Kuwait J.Sci., Vol.50, No.(1B),January.2023,pp(1-18)

Petrotectonic framework of Siwalik Group in Khairi Murat-Kauliar area, Potwar Sub-Basin, Pakistan

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Abstract

The Khairi Murat-Kauliar area lies between the Salt Range Thrust (SRT) in the south whereas Main Boundary Thrust (MBT) in the north which is the part of the Potwar Sub Basin. Eocene to Recent rock succession is exposed in the study area. The selected siliciclastic Siwalik Group display various facies in a fluviatile environment, with different lithologies, and sedimentary features. The petrographic studies of Siwalik Group delineate different microfacies including feldspathic litharenite, litharenite and sub arkose. The provenance study of sandstones depicted the terrane of dissected arc and recycled orogeny, indicating that the detritus was received from sedimentary, metamorphic, plutonic and volcanic rocks from the northern domain of Indian Plate, Karakoram Ranges and Kohistan Island arc. The Siwalik sandstone also contains heavy mineral assemblage such as tourmaline, garnet, epidote, hornblende and chlorite. This heavy detritus assemblage depicted that the deposits were received from metamorphic and igneous origin. A modified dynamic depositional stages of the Siwalik Group with respect to Himalayan orogeny is further built using outcrop data, microfacies and heavy minerals analysis. According to this concept, the group was deposited along Himalayan uprising and thrusting, on the depository in targeted area. The Siwalik Group depicted different phase of Himalayan tectonics and these molasse sequence were deposited in a subsiding foreland basin under the conditions of rapid erosion and quick deposition.

Keywords: Dissected arc; heavy minerals; lith arenite; recycled orogeny; siwalik group.

1. Introduction

The Khairi Murat-Kauliar area located in the northeastern wedge of Potwar Sub-basin (Figure 1). Surface stratigraphy dominantly comprised of molasse sediments of Siwalik Group. These sediments indicate the initial stage of basin evolution as well as prone to less deformation as compared to underlying Paleogene strata (Drewes 1995; Kazmi & Jan, 1997; Riaz *et al.,* 2019).

The key problem related to molasses, that they need to be analyzed in the capacity of their mineral assemblage, variation in microfacies and provenance determination. Petrography of the rock component of molasse belongs to Himalayan foreland domain has been executed by various workers.

Chaudhri, (1972) discussed initially the petrogenesis of Siwalik sediments of the northwestern Himalayas, India. Sigdel & Sakai (2013) worked on Siwalik sandstones of Karnali River section, Nepal and suggested different tectonic stages of Himalaya. Bilal, & Khan, (2017) described the petrography and provenance of Kuldana Formation, Kalamula and Khursheedabad area, Kahuta, Azad Kashmir. Goswami & Deopa, (2018) investigated the petrotectonic setting of the provenance of Lower Siwalik of Himalayan foreland basin, Kumaun Himalaya, India. Farooqui *et al.,* (2022) worked on Ispikan Conglomerate and concluded that the provenance of Ispikan detritus was located to the north composed of plutonic and volcanic rocks with minor metamorphic rocks. The present study has been conducted for litho facies and microfacies analysis as well as the distribution of heavy minerals in the Siwalik's; this is necessary to understand and identify the different tectonic stages in Potwar foreland stratigraphic framework.

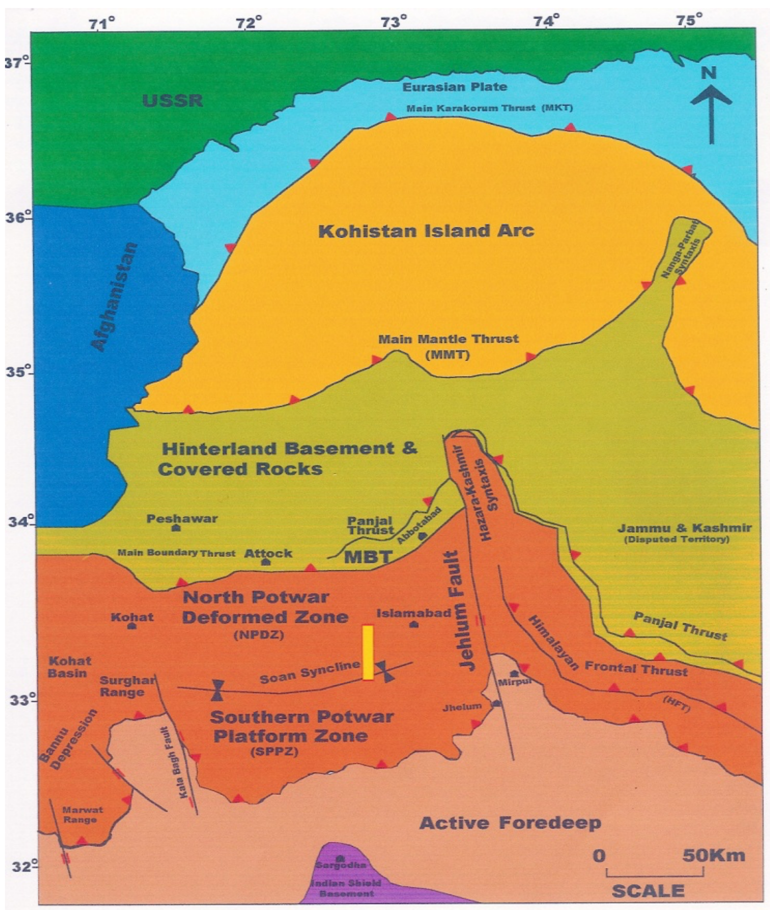

Fig. 1. Tectonic map of Northwest Himalayas, Pakistan. Yellow rectangle displayed the study area (modified after Khan *et al.* 1986).

