Journal of Himalayan Earth Sciences Volume, No., 2026 pp. 1-16

Petrography and Geochemistry of Sandstones in Rawalpindi Group, Islamabad Expressway Section, Islamabad, Pakistan

Zakariye Osman Abdi[1], Tahseenullah Khan[1], Mumtaz Ali Khan[1], and Sadik Sharif Abdullahi[2]

[1] Department of Earth and Environmental Sciences, Bahria University, Islamabad, Pakistan
[2] Department of Geology, Hormuud University, Mogadishu, Somalia
**Corresponding Author: zakiosmanabdi@gmail.com*

Submitted Date:27/11/2025 Acceptance Date: 15/04/2026 Publication Date:---------

Abstract

The Miocene Rawalpindi Group, which comprises the Kamlial and Murree formations and the Quaternary deposits are exposed along the Express Highway, Islamabad, near Korang Bridge. This study is focused on the Kamlial Formation. Detailed petrographic analysis reveals that the formation contains abundant fractured quartz which are often oriented in the form of micro-lenses. K-feldspar occurs in various forms, including microcline and micro-perthite, along with plagioclase. This mineral composition may suggest felsic plutonic and volcanic source rocks. Pyroxenes and amphiboles are additional indicators of mafic volcanic and/or mafic plutonic rock origin. Traces of garnet, epidote, chlorite, and biotite show their derivation from the metamorphic source rocks. The SiO_2 /Al_2O_3 ratio ranging from 1.7 to 7.1 (average ≈ 4) and the K_2O/Na_2O ratio from 1.7 to 7 (average ≈ 4) suggest mineralogical immaturity in the sandstones of the Kamlial Formation. The presence of fractured quartz and bent mica indicates that the area had undergone significant deformation resulting from regional folding. Based on geochemistry, the sandstones of the Kamlial Formation are litharenite, which shows a fluvial depositional environment derived from the Kohistan Island arc and/or the Lesser and Higher Himalayas.

Keywords: Miocene; Tectonic origin; Weathering; Sandstone; Petrography; Geochemistry.

1. Introduction

Sandstone is a siliciclastic sedimentary rock composed of quartz, feldspar, and lithic fragments. Sandstone rocks that are part of the molasse deposits are primarily found in the Miocene Rawalpindi Group (Kamlial and Murree formations) within the Himalayan region of the northwestern Himalayan fold-and-thrust belt (Islam et al., 2022; Majeed et al., 2026). This belt is further divided into the Kohat-Bannu and Potwar sub-basins (Raiverman, 2002).

The classification of sandstone and its litho-tectonic origin can be identified by analyzing variations in quartz and feldspar content and lithic-fragment composition (Javed et al., 2023). Determining the petrographic and geochemical analysis of clastic sedimentary rocks yields essential information about the tectonic environment, provenance, and ancient climatic conditions (e.g., Qasim et al., 2018, 2022; Khan et al., 2020; Bilal et al., 2022; Mehmood et al., 2023; Shahzad et al., 2024; Khattak et al., 2025; Khan et al., 2025; Majeed et al., 2026).

In Islamabad, the Miocene Kamlial Formation of the Rawalpindi Group is exposed along the Islamabad Expressway, in the vicinity of the Gulberg Housing Society, between latitudes 33°35′10″ and 33°35′24″ N and longitudes 73°08′34″ to 73°08′43″ E (Fig. 1). The formation comprises conglomerate, shale, siltstone, and intercalated sandstone. The formation has been extensively studied across various regions of Pakistan and Azad Jammu and Kashmir (AJK). For instance, petrographic and geochemical analyses have been employed to investigate the paleoclimate and source lithology of the western Himalayas, particularly in the southwestern Kohat Plateau (Ullah et al., 2015, 2025). Additional studies include the Kashmir Basin along the Kohala Bagh Road section, zircon U-Pb dating of rock samples from the Muzaffarabad area, and research on kinematics and tectonic fractures in the Khushalgarh region (Sayab and Jadoon, 2005). Khan et al. (2017) identified the origin of the Kamlial Formation as derived from igneous source rocks based on petrographic analysis. The general stratigraphy reveals a younger age of the Kamlial Formation to Murree Formation (Shah et al., 2000; Shah, 2009; Ullah et al., 2015; Qasim et al., 2022). However, in the study area, the Kamlial Formation seems to underlie the Murree Formation. Furthermore, the entire rock exposure in that specific road section is identified as the Kamlial Formation on a geological map of the area, without any investigation into the origin or depositional environment (e.g., Shah et al., 2000).

2. Tectonic and Regional Geological Setting

Pakistan lies partly on the northwestern edge of the Indian continental plate and along the northern boundary of the subducting Arabian Oceanic plate. Positioned between the colliding continental plates of Asia and India lies the Kohistan Island Arc (KIA) in North Pakistan, encompassing more than 40000 km^2 (Khan et al., 2020). KIA has a variety of rock types, including mafic-ultramafic, volcanics, granitoids, and sedimentary rocks with metamorphism up to amphibolite grade (Tahirkheli et al., 1979; Ullah et al., 2025).

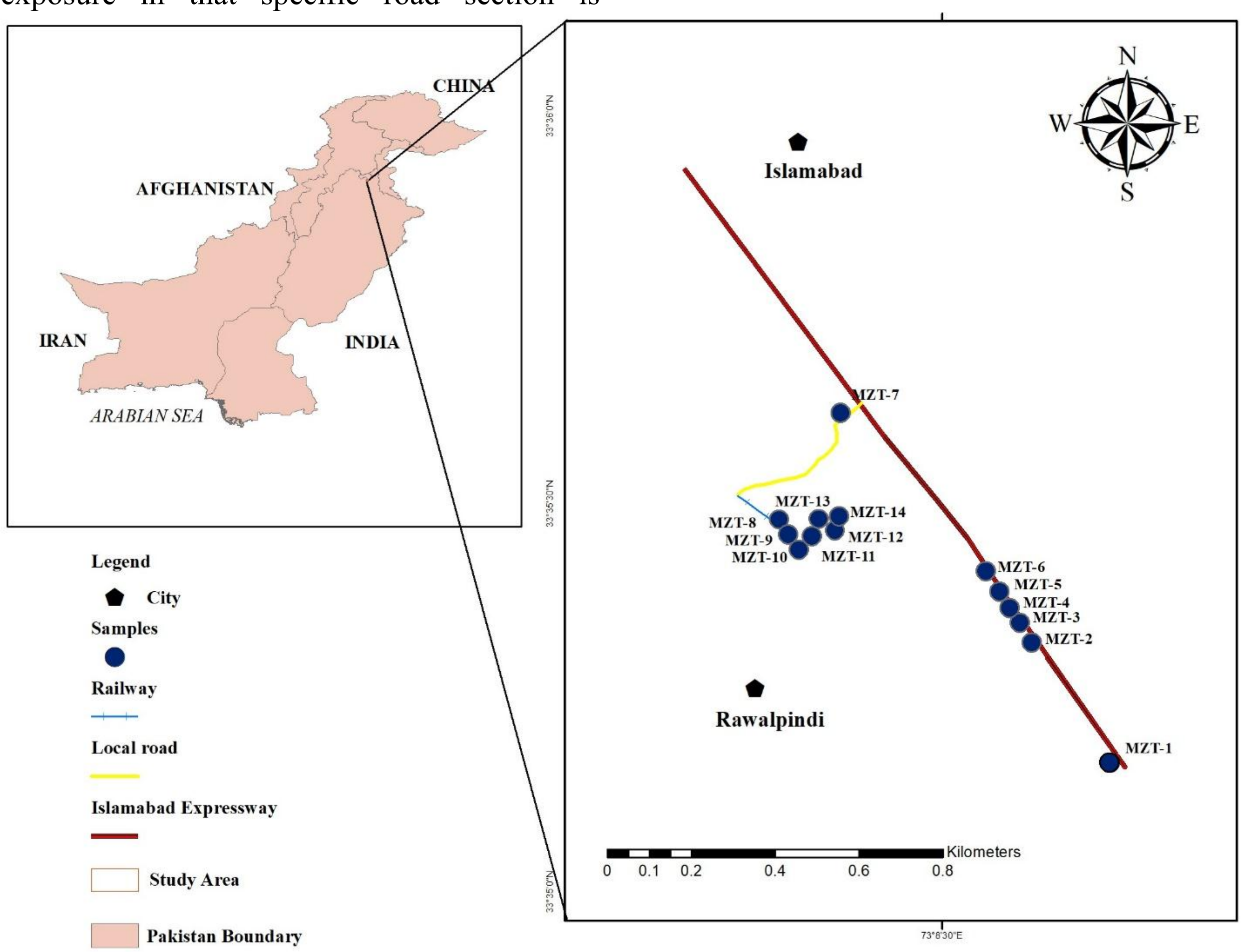

Fig. 1. Geographic location and accessibility map of the study area along the Islamabad Expressway, Pakistan. The map illustrates the national context of the study area. Sampling sites (MZT-1 to MZT-14) are shown as blue circles; the Islamabad Expressway is marked red.

