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Environmental controls on sedimentation, habitat development, and implications for palaeobiological reconstruction in the Middle Siwalik Group, Southern Indus Basin

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Abstract. The Middle Siwalik Group, located near Sehwan Town in the Northern Laki Range of the Southern Indus Basin, Sindh, Pakistan, extends for a stratigraphic thickness of approximately 1055 meters at the Kari Buthi Section (KBS). This study investigates the environmental controls on sedimentation and their role in the development of habitats within the region. The lithology of the area is composed of a range of sedimentary rocks, including Sandstone, Conglomerate, Conglomeratic Sandstone, Shale, Clay, and Mudstone. The facies analysis revealed six primary depositional facies: Conglomerate and Conglomeratic Sandstone (GT), Fine to Coarse-Grained Trough Cross-Bedded Sandstone (St), Fine to Coarse-Grained Flat-Bedded Sandstone (Sh), Shale (Fm), Mudstone (Mf), and Clay (Cf), each of which reflects distinct environmental and biological conditions during sediment deposition. Grain size distribution analysis, based on sieve data from seven representative loose sandstone samples, shows a mixture of fine to medium grains, with occasional very coarse grains. The sub-angular to sub-rounded grain shapes suggest a low-energy environment of deposition, characteristic of a braided fluvial system. Petrographic analysis conducted using a LEICA 2500p Transmitted Light Polarizing Microscope identified quartz (50-60%), feldspar (15-16%), and rock fragments (5%) as the primary constituents, with minor muscovite and biotite. This mineral composition, along with the sedimentary characteristics, indicates proximity to the sediment source, providing further evidence for the presence of a braided fluvial system. From a biological perspective, the sedimentary environment likely facilitated the development of various habitats for early biota, especially within the fine-grained deposits of mudstones and shales. These depositional settings would have provided potential substrates for microbial life and early forms of aquatic organisms, contributing to the overall habitat development within this ancient fluvial system. This study emphasizes the significant role of environmental factors-

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sediment supply, water energy, and biological influences in shaping both the sedimentary architecture and the habitat conditions of the Middle Siwalik Group. Understanding these interactions enhances our ability to reconstruct past ecosystems and the biological processes that governed sedimentation and habitat formation in the Southern Indus Basin.
Keywords: Petrography, Grain Size Distribution, Facies Categorization, Depositional Environment, Middle Sawilik Group of Northern Laki Range, Southern Indus Basin

Introduction

The Siwalik Group, a major Neogene-Quaternary stratigraphic unit of the Himalayan foreland basin, represents one of the most complete continental sedimentary archives of fluvial, climatic, and biological evolution in South Asia [1]. Extending in an east–west orientation along the southern Himalayan foothills, it provides an exceptional record of the interplay between tectonics, sedimentation, and biotic adaptation associated with the uplift of the Himalayas [2]. The Middle Siwalik Group, in particular, chronicles the phase of intensified Himalayan exhumation and foreland sedimentation, marking a key period of paleoenvironmental transformation and ecosystem diversification within the Indus Basin. These deposits capture the coupling between mountain-building processes, sediment dispersal systems, and biological responses to changing habitats and hydrological regimes [3].

The Siwalik Group extends over a 6-90 km wide belt across Bhutan, Nepal, India, and Pakistan, forming a regionally continuous fluvial succession that spans from the Middle Miocene to the Upper Pleistocene [4]. This broad temporal and spatial coverage provides an unparalleled opportunity to reconstruct the Neogene terrestrial paleoecology and sedimentary dynamics of the Himalayan foreland. Sedimentary structures typical of the Middle Siwaliks, such as trough cross-bedding, planar lamination, and ripple stratification, reflect high-energy braided and meandering fluvial processes that shaped both the geomorphic and ecological landscape [5]. Within these deposits, distinct lithofacies associations, including conglomerate and conglomeratic sandstone (Gt), trough cross-bedded sandstone (St), flat-bedded sandstone (Sh), shale (Fm), mudstone (Mf), and clay facies (Cf), record a spectrum of depositional environments from channel bars to floodplains [6].

In the present study, the Kari Buthi Section, located in the northern part of the Laki Range near Sehwan Town, District Jamshoro, Sindh, Pakistan, provides an excellent natural laboratory for investigating these fluvial and biological processes [7]. The section lies at coordinates 26°20'12"N and 67°50'42"E (Topographic Sheet No. 35N/15) and exposes one of the most complete Middle Siwalik successions in the southern Indus Basin (Figure 1), reaching a thickness of approximately 1055 feet near Manchar Lake [8]. Stratigraphically, the succession forms part of a sequence of five major formations: Laki, Kirthar, Nari, Middle Siwalik, and Dada Conglomerate, representing progressive sedimentary and tectonic evolution from marine to continental conditions in the Sindh region (Table 1)

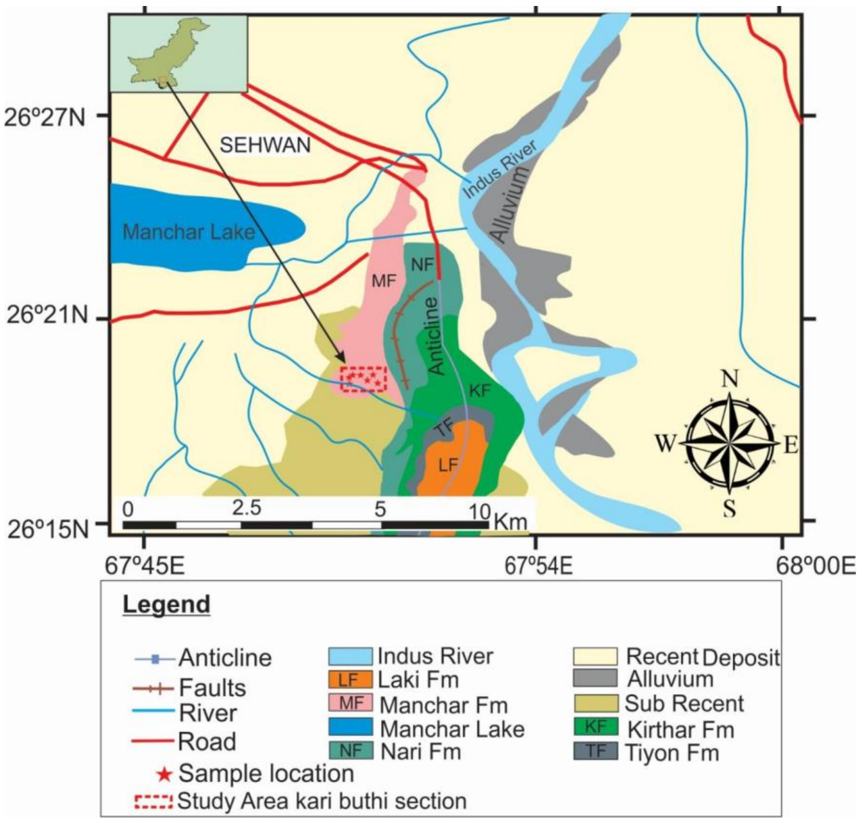

Figure 1. Geological setting of the Middle Siwaliks at southern Indus Basin

Lithologically, the Kari Buthi Section is composed primarily of interbedded sandstone, shale, and subordinate conglomerate layers [9]. The lower part of the succession is dominated by soft, yellowish-brown shale interbedded with fine-grained sandstone and siltstone (Figure 2), while the upper part transitions into grey to greenish-grey, gritty to pebbly sandstone with pronounced cross-bedding [10,11]. Conglomeratic beds are typically poorly cemented and contain sandstone pebbles along with fragments of arenaceous and fossiliferous limestone, suggesting periodic high-energy depositional episodes related to river channel migration and debris flow events sourced from the Himalayan hinterland [12]. These coarse-grained intervals record the proximal fluvial input of clastic detritus, whereas the fine-grained shale and mudstone represent low-energy overbank and floodplain deposits conducive to vegetation establishment and soil development.