2. Geological Setting and Stratigraphy

Potwar Sub-Basin is a broad Himalayan foreland basin, located on northwestern margins of Indian Plate. The imbricated and deformed zone in the northern Potwar over the Salt Range thrust sheet is called Northern Potwar Deformed Zone (NPDZ) (Jaswal, 1990: Figure 1). Salt Range Thrust bound the Potwar sub-basin in the south; represent the marginal foreland fold-and-thrust belt of Pakistan. In the Early Miocene, deformation propagated southward near the MBT, where unmetamorphosed lower Tertiary rocks are thrusted over Neogene molasse. In the latest phase in Pakistan, thrusting is transferred to the Salt Range Thrust where deformation is as young as 0.4 Ma (Yeats *et al.,* 1984). The Potwar sub-basin is nearly undeformed south of the Soan River but is deformed on its northern and eastern margins. Eastern Potwar represents strong deformation as compared to central and western Potwar (Figure 2). Southern Potwar though has been pushed at last twenty kilometers southward, yet it has been undergone almost no internal deformation, except broad, gently folded anticlines (Khan *et al.,* 1986). This phenomenon is due to the weak evaporite decollement and to the increase in the basement slope (Jaume and Lillie, 1988). The Siwalik Group is widely exposed in the northern and southern limbs of Soan Syncline. These strata are non-marine, time transgressive molassic facies that represents the erosional product of southward advancing Himalayan Thrust sheets. Thickness of molasse strata is about 5 km below the Soan Syncline (Lillie *et al.,* 1987). The Siwaliks have been deposited during the last 13 Ma. Top of Murree Formation is dated as 17 Ma. Johnson *et al.,* (1979) suggested that the fluvial and fluvio-deltaic Rawalpindi Group deposits indicate the initiation of significant Himalayan uplift. In the study area, exposed rocks ranges from Eocene to Recent. The stratigraphy of this domain displays tremendous outcrops along Khairi Murat Range (Figure 2; Table 1). Shah (2009) divided Siwalik Group into four formations which are Chinji, Nagri, Dhok Pathan and Soan Formations.

3. Methods and Material

The outcrops of Siwalik Group were recorded, sampled, and measured using standard procedures. Detailed analyses were performed to identify distinct litho facies intervals based on sedimentological properties such as lithology, depositional texture (Figure 3). About 120 samples of Siwalik Group were collected from various locations. For thin section preparation, samples were sent to the Hydrocarbon Development Institute of Pakistan (HDIP), Islamabad. Petrographic microscopy is used to analyzed thin sections by reflected and transmitted light with the help of Leica-DM-750P. To evaluate the provenance, several petrographic observations and parameters were recorded and measured. The classification of sandstone is based on an assessment of the percentages of the various grain types present in thin sections. Sandstones are classified by triangular diagram (McBride, 1963) with end members of quartz (Q), feldspar (F) and lithic fragments (L). The provenance of sandstone is determined from QFL provenance discrimination diagram of Dickinson *et al.,* (1983). Dickinson present four major provenance terrains i.e. stable craton, basement uplift, magmatic arc and recycled orogen. Stable cratons and basement uplifts form the continental blocks. Magmatic arcs included the continental and island arcs associated with subduction, and these are areas of volcanic, plutonic rocks and metamorphosed sediments. Recycled orogens are uplifted and deformed supracrustal rocks, which form mountain belts. Finally, a dynamic provenance stages are developed, based on the dynamics of the paleo-tectonics of northern margin of the Indian Plate, emphasizing the paleo geographic relevance of the Siwalik deposits.

4. Results and Discussion

The petrographic investigations related to the Siwalik set using the classification scheme of McBride, (1963) and Dickinson *et al.,* (1983) are as follows:

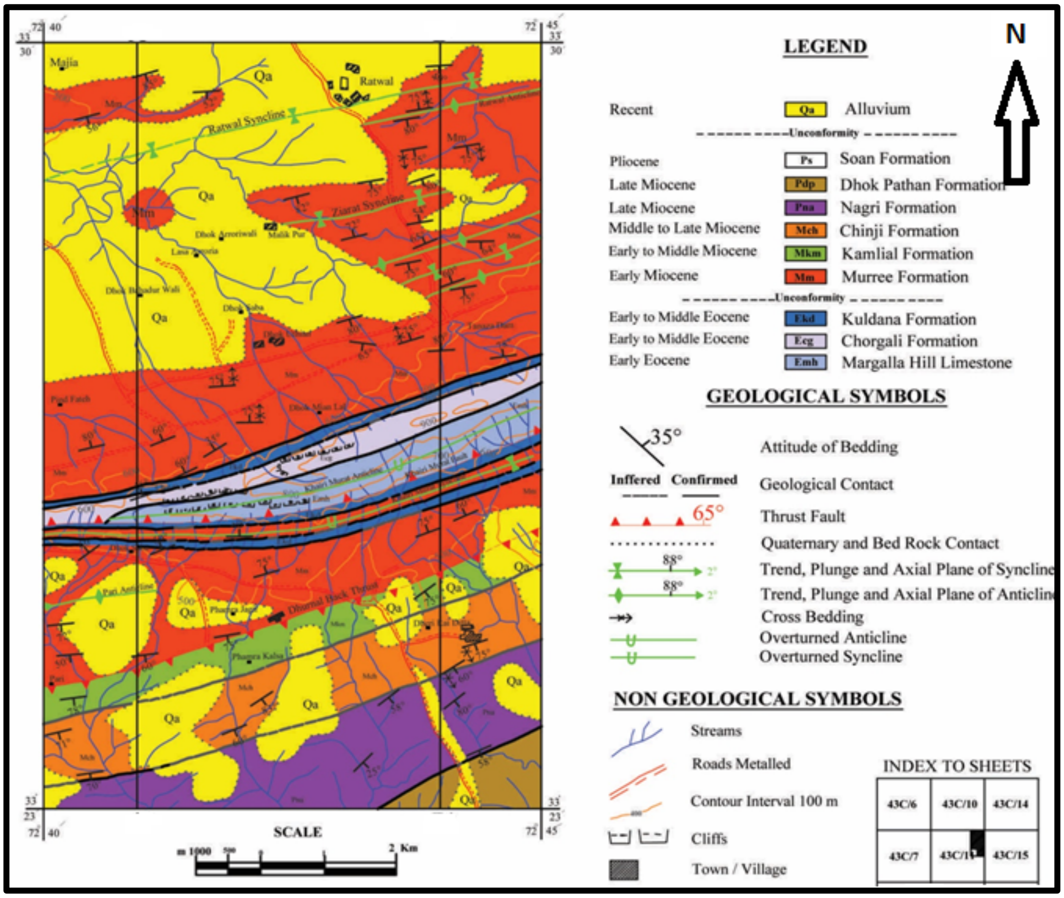

Fig. 2. Geological map of Khairi Murat-Kauliar area, Potwar Sub-Basin, Pakistan (after Kamran *et al.,* 2011).