Two suture zones, the Indus suture and/or the Main Mantle Thrust (MMT) in the south and the Shyok suture and/or the Main Karakoram Thrust (MKT) in the north, respectively, divide the Indian and Asian continental plates from the KIA (Tahirkheli et al., 1979; Kazmi and Jan, 1997). The Main Central Thrust (MCT), which divides the higher Himalaya from the lesser Himalaya, the Main Boundary Thrust (MBT), which separates the sub Himalaya from the lesser Himalaya, and the Salt Range thrust, which separates the Eo-Cambrian Salt Range Formation from the sub Himalaya are the three main components of the tectonic pile formed by the collision of the Indian and Asian continental plates between 40 and 55 million years in the past (e.g., Kearey et al., 2009; Qasim et al., 2018) (Fig. 2).

The research area, located in the sub-Himalayan region (Fig. 3), stretches into India, Nepal, and Bhutan (e.g., Bossart et al., 1988; Zaleha, 1997; Kundu et al., 2012; Aadil, 2013; Singh 2013; Mustafa et al., 2016; Khan et al., 2016; Abbasi and Khan, 2017; Zaheer et al., 2017; Iqbal et al., 2018; Goswami and Deopa, 2018; Sanyal et al., 2004; Javed et al., 2021; Debnath et al., 2021; Ali and Salam, 2018; Salam et al., 2024; Rai et al., 2021).

The primary rock types of the Kamlial and Murree formations of the Rawalpindi Group comprise conglomerates, clays, sandstone, and shale, like the molasses sediments of the Siwalik Group (Zaheer et al., 2022; Majeed et al., 2026). The upper contact of the Rawalpindi Group with the Chinji Formation of the Siwalik Group is conformable, and the lower contact with the Lower Eocene Kuldana Formation of the Charrat Group is unconformable (Iqbal et al., 2018) (Table 1).

The sub-Himalaya, which is also a part of the foreland fold and thrust belt, comprises the southern Potwar deformed zone (SPDZ) and the northern Potwar deformed zone (NPDZ as in Javid et al. (2023) aand Salam et al. (2024) (Fig. 2). The SPDZ is bounded by the Soan syncline and Salt Range thrust in the north and south, respectively, and the NPDZ is a duplex structure formed beneath the passive roof thrust (Jaswal et al., 1997).

Table 1: A generalized stratigraphic column of the Rawalpindi area, Potwar plateau region (after Iqbal et al., 2007).

Age	**Group**	**Formation**	**Lithology**
MIOCENE	Siwalik	Nagri	Sandstone and subordinate claystone and conglomerate
		Chinji	Claystone and sandstone
	Rawalpindi	Kamlial	Calcareous sandstone and claystone
		Murree	Sandstone, siltstone and claystone
OLIGOCENE UNCONFORMITY			
EOCENE	Cherrat	Kuldana	Marine and continental claystone, marl, limestone, and minor sandstone

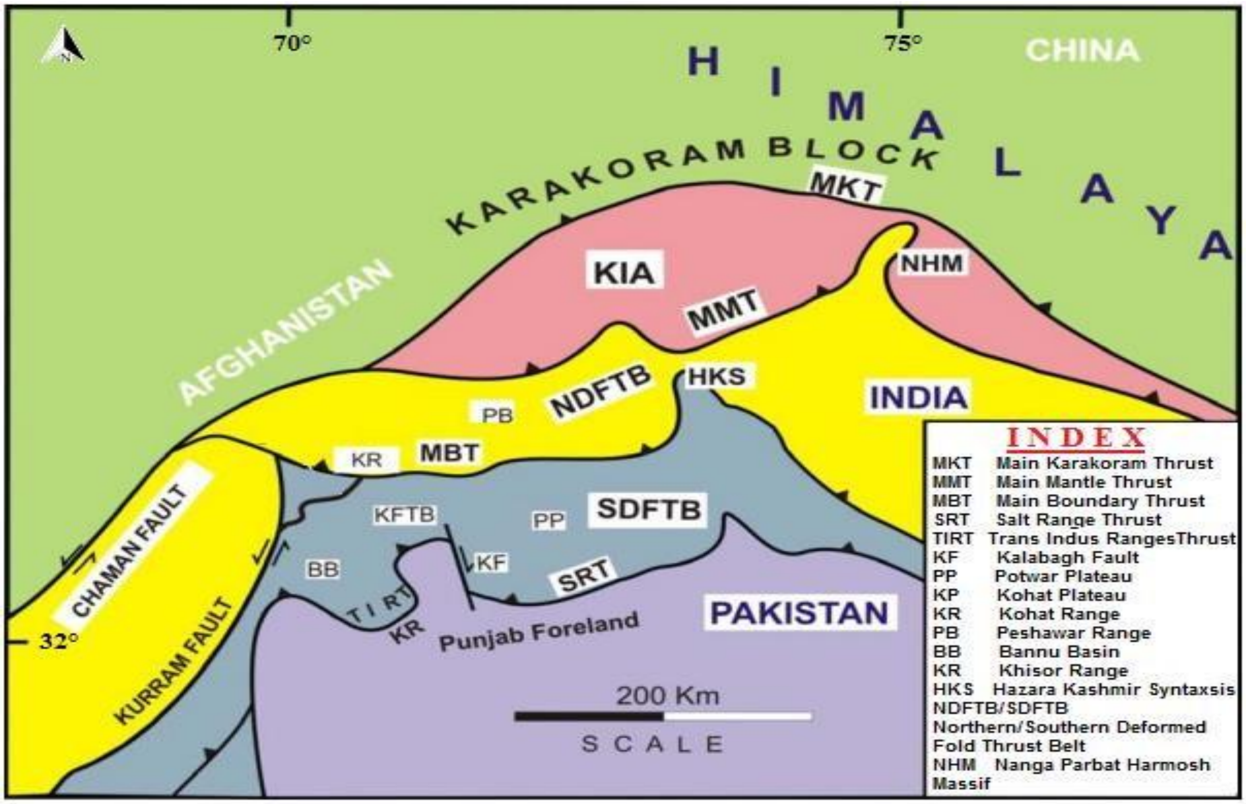

Fig. 2. Tectonic map demonstrating major structural features of northern Pakistan (after Kazmi and Rana, 1982)

3. Local Geological Setting

The Murree Formation in the study area comprises interbedded sandstones, shales, and intra-formational conglomerates. The sandstones are typically coarse- to medium-grained and often grey to purplish with interbedded, maroon-colored shales. The conglomerates contain clasts of sandstones and limestones. The sedimentary succession shows variations in dip from NW to SE with NE trends. At the contact with the Kamlial Formation, the strike and dip trends are N70ºE 80ºSE (Fig. 4a). The sandstone of the formation is well jointed (Fig. 4b). The modified geological map of the area is shown in Figure 3.

The Kamlial Formation comprises medium-to fine-grained sandstones, siltstones, mudstones, shales and intra-formational conglomerates. Besides, cross and graded bedding and conjugate joints can also be seen in the sandstone unit of the formation (Fig. 4c). At the contact with the Murree Formation, the sandstones of the Kamlial Formation trend N 20º W with N 70º E dip, which seems to be an overturned fold. A 300 m long east-west cross section shows lithological variation in the Murree Formation (Fig. 5). At the contact, the sandstone of the Murree Formation is greyish and calcareous, whereas the sandstone of the Kamlial Formation is greenish, containing mica and epidote.

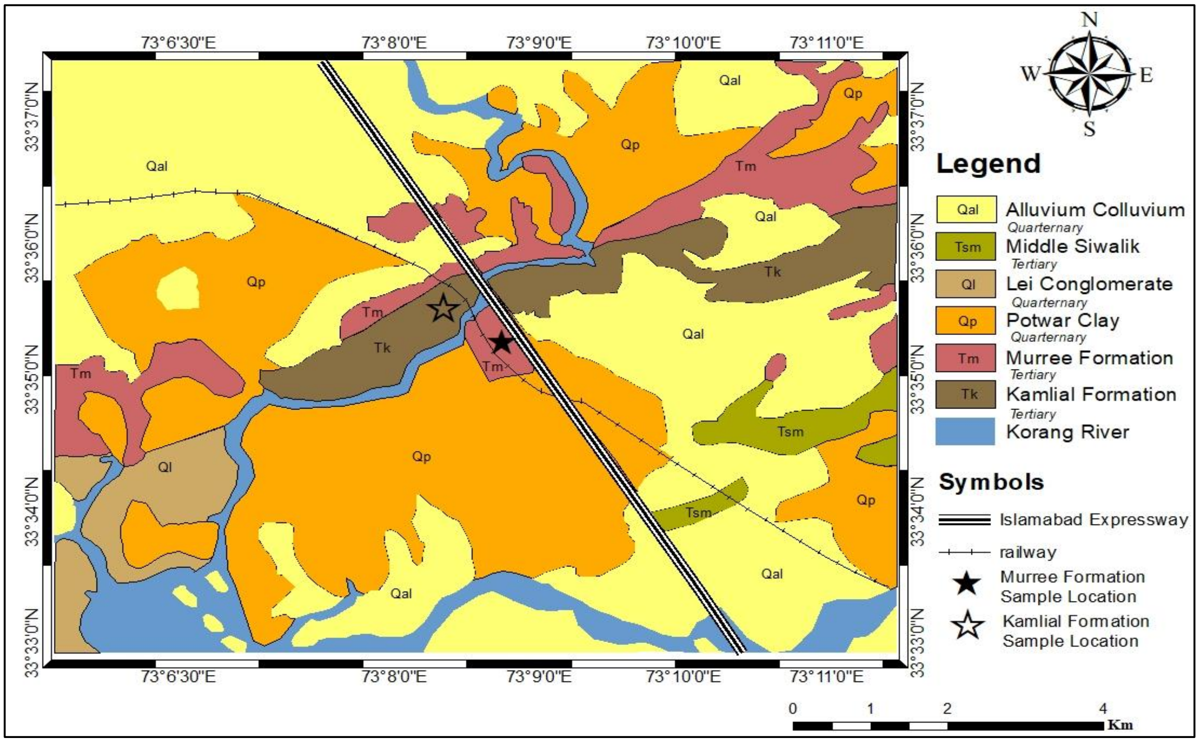

Fig. 3. Modified geological map of the study area (after Shah et al., 2000)

