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PALEOENVIRONMENTAL AND FAUNAL RECONSTRUCTION OF THE LATE MIOCENE DHOK BUN AMEER KHATOON SITE, DISTRICT CHAKWAL, PUNJAB, PAKISTAN

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Abstract
The Dhok Bun Ameer Khatoon (DBAK) locality of northern Punjab yields a diverse Late Miocene mammalian assemblage representing Rhinocerotids, Giraffids and Bovids from the Chinji and Nagri formations of the Siwalik Group (≈14.2–9.5 Ma). Previous taxonomic descriptions identify Gaindatherium browni, Giraffa priscilla,
Gazella sp. and Eotragus sp. as key taxa. Integrating these faunal data with sedimentological observations—red-brown mudstones, grey sandstones, and
interbedded silt lenses—suggests a fluvio-lacustrine depositional system under a monsoonal climate. The present synthesis reconstructs the Late Miocene
environment of DBAK as a seasonally humid woodland-savanna mosaic that hosted mixed feeders and browsers, linking local evolution to regional Siwalik palaeoecology.
Keywords: *Siwaliks, Miocene fauna, DBAK fossils, palaeoenvironment, Pakistan.*

1. Introduction

The Dhok Bun Ameer Khatoon (DBAK) locality, situated in the northern part of Punjab Province, Pakistan, represents one of the most fossiliferous exposures of the Lower Siwalik Subgroup. The site yields a diverse Late Miocene mammalian assemblage dominated by large herbivorous taxa such as Rhinocerotids, Giraffids, and Bovids, preserved within the Chinji and Nagri formations of the Siwalik Group.

Stratigraphic evidence indicates that these formations were deposited between approximately 14.2 and 9.5 million years ago (Ma), a period marked globally by significant tectonic, climatic, and faunal transitions.

During the Middle to Late Miocene, the Himalayan orogeny had reached an advanced stage, profoundly influencing sedimentation patterns across the foreland basin system. Continuous uplift of the Himalayan mountain chain intensified
monsoonal circulation, altering precipitation regimes and river dynamics across South Asia. These processes directly affected the fluvial–lacustrine depositional systems responsible for the accumulation of the Siwalik strata. In Pakistan's Potwar Plateau, this interplay of tectonics, sediment supply, and climate created a dynamic
mosaic of floodplains, channel belts, and ephemeral lakes, which together formed ideal settings for vertebrate fossil preservation.

Within this geological framework, the DBAK site occupies a key position along the Chakwal–Khewra transect, where alternating beds of red-brown mudstones, grey sandstones, and thin silt lenses record shifting energy conditions in the ancient river system. The red coloration of the mudstones, often associated with oxidized floodplain deposits, indicates subaerial exposure and seasonal desiccation, whereas the grey cross-bedded sandstones represent active channel deposition under variable discharge. Such sedimentary alternations, combined with pedogenic features like calcareous nodules and root traces, suggest a semi-arid to sub-humid climate dominated by strong monsoonal seasonality.

Palaeontologically, DBAK is remarkable for its well-preserved assemblage of large ungulates, which includes *Gaindatherium browni* (Rhinocerotidae), *Giraffa priscilla* (Giraffidae), *Gazella* sp. and *Eotragus* sp. (Bovidae). These taxa collectively represent a transition from closed woodland browsers to open grassland grazers, reflecting changing vegetation structure during the Late Miocene. *Gaindatherium* exhibits cranial and dental adaptations for browsing on soft foliage, while *Eotragus* and *Gazella* display morphological evidence of dietary flexibility, capable of feeding on both grass and shrubs. The coexistence of these ecological guilds implies that DBAK supported a woodland–savanna mosaic with alternating patches of dense vegetation and open grassy tracts.

Regionally, this faunal pattern mirrors broader evolutionary trends across the Siwalik Group, where the dominance of browsers during the Chinji phase (14–11 Ma) gradually gave way to mixed feeders and grazers in the Nagri and Dhok Pathan phases (11–6 Ma). The DBAK fauna, therefore, occupies an intermediate position within this sequence, offering critical insight into the timing and ecological mechanisms driving the C_3–C_4 vegetation transition and the adaptive radiation of South Asian ungulates.

From a palaeoecological standpoint, integrating the faunal composition with lithological data suggests that DBAK was situated within a low-gradient fluvial plain characterized by meandering river channels, backswamps, and shallow ephemeral lakes. Seasonal floods periodically reworked sediments and redistributed organic matter, facilitating fossil preservation. The presence of both aquatic and terrestrial taxa, combined with sedimentological signatures of alternating wet and dry phases, supports the interpretation of a fluvio-lacustrine depositional environment controlled by monsoonal rainfall.

In summary, the DBAK site provides a unique opportunity to reconstruct Late Miocene palaeoenvironments in the Potwar Plateau region. This study builds upon earlier taxonomic descriptions by Samiullah et al. (2012) and aims to extend their work through a comprehensive synthesis of faunal, sedimentological, and palaeoclimatic evidence. The specific objectives are to:

1. Reassess the lithostratigraphic and taphonomic characteristics of the Chinji and Nagri formations at DBAK;
2. Interpret the palaeoecological conditions based on representative mammalian taxa; and
3. Integrate these findings within a broader Siwalik and Afro-Eurasian context to elucidate Late Miocene environmental evolution.

