PETROGRAPHY AND TECTONO-SEDIMENTARY SIGNIFICANCE OF SANDSTONES FROM THE HIMALAYAN FORELAND: A CASE STUDY OF TATTA PANI, AJ&K, PAKISTAN.

Shamim Akhtar[1], Hasnain Haider[2], Muhammad Saleem Mughal[3], Abdul Shakoor Mastoi[4], Sharjeel Ali Malik[1] and Khawaja Muhammad Ibrar[3]

[1]Department of Earth Sciences, University of Sargodha, Sargodha 40100, Pakistan.
[2]Department of Geology, University of Yazd, Yazd, Iran.
[3]Institute of Geology, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan.
[4]Centre for Pure and Applied Geology, Faculty of Natural Sciences, University of Sindh, Jamshoro, Pakistan

ABSTRACT: The Tatta Pani area in District Kotli, Azad Jammu and Kashmir occupies a strategic location within the eastern limb of Hazara Kashmir Syntaxis (HSK) in the Sub Himalayas forming an essential segment of Himalayan Forland Basin. This study focuses on understanding the geological and petrographic characteristic of the sandstone exposed in this region, primarily belonging to Murree Formation. With contributions from the Siwalik Group, this area is tectonically influenced by significant structures such as Riasi Thrust and the Tatta Pani Anticline, which control the regional stratigraphy and deformation patterns. Sandstone successions in Tatta Pani area (Kotli), Azad Jammu and Kashmir, preserve important records of sediment provenance and tectonic evolution of the northwestern Himalayan orogenic Belt. This study the petrographic characteristics and tectonic setting of sandstones exposed in the Kotli area to explain their provenance, depositional setting, and source-area tectonics. In the following study, the detailed petrographic analysis performed by using thin-section microscopy and modal point counting to quantify framework grains, matrix, and cement. According to petrographic analyses, the sandstones are primarily lithic arenites, with quartz being the most prevalent mineral and frequently displaying both undulatory and non-undulatory extinction. In addition to accessory minerals like muscovite and tourmaline, the presence of fragments of igneous, metamorphic, and sedimentary rock indicates a recycled orogenic source connected to the Himalayan hinterland. Textural characteristic like angular to sub rounded quartz grains indicate a combination of proximal and distal sedimentary sources, while calcite and hematite act as the main cementing agents. Fluvial depositional environments are indicated by sedimentary features seen in the field, such as petrified wood, mud cracks, load cast and ripple marks. The integrated field and petrographic data confirm that the sediments were derived from Himalayan uplift and were deposited in a tectonically active foreland setting, preserving a record of complex basin evolution and sediment recycling processes.

Keywords: Petrography, Tectonic setting, Tatta Pani area, Himalayan Orogenic Belt, Fluvial deposition.

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INTRODUCTION

The study area lies between latitudes 33°32′14″N to 33°34′56″N and longitudes 73°52′52″E to 73°55′51″E, forming part of sub-Himalayan zone (Fig. 1). The Himalayan Foreland Basin, formed in response to the collision between the Indian and Eurasian Plate, represents one of the most tectonically active and geologically diverse regions on Earth (Fig. 2). Situated within this dynamic setting, the Tatta Pani area of District Kotli, Azad-Jammu and Kashmir, offers valuable insights into sedimentary processes, tectonic deformation, and provenance patterns (Najman, 2006). This zone is bounded by major thrust systems, notably the Main Boundary Thrust (MBT) to the north and the Himalayan Frontal Thrust (HFT) to the south (Gansser, 1983). The region's lithological diversity coupled with its structural complexity makes it ideal for investigating sandstone petrography and the tectonic sedimentary evolution of the foreland basin.

The primary focus of this study is the Murree Formation, a Miocene-aged succession of sandstones, siltstones, and shales, representing a key component of Rawalpindi Group (Ahmad & Chaudhry, 2008). The Murree Formation is well exposed in the Tatta Pani area, alongside other younger units of the Siwalik group, including the Chinji, Nagri, Dhok Pathan, and Soan Formation (Qasim & Ahmad, 2013). By integrating petrographic data with field observations and regional tectonic frameworks, this research aims to decode the depositional history, provenance, and tectonic significance of the Tatta Pani sandstones within the broader context of the Himalayan evolution (Kazmi & Snee, 1989).

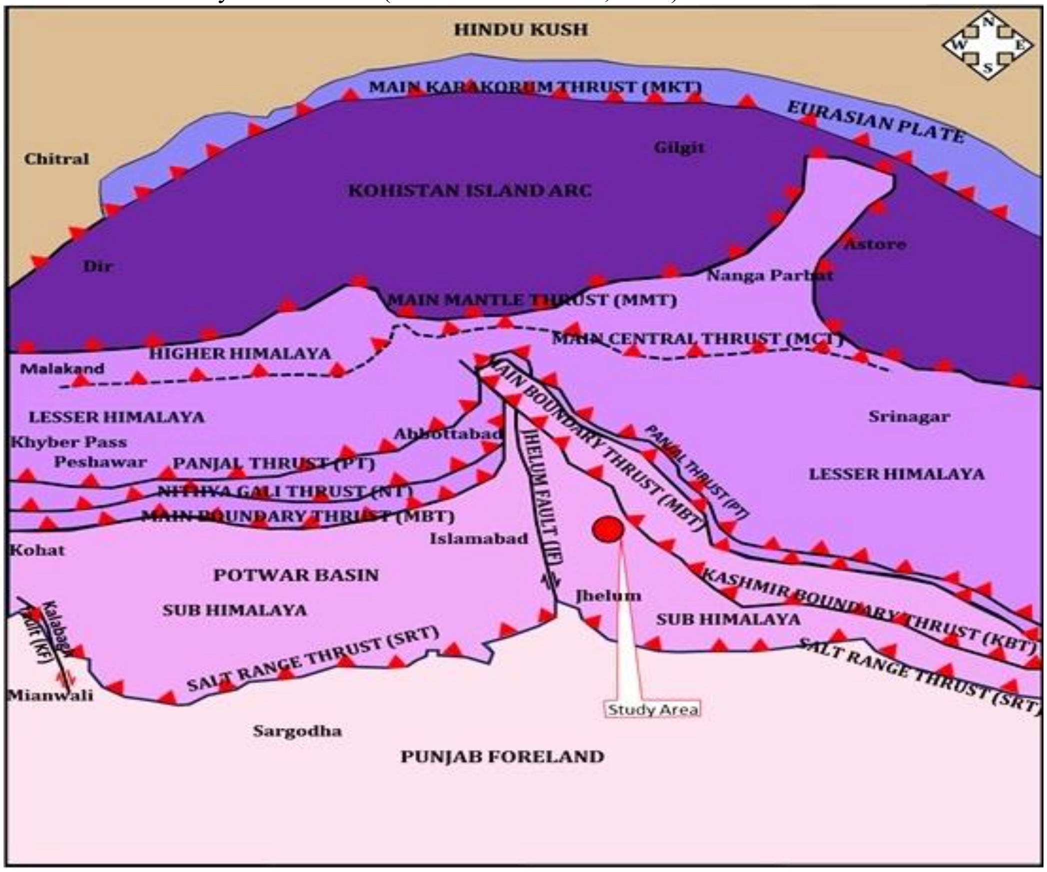

Fig. 1. Tectonic map of Himalayas, the Pin shows study area (modified after Gansser 1981; Kazmi and Rana 1982).