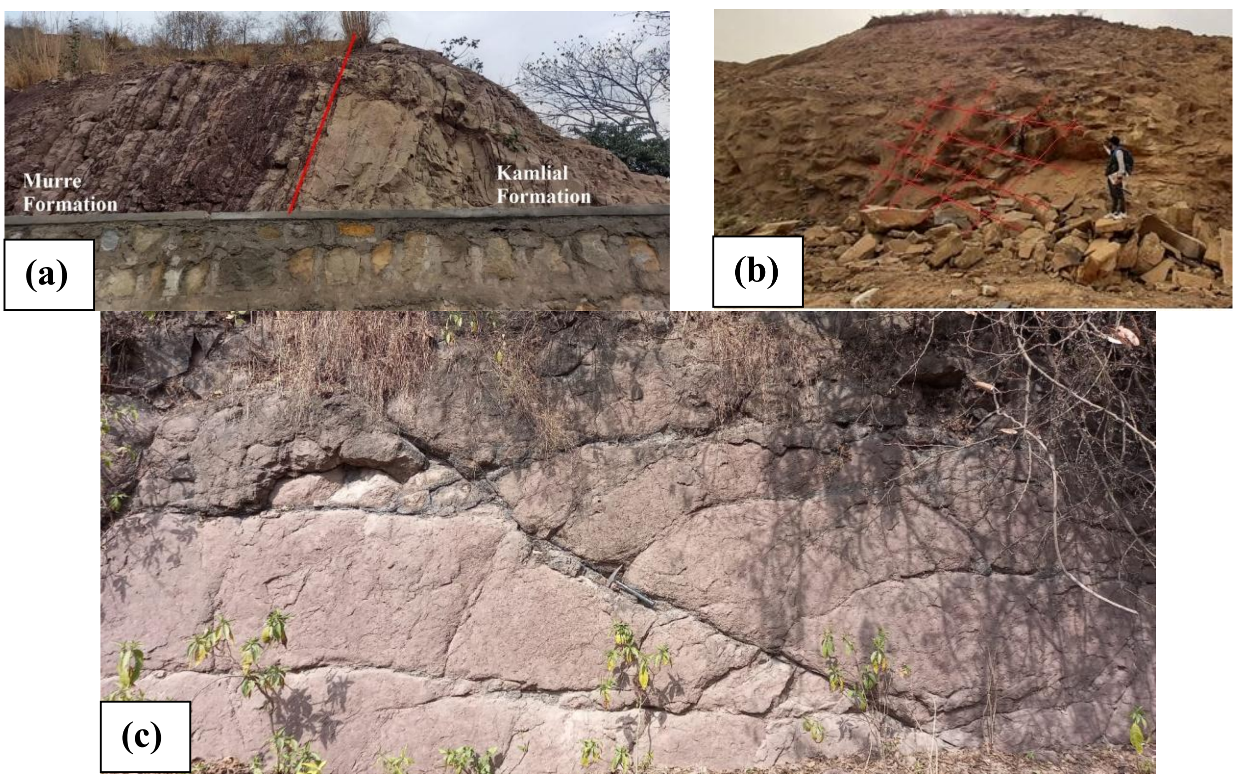

Fig. 4. Field photograph along Islamabad Expressway near Korang Bridge showing a) the contact between the Kamlial and Murree formations; b) Conjugate joints in sandstone of the Murree Formation; and c) Conjugate joints in the sandstone bed of the Kamlial Formation at 33°35′24″ N and 73°08′43″ E.

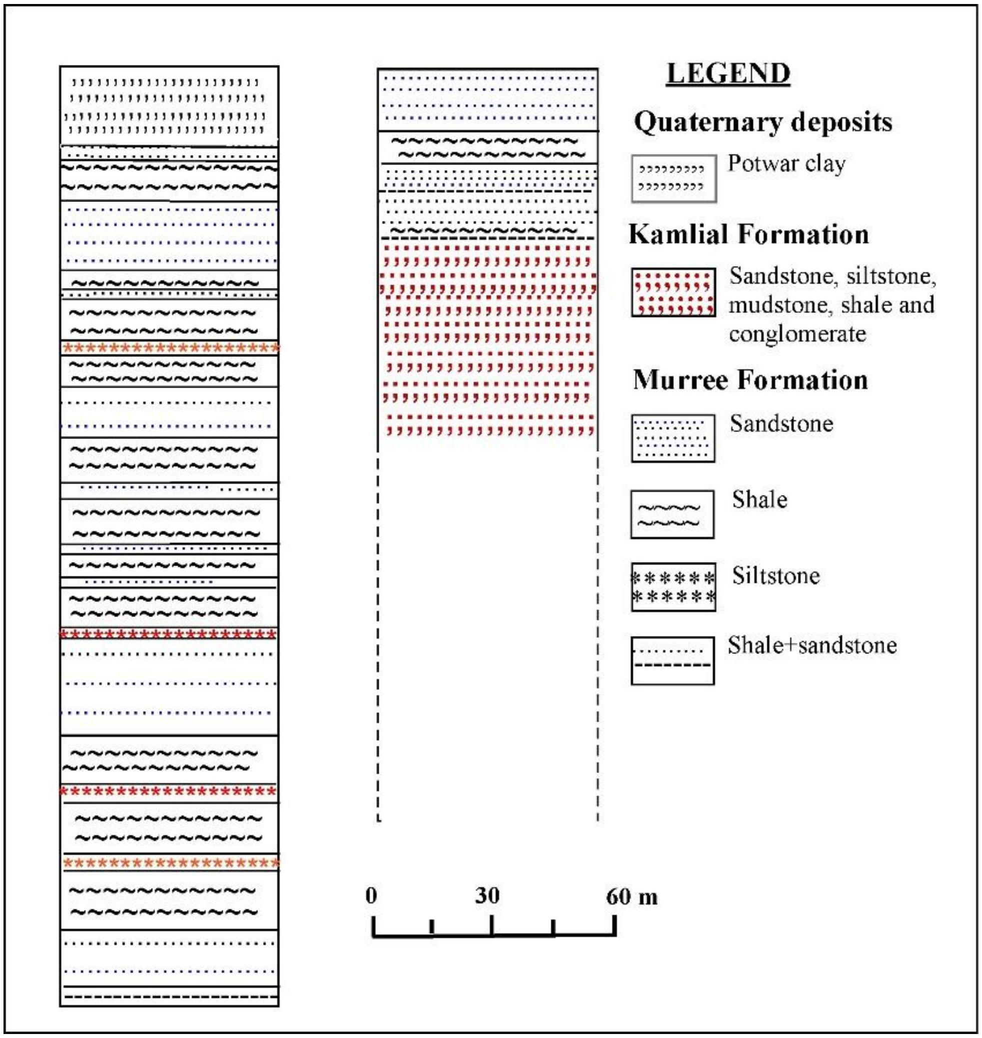

Fig. 5. Roadside E-W lithological cross section of the study area showing the Kamlial and Murree formations.

4. Methodology

For petrographic studies, 14 samples of compact, unweathered/fresh rock units were collected at intervals of ~1.5 m from the Kamlial and Murree Formations (Fig. 1). Preparations for thin sections were carried out in the Pakistan National Museum of Natural History, Islamabad. The modal abundance of each analyzed sample was determined through visual estimation under the petrographic microscope.

Geochemistry was conducted by the utilization of the Atomic Absorption Spectroscopy (AAS) technique, specifically for the analysis of major elements (as shown in Table 3). 10 samples (7 from Kamlial Formation and 3 from Murree Formation) were selected for this kind of analysis. These samples were ground into a fine powder and subjected to acid digestion with hydrofluoric and perchloric acids to dissolve the relevant elements. The quality control was maintained by using standard references. The test was conducted at the National Center of Excellence in Geology, University of Peshawar.