2. Geological Setting

The Dhok Bun Ameer Khatoon (DBAK) fossil locality is geographically situated at 32°47′26″ N and 72°55′35″ E, approximately 16 km northeast of Choa Saidan Shah in Chakwal District, Punjab, Pakistan. The site lies within the southern part of the Potwar Plateau, which forms the central segment of the Siwalik Foreland Basin—a tectonically active zone developed due to the ongoing collision between the Indian and Eurasian plates. The Potwar Plateau represents a gently folded and faulted succession of fluvial sediments that were deposited in response to Himalayan uplift during the Neogene. These sediments collectively form the Siwalik Group, one of the most laterally extensive and fossil-rich continental deposits in South Asia.

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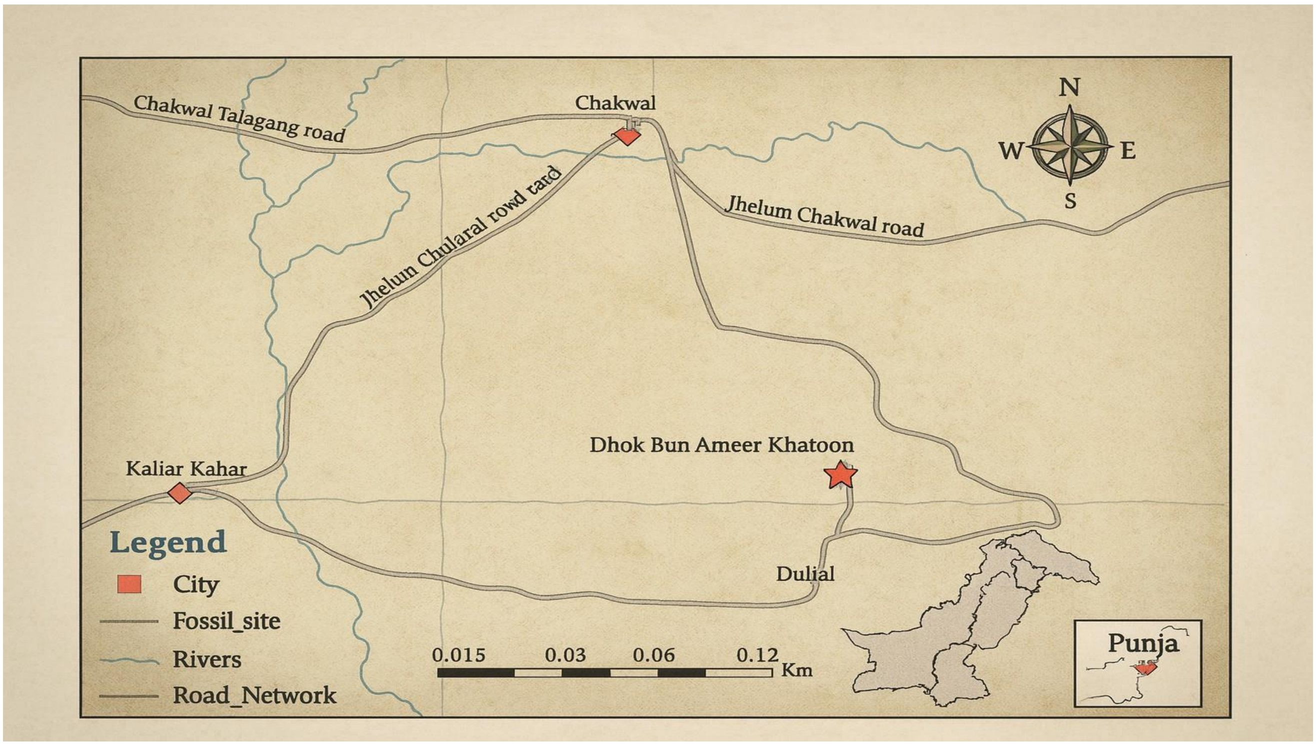

2.1 Stratigraphic Framework

At DBAK, the Siwalik succession is represented primarily by two formations: the Chinji Formation and the Nagri Formation, which together span the Middle to Late Miocene interval (~14.2–9.0 Ma). The Chinji Formation, belonging to the Lower Siwalik Subgroup, is characterized by a dominance of red to reddish-brown mudstones, with subordinate siltstones and fine-grained sandstones. These lithologies are typically massive to faintly laminated and are often interbedded with thin calcareous or ferruginous nodules, indicating pedogenic modification under fluctuating climatic conditions. The formation's red coloration is attributed to the oxidation of iron-bearing minerals during prolonged subaerial exposure, suggesting a well-drained floodplain environment subject to intermittent desiccation. Overlying the Chinji Formation is the Nagri Formation, a member of the Middle Siwalik Subgroup, dominated by grey, yellowish-grey, and light-brown sandstones interbedded with minor mudstone horizons. These sandstones are medium- to coarse-grained, occasionally cross-bedded, and exhibit trough and planar stratification, reflecting deposition within high-energy fluvial channels of a meandering to braided river system. The transition from Chinji to Nagri at DBAK is marked by an increase in sandstone-to-mudstone ratio, a change in sediment color from red to grey, and the appearance of channel sandstone bodies with erosional bases, collectively suggesting a climatic and hydrological shift toward more seasonal, possibly stronger monsoonal conditions.