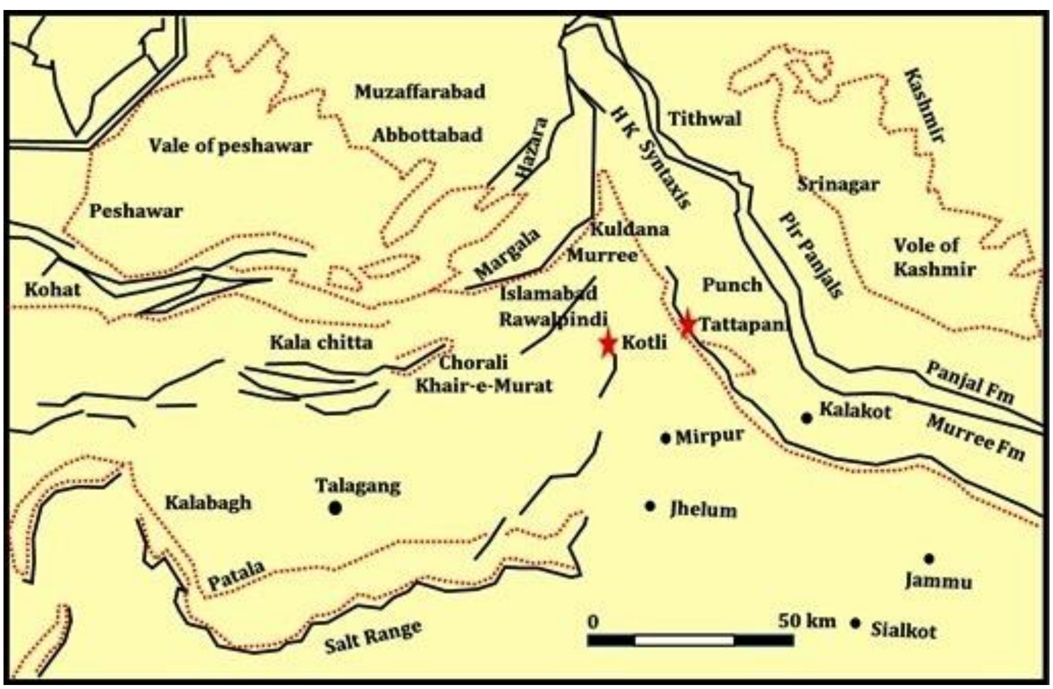

Fig. 2. Tectonic and geological setting of the study area showing Tatta Pani and Kotli regions in Azad Jammu and Kashmir, Pakistan (after Thakur *et al*., 2010). The map illustrates major geological features including the Hazara-Kashmir Syntaxes (HKS), Salt Range, Murree and Panjal formations.

Geological and Stratigraphic Setting: From the Pliocene Siwalik Group to the Cambrian Abbottabad Formation, the Tatta Pani region displays a well-preserved sedimentary record of the Himalayan foreland basin (Schwarz & Giuliani, 2001), (Burg & Chen, 1984). Clay, shale, and siltstone are interbedded with thick sequences of sandstones that dominate the stratigraphy (Sorkhabi, 2006). The base of the Rawalpindi group is Murre formation, which composed of fine to medium sandstones that range in color from reddish brown to greenish brown and are occasionally intraformational conglomerates (Valdiya, 1999). Geological map of Tatta Pani area and location of collected samples is shown in Fig. 3. The Soan, Dhok Pathan, Nagri, and Chinji formations, exhibiting an upward, gradually coarsening sequence associated with gravel deposition (Khan & Malik, 2014), (Fig. 4).

Structurally, the Riasi thrust marks the Murree Formation in the Hanging wall from the overlaying Dhok Pathan Formation in the footwall (Valdiya, 1995), which separates the Murree Formation in the Hanging wall from the overlaying Dhok Pathan Formation. The Tatta Pani Anticline folds the stratigraphy into a sequence of plunging folds and produces notable lateral facial variation, so further complicating the structural architecture (Ahmad & Farooq, 2018). The tectonic complexity and geological richness of the study area are emphasized by the juxtaposition of several tectonostratigraphic units ranging from the Precambrian basements to Cenozoic foreland sediments (DeCelles & Gehrels, 2009).

MATERIALS AND METHODS

Framework was carried out in several divisions ranging from Kotli to Tatta Pani. Using Digital Elevation Model (DEM), (Fig. 5), Brunton Compass and GPS, detailed geological mapping was done; stratigraphic logs were generated to record lithological changes. From the several stratigraphic levels, representative rock samples were collected with special attention for sandstone exposures. Thin sections of ninety sandstone samples were prepared for petrographic study under a polarizing microscope. Model analysis yielded relative abundance of lithic fragments, feldspar, and quartz. Modal point counting helps to quantify framework grains as well as classify matrix and cementing material. Ternary diagrams, with QFL plots, were used for sandstone classification and provenance interpretation. Additionally, data is compared with standard petrographic classification systems including those of Pettijohn (1975), Folk (1980), and Dickinson *et al*. (1983).

