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Lithofacies-based paleoenvironmental analyses and geochemistry the of the Lumshiwal Formation, Surghar Range, Pakistan

Analizy paleośrodowiskowe i geochemia litofacji formacji Lumshiwal, pasmo Surghar, Pakistan

Iftikhar Alam[1], Nazir-ur-Rehman[2], Shuja Ullah[3,*], Afrasiab[2], Sarfraz Khan[3], Nasim Javid[2], Khalid Khan[4]

[1] Pakistan Atomic Energy Commission, REO
[2] Khushal Khan Khattak University, Pakistan
[3] National Centre of Excellence in Geology, University of Peshawar, Pakistan
[4] Geological Survey of Pakistan

ABSTRACT: Rock samples from the Lumshiwal Formation exposed in Pannu Nala and Karandi Nala were collected near the Malla Khel area in the Surghar Range to analyze its depositional paleoenvironment, geochemistry, lithofacies, and reservoir potential. The lower contact of the Lumshiwal Formation with the Chichali Formation is transitional, and it is unconformably overlain by the Paleocene Hangu Formation. The thickness of the formation at the study area is 190 m. Field investigations suggest that the formation thins eastward along the EW transect of the Surghar Range. The formation is composed mostly of fine- to medium-grained sandstone, although a few sections exhibit medium- to coarse-grained textures, and it is almost devoid of fossils. Belemnite fossils were observed in the lowermost layers of the formation. Sandstones within the Lumshiwal Formation are categorized as subarkose to arkosic arenite based on their modal composition, with some samples classified as lithic arkose. Based on the lithofacies and geochemical (XRD) analyses, the depositional environment of the Lumshiwal Formation is interpreted as transitional, ranging from deltaic to shallow marine. Furthermore, the formation exhibits economically significant enrichment in carbonaceous material, with coal seams observed at multiple intervals.

Key words: Lumshiwal Formation, Surghar Range, depositional modeling, lithofacies analysis, geochemical analysis.

STRESZCZENIE: Próbki skał z formacji Lumshiwal, odsłoniętej w rejonach Pannu Nala i Karandi Nala, zostały pobrane w rejonie Malla Khel w paśmie Surghar w celu przeprowadzenia analizy paleośrodowiska sedymentacji, geochemii, litofacji oraz potencjału zbiornikowego. Dolna granica formacji Lumshiwal z formacją Chichali ma charakter przejściowy, a od góry przykrywa ją paleoceńska formacja Hangu. Miąższość formacji w badanym rejonie wynosi 190 m. Badania terenowe wskazują na zmniejszanie się miąższości formacji w kierunku wschodnim wzdłuż osi wschód-zachód pasma Surghar. Formacja zbudowana jest głównie z drobno- do średnioziarnistych piaskowców, choć w niektórych profilach występują również piaskowce średnio- i gruboziarniste. Jest ona niemal całkowicie pozbawiona skamieniałości – jedynie w najniższych warstwach formacji występują skamieniałości belemnitów. Piaskowce formacji Lumshiwal, na podstawie ich składu modalnego, sklasyfikowano jako subarkozowe do arenitów arkozowych, przy czym niektóre próbki zaklasyfikowano jako arkozowo-lityczne. Na podstawie analiz litofacjalnych i geochemicznych (XRD) paleośrodowisko sedymentacji formacji Lumshiwal określa się jako przejściowe, od deltowego po płytkomorskie. Ponadto, formacja wykazuje istotne ekonomicznie wzbogacenie w materiał węglonośny, z warstwami węgla występującymi w wielu poziomach.

Słowa kluczowe: formacja Lumshiwal, pasmo Surghar, modelowanie depozycji, analiza litofacji, analiza geochemiczna.

Introduction

The Lesser Himalayan Trans-Indus ranges in northwestern Pakistan include various mountain ranges such as the Marwat-Khisor, Pezu, Surghar, Bhittani, Sheikh Budin Hills, and Manzai ranges. Among these ranges, the Surghar and Khisor ranges exhibit a complex structural arrangement, particularly through asymmetrical to overturned folded anticlines. These anticlines are characterized by exposed Cambrian to Permian strata forming the cores of the folds, which are overlain by Mesozoic to Paleogene rocks (Ahmad et al., 1999). This distinctive geological architecture provides a unique opportunity to study sedimentation, tectonics, and reservoir characteristics, particularly in formations such as the Lumshiwal Formation (LF).

Corresponding author: S. Ullah, e-mail: *shuja_nceg@uop.edu.pk*

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The Lumshiwal Formation comprises whitish-gray to light-gray thick, massive, cross-bedded sandstone interlayered with glauconitic, sandy, and silty shale, showing cyclic bedding at its base. The sandstone is further characterized by its ferruginous and feldspathic nature and abundant carbonaceous material in its upper section, contributing to its reservoir potential (Shah, 2009; Rehman et al., 2022). Due to its unique mineralogical and sedimentological properties, the Lumshiwal Formation has been selected for an integrated sedimentological and mineralogical investigation aimed at understanding its depositional environment.

This study aims to thoroughly examine the sedimentological, mineralogical, and geochemical properties of the Lumshiwal Formation to evaluate its potential as a hydrocarbon reservoir. It seeks to fill the knowledge gap concerning the formation's depositional environment and lithological variations, which are crucial for assessing its economic significance in the study area. Previously, the Lumshiwal Formation was studied in southeastern Hazara in the context of depositional environment, diagenesis, and provenance (Rahim et al., 2018). Petrographic studies were also conducted in the Samana Range for provenance and diagenesis (Arif et al., 2009), and similar sandstone units were investigated in the Hazara areas for the provenance studies (Alam et al., 2023). However, this unit has not been studied in the context of the paleoenvironment, geochemical analysis, and diagenesis. Therefore, this study combines sedimentological, mineralogical, and geochemical data to comprehensively examine the depositional environment of the Lumshiwal Formation in the Surghar Range, Pakistan. It specifically aims to examine lithofacies variations to gain insights into sediment deposition. Additionally, detailed petrographic and geochemical analyses of rock samples from the Karandi and Punno Nala sections are conducted to assess the formation's mineralogical composition and chemical properties. Furthermore, the study evaluates the reservoir potential of the Lumshiwal Formation by analyzing key features such as porosity, permeability, and cementation. These parameters are crucial in determining the formation's suitability for hydrocarbon storage. This comprehensive approach will enhance our understanding of the geological characteristics and economic importance of the formation.

Geological Setting

The Surghar Range constitutes a significant element of the active deformational front within the Salt Range and Surghar-Shinghar ranges in northwestern Pakistan. This deformation is driven by the southwards movement resulting from the underthrusting of the Indian plate underneath the Eurasian plate (Ahmad et al., 1999; Ullah et al., 2016, 2017, 2022, 2023; Rehman et al., 2022, 2024) (Figure 1). The Surghar-Shinghar ranges, which form the easternmost part of the Trans-Indus ranges, extend along an east-west structural trend. They initially run parallel to the southern edge of the Kohat Basin before shifting to an NS orientation along the eastern flank of the Bannu Depression, located to the west of the Surghar Range. Within the Surghar Range, the Permian-Eocene succession is unconformably overlain by the rocks of the Siwalik Group (Figure 2). Across the range, these rocks become progressively thicker and more complete from east to west. The Surghar Range can be divided into two sections: an NS-oriented section extending along the southern extensions of the range from Qubul Khel to Mitha Khattak areas, and further stretching to Malla Khel, following the structural alignment of the range. The EW structural orientation of the Surghar Range is defined by prominent anticlines with smaller-scale synclinal entities. EW-trending faults intersect both the cores and the flanks of these structural elements. This section continues to the easternmost edge of the Surghar Range.