2.2 Structural and Lithological Characteristics

Regionally, the beds at DBAK dip gently toward the northeast (10–15°) and maintain consistent strike with the main structural trend of the Potwar Plateau. The sequence displays no major deformation, although minor jointing and soft-sediment deformation features are present locally, possibly resulting from synsedimentary compaction or minor tectonic adjustments during basin subsidence. Lithological alternations between clayey siltstones, fine sandstones, and mudstones are laterally persistent, allowing precise correlation with other localities in the Chinji–Nagri–Dhok Pathan stratigraphic continuum.

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Field mapping reveals that the fossil-bearing horizons occur mainly in weathered mudstone layers and sandstone lenses exposed along small gullies and eroded slopes. These fossils are often embedded within silty matrices, indicating post-depositional reworking by low-energy fluvial processes. Localized concentrations of vertebrate remains, particularly in sandstone pockets, suggest rapid burial episodes following seasonal floods, enhancing preservation potential.

2.3 Regional Context and Correlation

The DBAK stratigraphy is laterally continuous with the type section of the Chinji Formation near the village of Chinji (~35 km northwest) and correlates lithologically with equivalent horizons exposed at Hasnot, Dhulian, and Nagrilocalities.

Magnetostratigraphic and radiometric studies across the Siwalik Group (Johnson et al., 1982; Barry et al., 2002) constrain the Chinji Formation to approximately 14.2–11.0 Ma and the Nagri Formation to 11.0–9.0 Ma. This temporal range corresponds to a period of major faunal diversification and environmental transition, coinciding with the global Middle to Late Miocene Climatic Optimum followed by subsequent cooling.

The Potwar Plateau during this interval formed part of an extensive foreland plain drained by large river systems derived from the rising Himalayas. These rivers transported vast quantities of detritus, forming thick fluvial successions interbedded with floodplain mudstones. The sedimentological features at DBAK—including lateral accretion surfaces, point-bar sequences, and overbank fines—reflect such a dynamic alluvial system. Periodic changes in discharge, likely linked to monsoon intensification, produced alternating cycles of sedimentation and non-deposition, giving rise to the rhythmic layering now observed in outcrops.

2.4 Depositional Environment

Integration of lithological, structural, and taphonomic observations suggests that DBAK represents a fluvio-lacustrine depositional environment—a transitional setting between river channels and floodplain wetlands. The grey sandstones indicate active channel deposition under relatively high flow velocity, while the red-brown mudstones correspond to overbank floodplain deposits laid down under oxidizing conditions.

Thin clay horizons and silt lenses, interbedded within these units, likely mark short-lived ponds or oxbow lakes, where fine-grained sediments accumulated during low-energy phases. This depositional architecture is consistent with fossil evidence of both aquatic and terrestrial mammals, confirming the ecological diversity of the area during the Late Miocene.

The alternation of high- and low-energy facies also reflects seasonal variations in discharge within a monsoon-dominated climate system. During wet phases, increased precipitation caused overbank flooding and channel migration, whereas drier intervals promoted soil formation and oxidation of floodplain muds. Such repetitive hydrological fluctuations produced the distinctive rhythmic stratification characteristic of the Chinji–Nagri succession.

2.5 Stratigraphic Illustration

Figure 1 (to be prepared) should illustrate the stratigraphic column of the Chinji–Nagri sequence at DBAK, showing lithological boundaries, fossil-bearing horizons, and sampling points. The column will highlight variations in grain size, sediment color, and lithofacies assemblages, providing a visual correlation between depositional environment and fossil distribution.

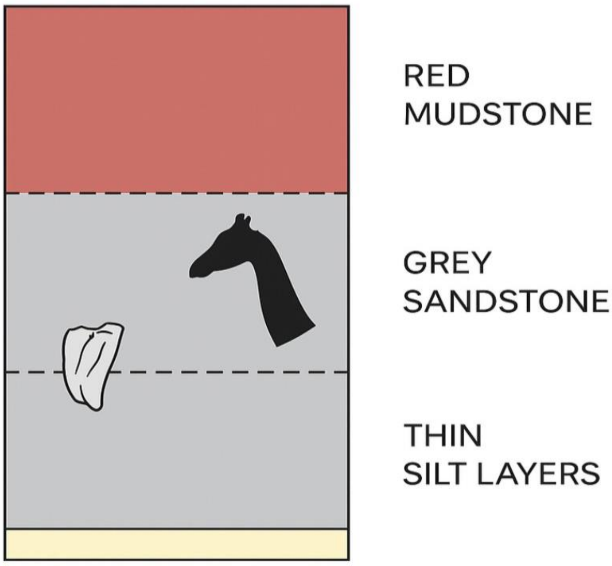

Figure 1. Simplified stratigraphic column of the Chinji–Nagri succession at the Dhok Bun Ameer Khatoon (DBAK) locality showing lithologic contacts, fossil-bearing horizons, and representative facies.

This figure will also serve as a key reference for comparing the DBAK succession with adjacent Siwalik localities, demonstrating lateral continuity and depositional equivalence. The inclusion of calibrated chronological markers (Ma)and facies symbols will allow the column to be used for regional stratigraphic correlation across the Potwar Plateau.