4.1 Petrography

For petrographic studies, fourteen relatively fresh sandstone samples, including six from the Murree Formation (MZT-1 to MZT-6) and eight from the Kamlial Formation (MZT-7 to MZT-14), were subjected to thin section study (Fig. 1; Table 2). This section observation reveals that the rocks are fine- to medium- grained and poorly to moderately sorted. Mineralogically, they consist primarily of quartz, rock fragments, and feldspar with varying proportions of cementing material and matrix. Quartz is anhedral to subhedral and fractured (Fig. 6).

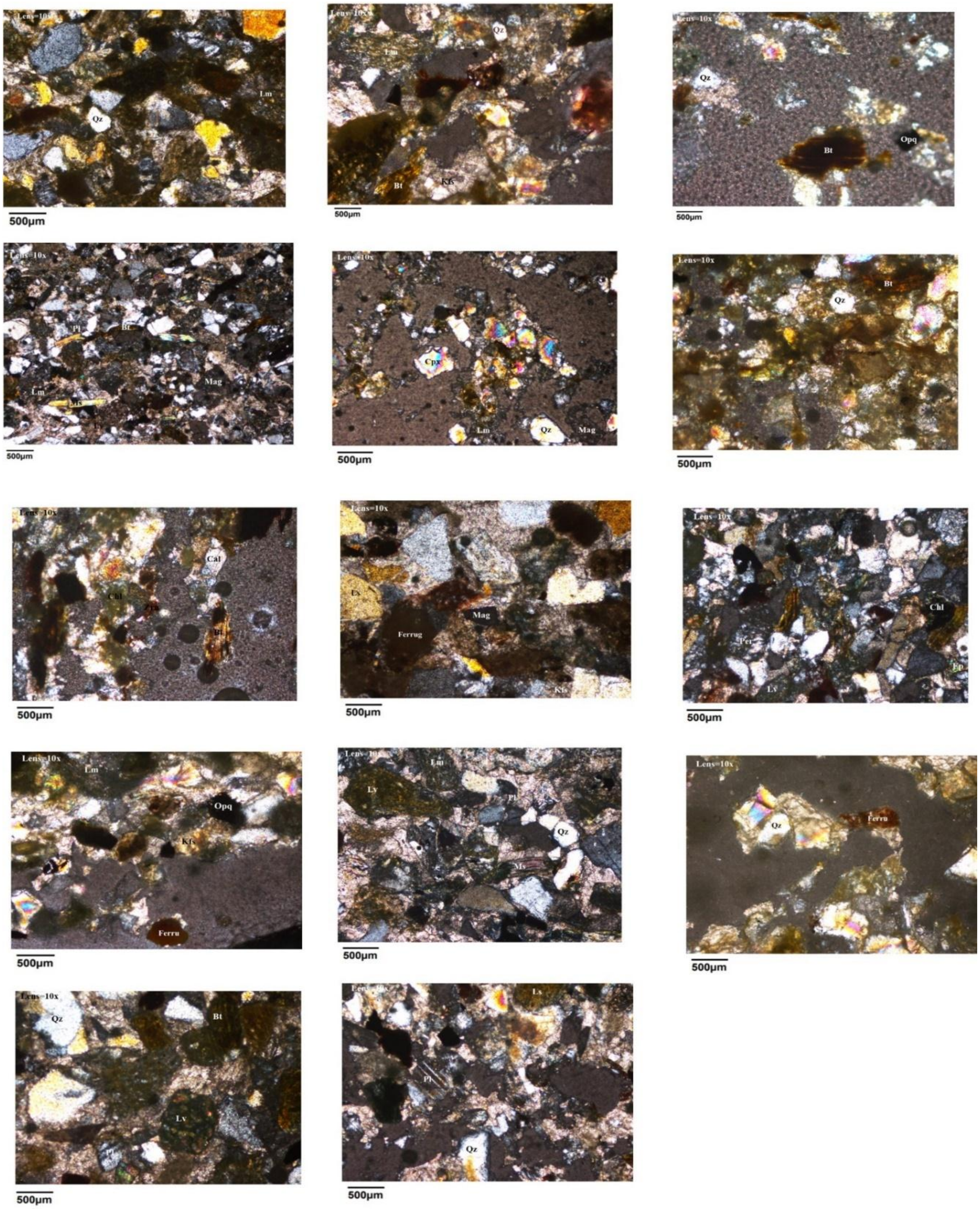

Fig. 6. Photomicrograph showing quartz (Qz), potassium feldspar (Kfs), biotite (Bt), opaque mineral (Opq), muscovite (Ms), magnetite (Mag), plagioclase (Pl), clinopyroxene (Cpx), chlorite (Chl), zircon (Zrn), calcite (Cal), ferruginous material (Ferru), epidote (Ep), micro-perthite (Per), volcanic lithic fragments (Lv), sedimentary lithic fragments (Ls), and metamorphic lithic fragment (Lm) in crossed polarized light

Both monocrystalline and polycrystalline quartz are found, with the former being more common (Fig. 7). The accessory minerals include chlorite, muscovite, biotite, epidote, calcite, garnet, pyroxenes, amphiboles, and zircon. Opaque minerals are mainly Fe-oxides. The cementing material is mainly ferruginous clay.

4.2 Geochemistry

Major element chemistry was carried out using atomic absorption spectroscopy (AAS) on ten rock samples, three from the Murree Formation (MZT-1, MZT-3 and MZT-5) and seven from the Kamlial Formation (MZT-7 to MZT-13) (Table 3). These analyses were employed to classify the sandstones (Blatt et al., 1980; Pettijohn et al., 1987). In the $MgO+Fe_2O_3$-Na_2O-K_2O ternary diagram of Blatt et al. (1980), the rock samples of the study area plot as litharenite. This indicates that the studied samples primarily consist of ferromagnesian potassic sandstones (Fig. 7). Based on information from Pettijohn (1963), Pettijohn et al. (1972), and Lindsey (1999) proposed that the typical litharenite is found inside the ferromagnesian potassic sandstone zone. On the log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3) scattergram (Fig. 8), the studied samples are predominantly classified as litharenite; however, only one sample does fall in the arkose field, which is consistent with the results derived from Figure 7.

The ratio of oxide elements, e.g., SiO_2/Al_2O_3 may act as an accurate indicator of sediment maturity. Roser et al. (1996) proposed that a SiO_2/Al_2O_3 ratio over 5 could be indicative of rising maturity in the sandstone. The SiO_2/Al_2O_3 ratio of 1.7-7.1 (average ≈4) and the K_2O/Na_2O ratio of 1.7-7 (average ≈4) (Table 3) indicate mineralogical immaturity of the sandstones of the Kamlial Formation. The immaturity of the sandstone is further indicated by the ongoing uplift of the region, active erosion, poor sorting, and the relatively short transportation distance from the source (Roser et al., 1996)

Climate is a key factor that affects both the intensity of weathering and the composition of sediments (Suttner and Dutta, 1986). To determine the paleoclimate conditions of the Kamlial sandstones, a bivariate plot of SiO_2 versus Al_2O_3 + K_2O + Na_2O was used. The results indicate that the samples fall within the semi-arid region and further show a progressive increase in chemical maturity (Fig. 9).

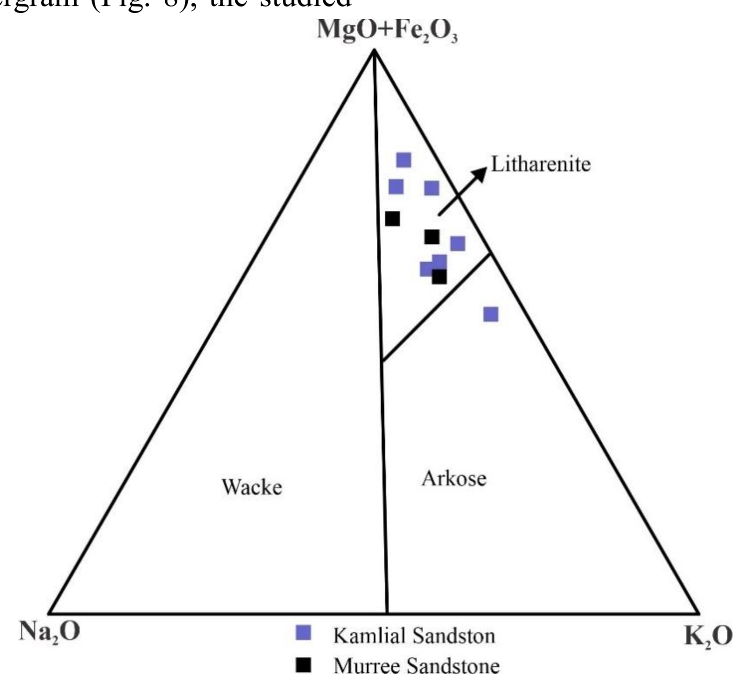

Fig. 7. Ternary diagram of the studied samples (after Blatt et al., 1980).