Stratigraphic Framework

The base of the outcropping succession in the study area is composed of the rocks of the Zaluch Group (Wargal and Chhidru formations), followed by the exposed rocks sequence of Triassic to Eocene platform sediments unconformably overlain by fluviatile sediments of Siwalik Group of Pliocene to Pleistocene age (Figure 2). The Lumshiwal Formation (LF) was first referred to as "Lumshiwal Sandstone" by Gee (1945). However, the Stratigraphic Committee of Pakistan later renamed it the Lumshiwal Formation due to significant lithological differences observed beyond its original location. Fatmi et al. (1968) and Fatmi et al. (1972) identified three main reference sections: Fort Lockhart Road section in the Samana Range, Jhamiri Village section along the Haripur-Jabri Road in Hazara, and the Wuch Khawar section in Nizampur. These identifications were based on lithological variations and differences in thickness. Correlation studies by Kadri (1995) linked the Gorru Formation of the axial belt and Lower Indus Basin to the Lumshiwal Formation. In the Surghar Range, the sandstone is distinguished by its ferruginous and feldspathic composition, with the upper part containing carbonaceous matter and cyclic bedding observed in the lower section (Alam et al., 2015). A transitional contact between the Lumshiwal and Chichali formations has been reported. In the southern Potwar and Trans-Indus Ranges, the Lumshiwal Formation is overlain by Tertiary formations. In its lowest portion, glauconite and sporadic fossils such as *Gryphaea* spp. and *Hibolites* spp. are found.

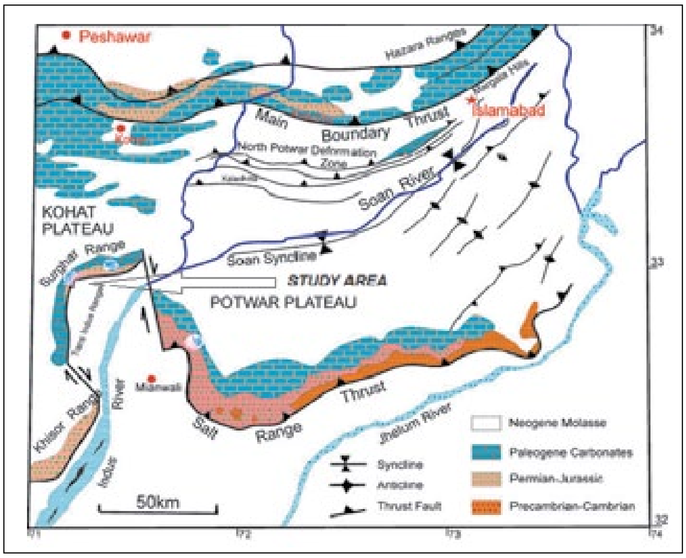


Figure 1. Geological map of the foreland folds and thrust belt. The arrow shows the location of the study area (modified after Ullah et al., 2022). The arrow points towards north

Rysunek 1. Mapa geologiczna fałdów przedpola i pasa nasunięć. Strzałka wskazuje lokalizację obszaru badań (zmodyfikowano na podstawie Ullah i in., 2022). Strzałka wskazuje kierunek północny

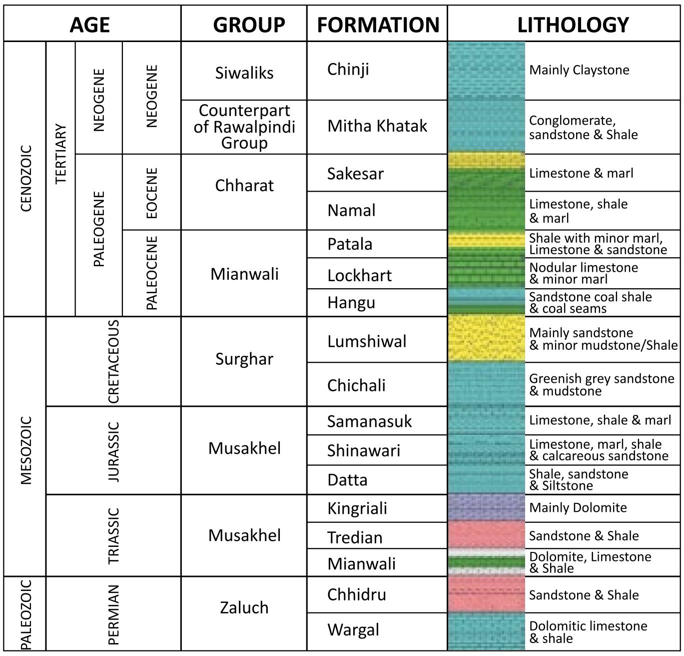


Figure 2. Stratigraphic framework of the Surghar-Shinghar Range (Alam, 2008)

Rysunek 2. Profil stratygraficzny pasma Surghar-Shinghar (Alam, 2008)

Materials and methods

The study employed a comprehensive investigative approach involving extensive fieldwork and meticulous laboratory investigations to evaluate the Lumshiwal Formation. Field studies were conducted to examine the texture and composition of the formation, with rock samples collected from representative lithofacies units exposed in key areas of the research region. Specifically, samples were obtained from two locations: the Karandi Nala section (32° 54′ 00″ N, 71° 10′ 10″ E) and the Punno Nala section (32° 56′ 33″ N, 71° 13′ 54.1″ E). These sites are situated at different elevations and exhibit noticeable variations in the types of rocks present. The collected samples provided essential data for understanding the depositional environment, structural features, and potential economic significance of the formation, particularly regarding its oil reservoir potential. Geochemical analyses of the rock samples were conducted in the laboratory to further examine the mineralogical composition of the formation. The samples were thoroughly examined using a Nikon Eclipse E200 petrographic polarizing microscope equipped with a Nikon digital sight DS-Fi2 camera to produce high-resolution photomicrographs. Rock classification was based on an analysis of mineral composition and texture, which allowed for the identification of significant lithofacies variations. The results were documented using photomicrographs that visually represent the mineralogical features of the rocks. In addition, modern geochemical techniques were applied to obtain quantitative data on the chemical composition of the rock samples, thereby enhancing the understanding of the formation's depositional history from a geochemical perspective. This methodology ensured the integration of field observations and laboratory analyses to provide a comprehensive assessment of the Lumshiwal Formation.

Results

Lithofacies analysis and depositional model of LF

Three significant lithofacies assemblages, representing a combination of terrestrial and marine environments, constitute the structure of the Lumshiwal Formation. From base to top, three distinct sandstone lithofacies associations – designated as "C" and "B", and "A" – were identified. These are interbedded with carbonaceous shale, siltstone, mudstone, and coal beds (Figure 3 and Table 2).