Table 1

Five formations are arranged from oldest to youngest: Laki, Kirthar, Nari, Middle Siwalik, and Dada Conglomerate Formations

Age	Formation	Lithology
Pleistocene	Dada Conglomerate	Conglomerate and Boulders and Pebbles
		Conglomerate and Sandstone

Miocene to Pliocene	Middle Siwalik Group	Shale and Conglomeratic Sandstone
		Mudstone
	Unconformity	
Oligocene	Nari Formation	Sandstone, Limestone and Shale
	Unconformity	
Eocene	Kirthar Formation	Limestone
	Laki Formation	Limestone, Shale, and Sandstone

The lithological composition of the Kari Buthi Section shows strong correlation with the Nari, Gaj, and Kirthar formations, all of which exhibit mixed siliciclastic and carbonate facies, reflecting the gradual transition from marine to continental sedimentation during the late Neogene [11]. The sedimentological features, such as trough cross-bedding, planar lamination, and gradational facies contacts, indicate an active fluvial regime dominated by alternating braided-channel and floodplain environments [13]. These dynamic depositional conditions were likely modulated by monsoonal climatic variations, leading to cyclic patterns of flooding, erosion, and soil formation.

Beyond its sedimentological importance, the Middle Siwalik Group is of profound biological and palaeoecological significance, preserving evidence of fluvial ecosystem evolution during the Neogene. Fossil plant remains, root traces, and paleosol horizons document the establishment of riparian vegetation and terrestrial habitats within this dynamic floodplain system. These vegetated surfaces played a critical role in sediment stabilization and nutrient cycling, representing early instances of biogeomorphic feedback between vegetation and sedimentation [14]. The alternation of high-energy channel fills with low-energy over bank deposits further suggests fluctuating ecological niches that supported diverse terrestrial and aquatic communities.

The present study, therefore, aims to evaluate the environmental controls on sedimentation, habitat development, and palaeobiological reconstruction of the Middle Siwalik Group in the Southern Indus Basin. By integrating lithofacies analysis, grain-size data, and petrographic observations with palaeoecological interpretations, this research seeks to elucidate how hydrodynamic variability, sediment supply, and biological adaptation collectively shaped the fluvial landscapes of the Middle Siwaliks. This multidisciplinary approach provides new insights into the linkages between sedimentary processes and ecosystem resilience, contributing to a more comprehensive understanding of Neogene paleoenvironmental evolution in the Himalayan foreland domain.

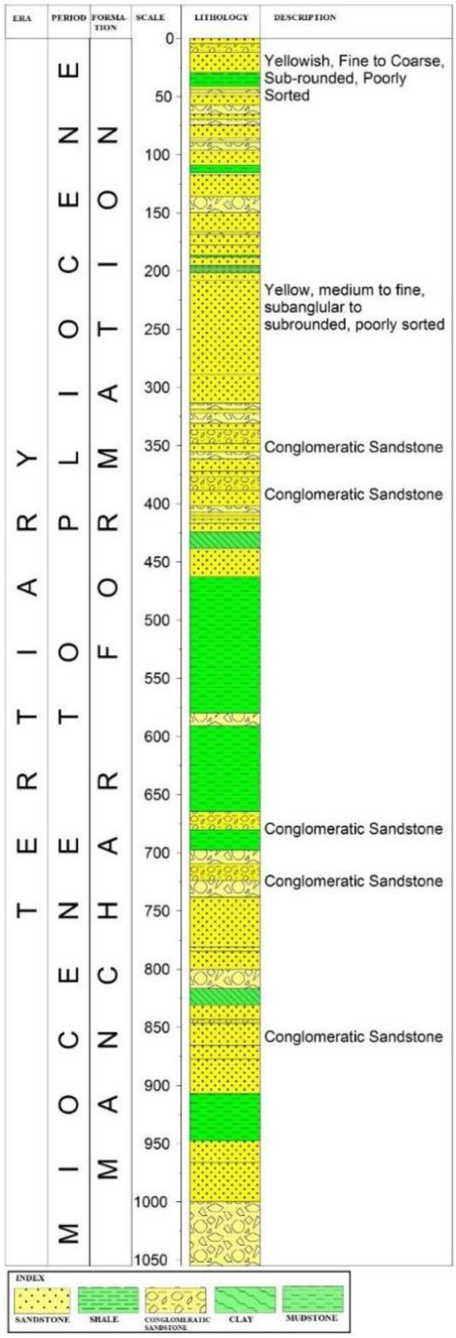

Figure 2. Columnar section of the Middle Siwaliks at southern Indus Basin

Materials and research methods

For the current study on the Middle Siwalik group, two primary methodologies were employed: fieldwork and laboratory analysis. A total of twenty sandstone samples, both loose and compact, were collected from the field. Seven of these samples underwent thin-section analysis at the laboratory of the Geological Survey of Pakistan. Field-based data collection involved the systematic sampling of outcrops, with a comprehensive stratigraphic section of the

Middle Siwalik at Kari Buthi being measured. Rock samples were collected for detailed analysis and further investigation.

Section measurement

The Kari Buthi Section was selected for this investigation, and the geological section was surveyed using the compass and tape method; the layers were measured directly where applicable. During the section measurement, 14 samples were selected from each lithofacies. The conformable contacts of the Middle Siwalik with the Nari Formation were chosen as the measurement's starting point (Figure 3), and it was measured continually with recent to sub-recent deposits up to its unconformity at the top of the section.

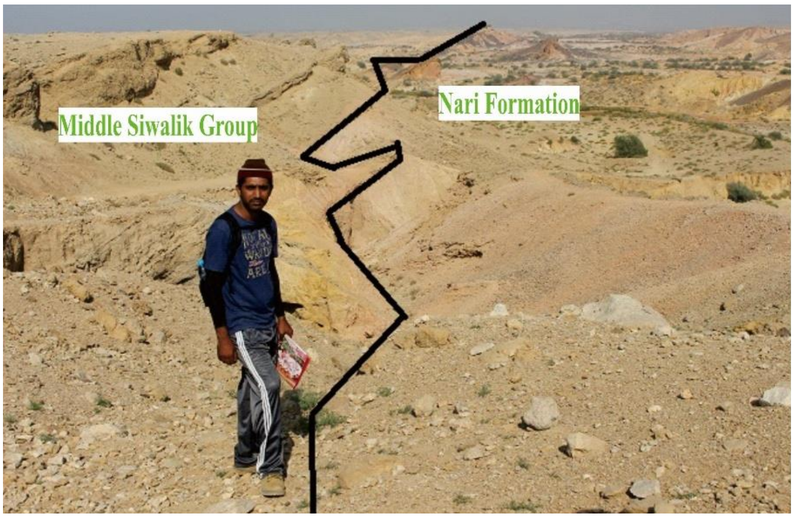

Figure 3. Lower contact of the Middle Siwalik group with the Nari Formation

At the Kari Buthi Section, the entire thickness of the Middle Siwalik group is 1055 meters (Figure 1). Sample (a) is provided by the Middle Siwalik Group on the Kari Buthi trend with a thickness of 2,719 m, (b) Samples were taken from a bed 4,436 m impenetrable. Calcareous cement was reacted with HCL. (c) It has a sub-angular to sub-rounded shape, is well-sorted, and measures 16.472 meters in unit thickness. (d) It has minimal sorting, a 24.629-meter bed thickness, and calcareous cement that can be identified by its reaction with HCl. (e) It is made up of a 5.56-meter-thick layer with calcareous cement visible, and the sandstone is grey with medium to fine grain sizes, angular to sub-rounded shapes, and is fairly sorted. (f) Its shape is subangular to subrounded, and the grain size is moderately sorted. Calcareous cement is present in the sandstone, and the bed thickness is 13.515 meters. (g) The sample has a sub-angular to sub-rounded shape, a poorly sorted texture, calcareous cement, and a bed thickness of more than 3 meters in the study area.