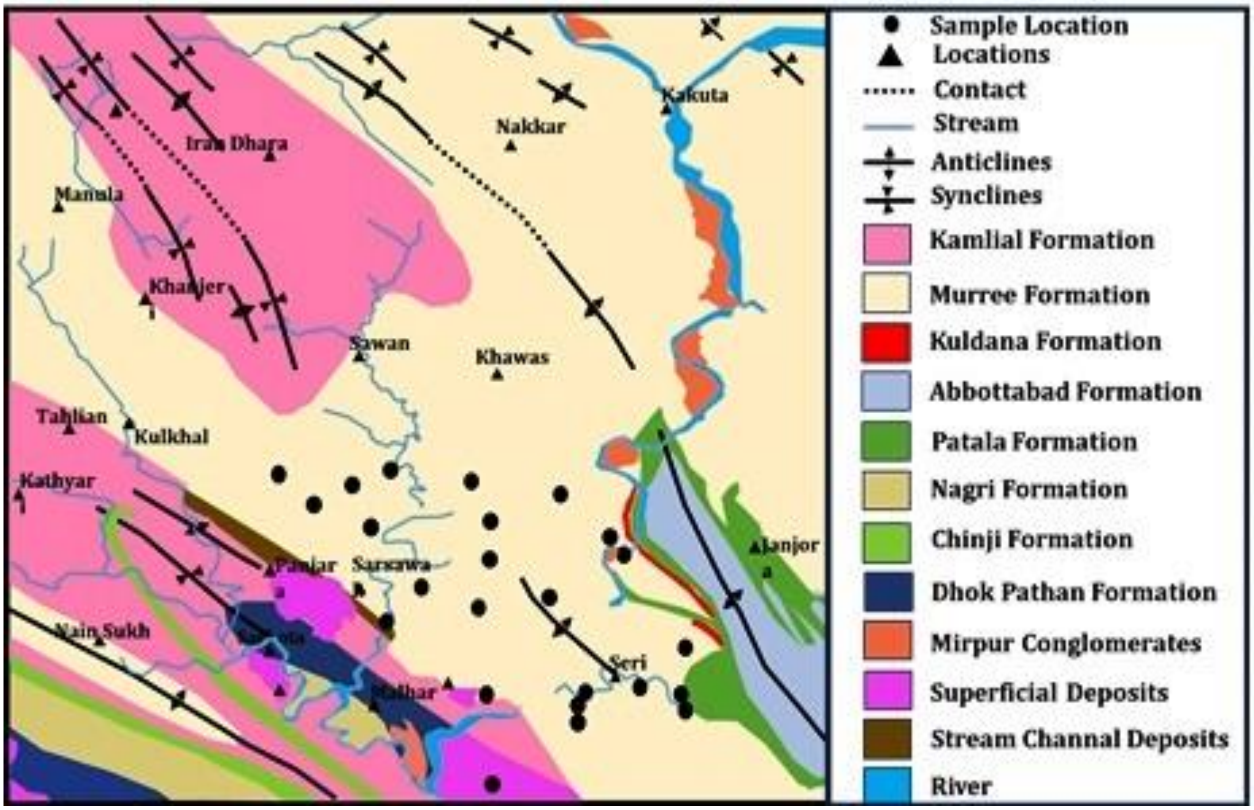

Fig. 3. Geological map of Tatta Pani area. Map also shows location of samples of thin section (after Mureed *et al.* 2004).

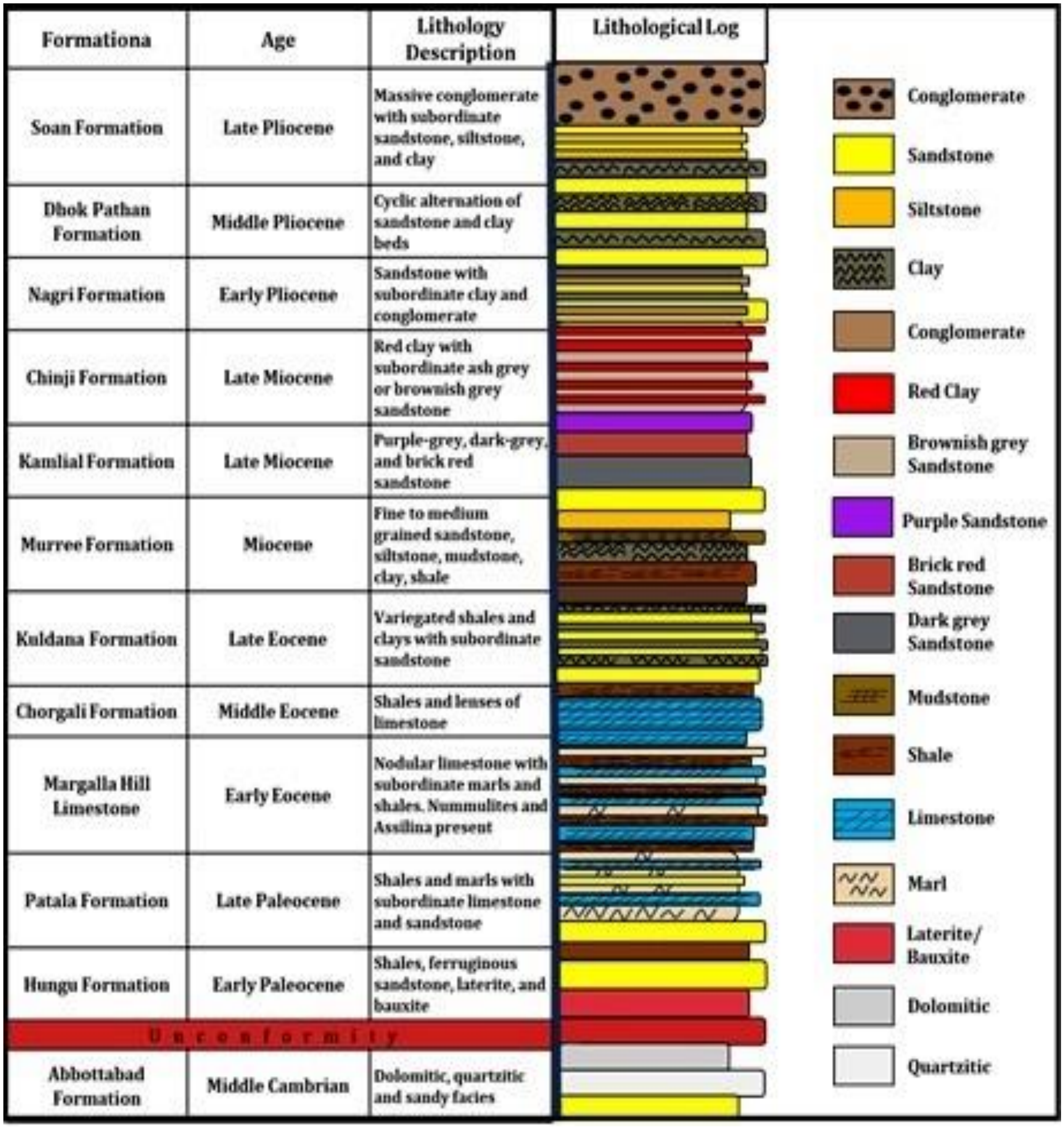

Fig. 4. Stratigraphic log of study area, showing lithological variations and formation boundaries (after Khan & Malik, 2014).

RESULTS

Megascopic Features of sandstone of Murree Formation: The sandstone of Murree Formation is fine to medium grained in texture, thin to thick bedded. Its fresh color is grey and greenish grey whereas weathered color is reddish brown. The clasts of igneous, sedimentary and metamorphic rocks are found in sandstone of Murree Formation. Lamination in sandstone is also observed at different places, Primary sedimentary structures like ripple marks, load cast, basal structures, mud cracks, groove marks, calcite vein, petrified wood, worm burrows, cross bedding and calcite concretion (Fig. 6 and 7), are observed in sandstone of Murree Formation which point to deposition in a tectonically influenced high energy river system.