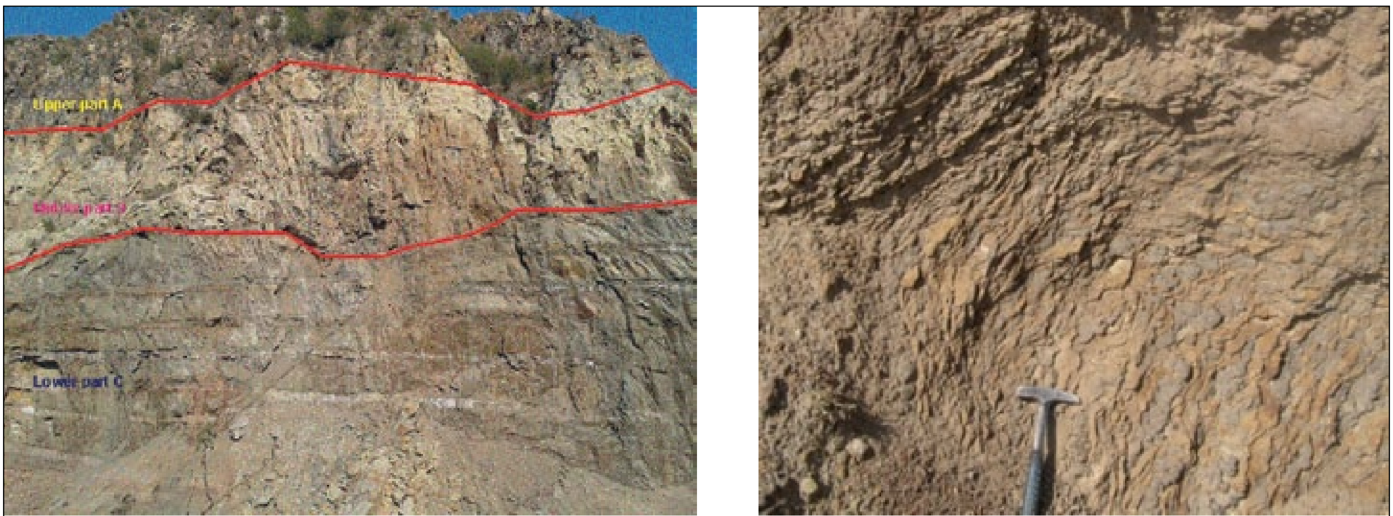
Lithofacies association C

This lithofacies assemblage is predominantly composed of sandstone with interbedded silty clays and is present in the lower part of the formation. The sandstone is fine-grained, thick-bedded, brownish-grey in color, well-sorted, and well-cemented. The silty clays and clays are green to brownish-grey in color, laminated, and thin-bedded, indicating cyclic deposition. Facies color varies and includes yellowish-grey, brownish-grey, olive-grey, pale yellowish-brown, and reddish-brown (Tables 1 and 2). The beds exhibit cyclic emergence and display parallel bedding (Figure 3). Measured bed thickness ranges from 1.5 to 2.0 m. Within the sandstone horizon, fine cross-bedding is also observed. At the base, there is thinly-bedded, silty, glauconitic sandy clayey shale interbedded with fine- to medium-grained, green to brown-grey sandstone containing burrows. The basal part is cracked, and veins filled with calcitic fluid are visible. This lithofacies contains ironstone nodules and hematitic staining and is approximately 76 m thick (Figure 3).

Table 1. Lithofacies analysis of Lumshiwal Formation in the study area

Tabela 1. Analiza litofacjalna formacji Lumshiwal na obszarze badań

Part	Thickness part [m]	Thickness facies [m]	Facies Description
Upper Lithofacies Association "A"	62.00	01.00	A reddish-brown laterite bed at the interface with the Hangu Formation, silty, sandy, clayey facies
		03.00	Medium- to fine-grained sandstone, well-cemented, silty, bearing a coal seam, green to brown in color
		01.00	Medium-grained sandstone, slightly cemented, dark brown
		09.00	Medium- to coarse-grained sandstone, massive and thick-bedded, greenish grey, moderately to well-cemented
		01.00	Medium- to fine-grained sandstone, reddish-brown, moderately cemented
		18.00	Massive, medium- to coarse-grained sandstone, greenish-grey to brownish-grey, moderately to well-cemented
		30.00	Massive, medium- to coarse-grained sandstone, moderately to well-cemented, greenish-grey to whitish-grey
Middle Lithofacies Association "B"	79.00	37.00	Massive, thick-bedded, medium- to coarse-grained sandstone, cross-bedded, variegated in color: green to reddish-brown, grey
		08.00	Medium- to thick-bedded shale interbedded with brownish black coal, dark grey to blackish-grey
		03.00	Olive-green laminated shale; soft to semi-hard
		06.00	Thin shale with olive to greenish-white, creamy tones
		25.00	Massive, medium- to coarse-grained cross-bedded sandstone, light grey to whitish-grey, fractured, with calcite-filled fractures
Lower Lithofacies Association "C"	76.00	30.00	Fine-grained, clayey, silty sandstone; light grey to greenish-grey; glauconitic, indicating cyclic deposition
		04.00	Clayey, silty, laminated to finely bedded shale; green to brownish-grey
		42.00	Thick-bedded, cross-bedded, fine-grained sandstone; grey to dark grey; well cemented



a) b)

Figure 3. a) Photographs showing the LF's top, middle, and bottom (the scale line in the lower left corner is approximately 20 m); b) Lithofacies association C – hammer for scale (30 cm in length)

Rysunek 3. Zdjęcia przedstawiające górną, środkową i dolną część formacji Lumshiwal (linia skali w lewym dolnym rogu ma około 20 m); b) zespół litofacyjny C. Młotek (o długości 30 cm) pozostawiono na potrzeby pokazania skali

Table 2. Petrographic results based on Folk's classification of sandstone (1974) for samples collected from the Lumshiwal Formation, Punno Nala section, Surghar-Shinghar ranges

Tabela 2. Wyniki analizy petrograficznej oparte na klasyfikacji piaskowców Folka (1974) dla próbek pobranych z formacji Lumshiwal, profil Punno Nala, pasmo Surghar-Shinghar

Serial No.	Sample No.	Minerals identified and their percentages																				Types of cement					Rock name
		clay minerals	silt grade minerals	bioclasts/belemnite	quartz	plagioclase	orthoclase	microcline	perthitic feldspar	rock fragments	glauconite	calcite/dolomite	carbonaceous matter	tourmaline	muscovite	epidote	pyrite	hematite	magnetite	accessory minerals	voids	calcite	jarosite	hematite	clays/ferruginous clays	glauconite	
1	CLP-1				13		8	2	2	2	13	15		1				29	1	2	12	A				12	glauconitic sandstone
2	CLP-2			36	2	A	2				22	24						3		1	4					13	glauconitic sandstone
3	CLP-3	65	28																		5						glauconitic shale
4	CLP-4				37	2	15	1	2	2	8	2		1	3	2		2	1	2	6	14			4		arkose
5	CLP-5				40	3	12	1	2	1	1				1	1	1	3	3	3	7	16		12		A	arkose
6	CLP-56				41	1	13	1	1	3	1		3	2	A	1		2	1	2	5	12	8		6	14	arkose
7	CLP-7				45		12		1	6						A		2	2		7			16	16		lithic arkose
8	CLP-8				53		16			5					1	1		2	2	1	5				12		subarkose
9	CLP-9				51		14			4			1	2	2			1	1	2	8		14				arkose
10	CLP-10	33	66															1	1		4						mudstone
11	CLP-11				52	A	18			2				1	3			2	1	2	9	15		8	11		arkose
12	CLP-12				50	A	17	1	1	1	1		2	1	1			1	A	1	10	12			12		arkose
13	CLP-13				48		19		1	8			1			1		1	2		7			16			lithic arkose
14	CLP-14				54		13			2					1			3	1	1	5				16		subarkose