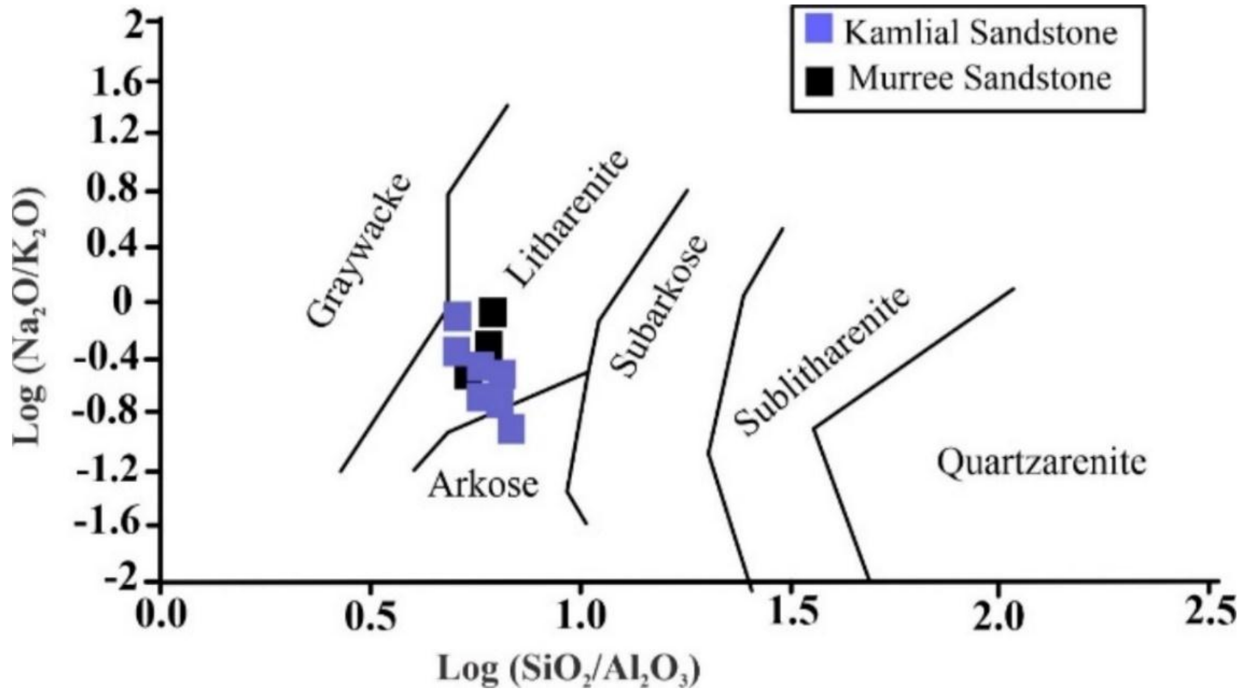

Fig. 8. Chemical classification of the samples based on the Pettijohn scheme (Pettijohn et al., 1972).

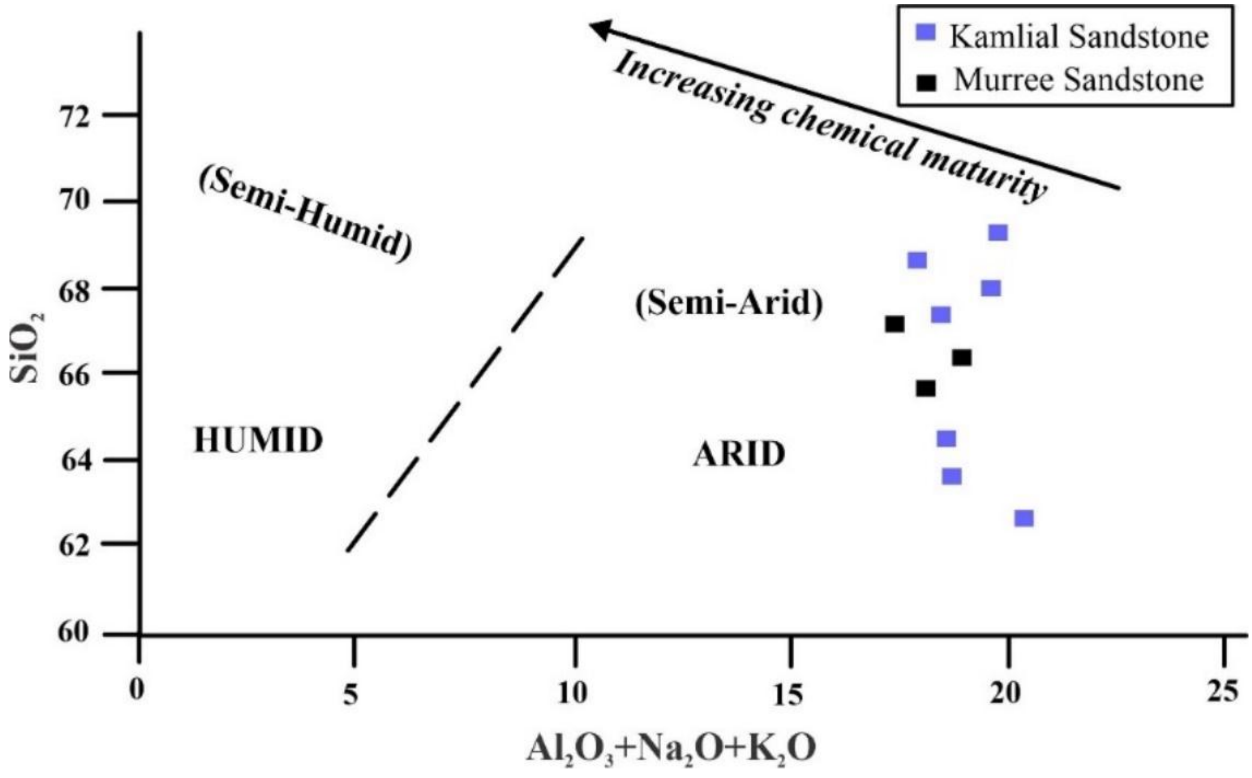

Fig. 9. Chemical maturity of sandstones expressed by a bivariate plot (after Suttner and Dutta, 1986).

5. Discussion

Based on petrography and geochemistry, the tectonic settings of sedimentary rocks can be determined (e.g., Bhatia, 1983; Roser and Korsch, 1986; Javed et al., 2023). Based on the Q-F-L triangular composition plot of Folk (1968), all the studied samples of both formations are classified as litharenite in composition (Fig. 10a). The tectonic setting provenance of the Kamlial Formation has been determined by utilizing the ternary diagram of Q-F-RF (Dickinson et al., 1983). In the Q-F--RF plot, where all samples are collectively plotted, is used to indicate the stability of the grains, as well as weathering, provenance, relief, and transport mechanisms (Khan et al., 2020). Here, all the samples fall in the recycled orogeny provenance (Fig. 10b).

A total of eight rock samples from both Kamlial and Murree Formations plot in the active continental margin domain of the tectonic discrimination diagram, whereas two rock samples occupy a passive continental margin field (Fig. 11a,b) (Roser and Korsch, 1986). This analysis identifies the tectonic environments in which the terrigenous clastic rocks were formed. The Kamlial Formation seems to have been deposited by sandy bedload or a major mixed-load river (e.g., Qasim et al., 2022).

The occurrence of feldspar in the Kamlial Formation suggests that the source location experienced a high relief (Qasim et al., 2022). The high proportion of alkali feldspar over plagioclase indicates the predominance of granite and acidic gneisses in the source region. However, this characteristic could also be due to the superior chemical stability of alkali feldspar compared to plagioclase during transportation (Tucker, 2001). The presence of microcline additionally supports the occurrence of granitic and pegmatitic origins. According to Michaelsen and Henderson (2000), most mica flakes are bent, which indicates that they originated from metamorphic or deformed assemblages. The presence of lithic grains of metamorphic origin, as well as grains of epidote and garnet, further suggests the same metamorphic origin. The bivariate plot (after Crook, 1974) of Na_2O versus K_2O of the samples studied shows that three samples are quartz-rich while the other two samples are quartz-intermediate (Fig. 11c). This demonstrates that they originated from a felsic source.

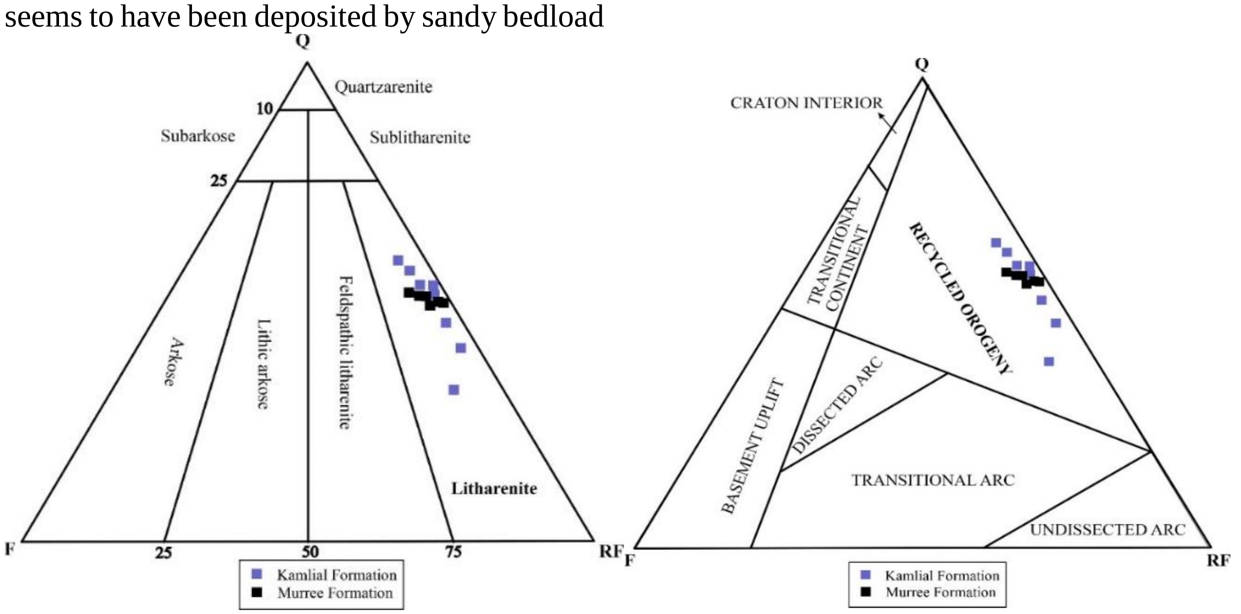

Fig. 10. a) Classification of sandstones based on framework grains (quartz, feldspar, rock fragments) (after Folk, 1968), b) Sandstone provenance in tectonic regions (after Dickinson et al., 1983).