Table 1. Surface stratigraphic sequence of the study area.

Epoch		Formation	Description
Recent		Alluvium	Silt & clay.
Pleistocene	SIWALIK	Soan Formation	Conglomerate.
Pliocene		Dhok Pathan Formation	Clay and sandstone with conglomerate
Pliocene		Nagri Formation	Massive sand stone with subordinate clays.
Miocene		Chinji Formation	Variegated clays with sandstone.
Miocene		Kamlial Formation	Sandstone.
Miocene		Murree Formation	Sandstone and clays.
Eocene		Kuldana Formation	Variegated color shale
Eocene		Chorgali Formation	Limestone with shale.
Eocene		Margalla Hill Limestone	Nodular limestone with shale.

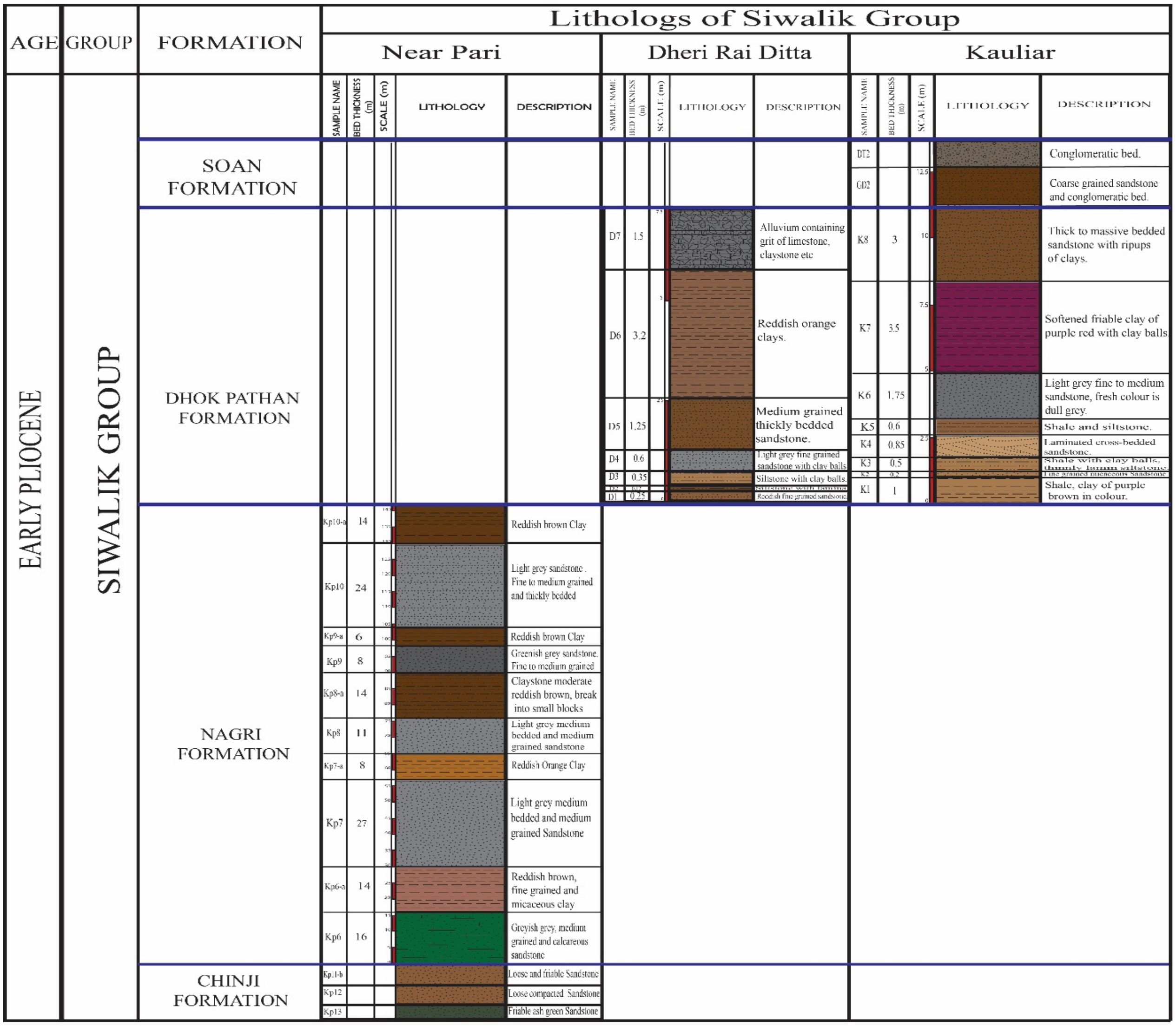

Fig. 3. Lithologs of Chinji, Nagri, Dhok Pathan and Soan Formations near Kauliar, Potwar Sub-Basin Pakistan.

4.1 Chinji Formation

Chinji Formation consists of dominantly brick red clay alternating with sandstone. Three samples were selected for petrographic study which delineates three microfacies (Figure 4).

4.1.1 Litharenite

On QFL diagram, one sample is recognized as litharenite. This type of sandstone is coarse grained, light grey to ash grey, soft and calcareous (Table 2). The texture is angular to sub angular and poorly sorted. Lithic fragments include sedimentary, metamorphic, igneous and volcanic rocks. The flakes of mica (5%), are frequently present. Litharenite sample falls in category of recycled orogen (Figure 5).