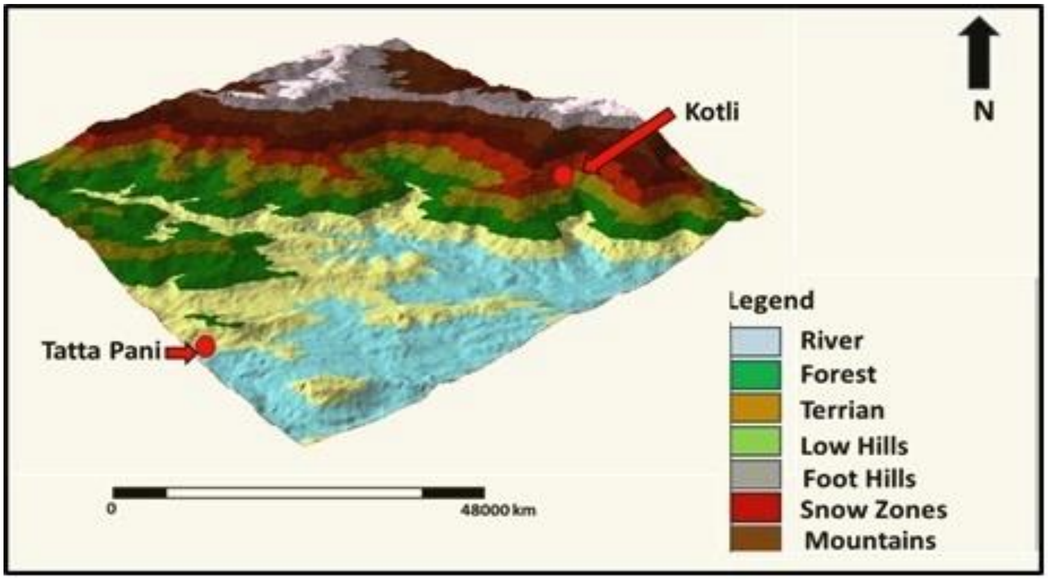

Fig. 5. Digital Elevation Model of Azad Jammu and Kashmir, red dots showing study area.

Fig. 6. Photographs showing sedimentary structures in sandstone of Murree Formation, A. Lamination, B. Ripple marks, C. Load casts, D. Basal structures, E. Mud cracks, F. Groove marks.

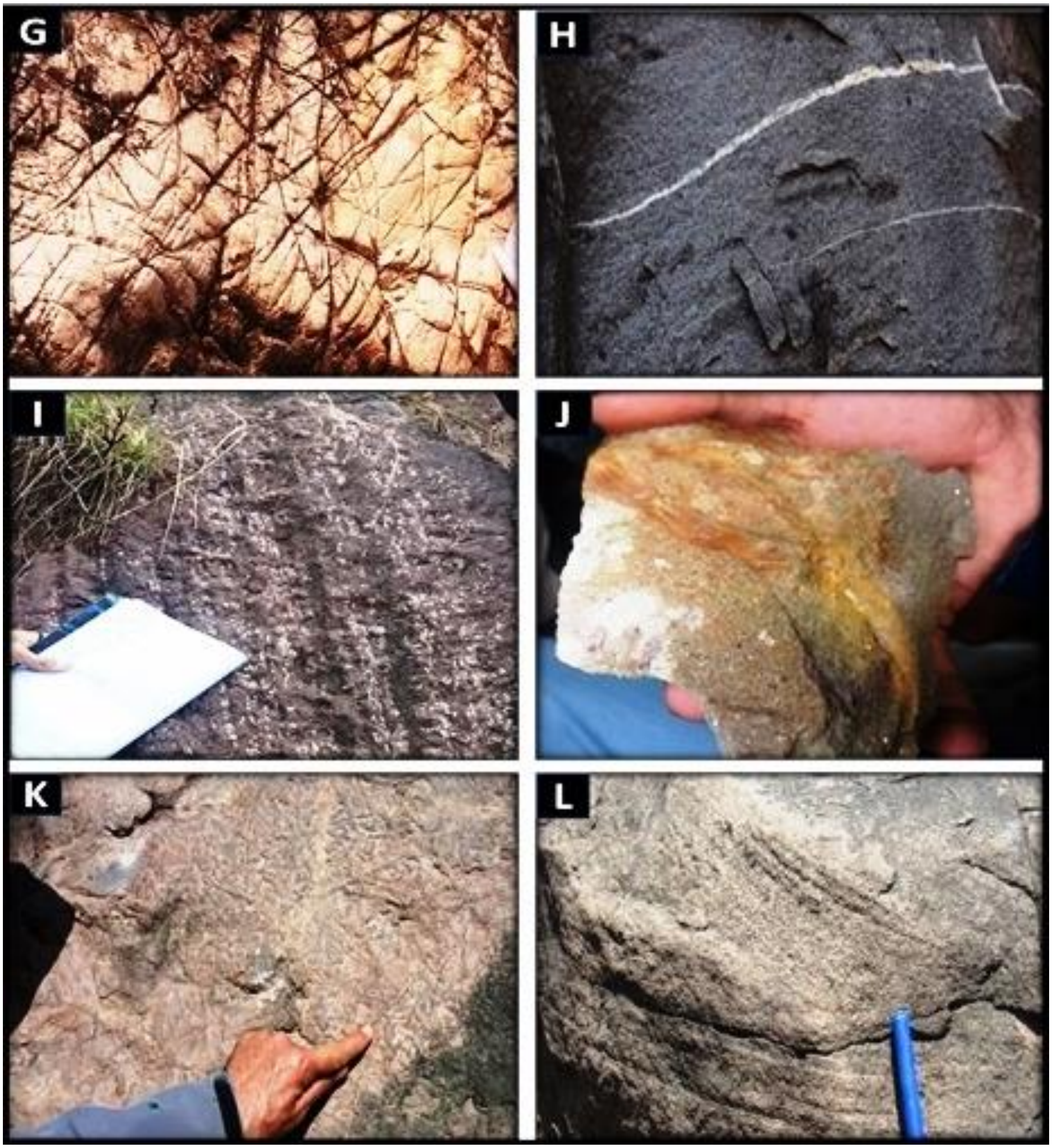

Fig. 7. Photographs showing sedimentary structures in sandstone of Murree Formation G. Chop board weathering, H. Calcite vein, I. Concretion, J. Petrified wood, K. Worm burrows, L. Cross bedding.