Petrographic analysis

For the petrographic study, standard thin sections were prepared from seven hard, consolidated to semi-consolidated materials. The selected samples for this section preparation (Figure 4) were dispatched to Geosciences Advance Research Laboratories, Islamabad. Thin sections were examined under the Polarizing Microscope at the Centre for Pure and Applied Geology, University of Sindh, Jamshoro, to assess the mineral composition and textural characteristics. The Sawliks group (Miocene to Pliocene) is exposed at Manchar Lake in Sehwan, Sindh, Pakistan; its lithofacies were studied to establish the environment and mechanism that caused its deposition [15]. Our current study has identified four lithofacies types in the Middle Siwaliks at the southern Indus Basin: (Gt, St, Sh, Fm), which occur in a particular sequence and are characterized by a coarsening upward trend in grain size. The Middle Siwalik group in the studied area is predominantly clastic, with lithology ranging from conglomerate to conglomeratic sandstone, sandstone, shale, clay, and mudstone [16]. Boring and burrows, wood fossils, and roots can be observed in conglomerate, conglomeratic sandstone, and sandstone with trough cross-bedding [17].

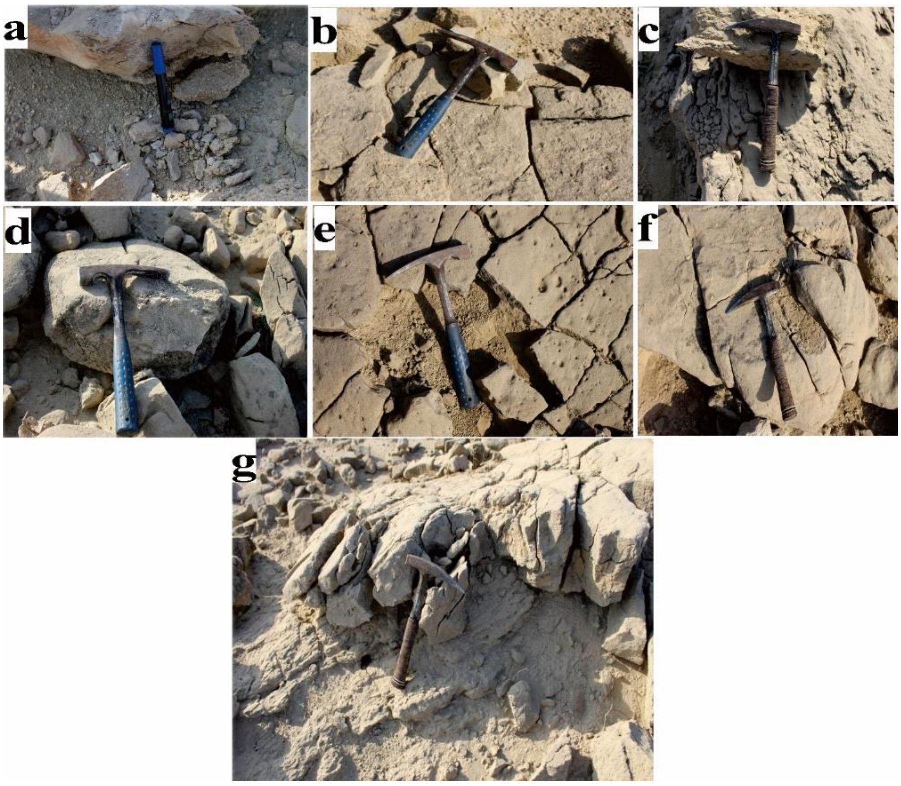

Figure 4. (a) The sample is sandstone, with fine to extremely fine grains and some coarse-grain particles. It is greenish-white. **(b)** Sandstone is semi-consolidated, fine to medium-grained in size, and yellow. The calcareous cement was identified when it was treated and reacted with HCL**. (c)** Sandstone reveals that it is grey and has a medium to fine grain size. **(d)** Sandstone is grey, with medium to small grain-size particles that are angular to surround it. **(e)** The sample of sandstone is grey in hue, with medium to fine grain size, angular to sub-round in shape, and fairly sorted. **(f)** Sandstone is grey in hue, with fine to very fine grain size**. (g)** Sandstone is grey, with medium to coarse grain sizes, it contains subangular to subrounded form, and a poorly sorted texture

Grain size distribution

Grain size analysis is one of the most important techniques in sedimentology for extracting geological information from loose sand and sandstone [18]. Defined that the size of grains and their statistical parameters are helpful in the interpretation of the depositional environment of friable sandstones and for facies characterization [19]. Tucker (1991) suggested that the transportation and deposition of pre-existing rock particles are well understood through grain analysis, and it also helps to know the lithologies of the different environments [20]. The grain size analysis helps to interpret the sedimentological process involved and the type of prevalent environment of deposition [21]. During fieldwork, four principle lithofacies were identified and seven (7), loose sandstone samples from those lithofacies were selected and prepared for sieving by using "The Octagon Digital sieve shaker" available at the sedimentological laboratory of the Centre for Pure and Applied Geology. The selected (-1 φ, 0φ,1φ,2φ,3φ,4φ, and Pan) mesh sizes were stacked on the sieving machine and operated for the standard time of ten minutes. After the finishing of the standard time of 10 minutes shaker sieve screens were removed, and every screen was weighed on the digital electronic balance and noted on the data sheet. Sieved data (raw data) was calculated by following the formula for the use of statistical work (cumulative frequency curves).

Results

Facies analysis

The Conglomeratic Sandstone Facies suggests stream flow deposits but may also result from rapid, decelerating, high-magnitude, gravel-dominated stream flow under flashy discharge conditions. Coarse channel-floor deposits form from lag gravel in deeper channel parts after finer material is winnowed. The subangular fragments and poor sorting indicate minimal stream reworking, likely due to the collapse of cohesive bank sediments into nearby channels, caused by rotational slumping that brecciates material below the thalweg depth. Some channel conglomerate bodies fine upward into sandstone, indicating flow diminution from channel diversion or lateral migration (Figure 5a). The Sandstone Facies (St) consists of laterally persistent sandstone sheets, dominated by large trough cross-stratification with subordinate small-scale planar and trough cross-stratification, interpreted as distal, sand-dominant braided fluvial deposits. Individual channel-fill sequences stack without vertical accretion deposits.