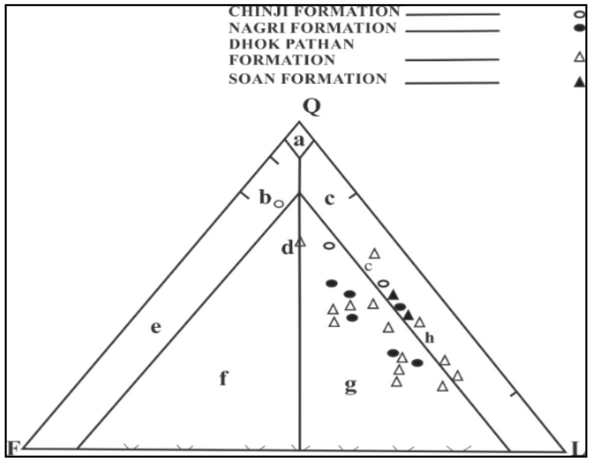

Fig. 4. QFL diagram (modified after McBride, 1963) of the Siwalik Group. The fields are: (a) Quartz arenite, (b) Sub arkose, (c) Sub Litharenite, (d) Lithic sub arkose, (e) Arkose, (f) Lithic arkose, (g) Feldspathic litharenite, (h) Lith arenite

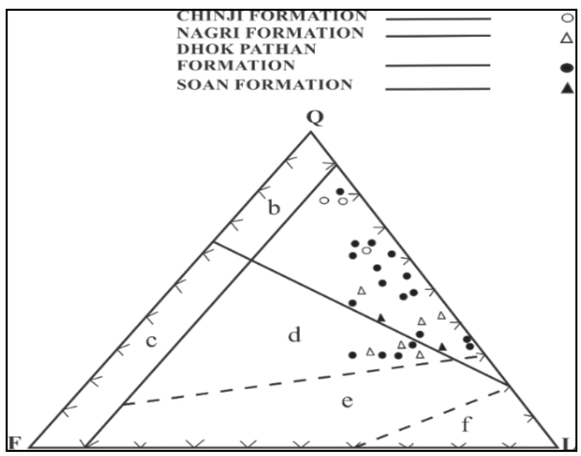

Fig. 5 QFL provenance discrimination diagram (Dickinson *et al.,* 1983) of the Siwalik Group. The fields are: (a) Recycled orogen, (b) Transitional continent, (c) Basement Uplift, (d) Dissected arc, (e) Transitional arc, (f) Undissected arc

Table 2. Modal percentage composition of sandstone of Chinji Formation

	Qm	Qp	Pl	Mc	L	Mus	Bt	Tm	C.M.	Ep	Gt	O.M	Class	Prov
Kp_{11-b}	30	06	4	2	20	02	3	1	05	2	--	10	Litharenite	R.O
Kp_{12}	30	10	4	2	12	02	7	4	-	3	1	15	L.Sub arkose	R.O
Kp_{13}	35	10	6	2	12	02	5	2	03	2	--	10	Sub-arkose	R.O

Abbreviations: Qm = Monocrystalline quartz, Qp = Polycrystalline quartz, Pl = Plagioclase, Mc = Microcline, L = Lithic Fragments, Ca = Calcite, Mus. = Muscovite, Bt = Biotite, Tm = Tourmaline, C.M =Clay minerals, Ep = Epidote, Gt = Garnet, O.M= Ore Minerals, Prov.= Provenance, R. O=Recycled orogen, D. A= Dissected arc

4.1.2 Lithic Sub arkose

Sample no. Kp_{12} is acknowledged as lithic subarkose in QFL diagram (Figure 4). The sandstone of this facie is coarse grained, brownish, grayish and soft. Concavo-convex contacts are observed between the quartz grains of mono and polycrystalline nature. Overall sub-angular to sub-rounded grains are seen with undulatory quartz. Feldspar flakes are mostly plagioclase nature with microcline. Lithic grains are received from metamorphic, igneous and sedimentary rocks. Tourmaline displays pleochroism out of pink-light green (Figure 6-a). A detrital matrix present in the lithic subarkose consists of calcite. According to QFL diagram the provenance is recycled orogen (Figure 5).

4.1.3 Subarkose

Sample no. Kp_{13} of lower Chinji Formation realized as subarkose (Figure 4). This is brownish, soft and coarse-grained sandstone. Texturally, this type of sandstone is well-sorted having a grain-supported fabric. Presence of monocrystalline along with polycrystalline quartz grains with sutured contacts depicted the presence of compaction. Plagioclase and microcline are present in fewer amounts. Lithic fragments found to be received out from igneous, sedimentary and metamorphic rocks. Deformed flakes of mica are also present consisting of stable muscovite and unstable biotite (Figure 6-b). Minor heavy minerals are also present in subarkose including tourmaline (2%) and epidote (4%). Calcite cement is dominant, whereas ferruginous and silica cements are also present in subarkose. According to QFL diagram, the provenance is recycled orogen (Figure 5). Diagenetic process such as cementation, replacement, mechanical compaction and authigenic overgrowth of quartz are common in this facie.

4.2 Nagri Formation

Six rock samples for petrographic studies were taken from the Nagri Formation's base to top. On the basis of petrography Nagri Formation are classified into two microfacies.

4.2.1 Feldspathic Lith arenite

Five samples (Kp_6, Kp_7, Kp_8, Kp_9 and $Kp_{11\text{-}a}$) are recognized as feldspathic Lith arenite (Figure 4; Table 3). This facie is comprised of grey sandstone interbedded with red clays. Quartz grains are found to be monocrystalline with subordinate polycrystalline quartz. Undulose quartz grains also occur in the rock. Feldspar includes plagioclase and microcline. The feldspar alters into sericite and clay minerals. Lithic fragments include quartz mica schists along with phyllite and slates. Clasts belongs to sedimentary rocks are of sandstone, shale, and older limestones. The flakes of micas are randomly oriented throughout the rocks (Figure 6-c, d). The cementing material is dominantly calcium carbonate. Calcite cement comprising microcrystalline aggregates and mosaic of anhedral sub hedral crystals. According to QFL diagram provenance of the two samples is recycled orogen. Three sample falls in dissected arc (Figure 5)