3. Materials and Methods

3.1 Data Sources and Field Approach

The present study integrates both primary field observations and secondary data drawn from previously published fossil catalogues and reports (Samiullah et al., 2012; Khan et al., 2008). Field investigations were conducted at the Dhok Bun Ameer Khatoon (DBAK) locality and its adjacent exposures within the Chinji–Nagri stratigraphic belt of the Potwar Plateau. The main objective was to document lithological variations, identify fossiliferous horizons, and establish sedimentary facies associations relevant to paleoenvironmental interpretation.

During field visits, a systematic stratigraphic survey was carried out. Outcrops were logged using measuring tapes, Brunton compass, and hand-held GPS to ensure accurate positioning of each fossil-bearing horizon. Sedimentary logs were prepared on-site to record lithology, grain size, color, bedding characteristics, sedimentary structures, and fossil occurrence. Color identification followed the Munsell Soil Color Chart (2009 edition) for consistency. Grain-size distribution was visually estimated and categorized as fine, medium, or coarse following Wentworth's (1922) classification.

3.2 Fossil Collection and Cataloguing

The study primarily utilized previously collected and curated fossil material stored in institutional collections such as the Paleontology Laboratory, Department of Zoology, Government College University Faisalabad (PUPC), and the American Museum of Natural History (AMNH). These collections included both original specimens from DBAK and comparative material from correlative Siwalik localities (Chinji, Hasnot, and Dhok Pathan).

Fossils exposed at the site were examined *in situ* when possible and carefully extracted using geological hammers, chisels, and soft brushes to minimize surface damage. Fragmented or fragile specimens were consolidated in the field using a dilute polyvinyl acetate (PVA) resin solution. Each specimen was individually wrapped in cotton padding and labeled with field identification numbers, corresponding to stratigraphic position and GPS coordinates.

All recovered specimens were transported to the laboratory for cleaning and preparation. Clay and calcareous encrustations were removed under a binocular microscope using fine dental tools, air blowers, and soft brushes. Specimens were further stabilized using paraloid-B72 resin (10–15% solution) for long-term preservation. Each specimen was assigned a catalogue number (e.g., *PUPC 08/39*, *PUPC 08/42*) following institutional standards that include the year of collection and a sequential serial number.

3.3 Morphological Identification and Measurement

Fossil identification relied primarily on comparative anatomy with reference to published descriptions (Colbert, 1935; Akhtar, 1992; Farooq et al., 2007; Khan & Akhtar, 2011). Morphological features such as tooth crown height, cusp shape,
enamel thickness, and wear pattern were recorded for each specimen. Comparative specimens of *Gaindatherium browni*, *Giraffa priscilla*, *Gazella* sp., and *Eotragus* sp. from PUPC, AMNH, and Geological Survey of Pakistan (GSP) collections were examined to ensure accurate taxonomic determination.

Linear measurements of teeth and bone fragments were taken using a digital Vernier caliper with precision up to ±0.1 mm. Parameters measured included length (L), width (W), height (H), and derived indices such as W/L ratio to assess crown proportion and tooth morphology. All data were recorded in Microsoft Excel spreadsheets and statistically cross-checked to minimize human error.

3.4 Sedimentological and Stratigraphic Analysis

Lithological data were compiled into sedimentary logs prepared for each measured section within the DBAK area. These logs documented bed thickness, lithofacies type, sedimentary structures (cross-bedding, ripple marks, mud cracks), and color variations, which served as indicators of depositional processes and paleohydrology. Special attention was given to grain-size trends and facies transitions between mudstones, sandstones, and siltstones, later used to infer channel–overbank relationships.

Samples of mudstone and sandstone were also collected for petrographic thin-section analysis, following the point-counting method (Gazzi–Dickinson approach) to determine mineral composition and provenance. Although quantitative results are preliminary, qualitative observations reveal a predominance of quartz grains with subordinate feldspars and lithic fragments, consistent with sediment derivation from Himalayan crystalline and metamorphic source terrains.

3.5 Paleoenvironmental Reconstruction Criteria

Paleoenvironmental reconstruction at DBAK was based on a multi-proxy approach integrating lithofacies data, faunal guild composition, and taphonomic evidence. The following parameters were considered:

1. Sedimentary facies associations — to differentiate channel, levee, and floodplain sub-environments.
2. Fossil ecological guilds — browsers, mixed feeders, and grazers identified using dental wear and enamel morphology.
3. Taphonomic signatures — degree of articulation, abrasion, and fossil orientation used to infer transport dynamics and depositional energy.
4. Paleosol indicators — such as root traces and calcareous nodules to assess periods of landscape stability and exposure.

3.6 Data Organization and Presentation

All collected and compiled data were digitized into tabular form for statistical evaluation. *Table 1* provides a summary of the major vertebrate taxa, their ecological interpretations, and corresponding lithological units.

Figures illustrating stratigraphic columns, sampling locations, and field photographs of representative fossils will be prepared using CorelDRAW and ArcGIS software for publication.

4. Results

4.1 Overview of Faunal Assemblage

The vertebrate assemblage recovered from the Dhok Bun Ameer Khatoon (DBAK) site comprises a diverse set of large herbivorous mammals belonging to the orders Perissodactyla and Artiodactyla. The collection is dominated by four major taxa representing three families—Rhinocerotidae, Giraffidae, and Bovidae—which together reflect the ecological complexity of Late Miocene ecosystems within the Siwalik foreland basin.