A - absent

Lithofacies Association B

Lithofacies association B represents a transitional complex between lithofacies association A and C, with a few sandstone units at the top resembling those of lithofacies association-A. This lithofacies is characterized by medium- to coarse-grained sandstone interbedded with olive-green shale (Tables 1 and 2). The thick-bedded to massive sandstone exhibits cross-bedding, while low-angle cross-beds are rarely observed in the lower and middle sections (Figures 2 and 3). The sandstone in this lithofacies is quartzose, ferruginous, and feldspathic. A notable bed within this unit, approximately 0.5 m thick, consists of quartz and feldspathic debris ranging in size from large pebbles to sub-angular to sub-rounded granules. Hematitic alteration is common, particularly in the upper sections of this association. Lithofacies association B is 79 m thick (Figure 3).

Lithofacies Association A

This lithofacies association is composed entirely of sandstone. In its lower part, the sandstone is coarse-grained, massive, and greenish-grey in color. In the middle section, the sandstone is massive to thick-bedded, brownish to greenish-grey in color, medium- to coarse-grained, well cemented, and well sorted. The upper part of this lithofacies assemblage consists of fine- to medium-grained sandstone, green to brownish in color, and includes thin coal seams (Tables 1 and 2). A few clay horizons are present in the upper part of the formation. Hematitic alteration is frequently observed in this section (Figure 3). The upper clay layers are reddish-brown in color, typically contain carbonaceous debris, and exhibit worm burrows. At the top of the formation, shale occurs as thin (< 0.5 m) interbeds within the sandstone lithofacies. This shale is gradational and interbedded with thinner laminae of claystone, carbonaceous shale, and coal beds, which are laterally sporadic and less than 0.3 m thick in the uppermost part of the formation. The carbonaceous claystone is frequently rooted and consists of coal beds and carbonaceous shale that grade beneath the clay (Figure 3). Lithofacies association A is 62 m thick.

Figure 4. Photograph showing measurement of the lower lithofacies association

Rysunek 4. Zdjęcie przedstawiające proces wykonywania pomiarów zespołu litofacyjnego

Depositional Environment

Lithofacies data, supported by previous studies, indicate that the Lumshiwal Formation was predominantly deposited in a shallow marine setting, characterized by varying energy levels and cyclic deposition (Warwick, 1995; Arif et al., 2009). Lithofacies association C, composed of variegated sandstone layers with fine-grained cross-beds and glauconitic sandy shale, suggests deposition in a shallow marine environment with alternating periods of exposure and submergence. A clay matrix with glauconite, strong bioturbation in certain areas, and an upward increase in grain size indicate that this lithofacies was most likely deposited in shallow marine, prodeltaic settings. This interpretation is supported by the presence of glauconite, a mineral typically found in low-oxygen shallow marine environments. Additionally, the occurrence of ferruginous and hematitic alterations within the lithofacies suggests episodes of oxidizing conditions, commonly associated with shallow marine settings where the water column interacts with the atmosphere (Arif et al., 2009). The presence of cross-bedded sandstone and interbedded shales in Lithofacies association B indicates deposition under high-energy conditions, likely in a nearshore zone dominated by wave action. Warwick (1995) similarly proposed a brackish-to-marine depositional environment for the upper Lumshiwal based on analyses of sandstone bodies. Previous research has also emphasized the abundance of quartz and the presence of glauconite as indicators of a shallow marine depositional environment (Rahim et al., 2018). Lithofacies association A consists mainly of thick-bedded sandstone with alternating thin coal seams, indicative of deltaic and nearshore

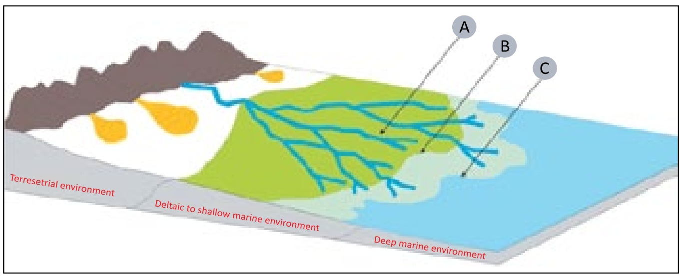


Figure 5. Schematic depositional model of LF, based on the identification of lithofacies associations A, B, and C

Rysunek 5. Schematyczny model sedymentacyjny formacji Lumshiwal, oparty na identyfikacji zespołów litofacyjnych A, B oraz C marine processes responsible for forming small peat lenses. This facies represents a shallow coastal environment extending slightly inland. Collectively, these characteristics suggest that the Lumshiwal Formation was deposited on a shallow marine shelf. The overall lithofacies-based depositional model of the LF association is shown in Figure 5.

Geochemical Analysis

The geochemical analysis of rock samples collected from various segments of the Lumshiwal Formation, specifically the Punno Nala and Karandi Nala sections, has provided valuable insights into compositional trends within the stratigraphic sequence. Samples were systematically collected in stratigraphic order from bottom to top, offering a comprehensive overview of elemental distribution throughout the succession. Analysis of the tabulated geochemical data reveals a distinct pattern: as indicated by the serial numbers representing the vertical sequence of samples, silica content exhibits a notable increase from the lowermost to the uppermost strata in the Karandi Nala section. Simultaneously, the concentrations of all other measured elements consistently decrease along the vertical profile, establishing a clear inverse relationship between silica content and the remaining constituents. These findings, summarized in Tables 3 and 4, highlight the dynamic geochemical evolution of the Lumshiwal Formation and provide valuable insights into its petrogenetic history and depositional environment.

Punno Nala Section

The sandstone samples are typically grey or greenish-grey in color, although occasional observations include yellowish to reddish-brown and off-white to whitish tones. A few samples showed traces of carbonaceous matter. The samples range from fine to medium grain size, with some exhibiting coarse to granule-sized grains. They are generally moderately to well cemented. Effervescence is observed in some samples upon application of 10% HCl.

Thin section observations reveal that feldspar and quartz are the primary constituents of the framework. Trace amounts of rock fragments are also present in most samples. Other minerals occurring in trace amounts include hematite, muscovite, magnetite, carbonaceous matter, glauconite, and calcite/dolomite.