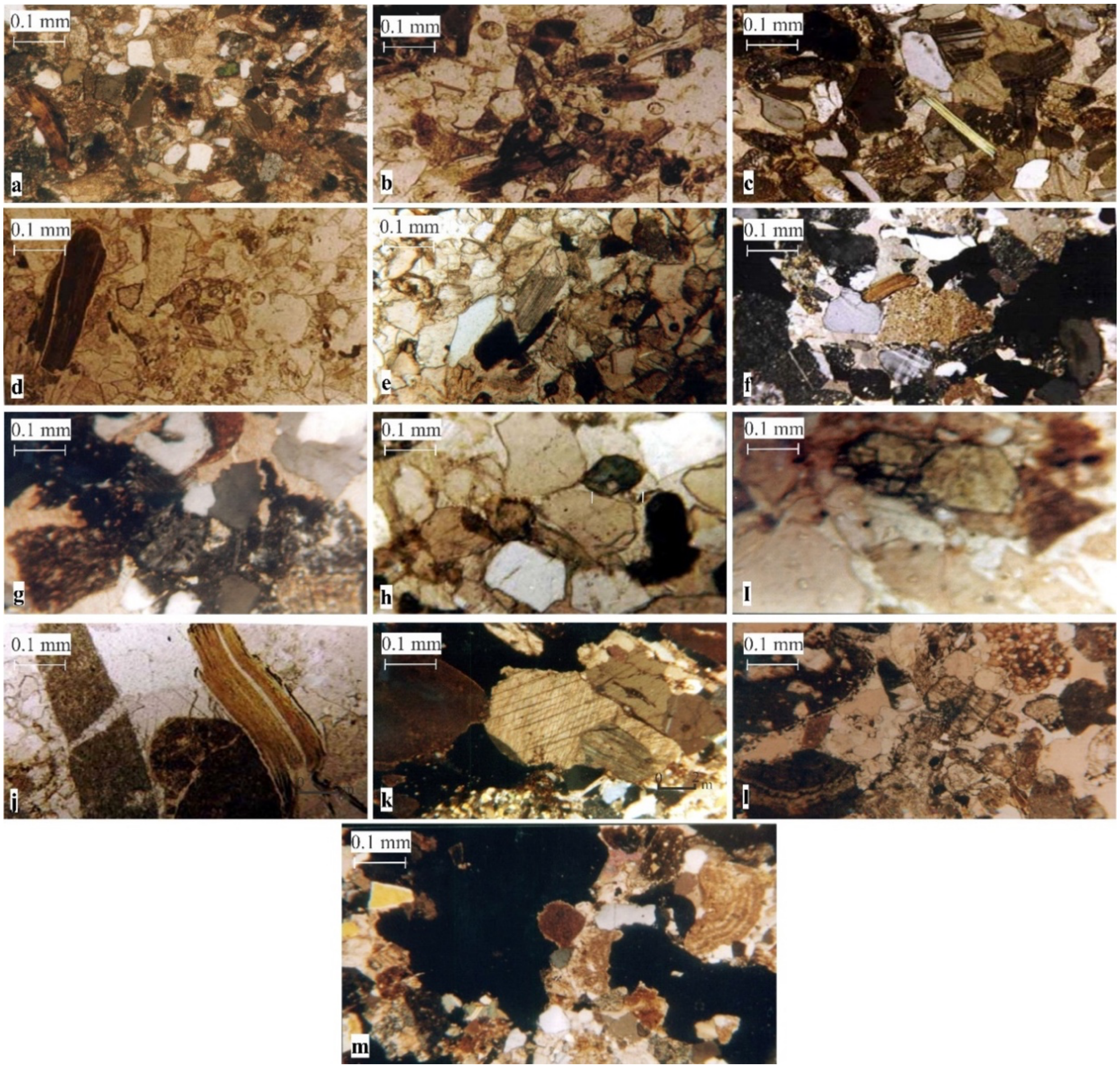

Fig. 6. Photomicrographs of sandstones of Siwalik Group (a) Lithic subarkose facie of Chinji Formation (Kp_{12}) showing green tourmaline in upper right portion, biotite flakes in lower left portion, and growth of calcite crystal between the pore spaces (Cross Nicol. x8). (b) Sub arkose facie of Chinji Formation (Kp_{13}) showing flakes of biotite at lower central portion, tourmaline grain at upper right and light brown garnet at central right portion (PPL. x8). (c) Feldspathic litharenite facie of Nagri Formation (Kp_{8}) showing plagioclase at upper central portion and muscovite in central portion (Cross Nicol. x8). (d) Feldspathic litharenite facie of Nagri Formation (Kp_{7}) showing large flake of biotite at left portion and green tourmaline in central right portion (PPL. x8). (e) Litharenite facie of Nagri Formation (Kp_{10}) showing well-developed cleavage in calcite crystal in the central portion (PPl. x10). (f) Feldspathic litharenite facie of Dhok Pathan Formation (Hc_{6}) showing microcline at lower central portion, shale fragment at center and biotite at upper right portion (Cross Nicol. x4). (g) Feldspathic litharenite facie of Dhok Pathan Formation (Dk_{2}) showing sutured contacts of quartz grains and development of embayment in quartz grain at upper central portion (Cross Nicol. x10). (h) Feldspathic litharenite facie of Dhok Pathan Formation (Dk_{8}) showing green, sub rounded tourmaline

at upper right portion, light brown garnet at center and quartz overgrowth at center left portion (PPL. x10). (i) Feldspathic litharenite facie of Dhok Pathan Formation (Hc_2) showing large, fractured light green tourmaline grain (PPl. x10). (j) Litharenite facie of Dhok Pathan Formation (Hc_5) showing large deformed biotite at right portion and fine-grained volcanic lithics (PPL. x10). (k) Litharenite Facie of Dhok Pathan Formation (Hc_4) showing crystals of calcite at central part and polycrystalline quartz at lower left portion (Cross Nicol. x2.5). (l) Litharenite facie of Soan Formation (GD_2) showing bioclasts at lower left portion and central portion and fragment of sandstone at upper right portion (PPL. x2.5). (m) Litharenite facie of Soan Formation (Dt_4) showing bioclasts at upper right portion and lithics of shale at the central portion (PPL. x2.5).

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Table 3. Modal percentage composition of sandstone of Nagri Formation.