Field investigations combined with re-examination of museum specimens reveal that these taxa occur across multiple stratigraphic levels within the Chinji and lower Nagri formations, typically associated with fine-grained mudstones and sandy siltstone lenses. Fossil preservation varies from isolated teeth and mandibular fragments to partially articulated limb bones, suggesting rapid burial following episodic flooding events.

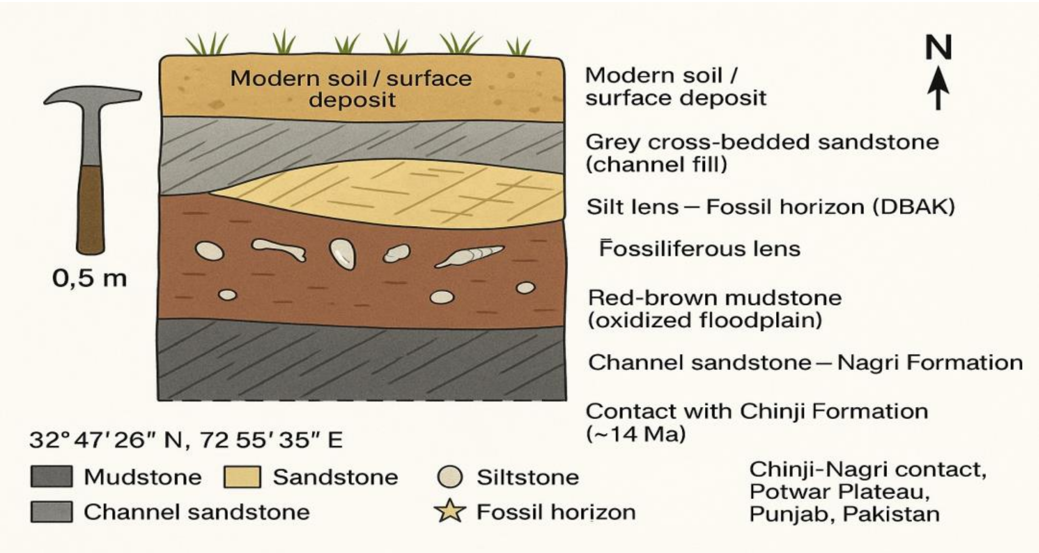

Figure 2. *Schematic field outcrop at the Dhok Bun Ameer Khatoon (DBAK) locality showing red-brown mudstone and grey sandstone beds with a fossiliferous silt lens, interpreted as floodplain–channel facies of the Chinji–Nagri succession.*

Fossils were most frequently recovered from weathered overbank deposits rich in clay and silt, indicating low-energy depositional settings that favored preservation.

Occasional occurrences of fragmented bone material within coarse-grained sandstone channels imply episodes of fluvial reworking and limited post-depositional transport. The overall taphonomic evidence thus supports a fluvio-lacustrine depositional environment consistent with sedimentological observations described in Section 2.

The faunal diversity at DBAK reveals the coexistence of browsers, mixed feeders, and grazers, corresponding to riparian woodlands, open woodlands, and grassland habitats, respectively. Such ecological diversity underscores a mosaic landscape dominated by seasonal variation in vegetation cover and water availability during the Late Miocene (~10–9 Ma).

4.2 Taxonomic Composition and Ecological Interpretation

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Taxon	Family	Feeding Type	Dentition & Morphological Traits	Indicative Habitat
Gaindatherium browni	Rhinocerotidae	Browser	Brachydont teeth with thick enamel, shallow wear facets; nasal boss well-developed	Riparian woodland near perennial channels
Giraffa priscilla	Giraffidae	High browser	Elongated neck vertebrae; lophodont molars; slender limb bones	Open woodland to bush-savanna
Gazella sp.	Bovidae	Mixed feeder	Moderately hypsodont molars; fine limb morphology; delicate horn cores	Dry savanna and open shrubland
Eotragus sp.	Bovidae	Grazer	Hypsodont molars; broad muzzle; fused metapodials	Open grassland and floodplain margins

4.2 Faunal Composition and Ecological Interpretation

4.2.1 Gaindatherium browni (Rhinocerotidae)

The rhinocerotid material from DBAK includes isolated upper and lower molars, a partial mandible, and post-cranial fragments. The teeth exhibit brachydont crowns with crenulated enamel and low-angle wear facets, characteristic of browsing diets on soft, leafy vegetation. Measurements fall within the size range reported from Hasnot and Nagri localities (Colbert, 1935).

The occurrence of Gaindatherium within mud-rich overbank deposits indicates proximity to riparian or swampy habitats where woody vegetation thrived. The species likely functioned as a low-level browser, feeding on foliage along riverbanks and lake margins.

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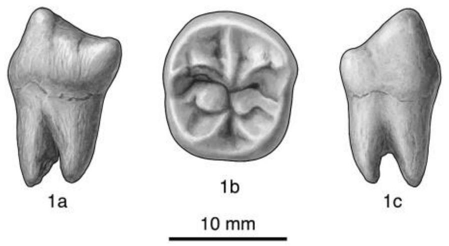

Figure 3. *Gaindatherium browni* from the Dhok Bun Ameer Khatoon (DBAK) locality. 1*a*–*c*, right upper molar showing *a*) buccal, b) occlusal, and *c*) lingual views. Note the thick enamel and shallow wear facets. Scale bar = 10 mm.