Microscopic Features of Murree Formation: According to preliminary petrographic analysis, the Murree Formation's sandstone is preliminary lithic arenites, which is made up of quartz (both monocrystalline and polycrystalline), feldspar and various lithic fragments from sedimentary, igneous and metamorphic sources. While epidote and sericite are secondary minerals found in altered feldspars; common accessory minerals include tourmaline, muscovite and chlorite. Calcite and hematite make up the majority of cementing materials, clay makes up less than 5% (Fig. 8 and 9). Mineralogically, it is composed of quartz 35-50 percent, feldspar 3-10 percent, rock fragment 10-35%, tourmaline 1%, biotite 1-4%, muscovite 1-5%, hematite 1-3%, opaque 1-5% and sericite 1-2%.

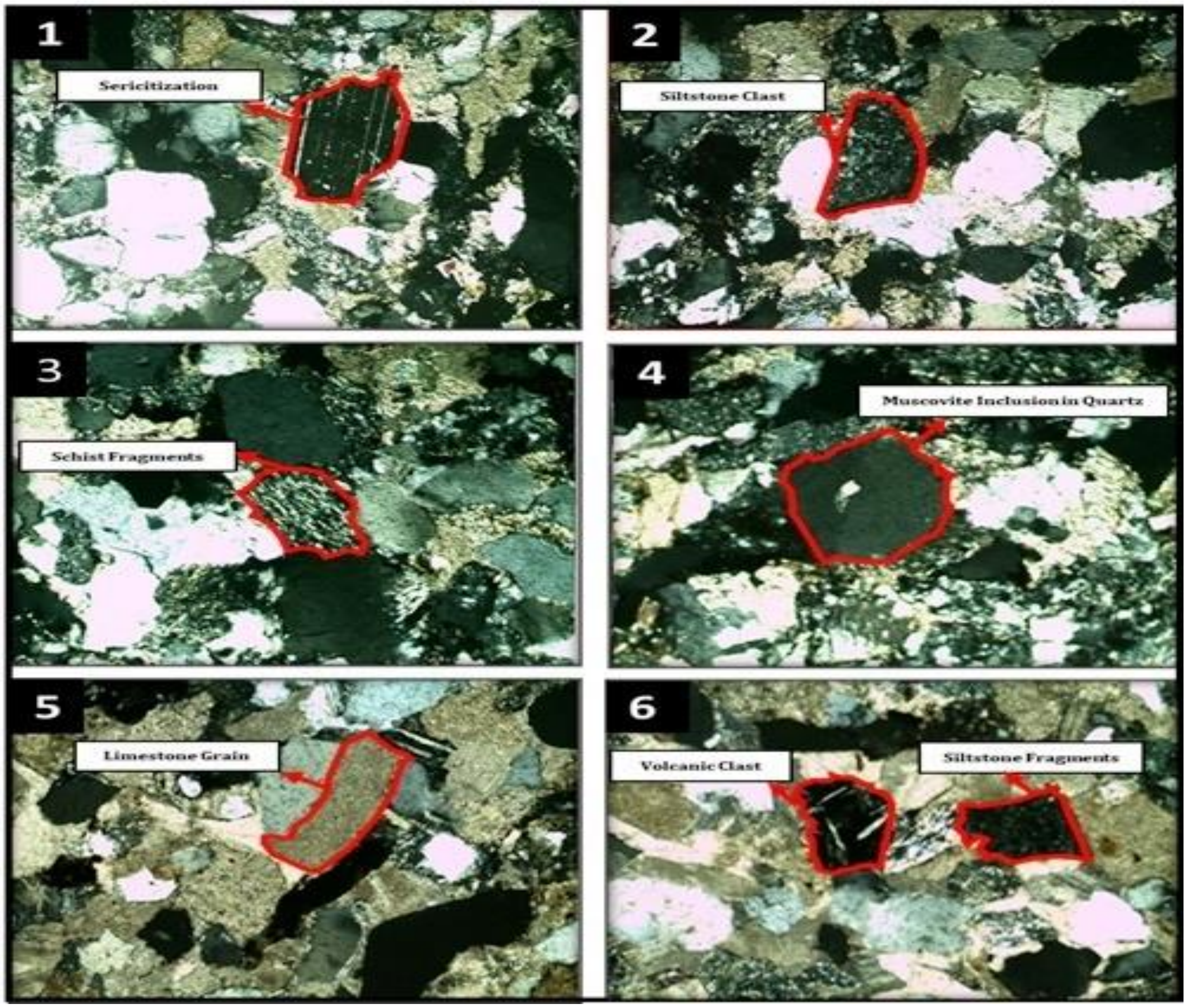

Fig. 8. Photomicrographs showing, 1. Sericitization, 2. Siltstone clast, 3. Schist fragments, 4. Muscovite inclusion in quartz, 5. Limestone grain, 6. Volcanic clast, Siltstone fragments, in sandstone of Murree Formation.

Plate no. 1,2: Thirty-five percent quartz of various shapes is found in the rock sample. Monocrystalline quartz grains occur up to 30%. The polycrystalline grains are 5%. The majority of quartz grains exhibited unit extinction while some grains are found to have undulatory extinction. Quartz grains have point, planar and concavo-convex contact. Feldspar occurrence is up to 3% in the rock sample. Plagioclase shows albite twining. It is altered into sericite. The rock fragments occur up to 20%. The clasts are of sedimentary and metamorphic rocks. Rock fragments are of various shapes from rounded to sub rounded and elongated. Sedimentary clasts of sandstone, siltstone, limestone, and chert collectively formed 5% of the sample. Metamorphic clast of slate and schist constitute 15%. Carbonates and hematite act as cementing material. Carbonate cement constituted up to 18% of the rock sample. The hematite cement constitutes up to 7%. Accessory minerals are collectively forming 15% of the rock sample. Muscovite and biotite occur up to 5% and 2% respectively. Hematite, clay matrix and other opaque minerals are up to 11% (Table. 1). Sericite is also present up to 1%.

Plate no. 3,4: Quartz is angular, sub angular and sub rounded up to 35%. The monocrystalline quartz grains are up to 31%. In contrast, the polycrystalline grains are 4%. Mostly grain shows unit extinction while a few grains have undulatory extinction. Some grains are fractured. Quartz grain shows point and planar contact. Muscovite inclusion in quartz grain is also observed. Feldspar occurrence is only 3% in the rock sample. Plagioclase has albite twining in the sample. The rock fragments occur up to 25%. The clasts are of igneous, sedimentary and metamorphic rocks. Rock fragments exhibited various shapes from rounded to sub rounded and elongated. The igneous fragments consist of 1% volcanic clasts of basaltic rocks. Sedimentary clasts of siltstone, limestone, dolomite and chert collectively formed 10%. Metamorphic clast of quartzite, slate, and schist collectively constitute 14% of the sample. The cementing material is calcite and hematite. Collectively it constitutes up to 20%. Calcite is dominant in the sample as compare to hematite. Muscovite occurs up to 3% and is deformed. Biotite occurs up to 1%. Tourmaline constituted up to 2%. Hematite is up to 4% and clay matrix also 4% (Table. 1) and opaque minerals are up to 5%.