	Qm	Qp	Pl	Mc	L	Ca	Mus	Bt	Tm	Ep	Gt	O.M	Class	Prov
Kp_6	22	07	10	04	24	15	05	05	01	02	1	08	Feldspathic Lith arenite	D.A
Kp_7	19	05	05	04	35	12	04	04	02	02	1	07		D.A
Kp_8	19	06	08	03	30	15	05	03	01	03	1	06		D.A
Kp_9	22	08	07	03	20	15	05	05	02	03	1	10		R. O
Kp_{10}	20	08	02	03	25	13	04	07	03	03	1	12		R. O
Kp_{11-a}	22	08	07	04	15	20	04	02	03	03	1	12	Lith arenite	R. O

4.2.2 Lith arenite

According to QFL diagram, one rock sample (Kp_{10}) is recognized as Lith arenite (Figure 4). The sandstone is grey to greenish grey, coarse grained, hard and calcareous. Lithic grains consist of resistant sedimentary, metamorphic and igneous rocks. Quartz grains are common and display wavy extinction. Feldspar grains present in minute amount (5%). Detrital micas (2-9%), along with muscovite is much more common. A suite of heavy minerals present comprising epidote, tourmaline and garnet. Calcite occurs as pore filling cement and form microcrystalline mosaic, cavity filling textures and also forming poikilotopic texture in which big crystals are interlocked irregularly (Figure 6-e). According to QFL diagram the provenance is recycled orogen (Figure 5). Calcite cementation took place before the main phase of silica cement, thus preventing the quartz overgrowth as nearly all pores were already occupied. The other diagenetic process is the compaction indicated by sutured contacts of quartz grains due to deep burial process called pressure solution.

4.3 Dhok Pathan Formation

Dhok Pathan Formation consists of cyclic deposits of clay and sandstone and forms the multi sandstone story (Figure 7). Sandstone is greyish, green, medium bedded, coarse grained and characterized by calcareous concretions. The clasts of igneous and volcanic rocks of variable sizes are embedded occasionally. Fifteen samples are classified into three microfacies.

Fig. 7. Multi sandstone story and clays of Dhok Pathan Formation near Kauliar, Potwar sub basin.

4.3.1 Feldspathic Litharenite

Nine samples (Bc_3, Hc_2, Dk_1, Dk_2, Dk_5, Dk_7, Dk_8, Dp_5 and Hc_6) are recognized as feldspathic litharenite (Figure 4; **Table 4**). This facie consists of sub-angular to sub rounded grains and grain size varies from fine to medium grained (Figure 6-f). Quartz grains are monocrystalline with subordinate polycrystalline. At few places authigenic over growth of silica around quartz grains have been observed. Some contacts of quartz grains are sutured (Figure 6-g). Feldspar grains are sub angular and include plagioclase and microcline. Lithic fragments are received from igneous, metamorphic and sedimentary rocks. Muscovite and biotite occur as small flakes. Minor clay minerals occur in the matrix but these are extremely fine grained. Some accessory minerals like tourmaline, epidote, rutile and garnet (Figure 6-h) are also present. Tourmaline found as light green showing moderately pleochroism from brownish green to dark brown (Figure 6-i). Garnet grains present rarely and these are sub angular to sub rounded. Epidote occurs as anhedral to subhedral grains showing various colors. The calcite is very important constituent of cement. According to QFL diagram, the provenance of seven rock samples is recycled orogen and two rock samples fall in dissected arc (Figure 5).

4.3.2 Lith arenite

According to QFL diagram five rock samples are recognized as Lith arenite (Figure 4). The sandstone is grey to greenish grey, coarse grained, hard and calcareous. This facie consists of lithics of low-grade metamorphic rocks and sedimentary rocks. Some carbonate lithics contain bioclasts are also present in rock samples. Feldspar grains present in relatively small amount.

Table 4. Modal percentage composition of sandstone of Dhok Pathan Formation.

	Qm	Qp	Pl	Mc	L	Ca	Mu	Bt	Tm	Hb	Ep	Gt	O.M	Class	Prov
BC_3	15	10	05	03	35	15	03	01	01	--	01	01	03		D.A
Hc_2	20	10	05	02	30	15	02	02	01	01	01	01	07		R.O
Dk_1	15	07	07	03	30	20	03	03	01	01	02	01	08		D.A
Dk_2	20	10	05	03	25	25	01	02	01	01	01	01	05		R.O
Dk_5	25	07	07	03	20	20	05	03	01	--	01	01	07	Feldspathic Litharenite	R.O
Dk_7	15	07	05	03	25	20	07	05	01	01	01	01	09		D.A
Dk_8	25	10	06	02	20	20	03	03	01	--	02	01	07		R.O
Dp_5	15	07	05	03	15	32	03	04	01	--	01	01	12		R.O
Hc_6	30	10	05	04	25	10	03	04	01	--	01	01	06		R.O
Bc_{1-a}	20	07	03	02	25	20	03	02	01	01	01	01	12		R.O
Dp_{16}	35	07	03	03	15	10	05	05	01	--	01	01	12	Lith arenite	R.O
Dp_{17}	25	10	03	02	15	20	06	05	02	01	02	01	10		R.O
Hc_4	10	10	05	01	45	10	02	01	--	--	01	--	10		D.A
Dp_7	30	10	05	03	10	20	02	08	02	--	01	01	06	Lithic sub-arkose	R.O

Detrital flakes of biotite and muscovite are frequent, which may possibly derive from metamorphic source (Figure 6-j). Some heavy minerals also increase in litharenite including tourmaline, garnet, epidote and hornblende. Calcite occurs as pore filling cement. Calcite crystals form microcrystalline mosaic or cavity filling poikilotopic texture (Figure 6-k). According to QFL diagram, the provenance of four rock samples is recycled orogen, while one rock sample fall in dissected arc (Figure 5).

4.3.3 Lithic Sub arkose

One sample (Dp_7) is recognized as lithic sub arkose in accordance with QFL diagram (Figure 4). The sandstone of this facie is brownish and soft. Both mono and poly-crystalline quartz grains are found having concavo-convex contacts. Grains shapes are found as sub-angular to sub-rounded. Feldspar grains are dominantly plagioclase and microcline with perthite texture. Lithic fragments are received from metamorphic, sedimentary and igneous rocks. Deformed flakes of biotite and muscovite are present. Minor heavy minerals are also present including tourmaline, garnet, hornblende and epidote. Cement consists of calcite. According to QFL diagram, the provenance is recycled orogen (Figure 5). The first diagenetic process is authigenic quartz overgrowth. The second common pore filling materials are calcite and clay minerals occur in patches and took place before the main phase of silica cement. The third diagenetic process is closer packing of grains due to mechanical compaction. Albitization of K-feldspar and calcic plagioclase is also observed in some rock samples.