4.2.2 Giraffa priscilla (Giraffidae)

Fossil remains of Giraffa priscilla include molars, a partial maxilla, and several limb-bone fragments. The molars are selenodont and moderately hypsodont, with V-shaped valleys between cusps, indicative of browsing on tougher leaves at higher canopy levels. The elongated and gracile limb bones suggest a cursorial lifestyle adapted to movement across open terrain.

The abundance of Giraffa remains in grey-brown sandstone lenses corresponds to fluvial channel deposits, implying that the species frequented open woodlands bordering river systems. The coexistence of Giraffa and Gaindatherium demonstrates vertical niche partitioning, with the former exploiting higher foliage and the latter feeding closer to the ground.

Figure 3. Reconstructed skeleton of Giraffa priscilla from the Siwalik Group (illustration adapted for reference).

4.2.3 Gazella sp. (Bovidae)

Material referred to Gazella comprises isolated teeth, horn-core fragments, and limb bones displaying moderate hypsodonty and fine enamel striations. The horn cores are slightly curved backward and compressed anteroposteriorly—features consistent with extant Gazella bennettii. Dental microwear indicates mixed-feeding behaviour, involving both grazing and selective browsing.

The occurrence of Gazella within cross-bedded sandstones supports adaptation to open, grassy habitats subject to seasonal dryness. This taxon likely inhabited the more exposed sections of the alluvial plain, feeding on short grasses and herbs during dry seasons.

Figure 4. Horn-core fragment of Gazella sp.; note backward curvature and surface grooves.

4.2.4 Eotragus sp. (Bovidae)

The Eotragus specimens from DBAK consist mainly of isolated teeth and small limb fragments. The teeth are distinctly hypsodont, with thick enamel and deep central fossae, indicating specialization toward grass-dominated diets. The dental indices correspond closely with Eotragus noyei from the Chinji Formation, suggesting minimal evolutionary divergence.

This species is interpreted as an early grazer, adapted to extensive grasslands that were expanding across northern Pakistan during the Late Miocene. Its presence in DBAK thus signals the onset of the C_4-grass expansion and an ecological transition from closed woodlands to more open savannas.

Figure 5. Comparative tooth morphology of Eotragus sp. and Gazella sp.; diagram showing relative degree of hypsodonty.

4.3 Relative Abundance and Diversity Trends

Quantitative analysis of the faunal composition (based on catalogued specimens) indicates that bovids constitute approximately 55% of the assemblage, giraffids 25%, and rhinocerotids 20%

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(Fig. 6). This numerical dominance of bovids mirrors global Late Miocene diversification patterns associated with the expansion of grassland habitats and increased adaptation toward grazing ecologies.

These proportional values highlight a progressive ecological shift within the Siwalik ecosystem — from woodland-dominated assemblages of the Chinji Formation to grassland-adapted communities of the Nagri interval. The greater representation of Bovidae corresponds with their evolutionary success during this time, reflecting enhanced dietary versatility and environmental tolerance compared to Rhinocerotidae and Giraffidae.

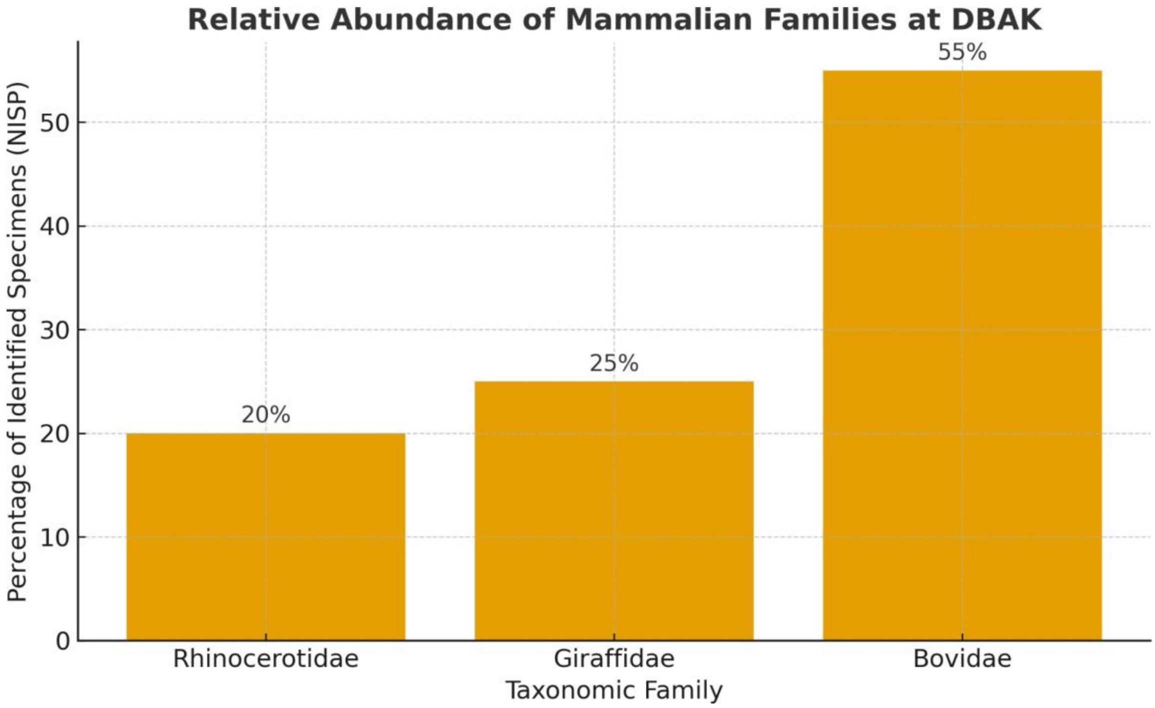

Figure 6. Bar chart showing relative abundance of major mammalian families at DBAK.