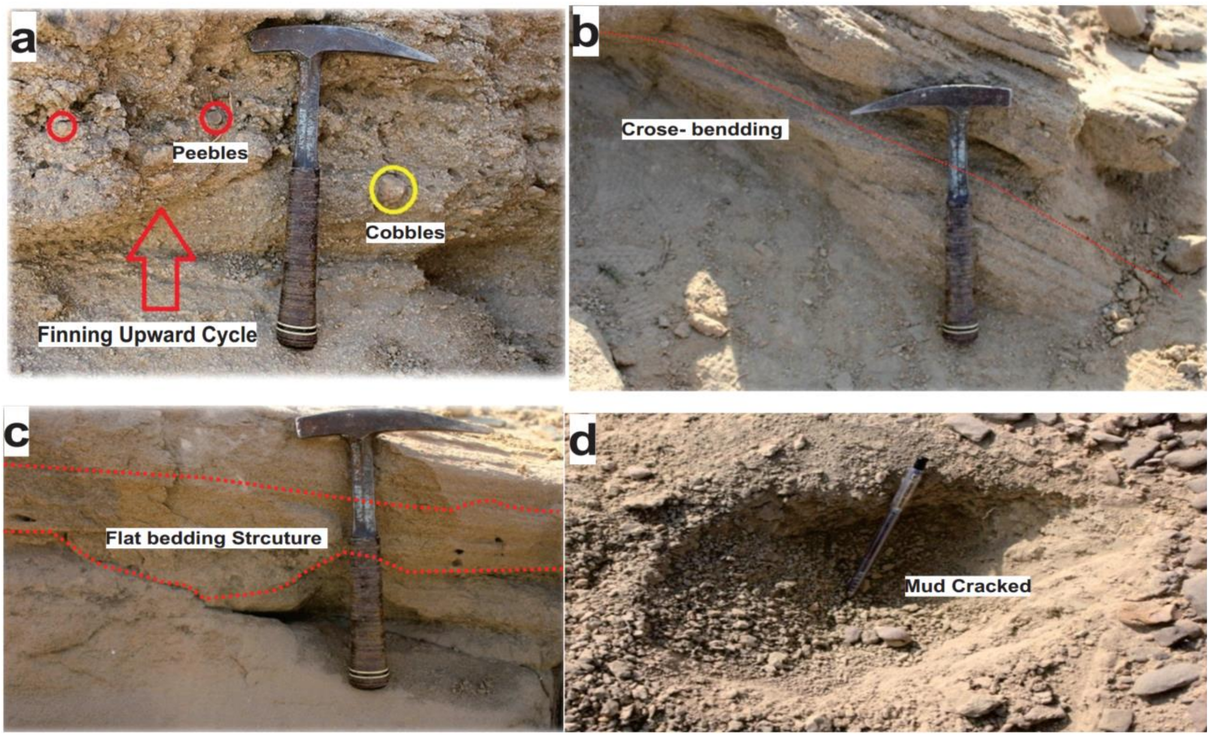

Figure 5. (a) Conglomeratic Sandstone Facies indicates stream flow deposits, (**b**) Sandstone Facies (St) with crose bending, **(c)** plane bedding sandstone (SH), **(d)** Shale facies (FM), sandy silt and mud-cracked

Large-scale inclined strata represent channel bar deposits from lateral migration or superposition of different bars or channel belts. Intraformational conglomerates along erosion surfaces represent cut-bank material eroded during lateral channel migration. Multistory sandstone bodies reflect channel bar superposition within aggrading belts before abandonment. Trough and planar cross-stratification suggest sinuous- and straight-crested dunes, with the latter forming under higher velocities. The absence of mud cracks and root traces indicates perennial river flow, while the lack of vertical accretion deposits points to the erosive capability of shifting channels (Figure 5b). The Fine to Coarse-grained Flat-bedding Sandstone (Sh) is a crevasse channel-fill deposit, with the lack of fining upward trends implying low sinuosity paleo-streams. Mud clasts, derived from levee and floodplain sediments, are intraformational. Rapid sedimentation from mixed-load streams is reflected in textural immaturity, while the upward increase in shaly lenses, burrows, and root traces suggests crevasse channel abandonment and waning current energy. Features like current ripple cross-lamination, trough cross-stratification, and planar stratification reflect deposition from migrating ripples, dunes, and upper-stage plane beds. Trace fossils and pedogenic features suggest overbank sand deposits were sites of insect burrowing, plant growth, and weak soil development (Figure 5c). The Shale Facies (Fm), consisting of sandy silt and mud-clay units, likely represents levee and distal splay deposits as indicated by burrows and calcareous concretions, with burrows and rootlets facilitating calcareous solution movement. The Middle Siwalik group at KBS typifies a braided river system, with variability in grain size reflecting differences in provenance and/or water stage fluctuations, while fine-grained lithological characteristics suggest significant overbank deposition (Figure 5d).

Grain size distribution analysis (GSD)

This report focuses on seven sandstone samples (Figure 6, KBS-3 to KBS-9), characterized through their respective cumulative frequency curves. These curves graphically represent the relationship between grain size, expressed in phi (φ) units, and the cumulative weight percentage of sediment finer than that size. The shape and position of these curves provide a visual representation of the sediment's sorting, a key indicator of the depositional environment. Samples KBS-3 and KBS-4 Exhibit steep cumulative frequency curves, signifying well-sorted sediments with a narrow range of grain sizes. This characteristic suggests deposition under relatively consistent hydrodynamic conditions, where prolonged or repetitive processes effectively sorted the grains based on size. Such well-sorted sediments are often associated with environments characterized by continuous winnowing and reworking, such as beach settings or aeolian dunes. In these environments, the constant action of waves or wind selectively transports and deposits grains of similar sizes. Conversely, samples KBS-5C and KBS-6B display more gradual curves, indicative of poorly sorted sediments with a wide range of grain sizes.

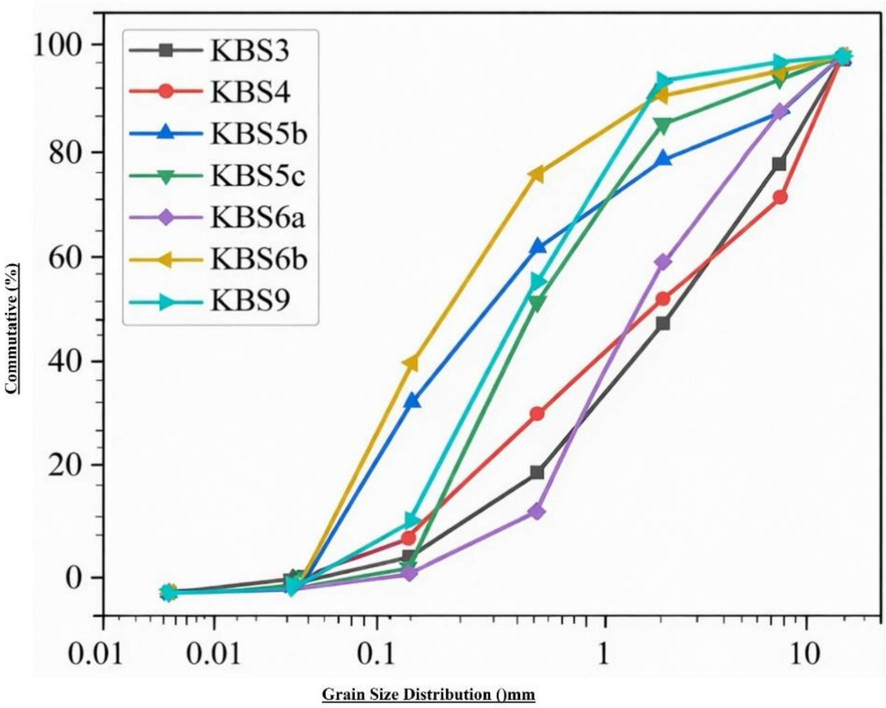

Figure 6. The grain size distribution of seven sandstone samples (KBS-3 to KBS-9) is represented as cumulative frequency curves. The x-axis depicts grain size using the phi (φ) scale, while the y-axis represents the cumulative weight percentage of sediment finer than the corresponding grain size

This pattern suggests deposition under fluctuating energy conditions, where rapid deposition or limited reworking prevented effective grain size sorting. Such poorly sorted sediments are commonly associated with environments characterized by rapid depositional events, such as alluvial fans, debris flows, or glacial outwash plains. In these settings, the sudden influx of sediment from various sources, coupled with limited reworking, results in a heterogeneous mixture of grain sizes. The inflection point of each curve offers further insights into the dominant grain size fraction within the sample. For instance, the rightward inflection of KBS-9 suggests a predominance of fine-grained material, potentially indicative of a low-energy depositional environment or the influence of suspension settling. This pattern could point towards deposition in a lacustrine or distal marine setting, where fine-grained sediments settle out of suspension in relatively calm waters. On the other hand, the more symmetrical curve of KBS-6A suggests a more balanced distribution of grain sizes, potentially reflecting a depositional environment with moderate energy levels and a mixed sediment supply (Figure 6).