Plate no. 5,6: Angular, sub angular, sub rounded quartz is up to 35% in this rock sample. Monocrystalline quartz grains are up to 32% and the polycrystalline quartz grains are up to 3% of the rock. Most grains of quartz have unit extinction while some grains have undulatory extinction. The feldspar includes both plagioclase and alkali feldspar. It constitutes up to 5%. It is altered into sericite. Plagioclase shows albite twinning. Rock fragments occur up to 25%. The clasts are of sedimentary, igneous and metamorphic rocks. Rock fragments are of various shapes from rounded to sub rounded and elongated. The igneous fragments are 2% and chiefly consist of volcanic clast. Sedimentary clasts of sandstone, siltstone, dolomite and limestone collectively formed 17%. Metamorphic clast of quartzite, slate and schist collectively constitutes 6% of the sample. The cementing material is carbonate and hematite in the rock up to 25%. Carbonate cement constituted up to 20% and the hematite cement constitute up to 5 percent. Accessory minerals collectively constitute 8% of the rock sample. Muscovite is present up to 2% of the sample. Biotite occurs up to 1 percent (Table. 1).

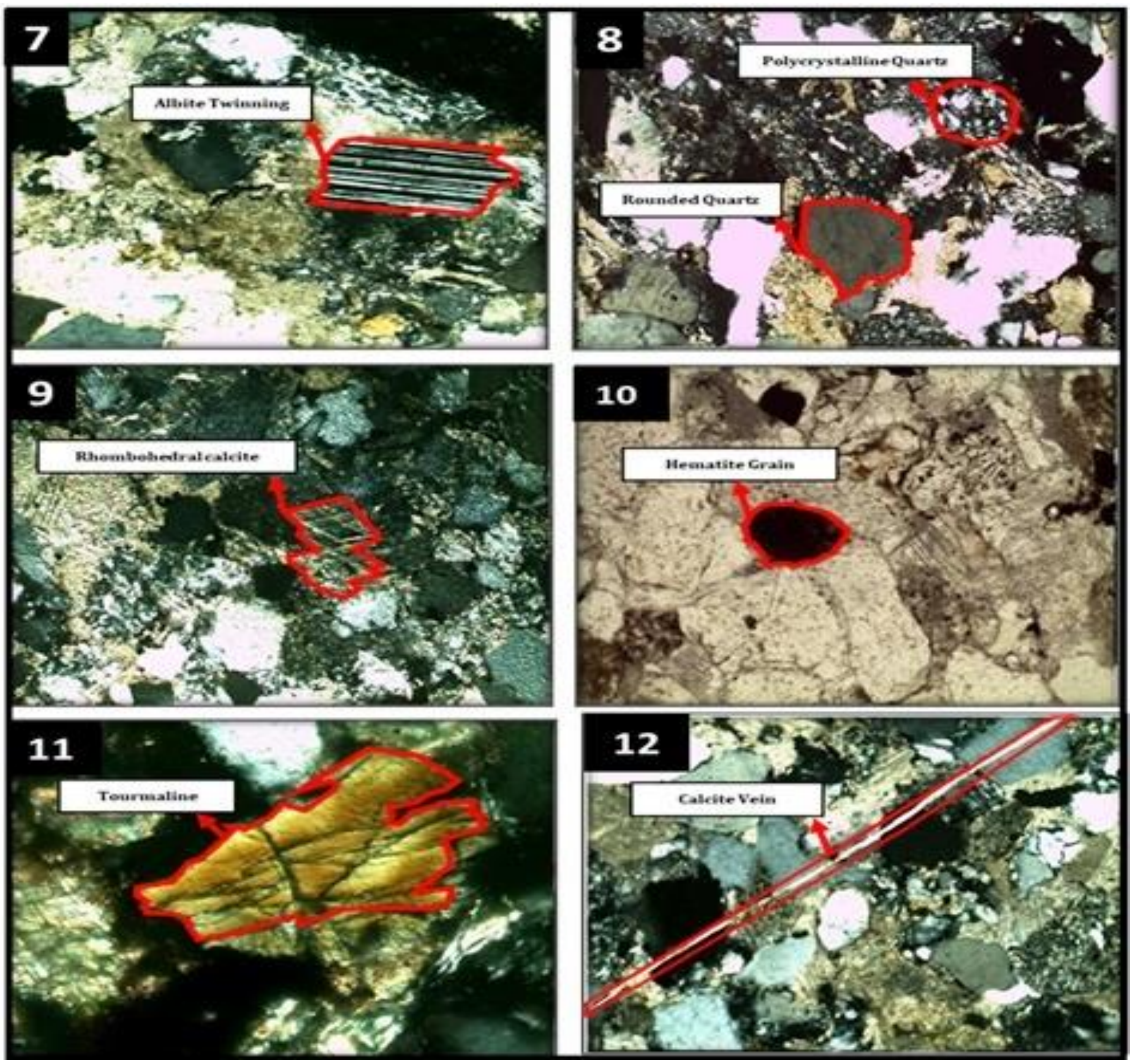

Fig. 9. Photomicrographs showing,7. Albite twinning, 8. Polycrystalline quartz, Rounded quartz, 9. Rhombohedral calcite, 10. Hematite grain, 11. Tourmaline, 12. Calcite vein, in sandstone of Murree Formation.

Plate no. 7: Quartz as an angular to sub angular rounded to sub rounded and stretched was found up to 40% in this rock sample. Monocrystalline quartz grains are up to 36%. Also, the polycrystalline quartz grains constituted up to 4%. The majority of quartz grains exhibited unit extinction while some quartz grains are found to be having undulatory extinction. Plagioclase and alkali feldspar are up to 3% and 1% respectively. Plagioclase showed albite twinning. Feldspar is altered into sericite. A total 30% rock fragments are found and included clasts of sedimentary and metamorphic rocks. Sedimentary clasts of sandstone, siltstone and chert constitute 7%. Sandstone and chert fragments are less than siltstone. Metamorphic clasts are of quartzite, slate and schist which occurs up to 23%. Very low-grade metamorphic rock fragments (slate) are abundantly found than quartzite and schist. Cementing material is mainly consists of hematite (an iron cement) and carbonate mineral is also act as a cementing material in the sample. Hematite constitutes up to 17% while the carbonate cement is up to 3% in the sample. Occurrence of muscovite is up to 2% which is deformed. Biotite occurs up to 1%. The opaque minerals present 1%. Clay matrix are 2 %. Epidote occurrence is 1% and tourmaline also presents 1% (Table. 1) in the sample. Trace amount of accessory mineral is also present.