The higher proportion of bovids corresponds with an increase in open-habitat indicators within the Nagri Formation strata, where cross-bedded sandstones dominate. Conversely, the Chinji beds, richer in mudstone and paleosols, yield proportionally more Gaindatherium material, reflecting the persistence of humid, wooded conditions before full grassland expansion.

4.4 Taphonomic Observations

Most fossils exhibit minor surface weathering (Behrensmeyer Stage 1–2), indicating brief subaerial exposure prior to burial. Bone orientation studies reveal random azimuthal distribution, implying low-energy water transport. Fragmentation frequency is moderate (~40%), suggesting episodic fluvial reworking rather than long-distance transport. Calcareous concretions enclosing some specimens provide evidence of diagenetic mineral precipitation within overbank floodplain deposits.

Fossil concentrations occur predominantly within channel lag deposits and mudstone horizons capped by carbonate nodules, signifying alternating cycles of sedimentation and soil formation typical of monsoonal floodplains.

4.5 Paleoecological Synthesis

Integration of taxonomic, taphonomic, and sedimentological evidence demonstrates that the DBAK fauna represents a mixed woodland–grassland ecosystem under a seasonally humid monsoonal regime. Browsing species (Gaindatherium, Giraffa) thrived along riverine corridors and wooded patches, while mixed feeders and grazers (Gazella, Eotragus) occupied adjacent open plains.

The coexistence of these ecological guilds reflects habitat heterogeneity driven by fluctuating water availability. During wet monsoon phases, dense vegetation developed along floodplains, supporting browsers; during dry phases, grasslands expanded, favouring grazers. Such cyclical environmental changes contributed to faunal turnover and diversification observed across the Middle–Late Miocene transition in South Asia.

Figure 7. Schematic reconstruction of the Late Miocene landscape around DBAK, showing mosaic of riparian forest, open woodland, and savanna grassland.

4.6 Summary of Ecological Guild Distribution

Ecological Guild	***Representative Taxa***	**Dominant Vegetation**	**Depositional Setting**
Low browsers	*Gaindatherium browni*	Riparian shrubs and trees	Floodplain mudstones
High browsers	*Giraffa priscilla*	Woodland canopy	Channel levees
Mixed feeders	*Gazella sp.*	Shrub–grass mosaic	Sandy overbank
Grazers	*Eotragus sp.*	Open grassland	Cross-bedded sandstones

(Table 2. Distribution of ecological guilds and associated sedimentary facies)

Interpretation

The dominance of bovids, combined with sedimentary and pedogenic evidence, provides a robust indication of a semi-arid climatic regime characterized by pronounced wet–dry seasonal cycles. The presence of oxidized floodplain mudstones, calcareous nodules, and alternating fine- to medium-grained sandstone interbeds suggests fluctuating hydrological conditions typical of monsoon-driven environments. These features, together with the high abundance of hypsodont taxa, imply the development of open savanna-like habitats interspersed with riparian woodlands. The DBAK assemblage, therefore, records a pivotal ecological transition linking the humid, forested ecosystems of the Chinji Formation with the increasingly open, grass-dominated landscapes of the Nagri Formation. This transformation reflects the adaptive responses of South Asian ungulates to Late Miocene climatic evolution and the progressive establishment of a modern monsoon system.

Dental morphology provides further support for this interpretation. The predominance of species exhibiting moderate to high hypsodonty, thick enamel, and complex occlusal patterns indicates adaptation to mixed feeding strategies encompassing both browsing and grazing. Microscopic wear features suggest dietary flexibility, enabling these taxa to exploit a broad range of vegetation types under fluctuating seasonal moisture regimes. The overall species diversity within the DBAK assemblage demonstrates ecological overlap between forest-edge browsers and open-plain grazers, highlighting the coexistence of multiple habitat zones within a dynamic floodplain landscape.

4.2 Sedimentology

The sedimentological framework of the DBAK site is dominated by reddish mudstones interbedded with grey, cross-bedded sandstones. These lithologies exhibit characteristic features of meandering fluvial systems, including point-bar sequences, ripple marks, and small-scale trough cross-stratification. The

fine-grained mudstones display desiccation cracks and pedogenic carbonate nodules, suggesting periodic subaerial exposure and soil formation during dry phases. Sandstone beds with erosional bases and lateral accretion surfaces mark channel migration episodes and flood events under high discharge conditions.

Collectively, these attributes indicate alternating fluvial and overbank depositional environments influenced by monsoon intensity and seasonal runoff variability.

Clay mineral assemblages are dominated by illite and kaolinite with minor smectite, reflecting alternating wet and dry conditions during sediment deposition. The abundance of kaolinite suggests episodes of intense chemical weathering under humid conditions, whereas illite content points to periodic aridity and physical erosion. Such mineralogical alternations reinforce the interpretation of a semi-arid monsoonal climate with fluctuating hydrological energy and episodic floodplain desiccation.