Petrography result

There exists a relationship between the detrital components of clastic sedimentary rocks and the tectonic context of their source location. It should be noted, however, that detrital composition is influenced by several other critical factors, including travel history. In addition to tectonic origin, the depositional environment and paleoclimate cannot be overlooked, nor can diagenetic alteration of sand composition. Climate and tectonics are intertwined. Statistical analyses of the relationship between composition and depositional facies revealed that the association remains weak and that the control imposed by changes in source-area geology was significantly overwhelmed by the relationship. With the use of petrography, sedimentary rocks may be easily identified and categorized by considering the megascopic and microscopic features of the constituent minerals. Standard thin slices are regularly made and examined under a polarized microscope for any petrographic inquiry. The consolidated to semi-consolidated samples of the Middle Siwalik group from the Kari Buthi Section were chosen for the thin section investigation in this regard. The constituent minerals, textural characteristics, and alteration products of all created thin sections were extensively examined. The outcomes are presented in the following sections (Figure 7a). Both types of feldspar (Plagioclase and Orthoclase) are present in the quartz (55 to 60%), which is sub-angular to sub-rounded, very fine to fine-grained, and occasionally coarse-grained. The 10% sedimentary lithic pieces are bonded to the grains with calcareous cement (Figure 7b).

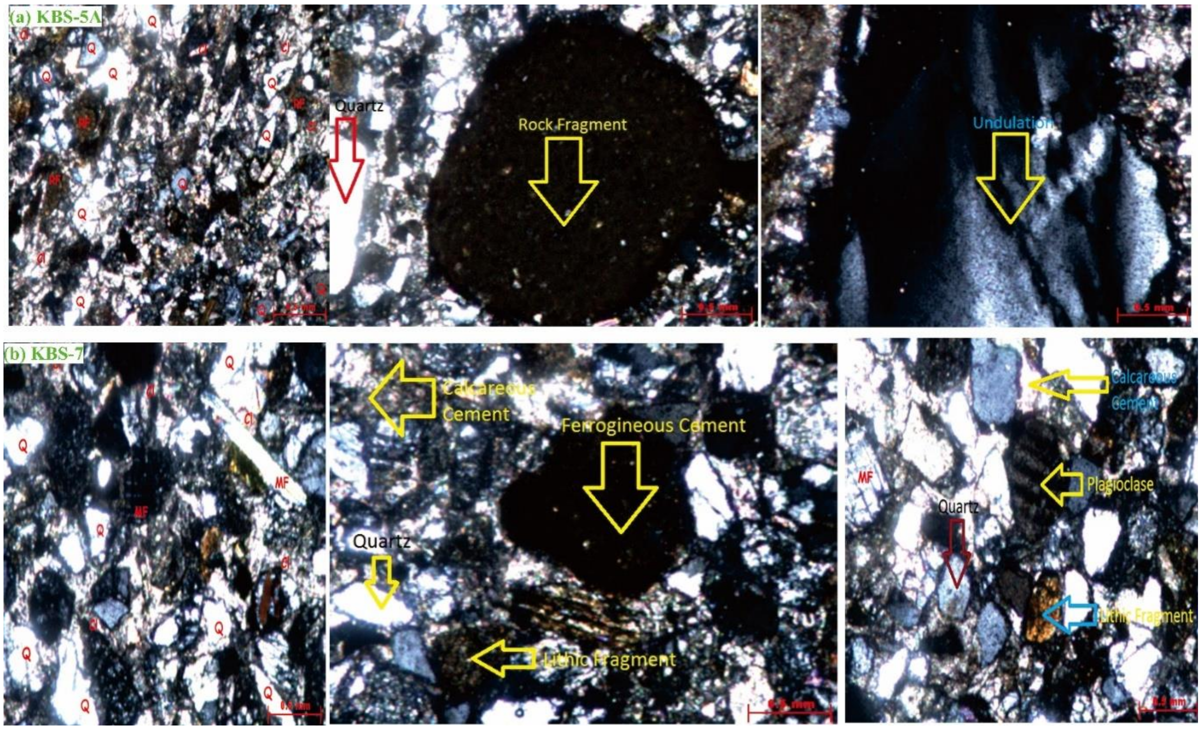

Figure 7. The appearance of sandstone thin section and photomicrograph of the middle sialic group at Kari Buthi section **(a)** quartz grain to fine grain and plagioclase, orthoclase, and calcareous. **(b)** Muscovite, biotite lithic pieces, Quartz ingredient

The main component, Quartz, is angular to sub-angular, fine to extremely fine-grained, and occasionally very coarse-grained (40 to 45 percent). The grains exhibit point-to-point contact. Both orthoclase and plagioclase feldspar are present, and a small percentage of straight muscovite and biotite flakes were also noted. It contains some sedimentary lithic fragments, and the grains are joined by calcareous cement. (Figure 8a). The fine to extremely fine quartz grains are encased in calcareous cement. The loose, angular to sub-angular shape and point contact of the grains indicate loose compaction. This sample's main components are quartz (between 55 and 60 percent), calcareous cement (between 35 and 37 percent), and lithic fragments (3 to 4 percent). Significant amounts of Plagioclase and K-feldspar are also present, along with 2% Muscovite and less than 1% Biotite (Figure 8b).

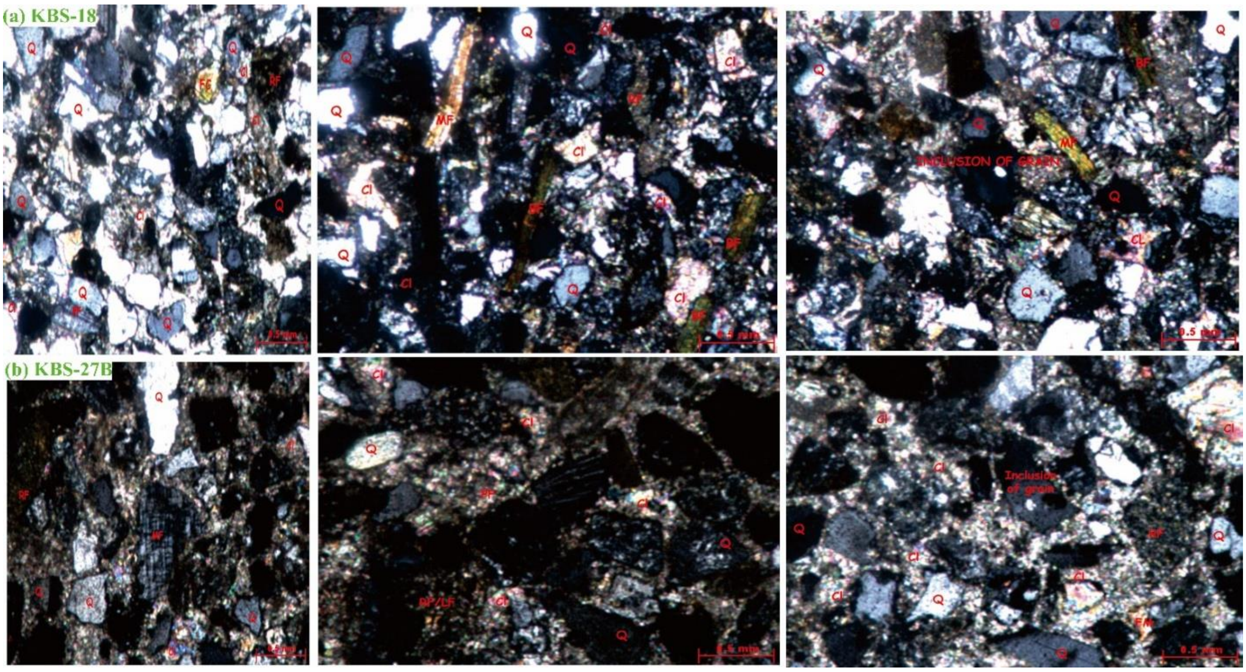

Figure 8. Show The appearance of sandstone thin section and photomicrograph **(a)** Lithic Fragments, Plagioclase Feldspar, K-feldspar, Quartz, and Biotite. **(b)** Plagioclase contains cross-aged rock fragments of Quartz and Biotite

