciji Kawagarh (vapnenci). Izmjerena propusnost u formaciji Chichali varira od 0 do 0,064 mD, odnosno od 0 do 0.014 mD u formaciji Kawagarh. Zapažen je međuzrnati, unutarzrnati, pukotinski i *vuggy* (otopljeni) tip primarne šupljikavosti. SEM analiza pokazala je prisutnost mikroporoznosti u krednoj sekvenciji, dok su kalcit, dolomit, kvarc, feldspat i pirit definirani kao glavni minerali. Formacija Chichali dobra je ležišna stijena, dok se formacija Kawagarh može opisati i kao ležište, ali i izolator, ovisno o tome jesu li tektonske pukotine ispunjene cementnim materijalom.

Ključne riječi:
himalajski borano-navlačni pojas, karakterizacija ležišta, južna Hazara (Pakistan), SEM analiza, šupljikavost uzorka

Author’s contribution

Bilal Ahmed (MS from National Centre of Excellence in Geology (NCEG), Petroleum Geology) performed the fieldwork, experiments, data analysis, investigation, interpretation of the results, and prepared the original draft. **Shahzad Bakht** (PhD student at College of Earth Sciences, Jilin University, Mineral Resource Prospecting and Exploration) drew and edited the maps, participated in the discussion, carried out proofreading, review and editing, and prepared the final manuscript. **Sohail Wahid** (PhD, Assistant Professor at NCEG, Structure Geology) supervised the research work, ensured funding and participated in the fieldwork. **Muhammad Hanif** (PhD, Associate Professor at NCEG, Sedimentology) provided suggestions in the interpretation of the results and participated in the discussion and conclusion. All the authors reviewed the results and approved the final version of the manuscript.