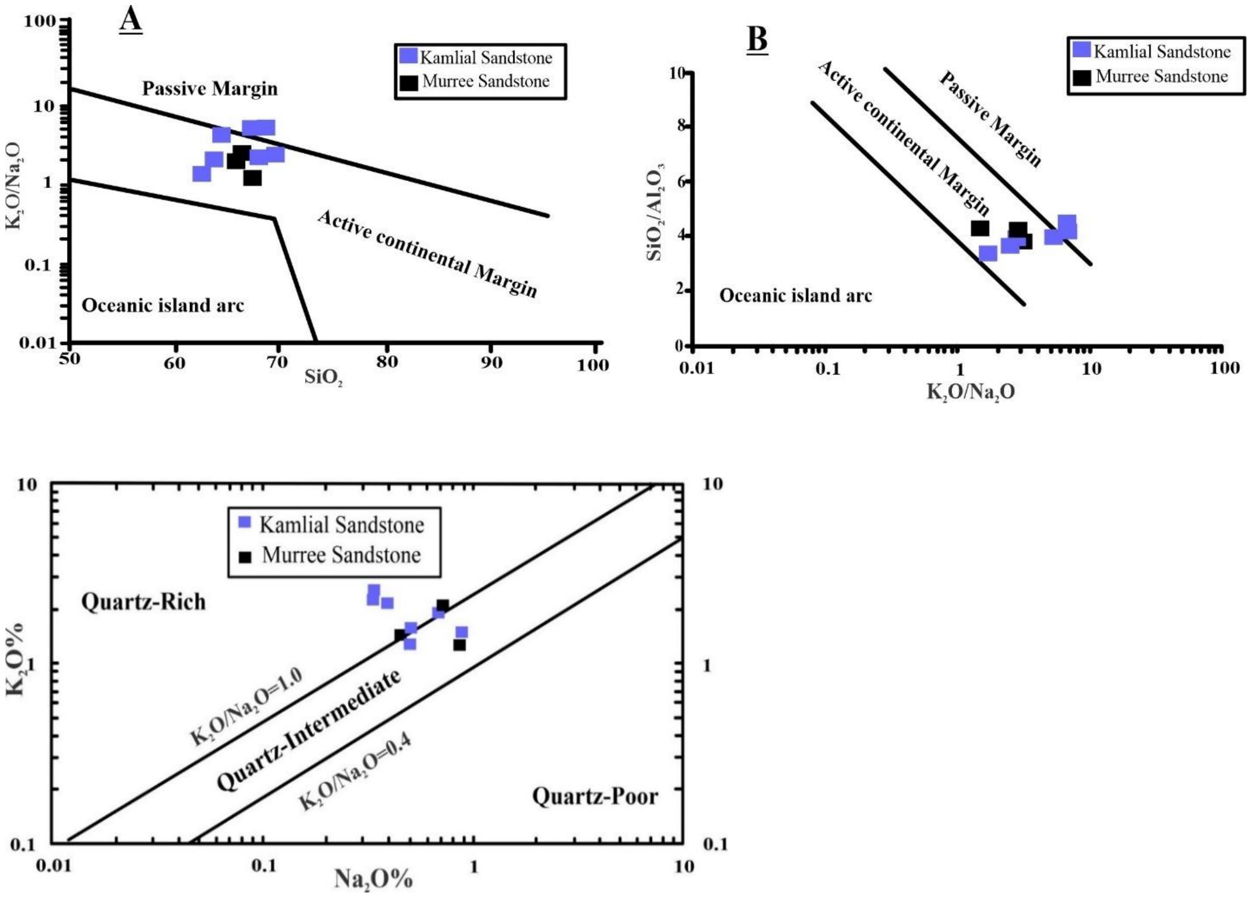

Fig. 11. a) Shows a tectonic discrimination plot for the studied samples (after Roser and Korsch, 1986); b) modified version of the same bivariate diagram; c) Bivariate plot of Na_2O versus K_2O of the Kamlial Formation showing quartz content (after Crook, 1974).

Table 2: The modal analysis data of sandstones of the Kamlial and Murree formations.

Samples	Quartz	Feldspar	Rock Fragments	Cementing Material	Matrix	Mica	Accessory minerals	Opaque Minerals
Murree Formation								
MZT-1	40	4	26	8	10	4	2	6
MZT-2	39	2	27	17	9	2	2	2
MZT-3	28	3	28	18	12	3	5	3
MZT-4	30	4	28	13	10	5	5	5
MZT-5	35	3	29	11	14	0	7	1
MZT-6	36	4	29	9	9	8	2	3
Kamlial Formation								
MZT-7	26	2	36	14	12	4	2	4
MZT-8	37	2	27	10	8	5	8	3
MZT-9	30	2	28	15	10	5	4	6
MZT-10	30	3	27	15	10	5	5	5
MZT-11	30	4	28	13	10	5	5	5
MZT-12	26	5	35	10	12	2	5	5
MZT-13	32	2	26	15	10	5	5	5
MZT-14	40	3	25	10	7	6	5	4

Table 3: Major elements chemistry (wt.%) of sandstones of the Kamlial and Murree formations.

Samples	MZT-1*	MZT-3*	MZT-5*	MZT-7	MZT-8	MZT-9	MZT-10	MZT-11	MZT-12	MZT-13
SiO_2	66.31	67.25	65.8	68.58	63.78	67.17	62.56	67.88	64.34	69.53
Al_2O_3	16.95	15.3	15.26	15.19	16.93	15.70	17.91	16.98	15.87	17.86
Na_2O	0.46	0.86	0.73	0.34	0.50	0.34	0.88	0.68	0.39	0.50
K_2O	1.47	1.30	2.09	2.40	1.30	2.42	1.50	1.96	2.20	1.57
CaO	9.60	8.10	9.64	5.10	6.86	8.97	7.53	6.30	7.62	6.53
Fe_2O_3	0.81	0.84	0.87	1.51	3.24	0.48	2.84	1.38	3.35	0.76
MgO	3.10	4.15	3.31	3.82	4.10	2.66	4.91	2.76	4.85	2.53
TiO_2	0.45	0.33	0.28	0.46	0.33	0.48	0.39	0.43	0.29	0.36
MnO	0.17	0.12	0.05	0.16	0.21	0.10	0.23	0.22	0.13	0.10
P_2O_5	0.29	0.44	0.37	0.24	0.34	0.14	0.47	0.23	0.37	0.13
LOI	1.36	0.579	1.37	1.89	1.034	1.38	0.624	1.68	1.46	1.74
Total	99.61	98.69	99.77	99.69	98.62	99.85	99.84	98.82	99.04	99.87
SiO_2/Al_2O_3	3.91	4.39	4.31	4.51	3.77	4.28	3.49	3.99	4.05	3.89
K_2O/Na_2O	3.20	1.51	2.90	7.0	2.60	7.10	1.70	2.88	5.60	3.14
Log (SiO_2/Al_2O_3)	0.59	0.64	0.63	0.65	0.58	0.63	0.54	0.60	0.60	0.59
Log (Na_2O/K_2O)	-0.50	-0.18	-0.46	-0.85	-0.41	-0.85	-0.23	-0.46	-0.75	-0.49
$MgO+Fe_2O_3$	3.91	4.99	4.18	5.33	7.34	3.14	7.75	4.14	8.20	3.29
$Al_2O_3+Na_2O+K_2O$	18.88	17.46	18.08	17.93	18.73	18.46	20.29	19.62	18.46	19.93

** Murree Sandstone.*

6. Conclusions

Based on the present study, the following conclusions are drawn.

1. The field study shows the exposure of the Miocene Rawalpindi Group (Kamlial and Murree formations) along the Islamabad Express Highway near Korang Bridge. The earlier published geological map of the Islamabad area placed this section entirely as the Kamlial Formation. It is further noted that the Kamlial Formation strikes in NE with a dip SE, underlying the Murree Formation, which may be due to an overturned fold.