The shale of the Lumshiwal Formation is thin, fissile, and ranges in color from reddish-brown to brownish-grey. Mineralogically, it is composed of silt- and clay-grade minerals. Clay-grade minerals include glauconite, which is occasionally associated with sericite and hematite. Kaolinite and glauconite were identified as clay minerals using X-ray diffraction spectroscopy. The silt-grade minerals include biotite, musco-

Table 3. Geochemical analyses of rock samples collected from the Punno Nala section

Tabela 3. Analizy geochemiczne próbek skał pobranych z profilu Punno Nala

Serial No.	1	2	3	4	5
Min Name	CLP-3	CLP-4	CLP-6	CLP-7	CLP-8
SiO_2 [%]	64.120	46.150	82.6000	73.660	46.1000
Co_3O_4 [%]	–	1.161	–	–	–
ThO [%]	–	–	–	0.003	–
TiO_2 [%]	0.729	–	0.1550	0.370	0.0350
Al_2O_3 [%]	9.446	5.435	2.2300	12.033	0.6930
Fe_2O_3 [%]	4.156	9.158	0.8670	0.421	3.5600
MnO [%]	0.015	0.045	0.0270	0.004	0.0050
CaO [%]	4.265	10.59	0.0730	0.121	0.1450
MgO [%]	0.807	1.595	0.0832	0.187	0.0310
Na_2O [%]	0.117	0.080	0.2240	0.114	0.4540
K_2O [%]	1.592	0.590	0.0451	0.215	0.0350
P_2O_5 [%]	0.055	0.069	–	0.150	0.0040
SO_3 [%]	2.230	9.070	0.7560	1.932	3.0900
Cl [%]	0.037	0.017	0.0150	0.028	–
Cr_2O_3 [%]	0.121	0.115	0.1210	–	0.0052
NiO_2 [%]	0.008	0.009	–	0.006	0.0030
Cu_2O [%]	0.070	0.009	0.0110	0.004	0.0020
ZnO_2 [%]	0.003	0.004	0.0030	0.003	–
SeO_2 [%]	0.001	0.003	–	0.001	–
Rb_2O [%]	0.006	0.004	–	0.002	0.0011
SrO [%]	0.016	0.032	0.0020	0.017	0.0070
Y_2O_3 [%]	0.003	0.003	–	0.002	–
ZrO [%]	0.064	0.074	0.0240	0.047	0.0050
Nb_2O_5 [%]	0.002	0.002	–	0.001	–
BaO [%]	0.016	–	–	–	–
CeO_2 [%]	0.023	–	–	0.016	–
PbO [%]	0.004	0.005	0.0030	–	–

– below detection level

Table 4. Geochemical analysis of the rock samples collected from the Karandi Nala section

Tabela 4. Analiza geochemiczna próbek skał pobranych z profilu Karandi Nal

Serial No.	1	2	3	4	5
Sample No.	CLK-2	CLK-3	CLK-6	CLK-7	CLK-8
SiO_2 [%]	68.50	75.50	86.20	89.60	92.60
TiO_2 [%]	0.59	0.56	0.16	0.79	0.11
Al_2O_3 [%]	7.55	3.70	1.09	2.83	2.46
Fe_2O_3 [%]	4.21	4.02	1.89	1.59	2.45
MnO_2 [%]	0.02	0.01	0.01	0.02	0.01
CaO [%]	0.15	0.13	0.08	0.07	0.09
MgO [%]	0.30	0.26	0.05	0.15	0.07
Na_2O [%]	0.15	0.16	0.09	0.05	0.04
K_2O [%]	0.89	0.69	0.10	0.20	0.17
V_2O_5 [%]	0.10	0.08	0.02	0.11	0.02
P_2O_5 [%]	0.05	0.05	0.05	0.02	0.01

vite, hematite, quartz, orthoclase, and glauconite. Glauconite is also observed in pellets form. This shale is classified as "Glauconitic Shale".

The mudstone sample is dark grey to brownish-grey in color and semi-hard in consistency. It comprises clay- and silt-grade minerals. The silt-grade minerals include quartz, muscovite, magnetite, orthoclase, hematite, and biotite. Sericite and kaolinite are the primary clay-grade minerals, with glauconite also observed in a few locations. Illite and kaolinite were confirmed as clay minerals through X-ray diffraction analysis. Based on Blatt's classification (1980), the sample is categorized as "Mudstone". Crook (1974) demonstrated that sandstones with low quartz content typically originate from active continental margins or orogenic belts, while those with very low quartz content are often associated with volcanogenic (magmatic island arc) sources. In contrast, quartz-rich sandstones are characteristic of passive continental margins. The present study supports this model, as evidenced by the petrographic and geochemical analyses of the investigated samples (Figure 7). According to Folk's sandstone classification (1974), the analyzed samples fall within the sub-arkosic to arkosic sandstone fields, characterized by 40–20 feldspar and 80–60 quartz (Figure 8), indicating a provenance between transitional continental and craton interior settings (Figure 7). These geochemical results suggest that the grains were derived from and transported across the regions indicated by Folk's triangle. The high quartz content relative to feldspar suggests a higher degree of mineralogical maturity. Textural maturity refers to the extent to which mechanical forces, such as currents and tides, have influenced the sediment during transport. This can be inferred from factors such as sorting, roundness, and clay content. Thin section analysis shows that detrital grains are generally sub-angular to sub-rounded, moderately to well sorted, which designate the textural development of grains.

Karandi Nala Section

Rock samples were collected from different parts of the Lumshiwal Formation along the Karandi section in a bottom-to-top sequence. In the tabulated geochemical analyses, the serial numbers represent the succession of samples from bottom to top. Silica content increases from the bottom upwards, while the concentrations of all measured elements decrease, indicating an inverse relationship (Table 5). Table 6 shows the ratios of various oxides identified in the analyses of the samples collected from the Karandi Nala section, located near the village of Malla Khel. It was observed that sample CLK-01 is rich in silica and alumina but has low sodium and potassium contents. This general trend is consistent across the remaining samples, as shown in Table 6.

Discussion

Three different lithofacies associations – C, B, and A – define the complex interplay of terrestrial and marine depositional settings revealed by the lithofacies analysis of the Lumshiwal Formation. Cyclic deposition and the presence of glauconitic sandy shales in Lithofacies association C indicate a shallow marine environment with periodic exposure. This facies is characterized by fine-to- medium-grained, well-sorted sandstone interbedded with silty clays. The occurrence of glauconite as both cement and pellets, along with belemnites near the base of the formation in the Karandi Nala area, provides conclusive evidence of a marine environment in the lower portion of the formation. This indicates that the early stages of the process occurred in a marine depositional environment. A shift to Lithofacies association B, composed of medium-to coarse-grained quartzose sandstones with olive-green shale interbeds, indicates higher energy conditions likely related to nearshore wave and tidal influences. Hematitic staining and ferruginous sandstone further support variable redox conditions within a dynamic depositional environment. Lithofacies association-A,