4.4 Soan Formation

This formation consists of compact, very large sized conglomerate bodies with subordinate interbeds of sandstone, siltstone and clay. The conglomerate consists of pebbles and boulders of different sizes. The formation contains pebbles and boulders of quartzite, granite, metamorphic, volcanic, limestone and sandstone ranging in size from 2 to 10 cm in diameter. Two samples were taken from the Soan Formation and classified into one microfacie ((Figure 4).

4.4.1 Litharenite

According to QFL diagram two samples are recognized as litharenite (Figure 4). The sandstone is light grey and grayish to reddish. These are coarse grained, poorly sorted, sub angular, conglomeratic sandstones **(**Table 5**)**. Litharenite contains about 45% or more lithic grains exceeding feldspar and quartz grains including all types of resistant sedimentary, metamorphic, igneous and volcanic rocks. The sedimentary lithics were derived from sandstone, clay stones, mudstone, shale, chert and carbonates (Figure 6-l). Feldspar present in relatively small amount (8%). Some Eocene bioclasts are also present (Figure 6-m). The most common cement is calcite. Some crystals of calcite are present as detrital grains with clear boundaries and not act as cement. Litharenite is immature sandstones and reflect provenance in the most effective manner because lithics carry by themselves the obvious proofs of their origin. Modal data indicate a provenance of recycled orogen (Figure 5).

Table 5. Modal percentage composition of sandstone of Soan Formation

S. No.	Qm	Qp	Pl	Mc	L	Ca	Mu	Bt	Tm	CM	Bio-clasts	O.M	Class	Prov
DT_4	15	12	02	03	30	10	02	02	01	05	01	10	Lith-arenite	R.O
GD_2	20	10	02	04	35	10	01	02	01	04	01	07		R.O

5. Heavy minerals in sandstone of Siwalik Group

Heavy minerals include many kinds of opaque and non-opaque or transparent minerals. According to Abbasi and Khan (1990) the common heavy minerals in the sediments of the Siwalik Group are epidote, garnet, tourmaline, zircon, mica, amphibole, kyanite and staurolite.

5.1 Opaque Minerals

In almost all the samples, the opaque minerals comprise the major bulk of the heavy concentrate. This group consists of hematite, ilmenite, magnetite and few pyrite. Ilmenite has a steal grey, sub-metallic lusture, magnetite has a silver gray lusture, hematite possesses a reddish brown and pyrite shows a brass yellow color under reflected light. The percentage of total opaque minerals range from 47-54% **(**Table 6**)**.

5.2 Tourmaline

Grains of tourmaline are irregular prismatic and strongly pleochroic. Inclusion and zoning are also present, and it varies from 8-11% (Figure 6-a, d, h, i).

5.3 Epidote

Epidote occurs as anhedral to subhedral grain and show typical green color with marked pleochroism to greenish yellow color. It varies from 9-14%.

5.4 Garnet

It is most predominant in all the samples and is mostly pink or colorless. Grains are irregular and sub angular, but some rounded grains are also observed. Percentage of garnet grains varies from 2-8% (Figure 6-h).

Table 6. Heavy mineral percentage in sandstone of Siwalik Group

Sr. No.	Formation	Epidote%	Garnet %	Biotite %	Tourmaline%	Hornblende%	Opaque %	Chlorite%
1	CHINJI	11	02	23	10	--	54	Traces
2	NAGRI	14	06	23	10	Traces	47	Traces
3	DHOK PATHAN	09	08	24	08	03	48	Traces
4	SOAN	10	05	21	11	--	53	--

5.5 Hornblende

Grains of hornblende are flat, prismatic and irregular in shapes. Color of the grains is green, bluish green to olive green. It varies from traces to 3%.

6. Provenance of Siwalik Group

According to Hubbard *et al.,* (2021) the continental collision process has made a large contribution to continental growth and reconfiguration of craton basin throughout Earth history. The molasse of the study area has direct relationship with uplifting sequences. According to Critelli & Garzanti (1994) during Miocene, when highly metamorphosed rocks of the Himalaya were carried southward, the mountain range began to rise to dramatic heights, and huge amounts of detritus started to feed the Siwalik foreland basin of Indus and Bengal Fans. The field investigations and petrographic evaluations of the sandstone also reflected that the detritus was eroded away from uprising Himalayan and were finally unlade in the Indus depression. These provenance studies are also supplemented with the evaluation of heavy minerals.

6.1 Provenance of Chinji Formation

The Chinji Formation is found as litharenite, lithic subarkose and subarkose and these are derived from the recycled orogen. Some quartz grains are polycrystalline and some show undulatory extinction. According to Mughal *et al.,* (2018) the polycrystalline quartz and undulatory quartz grains were derived from the felsic plutonic igneous rocks (granite), high grade metamorphic rocks and older sandstone provenances. The microcline and albite indicates that the granitic and gneissic rocks were exposed at the time of the deposition of sediments. The lithics are of metamorphic and sedimentary origin. The metamorphic clasts are of slates, phyllite, schist and gneisses. Kamran *et al*., (2011) shows that during the deposition of the Kamlial Formation (below the Chinji Formation), the more metamorphic and plutonic rocks eroded during the uplift of the Himalayan orogenic belt. Similarly, the presence of rock fragments and microfacies suggest that the sediments of Chinji Formation were also derived from the metamorphic and plutonic origin of northern margin of Indian Plate.

6.2 Provenance of Nagri Formation

The Nagri Formation is characterized as feldspathic litharenite and litharenite. These microfacies are derived from recycled orogen and dissected arc. The feldspar increases with respect to the underlying formation, which indicates that the igneous rocks were uplifted and eroded at this time. The sedimentary lithics dominate the metamorphic and igneous lithics. The garnet grains are also present in Nagri Formation and according to Abbasi & Khan, (1990) the major source of garnet in molasse sediments is interpreted as the metamorphic belts of the Indian plate exposed along its northern margin. The lenses of conglomerates consisting of igneous, metamorphic and sedimentary rock fragments. Thus it can be concluded that the abundance of garnet, increase of volcanic lithics and volcanic conglomerates of basalt and andesite show that the Kohistan magmatic arc was uplifted and eroded during the deposition of Nagri Formation.