2. The Kamlial and Murree Formations contain abundant quartz, which is fractured and oriented as micro-lenses along with K-feldspar and albite to andesine plagioclase feldspar, indicating felsic plutonic origin. Moreover, the presence of pyroxenes and amphiboles also indicates a mafic volcanic and/or mafic plutonic rock source. The presence of metamorphic rock fragments and traces of garnet, epidote, chlorite, biotite, and muscovite shows metamorphic source rocks for the studied sandstones. Micro-lenses of the detrital grains and bent mica may indicate earlier deformation of the source rocks.

3. Based on petrographic and geochemical studies, the sandstones of the Rawalpindi Group are Litharenite. Cross- and graded bedding in sandstone, occurrence of mudstone and intraformational conglomerate in the Kamlial Formation support a fluvial depositional environment. The sandstones of the formation illustrate that the sediments were derived from an oceanic island arc, namely the Kohistan Island arc, and probably from the Lesser and higher Himalayas.

Authors' Contribution

Zakariye Osman, Tahseenullah Khan, and Mumtaz Ali Khan conceived the main concept of the study. Field data were collected by Zakariye Osman and Tahseenullah Khan with the assistance of Sadik Sharif Abdullahi. Zakariye Osman prepared the manuscript under the supervision of Tahseenullah Khan. Mumtaz Ali Khan conducted the technical *review and proofreading of the manuscript prior to submission.*

Acknowledgment

We appreciate the NCE in Geology, University of Peshawar, and the E&ES department at Bahria University in Islamabad for facilitating this research. We appreciate the company of Mr. Sadiq Sharif and Mr. Safadar Khan during the fieldwork activity.

Data Availability: The data generated are presented in this article

References

Aadil, N. (2013). Stratigraphy and structure of Sarda, Manil, Changpur, and Naghal areas, district Kotli, Jammu & Kashmir. *Journal of the Geological Society of India, 82*(5), 639–648. https://doi.org/10.1007/s12594-013-0202-8

Abbasi, N., & Khan, M. S. (2017). Sedimentary facies analysis of Nagri Formation, Kashmir Basin, Sub-Himalayas, Pakistan. *Pakistan Journal of Geology, 1*(1), 3–6. https://doi.org/10.26480/pjg.02.2017.03.06

Ali, A., & Salam, H. (2018). Tectonic evolution of the metamorphic core complex around the Kotah and Loe Sar Domes, Swat, North Pakistan. In *Conference of the Arabian Journal of Geosciences* (pp. 37–40). Springer International Publishing.

Blatt, H., Middleton, G. V., & Murray, R. C. (1980). *Origin of sedimentary rocks* (2nd ed.). Prentice Hall.

Bhatia, M. R. (1983). Plate tectonics and geochemical composition of sandstones. *Journal of Geology, 91*, 611–627. https://doi.org/10.1086/628815

Bilal, A., Mughal, M. S., Janjuhah, H. T., Ali, J., Niaz, A., Kontakiotis, G., Antonarakou, A., Usman, M., Hussain, S. A., & Yang, R. (2022). Petrography and provenance of the Sub-Himalayan Kuldana Formation: Implications for tectonic setting and palaeoclimatic conditions. *Minerals, 12*(7), 794. https://doi.org/10.3390/min12070794

Bossart, P., Dietrich, D., Greco, A., Ottiger, R., & Ramsay, J. G. (1988). The tectonic structure of the Hazara-Kashmir syntaxis, southern Himalayas, Pakistan. *Tectonics, 7*(2), 273–297. https://doi.org/10.1029/TC007i002p00273

Critelli, S., & Garzanti, E. (1994). Provenance of the Lower Tertiary Murree redbeds (Hazara-Kashmir syntaxis, Pakistan) and initial rising of the Himalayas. *Sedimentary Geology, 89*(3–4), 265–284. https://doi.org/10.1016/0037-0738(94)90097-3

Crook, K. A. W. (1974). Lithostratigraphy and geotectonics: The significance of composition variation in flysch arenites (graywackes). In R. H. Dott Jr. & R. H. Shaver (Eds.), *Modern and ancient geosynclinal sedimentation* (pp. 304–310). Society of Economic Paleontologists and Mineralogists. https://doi.org/10.2110/pec.74.19.0304

Debnath, A., Taral, S., Mullick, S., & Chakraborty, T. (2021). The Neogene Siwalik succession of the Arunachal Himalaya: A revised lithostratigraphic classification and its implications for the regional paleogeography. *Journal of the Geological Society of India, 97*(4), 339–350. https://doi.org/10.1007/s12594-021-1692-4

Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., Knepp, R. A., Lindberg, F. A., & Ryberg, P. T. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin, 94*, 222–235. https://doi.org/10.1130/0016-7606(1983)94

Folk, R. L. (1968). *Petrology of sedimentary rocks*. Hemphill Publishing

Goswami, P. K., & Deopa, T. (2018). Petrotectonic setting of the provenance of Lower Siwalik sandstones of the Himalayan foreland basin, southeastern Kumaun Himalaya, India. *Island Arc, 27*(1), e12242. https://doi.org/10.1111/iar.12242

Islam, F., Ahmad, M. N., Janjuhah, H. T., Ullah, M., Islam, I. U., Kontakiotis, G., Skilodimou, H. D., & Bathrellos, G. D. (2022). Modelling and mapping of soil erosion susceptibility of Murree, Sub-Himalayas using GIS and RS-based models. *Applied Sciences, 12*, 12211. https://doi.org/10.3390/app122312211

Iqbal, O., Baig, M. S., Pervez, S., & Siddiqi, M. I. (2018). Structure and stratigraphy of Rumbli and Panjar areas of Kashmir and Pakistan with the aid of GIS. *Journal of the Geological Society of India*, *91*(1), 57–66. https://doi.org/10.1007/s12594-018-0820-2

Jaswal, T. M., Lillie, R. J., & Lawrence, R. D. (1997). Structure and evolution of the Northern Potwar Deformed Zone, Pakistan. *AAPG Bulletin, 81*(2), 308–328. https://doi.org/10.1306/522B431B-1727-11D7-8645000102C1865D

Javed, A., Khan, K. F., & Quasim, M. A. (2023). Petrography of the Bajocian sandstone of Joyan Member, Jaisalmer Basin, western Rajasthan: Implications for provenance and basin evolution. *Journal of the Geological Society of India, 99,* 73–87. https://doi.org/10.1007/s12594-023-2269-1

Javed, A., Wahid, A., Mughal, M. S., Khan, M. S., Qammar, R. S., Ali, S. H., Siddiqui, N. A., & Iqbal, M. A. (2021). Geological and petrographic investigations of the Miocene molasse deposits in Sub-Himalayas, District Sudhnati, Pakistan. *Arabian Journal of Geosciences, 14*(1), 1–24. https://doi.org/10.1007/s12517-021-07529-x

Javid, N., Sulaiman, N., Nayab, S., Salam, H., & Ishfaque, M. (2023). Tectonic evolution and structural modeling of Banda Daud Shah–Surghar and Mardan Khel–Soor Dag transects, Kohat Basin, Pakistan. *Journal of Himalayan Earth Sciences, 56*(2), 105–121.

Kazmi, A. H., & Jan, M. Q. (1997). *Geology and tectonics of Pakistan*. Graphic Publishers.

Kazmi, A. H., & Rana, R. A. (1982). *Tectonic map of Pakistan* [Map]. Geological Survey of Pakistan.

Kearey, P., Klepeis, K. A., & Vine, F. J. (2009). *Global tectonics* (3rd ed.). Wiley-Blackwell.

Khan, M. A., Khattak, N. U., Ali, B., Yar, M., Mahmood, M. F., Abuzar, K., & Shakir, U. (2017). Petrographic and economic aspects of the sandstone unit of the Kamlial Formation, Karaat Hills, southeastern Kohat Plateau, NW Pakistan. *The Nucleus, 54*(3), 154–160.