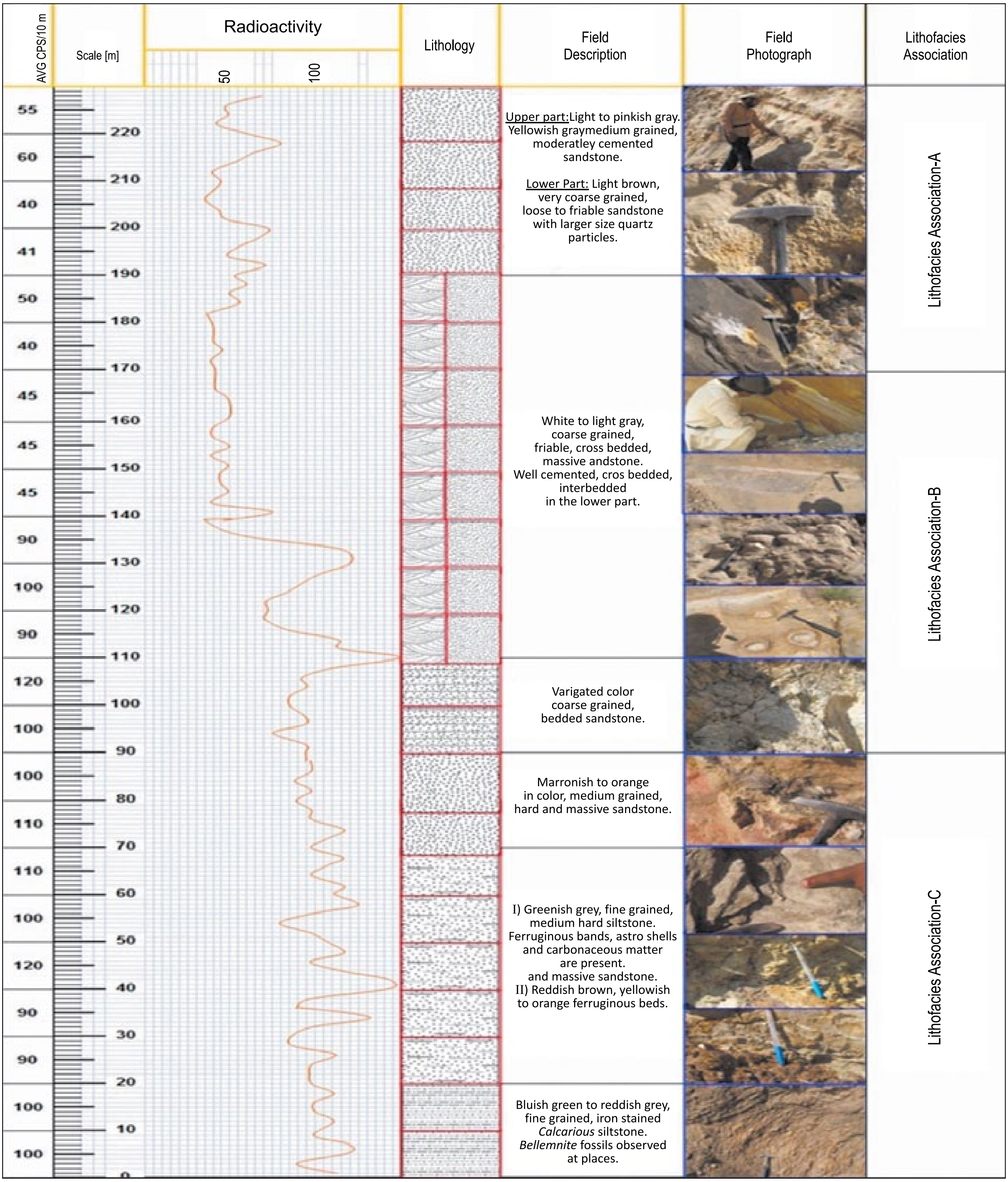


Figure 6. Lithofacies measured across the LF in Karandi Nala, Surghar-Shinghar ranges. Radioactivity units are in API

Rysunek 6. Litofacje zmierzone w formacji Lumshiwal w rejonie Karandi Nala, w paśmie Surghar-Shinghar. Radioaktywność podano w jednostkach API

comprising thick-bedded sandstones intercalated with coal seams, carbonaceous shale, and claystone, reflects a more deltaic to nearshore environment characterized by variable peat deposition and sediment supply over time. This interpretation is corroborated by geochemical analyses of the Punno Nala and Karandi Nala sections, which show increasing silica content

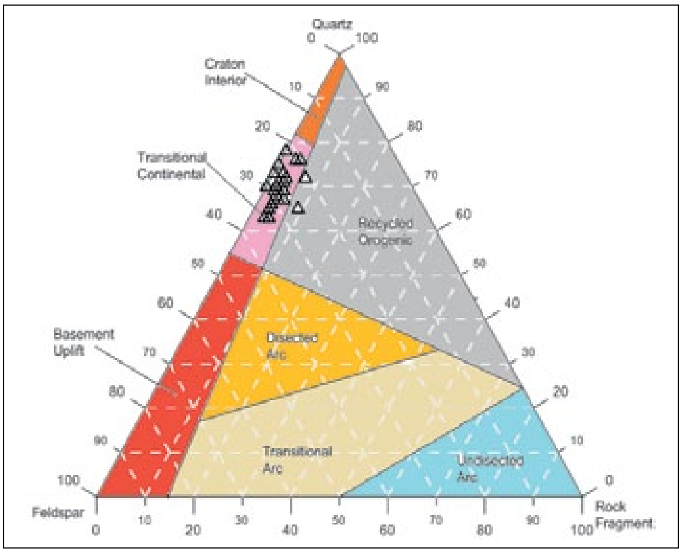


Figure 7. Triangular quartz-feldspar-lithic fragment plot illustrating the relationship between sandstone composition and tectonic setting (after Dickinson and Suczek, 1979)

Rysunek 7. Trójkątny diagram kwarcowo-skaleniowo-litowy ilustrujący związek między składem piaskowców a warunkami tektonicznymi (według Dickinsona i Suczka, 1979)

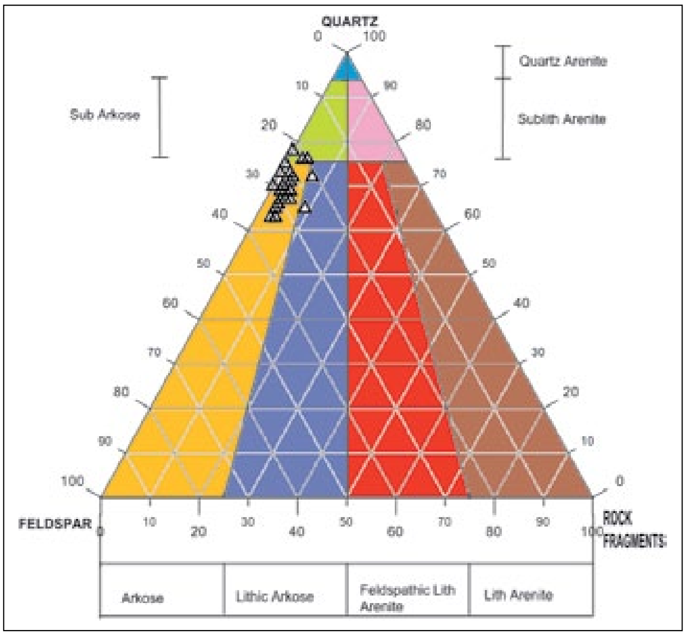


Figure 8. Folk's sandstone classification (1974)

Rysunek 8. Klasyfikacja piaskowców Folka (1974)