Plate no. 8: Quartz occurs up to 40% in the rock. It is angular, sub angular, sub rounded slightly fractured and a few grains are stretched in this sample. Mostly quartz grains are present in mono-crystalline form 37% and remaining 3% are in polycrystalline form. Alkali feldspar and Plagioclase are up to 1% and 4% respectively. Plagioclase showed albite twinning while alkali feldspar displayed microcline twinning. Lithic fragments are present up to 20% including sedimentary and metamorphic rock fragment. Sedimentary rock clasts are 18% (sandstone, siltstone and dolomite). Dolomite and sandstone are less as compare to siltstone. Metamorphic rock fragments are 2%. Cementing material is up to 25% in the representative sample. Major cementing material is calcite up to 20% in the sample. Other cementing materials are also present i.e. hematite, dolomite and clay 3%, 1 % and 1% respectively. Accessory minerals muscovite is 3% (Table. 1) which is slightly deformed. Biotite is present up to 2% clay matrix 3% and opaque minerals are 3%.

Plate no. 9: 40% of quartz grains are found in this sample. The huge occurrence was that of the monocrystalline quartz grains that is 37%. In contrast, the polycrystalline grains are 3%. The majority of quartz grains exhibited unit extinction while some strained grains were found. Quartz grains show point, concavo-convex and planar contacts with each other in the sample. The plagioclase and alkali feldspar are found up to 3%. Albite twining is shown by plagioclase. It is altered into sericite. Up to 29% rock fragments are in the sample. The clasts are of sedimentary and metamorphic rocks. Rock fragments exhibited various shapes from rounded to sub rounded and elongated. Sedimentary clasts of sandstone, siltstone and limestone constitute 5%. Metamorphic clast of quartzite, slate, and biotite schist occur up to 24%. Carbonate and hematite are the cementing material. Both cementing materials constitute up to 6% of the sample. Muscovite is up to 7%, biotite is 3%, and tourmaline 3% and hematite 2%, clay matrix 3% and 4% opaque minerals are found in the rock sample (Table. 1).

Plate no. 10: Forty percent quartz was found in the various shapes such as angular, sub angular, sub rounded, whereas some quartz grains are fractured and stretched. The monocrystalline quartz grains constitute 35% of the rock. In contrast, the polycrystalline grains are 5%. The majority of quartz grains exhibited unit extinction while some strained grains were found to be having undulatory extinction. Quartz grains are showing point, concavo-convex and sutured contacts. Feldspar including both plagioclase and alkali feldspar occurred up to 5%. Plagioclase has albite twinning in this rock sample. Feldspar is frequently altered into sericite. A total of 20% rock fragments were found and included clasts of sedimentary, igneous and metamorphic rocks. The igneous fragments chiefly consisted of 2% volcanic clasts. Calcium plagioclase phenocrysts were present in basaltic clast. Sedimentary clasts of sandstone, siltstone, dolomite and limestone constitute 13%. Sandstone and carbonate fragments are less than siltstone. Metamorphic clasts are of quartzite, slate and schist and their occurrence is up to 5%. A total sum of cement is up to 25%. The carbonates are the main cementing material. Some opaque minerals such as hematite also acted as cementing material. Carbonate cement constitutes up to 18%. The hematite cement constitutes up to 7%. Muscovite is up to 1% of the sample. Biotite occurs up to 1%, hematite is also present up to 4 percent, clay matrix is up to 2% and other opaque minerals are also present up to 4% (Table. 1). Moreover, a calcite vein is also observed in the sample.

Plate no. 11: 40% of quartz grains are found in this sample. The huge occurrence was that of the monocrystalline quartz grains that is 37%. In contrast, the polycrystalline grains are 3%. The majority of quartz grains exhibited unit extinction while some strained grains were found. Quartz grains show point, concavo-convex and planar contacts with each other in the sample. The plagioclase and alkali feldspar are found up to 3%. Albite twining is shown by plagioclase. It is altered into sericite. Up to 29% rock fragments are in the sample. The clasts are of sedimentary and metamorphic rocks. Rock fragments exhibited various shapes from rounded to sub rounded and elongated. Sedimentary clasts of sandstone, siltstone and limestone constitute 5%. Metamorphic clast of quartzite, slate, and biotite schist occur up to 24%. Carbonate and hematite are the cementing material. Both cementing materials constitute up to 6% of the sample. Muscovite is up to 7%, biotite is 3%, and tourmaline 3% and hematite 2%, clay matrix 3% and 4% opaque minerals are found in the rock sample (Table. 1).

Plate no. 12: In this representative sample of rock quartz is abundantly found. 45% quartz grains are found in the representative sample of which 40% grains are monocrystalline and 5% are polycrystalline. Most of the quartz grains have unit extinction while some grains showing undulatory extinction. Most of the quartz grains have planar, point and concavo-convex contacts. The occurrence of plagioclase and alkali feldspar collectively constituted up to 3%. Plagioclase grains showing albite twining. The rock fragments are found up to 10% and include clasts of sedimentary and metamorphic rocks. Sedimentary lithic fragments constitute 5% and include grains of siltstone, limestone and chert. Metamorphic clasts of slate and schist occurred up to 5%. Cementing material in the rock sample is up to 30%. Hematite is the main cementing material and occurred up to 18% while calcite is also acting as cementing agent and present up to 12%. Accessory minerals are found in the rock sample. Muscovite occurs up to 2% of the sample and is deformed. Biotite occurs up to 1%. Epidote occur up to 1%. Clay matrix is up to 4%. Opaque minerals hematite and others constitute 6% (Table. 1) of the sample.

Table. 1. Model mineralogical composition of sandstone samples from Murree Formation.

Model Mineralogical Composition			Samples								
			(1,2)	(3,4)	(5,6)	(7)	(8)	(9)	(10)	(11)	(12)
Quartz	Monocrystalline		30	31	33	36	37	36	35	37	40
	Polycrystalline		5	4	3	4	3	4	5	3	5
Feldspar	Microcline		-	-	1	-	1	-	-	-	-
	Perthite		1	-	1	1	-	-	1	-	-
	Plagioclase		2	3	3	3	4	3	4	3	3
Rock Fragments	Igneous	Volcanics	-	-	2	-	-	3	2	-	-
	Metamorphic	Quartzite	-	1	1	-	-	-	2	-	-
		Slate	10	1	2	1	-	5	1	15	2
		Phyllite	-	-	-	2	-	-	-	-	-
		Schist	5	6	3	12	-	2	2	9	3
	Sedimentary	Sandstone	-	7	1	8	1	-	2	-	-
		Siltstone	1	-	5	2	3	2	7	2	2
		Limestone	1	5	10	3	15	2	3	2	1
		Dolomite	1	2	1	-	-	1	1	1	-
Accessory Minerals	Muscovite		5	1	2	-	1	3	1	7	2
	Biotite		2	3	1	2	3	1	1	3	1
	Tourmaline		-	1	-	-	2	-	-	3	-
	Epidote		-	2	-	1	-	1	-	-	1
	Sericite		1	-	-	1	-	-	-	-	-
	Hematite		2	-	3	-	-	3	4	2	3
Cement	Calcite		18	4	20	1	3	10	18	3	12
	Hematite		7	15	4	3	20	20	7	3	18
	Silica		-	-	1	-	-	-	-	-	-
Opaque minerals			5	5	2	17	3	4	1	4	3
Clay Matrix			4	5	1	1	1	2	2	3	4
Calcite veins			-	4	-	2	3	-	1	-	-
Total			100	100	100	100	100	100	100	100	100