Quartz has parts with small grain size and parts with medium to coarse grain size in the thin section. From point-to-point grain contact, it is angular to sub-angular in shape and loosely compacted. The main component of the sample is quartz (55 to 60%). Both feldspar types (Plagioclase and Orthoclase) have been identified, but only Plagioclase exhibits cross-aged twinning and contains significant amounts of calcareous cement (30 to 33%), rock fragments, and other minerals like Biotite (1%). (Figure 9a) In the thin section, quartz accounts for (50 to 55%). Microcline and K-plagioclase are examples of feldspar that are found. While ferruginous cement is only found in a small amount, it contains 30-35 percent calcareous cement. There are fewer than 1% sedimentary lithic fragments, Biotite, and Muscovite found. (Figure 9b) Quartz appears to be the most abundant mineral, accounting for 55 to 58% of all minerals. Plagioclase and Orthoclase are the two types of feldspars discovered in the thin section. Calcareous cement (30-32%), sedimentary lithic fragments, and needle inclusions in quartz are abundant in the thin sections. (Figure 8c). It is composed of medium to coarse-grained elements that range in shape from sub-angular to sub-rounded. It has poor compaction due to point-to-point contact. Needle inclusions can be seen in quartz. Quartz is the most common mineral found in this sample (55 to 56%), along with both types of feldspar (Orthoclase and Plagioclase), as well as calcareous cement (30%) and lithic fragments (4%). Biotite (less than 1%) and Muscovite (less than 1%).

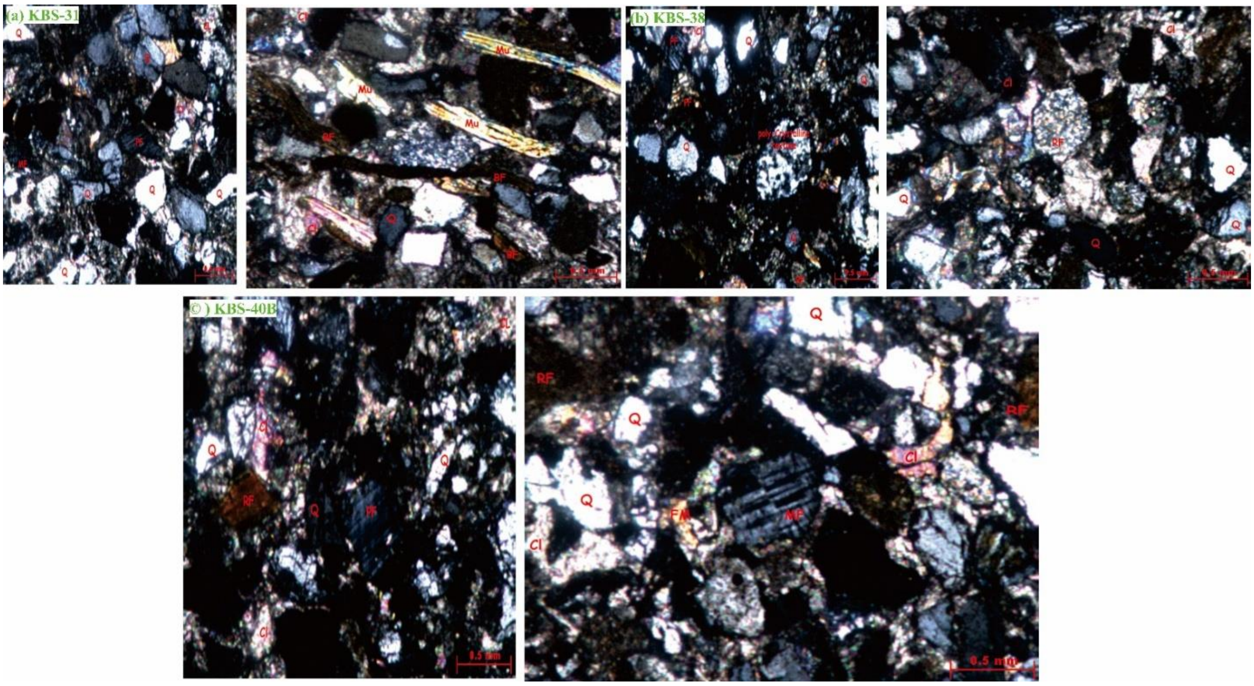

Figure 9. Show the appearance of sandstone thin section and photomicrograph of the middle sialic group at Kari buthi section **(a)** Microcline and k-plagioclase, Quartz and other sedimentary lithic fragments, Biotite and Muscovite. **(b)** Plagioclase, orthoclase, and sedimentary lithic fragments such as quartz. **(c)** Quartz is common in Orthoclase, Plagioclase, Biotite, and Muscovite

The QFR (Quartz-Feldspar-Rock Fragments) triangular classification diagram categorizes sandstones based on the Dot classification. The apexes represent quartz (Q), feldspar (F), and rock fragments (RF). The findings show over 90% quartz as Quartzarenite, located at the top. Subarkose and Sublitharenite occupy intermediate fields between Quartz arenite and the other two components, with 75–90% quartz, indicating moderate amounts of feldspar and rock fragments. Arkose, on the left, signifies feldspar-dominant sandstones (over 25%), while Lithic Arenite, on the right, marks sandstones with a greater proportion of rock fragments. The red dots represent samples primarily composed of quartz with moderate amounts of feldspar and rock fragments, placing them near the boundaries between Subarkose and Sublitharenite. The matrix percentage (0-15%) at the bottom corresponds to the proportion of finer material in the sandstone (Figure 10).

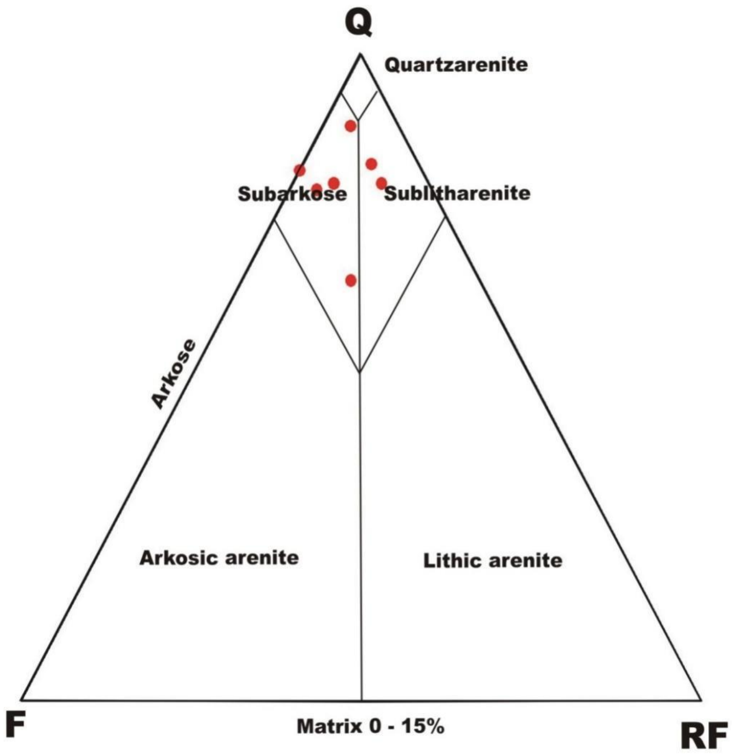

Figure 10. Show the Dot Classification of Middle Siwaliks at southern Indus Basin

Discussion

Sedimentary architecture and environmental controls

The Middle Siwalik Group exposed near Manchar Lake, Sehwan Town, District Jamshoro, Sindh, Pakistan, represents a dynamic fluvial succession shaped by variable hydrological regimes and climatic oscillations. Lithofacies, textural, and petrographic analyses collectively suggest deposition within a braided fluvial system characterized by alternating high- and low-energy depositional episodes. The dominance of conglomeratic sandstone (Gt), trough cross-bedded sandstone (St), and fine-grained flat-bedded sandstone (Sh) indicates a complex interaction between channel migration, sediment supply, and flow variability [22–24].