6.3 Provenance of Dhok Pathan Formation

The sandstone is mainly feldspathic litharenite to litharenite and lithic subarkose. These microfacies were derived from recycled orogen and dissected arc. The feldspar increases throughout the formation. More abundant plagioclase in sandstones indicates it was derived from volcanic rocks (Boggs, 2006). Phenocrysts of microcline, perthite and quartz are also present. The metamorphic rock fragments include quartz mica schist and garnet mica schist. Igneous rock fragments are granite and granite gneiss and fine-grained volcanics. These lithics show that the uplift and erosion of Kohistan Island arc and northern margin of the Indian Plate was continued during the deposition of this formation. The garnet grains are also present and these are derived from medium to high-grade metamorphic and plutonic rocks of the Indian Plate including Tanol Formation and Besham Basement rocks. Blue green amphiboles first appear in this formation. The presence of green and brown hornblende indicates that Kamila amphibolites of Kohistan Island arc were exposed at the time of deposition of Dhok Pathan Formation. During the field investigations the conglomerates of andesite, rhyolite, diorite, phyllite, slates, schists and quartzite are found. The sedimentary particles are of Sakesar and Margalla Hill Limestones showing their derivation from rocks exposed along MBT. The conglomerates also strengthen the fact that northern margin of the Indian Plate, Kohistan Island arc and probably mélanges zones were provenance for this formation. Volcanic rocks are also exposed in southeastern Kohistan like Alai and Babusar area. Kohistan Island arc at this time was not only uplifted but was sufficiently unroofed to provide plutonic detritus. The presence of porphyritic granite clasts in the Dhok Pathan Formation suggests the uplifting and unroofing of the Mansehra Granite. The provenance study of Dhok Pathan Formation suggests that detrital material derived from the plutonic, volcanic, metamorphic and sedimentary rocks of uplifting Himalayan collision belt in the north.

6.4 Provenance of Soan Formation

The Soan Formation is mainly consisting of Lith arenite facie. The lithic fragments of limestone of Lockhart, Sakesar, Margalla and Chorgali Formations are also present. This suggests that uplift of

Kala Chitta Range along MBT and Khairi Murat Range was responsible for providing detritus of the rocks exposed due to faulting. This evidence is supported by the presence of bioclasts derived from Eocene rocks present in Soan Formation. Similarly, the clasts of intrabasinal conglomerates and higher proportion of sandstone rock fragments suggest that rocks of Siwalik Group were also involved during the deposition of Soan Formation due to uplifting of nearby ranges.

7. Modal composition of sandstone and their implications for tectonics

Petrographic data provide different compositional stages which were recorded in sandstone during the field observation and petrographic studies.

7.1 Stage I: Chinji Formation

The rock fragments and detritus minerals reveal that Indian Plate after collision was continuously pushing the Asian landmass, which resulted ongoing uplifting and erosion of northern margin.

7.2 Stage II: Nagri Formation

Nagri stage shows entrance of volcanic rock fragments. This indicates that volcanic Island arc was eroded and detritus was deposited in this sandstone. The clasts of metamorphic, plutonic rocks and increase in garnet contents suggest that unroofing of the basement sequence in the north was initiated.

7.3 Stage III: Dhok Pathan Formation

The petrographic and field study exhibit that detritus of granitic rocks, high grade metamorphic rocks, volcanics and sedimentary rocks present in this sandstone was derived from the crustal and sub crustal rocks of northern margin of Indian Plate. This suggests that tectonics was active resulting in exposure of deep crustal rocks of the Indian Plate and Kohistan Island arc. Tectonic activity also migrated southward and resulted in deformation, uplifting and thrusting in the northern Potwar region.

7.4 Stage IV: Soan Formation

This formation indicates that in addition to the tectonic activity the northern Potwar basin was locally faulted and folded. The thrust faults were developed due to continued uplifting of the Himalayan fold-and-thrust belt and southward progradation of tectonics. These thrust faults cut and exposed the Tertiary sequence onto the surface. The rock fragments of these sequences provide further evidence that thrust tectonics was initiated and propagated towards Potwar sub-basin. The major thrusting and faulting events at the time of deposition are MBT and Khairi Murat Fault. These faults exposed Eocene carbonates above molasse deposits.

8. Conclusion

The study area is a zone of the active foreland fold-and-thrust belt related to the Himalayas. In this zone carbonate deposition was stopped at the end of Early Eocene time due to the increase of orogenic uplift. As a result of this tectonic activity a major unconformity was formed on the top of the Eocene carbonate and clastic sediments of Kuldana Formation. The molasse sediments of Rawalpindi and Siwalik Groups deposited during Miocene to Pleistocene time. Petrographic evaluation related to the Siwalik Group displays variegated types of microfacies comprising feldspathic litharenite, litharenite as well as sub arkose. Study of provenance depicted dissected arc along with recycled orogeny, deducted that the material was received from the metamorphic, volcanic, plutonic and sedimentary sources present to the northern edge of Indian Plate, Kohistan Island arc as well as Karakoram Ranges in northern Pakistan. Northern Indian Plate's edge displays a detailed sequence of low-grade metamorphic to eclogite facies. Heavy mineral assemblage contains opaque minerals, garnet, tourmaline, rutile, epidote and hornblende. These typical minerals also showed that the sediments of these deposits came from the northern edges of Indian Plate. Petrographic analysis depicted that Siwalik suit were unlading in a subsiding foreland basin along the foothill under the environment of fast erosion leading to quick deposition. These deposits indicate inverted stratigraphy of the northern margin of the Indian plate showing the older metamorphic rocks of Kohistan Island Arc and Karakoram Range in younger Dhok Pathan and Soan Formations. Siwalik deposits also indicating the fluviatile environment of deposition which is the product of the Himalayan orogeny. During the deposition of Siwalik Group, the tendency of sediment deposition was north to south along perfect fluvial system. As a result, the Siwalik succession's thickness rises from north to south over the Potwar Sub basin.

ACKNOWLEDGMENTS

We are very thankful to the Director of Institute of Geology, UAJK, Muzaffarabad for his facilitation during this research work.

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Submitted: 06/12/2021
Revised: 21/02/2022
Accepted: 08/03/2022
DOI: 10.48129/kjs.17577