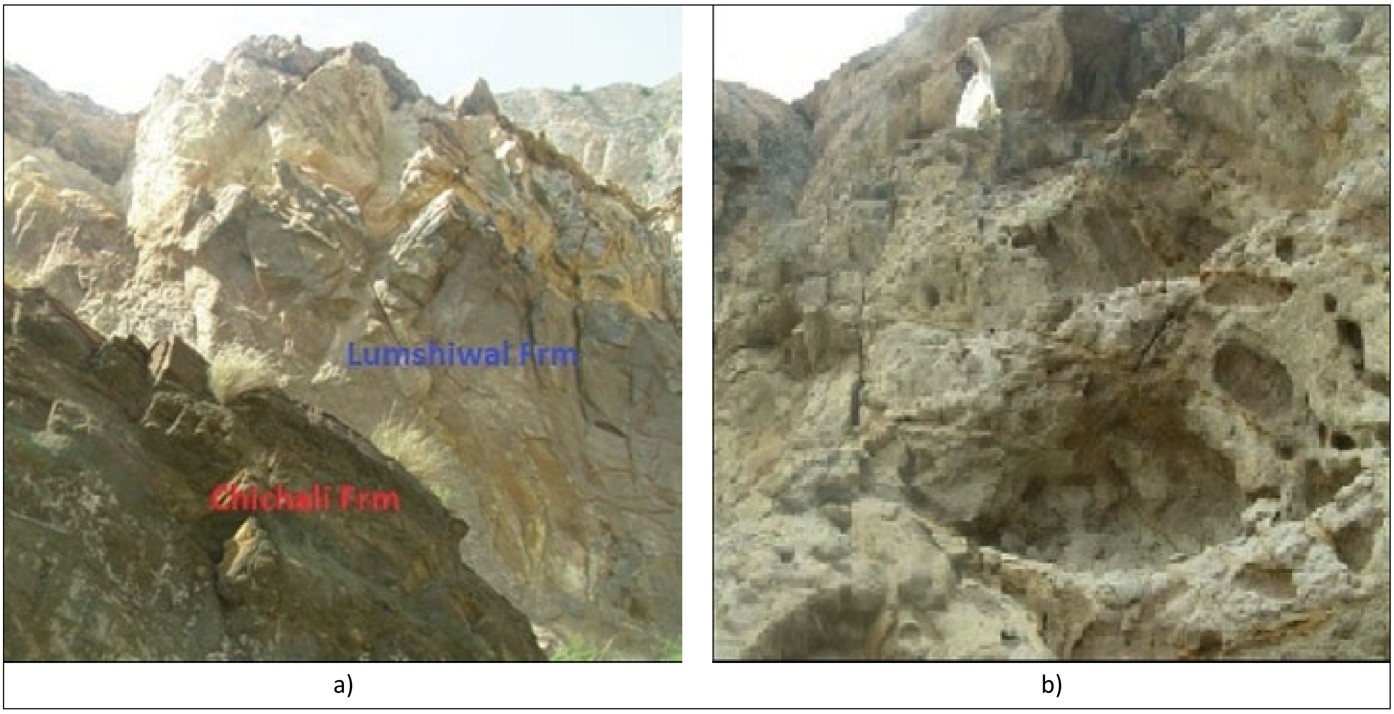


Figure 9. Fractures (a) and hollows (b) formed by tectonic and diagenetic processes

Rysunek 9. Szczeliny (a) i zagłębienia (b) powstałe w wyniku procesów tektonicznych i diagenetycznych

and a concurrent decline in the concentration of other elements. This geochemical trend implies increasing sediment maturity and possible winnowing effects due to prolonged exposure to hydrodynamic processes. Periodic deltaic intrusions add to the reported facies variability. The integration of lithofacies and geochemical data supports a depositional model of a shallow marine shelf influenced by tidal and wave activity. The sandstone's high quartz content suggests a metamorphic provenance, while its textural maturity, evidenced by the well-sorted, sub-angular to sub-rounded detrital grains, reflects sediment transport processes that enhanced sorting and reduced clay content – an important indicator of sediment maturity.

The presence of sub-arkosic to arkosic arenite sandstones suggests that the sediments originated from transitional con-

Figure 10. Thick laterite bed (a, d) and thin, medium, and thick coal seams (b, c) in the Lumshiwal Formation

Rysunek 10. Gruby pokład laterytu (a, d) oraz cienkie, średnie i grube pokłady węgla (b, c) w formacji Lumshiwal

tinental to cratonic sources, likely derived from uplifted basement rocks. The occurrence of intergranular voids in the coarse-grained layers (Table 1), along with the compositional features, increases the potential of the formation to act as a reservoir.

Diagenetic activity in the lower half of the formation led to the filling of fractures with calcitic solutions. Additionally, tectonic features are present in the upper portion of the formation (Figures 9a and 9b). These processes contribute to enhanced porosity, thereby increasing the economic potential of the formation. The presence of laterite beds and coal seams in the upper section suggests a gradual transition from marine to continental depositional settings, further supporting the formation's suitability as a hydrocarbon reservoir (Figures 10a–10d).

Overall, the geochemical analyses and lithofacies model conclusively demonstrate that the Lumshiwal Formation represents a significant geological unit capable of accumulating hydrocarbons. Its reservoir properties are greatly enhanced by the existence of geologically formed empty spaces and voids, making it an ideal candidate for further investigation and exploitation.

Table 5. Whole-rock geochemical composition of samples collected from the Karandi Nala section, Surghar-Shinghar Ranges
Tabela 5. Skład geochemiczny całej skały – próbki pobrane z profilu Karandi Nala, pasmo Surghar–Shinghar

Serial No.	Sample No.	Formation	Locality	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO_2	CaO	MgO	Na_2O	K_2O	V_2O_5	P_2O_5
				[%]										
1	CLK-01	Lumshiwal	Karandi	66.00	0.69	11.20	2.97	0.010	1.14	0.32	0.050	1.52	0.10	0.050
2	CLK-02	Lumshiwal	Karandi	73.60	0.60	8.82	1.73	0.010	0.14	0.37	0.060	1.32	0.09	0.040
3	CLK-03	Lumshiwal	Karandi	43.90	0.42	11.90	10.40	0.030	3.22	0.68	0.070	1.48	0.06	0.070
4	CLK-04	Lumshiwal	Karandi	67.90	0.69	6.64	4.01	0.010	0.17	0.20	0.130	0.92	0.10	0.050
5	CLK-05	Lumshiwal	Karandi	72.70	0.54	3.72	3.02	0.010	0.12	0.24	0.110	0.66	0.08	0.050
6	CLK-06	Lumshiwal	Karandi	88.80	0.88	4.87	3.13	0.010	0.18	0.27	0.060	0.38	0.12	0.040
7	CLK-07	Lumshiwal	Karandi	91.60	0.10	2.36	2.35	0.020	0.07	0.08	0.060	0.15	0.02	0.010
8	CLK-08	Lumshiwal	Karandi	86.90	0.80	2.73	1.60	0.010	0.06	0.13	0.060	0.19	0.11	0.040
9	CLK-09	Lumshiwal	Karandi	88.10	0.05	2.18	1.85	0.020	0.03	0.04	0.050	0.02	0.01	0.010
10	CLK-10	Lumshiwal	Karandi	88.40	0.18	1.08	1.79	0.020	0.07	0.07	0.100	0.09	0.02	0.050
			Average	76.79	0.49	5.55	3.28	0.015	0.52	0.24	0.075	0.67	0.07	0.039

Table 6. Ratios of selected oxides in samples taken from the Karandi Nala section, Surghar Range
Tabela 6. Stosunki wybranych tlenków w próbkach z profilu Karandi Nala, pasmo Surghar

Sample No.	CLK-01	CLK-02	CLK-03	CLK-04	CLK-05	CLK-06	CLK-07	CLK-08	CLK-09	CLK-10
Al_2O_3/SiO_2	0.169	0.119	0.271	0.0977	0.0511	0.097	0.0257	0.0314	0.0247	0.0122
Fe_2O_3/MgO	3.290	2.100	11.080	4.2100	3.2600	3.400	2.4300	1.7300	1.8900	1.8600
K_2O/Na_2O	30.400	22.000	21.140	7.0700	6.0000	6.300	2.5000	3.1000	0.4000	0.9000

The Lumshiwal Formation is correlated with the Goru Formation, a significant reservoir horizon in the lower Indus Basin. Field observation additionally reveals hairline fractures, dissolution cavities, fractures, and interconnected pore spaces (permeability). Furthermore, to fulfill the parameters of a petroleum system, the Chichali Formation may serve as the source rock, while the Laterite bed and the Hangu Formation may function as seal rocks.