The Gt facies, with a total thickness of 263.334 m (24.952% of the succession), represents proximal channel deposits formed under rapid sediment aggradation and turbulent flow. These coarse-grained, matrix-supported conglomerates reflect episodic floods that transported sediments from the Himalayan hinterland through high-gradient channels [24]. The St facies (168.308 m; 15.948%) developed from the migration of sinuous-crested dunes in moderate flow conditions, representing point-bar and mid-channel accretion surfaces [25–28]. The Sh facies (395.692 m; 37.494%) corresponds to lower-energy bar-top and levee deposits, where finer sediments accumulated from waning flows [27]. The Fm facies (20.862 m; 1.976%) marks suspension fallout in floodplain and overbank settings during low-energy episodes. Collectively, these facies record lateral and vertical facies transitions typical of multi-channel braided systems dominated by episodic floods and sediment pulses [23].

Hydrological variability, likely governed by monsoonal climate forcing, exerted primary control on sedimentation. Intense rainfall during peak monsoons led to flash floods, high sediment discharge, and channel avulsion, while dry phases promoted pedogenic stabilization and vegetation colonization. These alternating processes established a sedimentary architecture in which energy regimes directly influenced habitat structure, setting the foundation for subsequent biotic colonization and paleoecological development.

Textural and petrographic signatures of environmental energy

Grain size and textural parameters provide crucial evidence of depositional processes and paleoenvironmental energy. Based on Folk's (1951) classification [29], the sandstones of the Middle Siwalik Group range from immature to sub-mature, characterized by moderate to poor sorting and subangular to subrounded grains. The presence of >5% clay matrix in some horizons indicates limited sedimentary reworking and rapid deposition, consistent with proximal alluvial and braided river settings. These immature textures, coupled with high feldspar (10-12%) and lithic fragment content (6–7%), point to a short transport distance from the Himalayan arc and minimal compositional maturity.

Petrographically, the Manchar Lake sandstones are composed predominantly of quartz (50-55%), cement (30-32%), and minor feldspar and lithic fragments, corresponding to lithic arenite to sublitharenite composition. The high cement proportion suggests early diagenetic processes under fluctuating groundwater saturation conditions, reflecting alternating wet-dry cycles typical of monsoon-dominated floodplains [24]. These mineralogical and textural features underscore the rapid sedimentation and dynamic hydrological regime that governed the environmental evolution of the Middle Siwalik landscape.

Fluvial habitat zonation and ecosystem structuring

The sedimentary framework of the Middle Siwalik Group provides a basis for reconstructing fluvial habitat zonation and associated biological gradients. High-energy channels (Gt and St) formed unstable habitats dominated by sediment mobility and scouring, restricting permanent vegetation but allowing colonization by pioneer flora during hydrological recessions. Root traces and rhizoliths preserved within bar-top and levee deposits (Sh facies) record phases of riparian vegetation establishment following flood events [30].

These vegetation patches, likely comprising flood-tolerant angiosperms, grasses, and early C_4 taxa, acted as biogeomorphic agents, reinforcing channel banks through root stabilization and influencing sediment entrainment dynamics [31-33]. The development of root mats within fine-grained intervals indicates repeated colonization and erosion cycles, evidencing close feedback between biological stabilization and sedimentary reorganization. Over time, these processes facilitated the emergence of riparian microhabitats characterized by high nutrient turnover, moisture retention, and bioturbation activity.

In contrast, low-energy floodplain and overbank environments represented by Fm facies hosted stable, waterlogged substrates suitable for aquatic and semi-aquatic communities. The fine-grained, anoxic shales and mudstones likely supported benthic invertebrates, ostracods, mollusks, and early fish larvae. Trace fossils and burrow structures preserved in these facies indicate a thriving benthic ecosystem with microbial mat colonization as the basal trophic component [34,35]. Photosynthetic algae and cyanobacterial biofilms contributed to organic matter cycling and sediment biostabilization, forming micro-ecosystems resilient to hydrological fluctuations [34,35].

Bio-geomorphic feedback and environmental evolution

The interaction between biological colonization and sedimentary dynamics established biogeomorphic feedback mechanisms that shaped habitat persistence and sedimentation patterns. Vegetation colonization on bar surfaces reduced flow velocity, encouraged fine-sediment deposition, and led to localized overbank accretion. Conversely, vegetation removal during floods accelerated erosion, resetting ecological succession. These alternating processes created a patchy mosaic of habitats, ranging from bare sandbars to vegetated levees and organic-rich floodplains, that collectively enhanced biodiversity and ecological resilience.

Sedimentological evidence, such as interbedded root traces, mud drapes, and pedogenic horizons, attests to short-lived stability phases between successive floods [30,31]. Such cycles of disturbance and recovery likely drove evolutionary pressures favoring species with rapid life cycles, dispersal capabilities, and physiological tolerance to moisture stress. The recurring colonization events reflect an ecosystem functioning under disturbance-mediated equilibrium, where resilience and opportunism determined biotic survival and proliferation [36, 37].

Conclusion

This study provides a detailed sedimentological and paleoecological assessment of the Middle Siwalik Group at the Kari Buthi Section, Southern Indus Basin. The findings present the first integrated analysis of facies architecture, depositional environment, and biological interactions within this Neogene fluvial system. The succession is characterized by repetitive fining-upward cycles composed of four major lithofacies: conglomeratic sandstone (Gt), trough cross-bedded sandstone (St), flat-bedded sandstone (Sh), and shale (Fm). These facies reflect deposition in a braided fluvial environment where alternating high- and low-energy regimes controlled sedimentation. The Gt facies, consisting of coarse-grained, poorly sorted conglomerates, represents high-energy channel deposits formed by rapid aggradation during flood events. The St and Sh facies correspond to moderate-energy bar and levee deposits formed under fluctuating discharge conditions, whereas the Fm facies marks fine-grained overbank and floodplain accumulation during flow quiescence.

Grain-size and textural analyses indicate that the sandstones are immature to sub-mature, with poorly sorted, subangular to subrounded grains. High feldspar (10–12%) and lithic fragment contents (6–7%) suggest a proximal Himalayan source and short transport distance. Petrographic observations reveal quartz dominance (50–55%) with calcareous cement (20–30%), supporting rapid burial and limited diagenetic alteration. According to the DOT classification, these sandstones range from sub-arkosic to sublitharenite, consistent with active fluvial channel deposition in a tectonically dynamic foreland basin.