Khan, M. R., Hameed, F., Mughal, M. S., Basharat, M., & Mustafa, S. (2016). Tectonic study of the Sub-Himalayas based on geophysical data in Azad Jammu and Kashmir and northern Pakistan. *Journal of Earth Science, 27*(6), 981–988. https://doi.org/10.1007/s12583-016-0681-9

Khan, W., Khattak, S. A., Anwar, S., Solangi, S. H., Wang, L., Kontakiotis, G., & Dhas, S. S. J. (2025). Petrophysical characterization and reservoir potential of the Lower Goru Sandstone: A case study from the Sinjhoro Gas Field, Pakistan. *Journal of Natural Gas Geoscience, 10*(3), 179–197. https://doi.org/10.1016/j.jnggs.2025.05.002

Khan, Z., Quasim, M. A., Amir, M., & Ahmad, A. H. M. (2020). Provenance, tectonic setting, and source area weathering of Middle Jurassic siliciclastic rocks of Chari Formation, Jumara Dome, Kachchh Basin, western India: Sedimentological, mineralogical, and geochemical constraints. *Geological Journal, 55*(5), 3537–3558. https://doi.org/10.1002/gj.3612

Khattak, S. A., Khan, N., Khan, W., Dhas, S. S. J., Kontakiotis, G., Islam, I., et al. (2025). Sedimentology and reservoir characterisation of Lower Jurassic clastic sedimentary rocks, Salt and Trans Indus Ranges, Pakistan: Evidence from petrography, scanning electron microscopy and petrophysics. *The Depositional Record, 11*, 698–717. https://doi.org/10.1002/dep2.325

Kundu, A., Matin, A., & Mukul, M. (2012). Depositional environment and provenance of Middle Siwalik sediments in Tista Valley, Darjeeling District, eastern Himalaya, India. *Journal of Earth System Science, 121*(1), 73–89. https://doi.org/10.1007/s12040-012-0154-1

Lindsey, D. A. (1999). *An evaluation of alternative chemical classifications of sandstones* (U.S. Geological Survey Open-File Report 99–346). U.S. Geological Survey. https://doi.org/10.3133/ofr99346

Majeed, K. U., Mughal, M. S., Kontakiotis, G., et al. (2026). Sedimentological and chemostratigraphic constraints on the provenance of sandstones and mudstones from the Kuldana and Murree formations in the Sub-Himalayas. *Discover Geoscience, 4*, Article 37. https://doi.org/10.1007/s44288-026-00391-y

Mehmood, M., Naseem, A. A., Saleem, M., Rehman, J. U., Kontakiotis, G., Janjuhah, H. T., Khan, E. U., Antonarakou, A., Khan, I., Rehman, A. U., et al. (2023). Sedimentary facies, architectural elements, and depositional environments of the Maastrichtian Pab Formation in the Rakhi Gorge, eastern Sulaiman Ranges, Pakistan. *Journal of Marine Science and Engineering, 11*(4), 726. https://doi.org/10.3390/jmse11040726

Michaelsen, P., & Henderson, R. A. (2000). Sandstone petrofacies expressions of multiphase basinal tectonics and arc magmatism: Permian–Triassic North Bowen Basin, Australia. *Sedimentary Geology, 136*, 113–136. https://doi.org/10.1016/S0037-0738(00)00090-7

Mustafa, S., Khan, M. A., Khan, M. R., Sousa, L. M., Hameed, F., Mughal, M. S., & Niaz, A. (2016). Building stone evaluation: A case study of the Sub-Himalayas, Muzaffarabad region, Azad Kashmir, Pakistan. *Engineering Geology, 209*, 56–69. https://doi.org/10.1016/j.enggeo.2016.05.007

Pettijohn, F. J. (1963). Chemical composition of sandstones, excluding carbonate and volcanic sands. In M. Fleischer (Ed.), *Data of geochemistry* (U.S. Geological Survey Professional Paper 440-S). U.S. Geological Survey. https://doi.org/10.3133/pp440S

Pettijohn, F. J., Potter, P. E., & Siever, R. (1972). *Sand and sandstone*. Springer. https://doi.org/10.1007/978-1-4615-9974-6

Pettijohn, F. J., Potter, P. E., & Siever, R. (1987). *Sand and sandstone* (2nd ed.). Springer-Verlag. https://doi.org/10.1007/978-1-4612-1066-5

Qasim, M., Ding, L., Khan, M. A., Jadoon, I. A., Haneef, M., Baral, U., Cai, F., Wang, H., & Yue, Y. (2018). Tectonic implications of detrital zircon ages from Lesser Himalayan Mesozoic–Cenozoic strata, Pakistan. *Geochemistry, Geophysics, Geosystems, 19*(5), 1636–1659. https://doi.org/10.1002/2017GC006895

Qasim, M., Tanoli, J. I., Ahmad, L., Ding, L., Rehman, Q. U., & Umber, U. (2022). First U–Pb detrital zircon ages from Kamlial Formation (Kashmir, Pakistan): Tectonic implications for Himalayan exhumation. *Minerals, 12*(3), 298. https://doi.org/10.3390/min12030298

Rai, L. K., Yoshida, K., & Kuritani, T. (2021). Reconstruction of the exhumation history of the eastern Nepal Himalaya based on provenance changes. *Sedimentary Geology, 420*, 105920. https://doi.org/10.1016/j.sedgeo.2021.105920

Raiverman, V. (2002). *Foreland sedimentation in the Himalayan tectonic region: A relook at the orogenic process*. Bishen Singh Mahendra Pal Singh.

Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology, 94*, 635–650. https://doi.org/10.1086/629071

Roser, B. P., Cooper, R. A., Nathan, S., & Tulloch, A. J. (1996). Reconnaissance sandstone geochemistry, provenance, and tectonic setting of the Lower Paleozoic terranes of the West Coast and Nelson, New Zealand. *New Zealand Journal of Geology and Geophysics, 39*(1), 1–16. https://doi.org/10.1080/00288306.1996.9514690

Salam, H., Turab, S. A., Ali, A., Jan, M. Q., Sulaiman, N., & Basori, M. B. I. (2024). Kahi mélange complex in Kurram and Waziristan, NW Pakistan: An integrated approach for tectonic implications to India–Afghan suturing. *Gondwana Research, 126*, 79–95.

Sanyal, P., Bhattacharya, S., Kumar, R., Ghosh, S., & Sangode, S. (2004). Mio–Pliocene monsoonal record from the Himalayan foreland basin (Indian Siwalik) and its relation to vegetational change. *Palaeogeography, Palaeoclimatology, Palaeoecology, 205*(1–2), 23–41. https://doi.org/10.1016/j.palaeo.2003.11.013

Sayab, M., & Jadoon, Q. K. (2005). Kinematics of tectonic fracture development during regional folding in sandstones of the Kamlial Formation, Khushalgarh, northern Pakistan. *Geological Bulletin, University of Peshawar*, *38*, 65–79.

Shah, S. M. I. (2009). *Stratigraphy of Pakistan* (Geological Survey of Pakistan Memoir No. 22). Geological Survey of Pakistan.

Shah, S., Khan, N., Bhatti, M., & Bhutta, A. G. (2000). *Geological map of Islamabad and surroundings* [Map]. Geological Survey of Pakistan.

Shahzad, A., Kontakiotis, G., Adatte, T., et al. (2024). Multi-elemental chemostratigraphy, sequence development, depositional history, and environmental importance of Early Eocene red beds (Kuldana Formation) in NW Himalayas, Pakistan. *Journal of Earth Science, 35*, 349–375. https://doi.org/10.1007/s12583-023-1860-6

Singh, B. (2013). Evolution of the Paleogene succession of the western Himalayan foreland basin. *Geosciences Frontiers*, *4*(2), 199–212. https://doi.org/10.1016/j.gsf.2012.09.002Suttner, L. J., & Dutta, P. K. (1986). Alluvial sandstone composition and paleoclimate: Framework mineralogy. *Journal of Sedimentary Petrology*, *56*, 329–345. https://doi.org/10.1306/212F8909-2B24-11D7-8648000102C1865D

Tahirkheli, R. K., Mattauer, M., Proust, F., & Tapponnier, P. (1979). The India–Eurasia suture zone in northern Pakistan: Synthesis and interpretation of recent data at plate scale. In *Geodynamics of Pakistan* (pp. 125–130).

Tucker, M. E. (2001). *Sedimentary petrology: An introduction to the origin of sedimentary rocks* (3rd ed.). Blackwell Science.

Ullah, K., Arif, M., & Shah, M. T. (2015). Petrography and geochemistry of the Kamlial Formation, southwestern Kohat Plateau, Pakistan: Implications for paleoclimate of the western Himalayas. *Turkish Journal of Earth Sciences*, *24*(3). https://doi.org/10.3906/yer-1410-21

Ullah, I., Siyar, S. M., Khan, M. A., Zafar, M., Jalil, R., Orakzai, A. U., Ali, T. U. H., Ullah, F., Kontakiotis, G., Khan, S. F., & Shams, K. (2025). Petrogenetic and petrographic investigation of Kumrat Granite, Kohistan Island Arc, northwestern Pakistan. *Acta Geodynamica et Geomaterialia*, *22*(2), 233–244. https://doi.org/10.13168/AGG.2025.0016

Zaheer, M., Khan, M. R., Mughal, M. S., Janjuhah, H. T., Makri, P., & Kontakiotis, G. (2022). Petrography and lithofacies of the Siwalik Group in the core of the Hazara–Kashmir Syntaxis: Implications for middle-stage Himalayan orogeny and paleoclimatic conditions. *Minerals*, *12*(8), 1055. https://doi.org/10.3390/min12081055

Zaheer, M., Khan, M. S., Mughal, M. S., & Abbasi, N. (2017). Petrography, provenance, diagenesis, and depositional environment of the Murree Formation in Jhelum Valley, Sub-Himalayas, Azad Jammu and Kashmir, Pakistan. *Arabian Journal of Geosciences, 10*(1), 1–22. https://doi.org/10.1007/s12517-017-3277-5

Zaleha, M. J. (1997). Intra- and extrabasinal controls on fluvial deposition in the Miocene Indo-Gangetic foreland basin, northern Pakistan. *Sedimentology*, *44*(3), 369–390. https://doi.org/10.1111/j.1365-3091.1997.tb01530.x