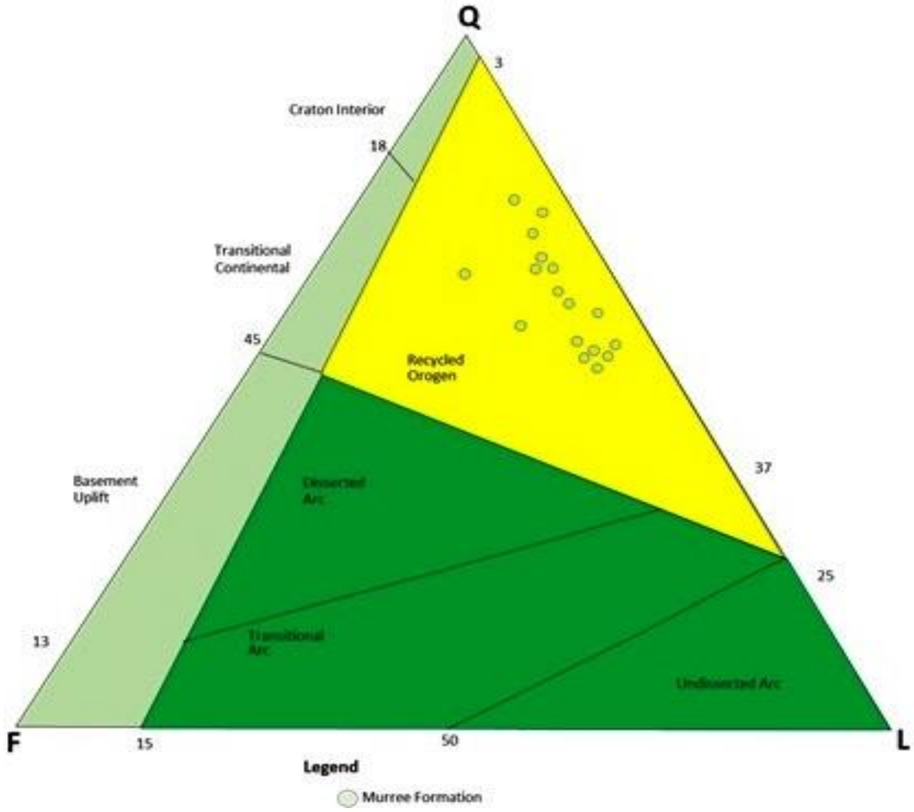

Fig. 10. Standard Triangular Plot (QFL) for provenance interpretation of sandstone of Murree formation. The field boundaries are after Dickenson *et al*. (1983). Q. Total quartz grains; F. Total feldspar grains, L. Total igneous, metamorphic and sediment.

DISCUSSION

The Murree Formation is a well-known example of Himalayan molasse deposit formed in a foreland basin during the Tertiary collision between the Indian and Eurasian plates. This foreland basin developed as a result of the Indian plate flexural down wrapping in response to crustal loading from advancing Himalayan orogen. As a result of folding, uplift and thrusting that followed high energy fluvial system rapidly eroded and delivered sediments into basin. The petrographic analysis of Murree Formation shows that the sandstones of Murree Formation are primarily lithic arenites consisting of feldspar, volcanic metamorphic and sedimentary clasts as well as quartz (both monocrystalline and polycrystalline).

Together with characteristics like undulatory extinction and deformation in quartz, the grains are angular to sub-rounded in shape, suggest a mixed provenance from both igneous and metamorphic sources, which is consistent with erosion of the rising Himalayas. A recycled orogenic origin is further supported by accessory minerals like muscovite, tourmaline, biotite, chlorite, and epidote. The feldspar also suggest derivation from metamorphic and igneous terranes, especially plagioclase exhibiting sericitization and albite twinning.

Different sedimentary features like ripple marks, cross bedding, mud cracks, groove marks, and intra-formational conglomerates provide field observations that support a fluvial depositional setting. Sandstone that ranges from grey to reddish brown representing variations in cementing material like hematite and calcite. The sandstones are found in recycled orogen field as indicated by provenance discrimination diagram and QFL (Fig. 10). This is in line with global models of foreland basin evolution which show that tectonic uplift, erosion and reworking result in multiple sedimentary cycles. Because of structural controls like a Riasi Thrust and Tatta Pani Anticline which have affected basin architecture and sediments pathways the stratigraphy and depositional environments of the region are more complex.

Conclusion: The Tatta Pani area of district Kotli, AJK offers a valuable geological insight into the tectono-sedimentary evolution of the Himalayan foreland basin. Detailed petrographic and field-based investigation of the Murree Formation and overlaying Siwalik Group reveal that the region lies within the eastern limb of the Hazra Kashmir Syntaxis, a structurally complex zone of the Sub Himalayas. Sandstones of Murree Formation are dominantly lithic arenites, as evidenced by their mineral composition and low clay matrix content. The presence of both angular to sub angular and rounded to sub rounded quartz grains suggests a dual provenance, nearby metamorphic and igneous sources for angular grains and more distance sources for rounded grains, indicating variable transport distance. While monocrystalline, non-undulatory quartz and feldspars like plagioclase and microcline indicate granitic sources, quartz grain textures such as undulatory extinction and polycrystalline confirm derivation from metamorphic rocks like schist, Phyllite, and quartzite. The impact of semi-arid to semi-humid depositional conditions with different levels of chemical weathering is reflected in the variation of feldspar to sericite. A provenance including high graded metamorphic and granitic terrains is further supported by the occurrence of accessory minerals such as tourmaline and muscovite. The main cementing agents, calcite and hematite, suggest post-depositional diagenetic processes.

Together with tectonic features like the Riasi Thrust and Tatta Pani Anticline, sedimentary features like intraformational micro-conglomerate, ripple marks, mud cracks and calcite veins show a dynamic depositional setting governed by continuous Himalayan uplift. As a record of Himalayan tectonic and sedimentary processes, the Murree Formation is important, and this study emphasizes the importance of merging petrography, field geology, and structural analysis in reconstructing the histories of foreland basins.

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