From a biological perspective, the Siwalik fluvial system hosted dynamic riparian ecosystems adapted to frequent disturbance. Root traces and rhizoliths within the Sh facies record colonization by flood-tolerant vegetation that stabilized sediments and modified local hydrology. Fine-grained Fm deposits, representing low-energy settings, supported aquatic and benthic communities, including invertebrates, ostracods, and microbial mats. These organisms contributed to organic matter cycling and substrate bio stabilization, forming an early example of biogeomorphic feedback within a foreland river system.

Overall, the lithological, petrographic, and biological evidence collectively indicate that the Middle Siwalik deposits at Kari Buthi formed in a braided river system influenced by monsoonal climate and Himalayan tectonism. Environmental energy regimes, sediment supply, and vegetation interactions jointly controlled sediment dispersal, habitat development, and fossil preservation, providing new insights into Neogene fluvial ecosystem evolution within the southern Indus Basin.

Author Contributions

S.S.J. – Writing–review and editing, writing original draft, visualization, validation, software, methodology, formal analysis, data curation, and conceptualization; **A.A.K. –** Review and editing, visualization; **K.J. –** Review and editing, visualization; **M.A.N. –** Validation, formal analysis, data curation; **N.A. –** Review and editing.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could possibly influence the results of the work presented in this article.

Compliance with ethical standards

This article does not contain a description of studies performed by the authors involving people or using animals as objects.

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Оңтүстік Инд бассейнінің Орта Сивалик тобында шөгінділердің түзілуіне, тіршілік ету ортасының дамуына қоршаған орта факторларының әсері және олардың палеобиологиялық қайта құрудағы маңызы

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Аңдатпа. Пәкістанның Синд қаласындағы Оңтүстік Инд бассейнінің Солтүстік Лаки жотасындағы Сехван қаласының маңында орналасқан Орта Сивалик тобы Кари Бути учаскесінде (KBS) шамамен 1055 метр стратиграфиялық қалыңдыққа созылып жатыр. Бұл зерттеу шөгінділердің түзілуіне және олардың аймақтағы тіршілік ету ортасының дамуындағы рөліне қоршаған ортаны бақылау шараларын зерттейді. Ауданның литологиясы құмтас, конгломерат, конгломерат құмтасы, тақтатас, саз және балшық тас сияқты шөгінді жыныстардың кең ауқымынан тұрады. Фацияларды талдау алты негізгі шөгінді фациясын анықтады: конгломерат және конгломерат құмтасы (GT), ұсақтан ірі түйіршікті ойпатқа дейінгі көлденең қабатты құмтасы (St), ұсақтан ірі түйіршікті жалпақ қабатты құмтасы (Sh), тақтатас (Fm), балшық тас (Mf) және саз (Cf), олардың әрқайсысы шөгінділердің шөгіндісі кезіндегі әртүрлі экологиялық және биологиялық жағдайларды көрсетеді. Жеті типтік борпылдақ құмтас үлгілерінен алынған елек деректеріне негізделген түйіршік өлшемінің таралуын талдау ұсақтан орташа түйіршіктердің қоспасын, кейде өте ірі түйіршіктерді көрсетеді. Бұрыштан дөңгелектенген түйіршік пішіндері өрілген өзен жүйесіне тән төмен энергиялы шөгінді ортасын көрсетеді. LEICA 2500p жарық поляризациялық микроскопын пайдаланып жүргізілген петрографиялық талдау кварцты (50-60%), дала шпаты (15-16%) және тау жыныстарының сынықтарын (5%) негізгі құрамдас бөліктер ретінде, аз мөлшерде мусковит пен биотитпен анықтады. Бұл минералды құрам, шөгінді сипаттамаларымен қатар, шөгінді көзіне жақындығын көрсетеді, бұл өзен жүйесінің өрілген жүйесінің болуының қосымша дәлелдерін береді. Биологиялық тұрғыдан алғанда, шөгінді орта ерте биота үшін әртүрлі тіршілік ету орталарының дамуына ықпал еткен болуы мүмкін, әсіресе балшық тастар мен тақтатастардың ұсақ түйіршікті шөгінділерінде. Бұл шөгінді орталары микробтық тіршілік пен су организмдерінің ерте формалары үшін әлеуетті субстраттарды қамтамасыз етіп, осы ежелгі өзен жүйесіндегі тіршілік ету ортасының жалпы дамуына ықпал еткен болар еді. Бұл зерттеу қоршаған орта факторларының - шөгінділермен қамтамасыз етудің, су энергиясының және биологиялық әсерлердің Орта Сивалик тобының шөгінді архитектурасын да, тіршілік ету ортасының жағдайларын да қалыптастырудағы маңызды рөлін атап көрсетеді. Бұл өзара әрекеттесулерді түсіну өткен экожүйелерді және Оңтүстік Инд бассейнінде шөгінділер мен тіршілік ету ортасының қалыптасуын басқаратын биологиялық процестерді қалпына келтіру мүмкіндігімізді арттырады.

Түйін сөздер: Петрография, түйіршіктердің мөлшерінің таралуы, фациялардың жіктелуі, шөгінді ортасы, Солтүстік Лаки жотасының ортаңғы Савилик тобы, Оңтүстік Инд бассейні

Влияние факторов окружающей среды на осадконакопление, развитие местообитаний и их значение для палеобиологической реконструкции в Средней группе Сивалик, Южный бассейн Инда

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Аннотация. Средняя группа Сивалик, расположенная недалеко от города Сехван в северной части хребта Лаки Южного бассейна Инда, Синд, Пакистан, простирается на стратиграфическую мощность приблизительно 1055 метров в разрезе Кари Бути (KBS). В данном исследовании изучаются факторы окружающей среды, влияющие на осадконакопление, и их роль в развитии местообитаний в этом регионе. Литологический состав района включает в себя различные осадочные породы, в том числе песчаник, конгломерат, конгломератный песчаник, сланец, глину и аргиллит. Фациальный анализ выявил шесть основных фаций осадконакопления: конгломерат и конгломератный песчаник (GT), мелко- и крупнозернистый косослоистый песчаник (St), мелко- и крупнозернистый плоскослоистый песчаник (Sh), сланец (Fm), аргиллит (Mf) и глина (Cf), каждая из которых отражает различные экологические и биологические условия во время осадконакопления. Анализ гранулометрического состава, основанный на данных ситового анализа семи репрезентативных образцов рыхлого песчаника, показывает смесь мелких и средних зерен с редкими очень крупными зернами. Субоугловая и субокруглая форма зерен указывает на низкоэнергетическую среду осадконакопления, характерную для разветвленной речной системы. Петрографический анализ, проведенный с использованием поляризационного микроскопа LEICA 2500p, выявил кварц (50-60%), полевой шпат (15-16%) и фрагменты горных пород (5%) в качестве основных компонентов, а также незначительное количество мусковита и биотита. Этот минеральный состав, наряду с характеристиками осадконакопления, указывает на близость к источнику осадочного материала, что является дополнительным доказательством наличия разветвленной речной системы. С биологической точки зрения, осадочная среда, вероятно, способствовала развитию различных местообитаний для ранней биоты, особенно в мелкозернистых отложениях аргиллитов и сланцев. Эти условия осадконакопления могли обеспечить потенциальные субстраты для микробной жизни и ранних форм водных организмов, способствуя общему развитию местообитаний в этой древней речной системе. Данное исследование подчеркивает значительную роль факторов окружающей среды - поступления осадочного материала, энергии воды и биологических факторов - в формировании как осадочной архитектуры, так и условий обитания Средней Сиваликской группы. Понимание этих взаимодействий расширяет наши возможности по реконструкции прошлых экосистем и биологических процессов, которые определяли осадконакопление и формирование местообитаний в южной части бассейна Инда.

Ключевые слова: Петрография, гранулометрический состав, категоризация фаций, условия осадконакопления, средняя группа Савилик северного хребта Лаки, южная часть бассейна Инда

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