Thus, in the study area, Lumshiwal Formation may serve as a hydrocarbon reservoir. The formation's primary components include burrow-like openings and fractures created by tectonic and diagenetic processes, which significantly increase the horizon's porosity and permeability. These features support its interpretation as a prospective reservoir horizon for the hydrocarbon accumulation. The middle and upper portions of the formation, in particular, are composed primarily of coarse-grained to granule-sized particles, with occasional pebble-sized particles. It is visually evident that these regions possess significantly more intergranular void spaces than the lower portions of the formation (Figure 9b). However, the lower part of the formation appears to be substantially tectonically fractured, and these fractures are partially filled by calcite/silicate solutions in the form of veins. The upper portion of the formation frequently displays tectonic fractures, while the lower-middle and lower parts exhibit hollows and burrows that may have formed by diagenetic processes and are economically significant in terms of petroleum development. The upper portion of the formation is composed of thickly bedded, white to milky-white, coarse-grained, soft to friable quartzose sandstone, which resembles silica sand in considerable quantities. This horizon, which extends laterally for 40 km from Makarwal to the easternmost edge of the Surghar-Shinghar ranges up to the Kalabagh fault, is 100 m thick (Alam, et al., 2015; Rehman et al., 2024). It can be extracted or quarried as a source of raw glass sand for the production of glass sheets and other related glass industry products.

In addition, mineable coal seams are present within the projected horizon of LF, particularly in the upper portion where it contacts the Hangu Formation. These seams are of economically viable thickness in locations where values have been noted and mining is straightforward (Figures 10a–10d). Iron staining and iron nodules in the form of protuberances along bedding planes are observed in the uppermost, lower middle, and basal parts of the formation. Notably, economically significant laterite beds occur at both the base of the formation and at the interface with the Hangu Formation, where the thickness exceeds 1 m. These deposits could be exploited as raw materials for the steel and cement industries.

Conclusions

This study has led to the following conclusions:

1. The comprehensive lithofacies analysis of the Lumshiwal Formation indicates a complex interaction of depositional environments, shifting from shallow marine to marginal marine and deltaic settings.
2. Lithofacies association C, mostly consisting of fine-grained glauconitic sandstones interbedded with silty clays and sandy shales, signifies deposition in a prodeltaic, shallow marine environment marked by low-energy, cyclic conditions.
3. Lithofacies association B comprises medium- to coarse-grained sandstones with ferruginous and feldspathic components interspersed with shales, indicating a more dynamic nearshore environment shaped by higher energy conditions and fluvial input.
4. Lithofacies association A comprises massive, well-sorted sandstones intercalated with thin coal seams and carbonaceous shales, indicative of deposition in a delta plain to coastal swamp environment, situated further inland yet still subject to intermittent marine influence.
5. These correlations collectively document a progressive regressive sequence and imply a depositional model transitioning from shallow marine shelf to deltaic and fluvial-dominated systems, indicating a gradual shift in depositional energy and paleoenvironmental conditions across the Lumshiwal Formation.
6. The sandstone samples from the Punno Nala section are mostly fine- to medium-grained, moderately to well-cemented, and composed chiefly of quartz and feldspar, with minor lithic fragments and accessory minerals such as glauconite, hematite, muscovite, and calcite/dolomite.
7. Thin sections studies indicate that the sandstones are arkosic to sub-arkosic in composition, placing them within the transitional continental to craton inner zone of Folk's sandstone classification, suggesting derivation from a continental block environment.
8. The shale and mudstone of the Lumshiwal Formation at Punno Nala contain glauconite, kaolinite, illite, and sericite, indicating deposition in a shallow marine setting with low oxygen conditions, with some volcanic influence.
9. Textural maturity is demonstrated by moderately to well--sorted, sub-angular to sub-rounded detrital grains, indicating mechanical reworking and transport by moderate- to high-energy currents.
10. The Karandi Nala section exhibits a consistent geochemical trend, characterized by an upward increase in silica concentration within the stratigraphic sequence, while other elemental oxides (e.g., Na_2O, K_2O) show a declining trend, indicating increasing compositional maturity.
11. Sample CLK-01 from the base of the Karandi section demonstrates elevated silica and alumina content, along with low alkali concentrations. This trend continues upward, indicating increased quartz enrichment and feldspar depletion due to extensive weathering and sediment recycling.
12. The inverse geochemical correlation between silica and other oxides in the Karandi Nala samples reflects a pattern of enhanced textural and mineralogical maturity in the upper stratigraphic layers.

Overall, the sandstones of the Lumshiwal Formation are classified as subarkose to arkosic arenite based on mineralogical composition. The origin of the sandstone samples, categorized as "transitional continental", lies between cratonic interior and basement uplift settings, as illustrated by the quartz-feldspar-lithic fragment triangle plot. The Lumshiwal Formation was deposited in environments ranging from shallow marine to deltaic settings.

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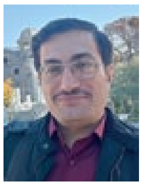
Nazir Ur REHMAN, Ph.D.
Assistant Professor at the Department of Geology, Khushal Khan Khattak University Karak
Karak, 27200, KP, Pakistan
E-mail: *nazirurrehman@kkkuk.edu.pk*

Shuja ULLAH, Ph.D.
Research Assistant at the National Centre of Excellence in Geology, University of Peshawar
Rahat Abad, Peshawar, 25130, KP, Pakistan
E-mail: *shujageo@gmail.com*

AFRASIAB, M.Sc.
Lecturer at the Department of Geology, Khushal Khan Khattak University Karak
Karak, 27200, KP, Pakistan
E-mail: *geo.afrasiab@gmail.com*



Sarfraz KHAN, Ph.D.
Assistant Professor at the National Centre of Excellence in Geology, University of Peshawar
Rahat Abad, Peshawar, 25130, KP, Pakistan
E-mail: *sarfraz_nceg@uop.edu.pk*

Nasim JAVID, M.Sc.
Lecturer at the Department of Geology, Khushal Khan Khattak University Karak
Karak, 27200, KP, Pakistan
E-mail: *nasim.javid@kkk*

Iftikhar ALAM, Ph.D.
Principal Geologist at Pakistan Atomic Energy Commission, REO
1114, Islamabad, Pakistan
E-mail: *iakhattak40@yahoo.com*

Khalid KHAN, M.Sc.
Director at Geological Survey of Pakistan
Park Road, Link Kuri Road, Shehzad Town
Islamabad, Pakistan
E-mail: *khalidkhan@gsp.gov.pk*