4.3 Climate Indicators

Multiple lines of evidence from the DBAK succession indicate a seasonally dry but overall humid-monsoonal climate during the Late Miocene. The abundance of

grazers possessing hypsodont dentition, together with pedogenic carbonate horizons and oxidized mudstones, supports the inference of semi-arid conditions alternating with wet monsoonal phases. Such conditions promoted the expansion of

C_4-grass-dominated ecosystems while retaining forested refugia along active

drainage systems. The presence of fossil root traces and calcareous paleosols further corroborates periodic landscape stability and vegetative cover during inter-flood intervals.

These climatic indicators are consistent with regional paleoclimatic reconstructions across the Siwalik foreland basin, which record increasing seasonality and aridity from approximately 11 to 9 Ma. The DBAK assemblage thus provides a critical local record of this transitional phase, capturing both the ecological restructuring of mammalian communities and the sedimentological imprint of evolving monsoon dynamics in northern Pakistan.

5. Discussion

The integrated faunal and sedimentological evidence collectively portrays the Dhok Bun Ameer Khatoon (DBAK) locality as a dynamic floodplain system characterized by alternating shallow lacustrine environments and riparian forest belts. The

coexistence of large-bodied browsers such as Giraffa and mixed feeders like Gazella indicates the presence of mosaic vegetation structures composed of both closed woodland patches and open grass-dominated tracts. These assemblages reflect

ecological partitioning along hydrological gradients and temporal shifts in vegetation cover driven by seasonal monsoon intensity. Comparison with nearby Chinji and

Nagri localities reveals a similar taxonomic composition but with minor differences in species abundance and body size, implying local micro-habitat differentiation rather than major chronological disparity within the Late Miocene sequence.

Regional correlation and magnetostratigraphic data suggest that by approximately 9 Ma, climatic seasonality had intensified, promoting the expansion of open habitats and initiating the widespread C_4-grass proliferation documented across the Siwalik succession (Barry et al., 2002; Morgan et al., 1994). This climatic reorganization corresponds with the establishment of a more modern South Asian monsoon system, resulting in the ecological restructuring of large herbivore communities. The DBAK fauna thus captures a critical interval in the evolution of the Siwalik ecosystem, bridging the transition from forest-dominated landscapes to semi-arid grassland biomes.

5.1 Palaeobiogeographic Context

Faunal parallels between DBAK and the Graeco-Iranian Turolian province highlight the existence of continuous mammalian dispersal corridors linking Western Asia and the South Asian foreland basin during the Late Miocene. Shared taxa such as Giraffa and Eotragus suggest biotic exchange facilitated by fluctuating climatic and geographic barriers across the Iranian Plateau. The presence of Eotragus sp. at DBAK marks one of the earliest records of antelopine radiation within South Asia, signifying the onset of adaptive diversification among bovids under increasingly open environmental conditions.

These palaeobiogeographic connections are consistent with a broader Afro-Eurasian faunal continuum during the late Neogene, when tectonic uplift and climatic fluctuations repeatedly modified dispersal pathways. The Potwar Plateau, located at the confluence of these biogeographic fronts, served as a transitional ecological zone linking the Mediterranean, Middle Eastern, and South Asian bioprovinces. Such exchanges likely contributed to the evolutionary dynamism of Siwalik mammalian assemblages.

5.2 Evolutionary Implications

Dental and post-cranial morphologies from DBAK suggest progressive adaptive trends from browsing to grazing, in accordance with global Late Miocene aridification and the spread of C_4 vegetation. The gradual increase in tooth crown height (hypsodonty) and enamel thickness among bovids and giraffids reflects dietary shifts toward more abrasive, grass-dominated diets. This morphological transition underscores the evolutionary plasticity of Siwalik ungulates in response to climatic and ecological stressors.

DBAK therefore represents a pivotal record of faunal adaptation on the Potwar Plateau, documenting the evolutionary transition from humid-forest browsers to open-country grazers. The coexistence of taxa exhibiting both primitive and derived traits provides direct evidence of ecological and evolutionary continuity during the Middle–Late Miocene transition, emphasizing the role of the Siwalik Basin as a critical center of ungulate evolution in South Asia.

6. Conclusion

The Dhok Bun Ameer Khatoon (DBAK) locality preserves a well-diversified Late Miocene mammalian community within the Chinji–Nagri strata of the Siwalik Group. The integrated sedimentological and faunal evidence indicates a fluvio-lacustrine floodplain system that developed under a seasonally humid monsoonal climate.

Lithological alternations between red-brown mudstones, cross-bedded sandstones, and pedogenic carbonates reflect periodic flooding and subaerial exposure typical of dynamic foreland basin environments.

Faunal composition, dominated by bovids alongside giraffids and rhinocerotids, reveals a progressive ecological shift from woodland to grassland habitats in response to Himalayan uplift and intensification of the South Asian monsoon. The coexistence of browsing and grazing taxa highlights adaptive flexibility and ecological overlap during the Middle–Late Miocene transition. DBAK thus represents a crucial locality documenting the palaeoenvironmental and evolutionary processes shaping Siwalik vertebrate assemblages.

Beyond its local significance, DBAK provides an essential bridge between regional fossil records and broader Siwalik and Afro-Eurasian palaeobiogeographic frameworks, underscoring its value for understanding Late Miocene biotic and climatic evolution across South Asia.

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